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Preface

Paper: A major commodity in our life.

During its long history, paper has changed from a rare artisan material to a commodity product, with high practical value in communication and in educational, artistic, hygienic, sanitary, and technical applications. Today, nobody can imagine a world without paper. A large variety of paper grades are produced to suit the special requirements of each application: graphic paper grades, packaging papers and board, hygienic papers, and speciality paper grades. Paper can be impregnated, coated, laminated, creped, molded and so on. Paper products embellish our homes, and sanitary products made of paper ease our daily life. An easier life is also more likely with a sufficient number of banknotes in the briefcase. Packaging papers and board grades support supermarket logistics and product presentations. Computer printouts and other graphic papers such as newspapers, magazines, and books accompany us through our life. Even today, in our digital world paper is a reliable means of long-time documentation and data preservation.

A concise description of the fascinating art and technology of papermaking is given in this second edition of this handbook. It also includes the further use of paper and board in converting and printing. So a comprehensive view on the technical, economic, ecologic and social background of paper and board is provided. In-depth knowledge is a prerequisite for evaluating the optimum choices needed for the efficient production of paper and board. Converters and final customers need to be considered. Converters also have to build up some knowledge in papermaking, just as the papermaker needs to appreciate the conversion processes more. Waste handling and energy supply are even more in focus today. Economic success now requires more appreciation of all these sectors.

The first edition of this handbook found high interest worldwide. It has been widely accepted used in offices, universities, training, and as lecturing material, and general resource. The second edition is an updated and largely extended version and provides both the technical and technological state of the art in paper making in a concise form and as important information on paper-related technologies.

More than 60 authors have contributed to this project. They are all professionals from practice, companies, institutes, and universities from several countries—well-known experts or young specialists—each of them with detailed knowledge in their areas. The variety of their points of view is certainly one of the

advantages of this book. My thanks go to these colleagues for their cooperation in sharing their knowledge in spite of their daily work load, and to the individual companies for providing information material. All these efforts resulted in the second edition of the “Handbook of Paper and Board” which is thought to provide professionals in the field, papermakers, converters and printers, as well as lay readers, students, politicians, and other interested people with most recent information on the state of the art of all the techniques and aspects involved in paper making and converting.

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1

Introduction

1.1

Paper and Board Today

Herbert Holik

The history of paper is also the history of human culture and civilization. The Egyptians, Greeks, and Romans wrote on “papyrus,” a paperlike material. The kind of paper used now was first developed and used in China. Paper was the most important carrier of information in the past. It was only with increasing paper production that the transfer of knowledge, education, art, and information to a larger part of society became possible. With paper, emperors were able to administrate large empires more easily. In former times, paper was a valuable product, and papermaking an art – an art that was often kept secret because of the outstanding advantages of the product.

The worldwide consumption of paper will further increase. Owing to CEPI (Confederation of European Paper Industry), the paper consumption will increase from about 400 million t year⁻¹ in 2010 to about 530 million t year⁻¹ in 2020 and 605 million t year⁻¹ in 230. The growth in individual countries can be mostly related to their increase in gross national product and to their growth in population. So the consumption and production in countries such as China or India have increased over recent years on a large scale. In mature markets such as Central Europe, Japan, and North America production and consumption have stagnated or even decreased.

The ratio of the worldwide consumption of the different paper and board grades has changed in the past and will change in the future according to technical, economical, and social evolution and developments in the individual countries and in the world as a whole. Packaging grades have increased, graphic paper grades have stagnated, and newsprint consumption has declined. The pressure from increased sales of industrial products, the growth in internet shopping, and the sharp upward demand for small packaged foods have all increased the demand on packaging materials. The newsprint sector has suffered from the big increase in internet and phone download users as these technologies impact on the need for the printed page. The demand for copy paper and home printing papers for holding as “hard

copy” is still important for easy access of preselected information. The impact of e-book on paper usage has yet to be felt.

The paper and board market is global, and so is the paper industry where an evident consolidation has occurred over the last decades. The concentration of companies has continued under globalization, and the economic ups and downs have affected rising markets and various geographical areas unevenly. The investment costs for new production facilities are high. The capital demand for a new mill lies in the order of magnitude of more than €500 million. The most recent new paper and board mills were mainly installed in the Far East. These high-tech mills show the distinct progress in papermaking, in both technique and technology and new world records in production and machine speed have been set. So it seems that the paper comes back to its roots: China has developed in the last few years to the largest paper and board producer in the world.

The furnish used in paper and board production worldwide are secondary fibers from recovered paper, primary fibers (chemical pulp, mechanical pulp), pigments, and chemical additives. Paper is mainly based on fibers from cultured woods, and is a renewable and recyclable raw material as its strength is given by natural bonding between the individual fibers, which is then loosened by water during recycling.

In former times, with mainly virgin fiber consumption, a paper mill was located close to the wood (and the water and energy resources). This is still true for regions of Portugal, Spain, and Brazil with eucalyptus plantations used mainly for copy or similar paper grades. One result of the increased use of recovered paper is that certain new “green field” paper mills are established currently in the vicinity of highly populated areas to have easier access to recovered paper resources and to be closer to the market.

Increased paper recycling and sustained foresting (“planting and harvesting”) as well as use of the whole tree help to preserve the wood resources of the earth. Owing to the need of wood fiber resources, the paper industry competes strongly with the building and furniture industries, and also with the energy sector using fibers for biofuel production and solid-fuel heating. There is a strong need to optimize the wood resource and use the best fiber for paper, building, and furniture products first, before using the waste and recycled material as a fuel. This way has proved successful in the oil and plastic products over several decades. The paper industry has started to adopt this to a greater extent. It also makes even more use of cogeneration and mill integration. So paper may play a new, promising role in the discussion about CO₂ footprint.

The paper industry has steadily improved its standards in complying with environmental demands as related to water consumption and water effluents, energy consumption, and primary (and secondary) fiber consumption. These standards have to be maintained and even improved in the future because of further increasing paper and board consumption and limited fiber resources.

Papermaking has changed from an “art” to an industry with high-tech production facilities and with a scientific approach making use of new technologies by adopting them to their special needs. At present papermaking is a mature technology, and

now more focus must be laid on reliable energy supply, waste handling and use, as well as on the optimum integration of all of the subsystems in the mill.

At present high quality demands are placed on the paper and board properties and their uniformity. The functionality of paper as an information carrier is more pronounced and requires high surface quality, for example, for new printing technologies and for more radio-frequency identification (RFID) application. Only high-quality products – at low price – satisfy the expectations of the customer and the end user.

As paper is a commodity, low-cost production is mandatory. One of the challenges is, for example, the huge production quantities per unit with machine downtime costs in the calculation of the paper mill which ranges from about €10000 to 40 000 h⁻¹. So the downtime should be kept as short as possible and unplanned downtime must be avoided. This calls for predictive maintenance and computerized maintenance management systems.

As the fiber raw material is the main cost factor in paper production, the need is for lowest possible basis weight and as much filler as acceptable. Their increased retention during web forming may be supported by nanotechnology and thus further improve paper quality as well. For the same economic reason, recovered paper has become the main fiber stock material worldwide and its proportion will increase further. Several grades, such as newsprint and many packaging and board grades, can be – and are – entirely based on recycled fibers. Recovered fibers must be used in paper grades similar to the recovered paper grade; downgrading of recovered paper (high-quality fibers for lower-quality paper products) is no longer economically or ecologically acceptable. Hence, in some places, recovered paper is presorted automatically, for example, into deinking stock, warehouse furnish, and mixed qualities.

The electronic media are not only a competition to paper as an information carrier but also a challenge in the use of recovered paper as the water-based printing inks degrade the recovered paper. Paper recycling for food packaging grades at present can be threatened by migrating substances. Therefore, all partners in the whole papermaking chain “from cradle to cradle” have to contribute in order to establish and to maintain a sound cycle.

1.2

Paper and Board Manufacturing – an Overview

Herbert Holik

Modern paper mills are large industrial units, one of the latest installations of a paper production line having a maximum production capacity of 4500 t day⁻¹. This involves many demanding actions, for example, in logistics, for raw material supply and shipment of the finished product or to ensure continuous production. A paper production line usually comprises the stock preparation, the paper machine, waste and wastewater handling, and energy generation. Several production lines can be installed in a paper mill.

The furnish components used in paper and board production are secondary and primary fibers, pigments, and chemical additives. Their approximate ratio is

Table 1.1 Furnish components used in paper and board production and their typical ratio in CEPI countries.

Raw material		Approximate mass ratio (%)
Fiber material	Secondary fibers	40
	Chemical pulp	40
	Mechanical pulp	10
Minerals	Coating pigments	4
	Fillers	3
Chemical additives	All kinds	3

Based on CEPI statistics and Sections 2.1.3 and 26.2.

listed in Table 1.1. The ratio largely varies from country to country and depends on the produced grades. The paper strength results from the hydrogen bonding between the individual fibers (without any artificial gluing). Only in certain cases is the strength enhanced by the addition of starch or wet strength additives. The hydrogen bonds are loosened by rewetting the paper, which allows easy recycling.

Papermaking at present includes, in principle, the same process steps as applied for centuries: preparation of the fiber material, sheet or web forming, pressing, drying, sizing, and smoothing. However, in the last two centuries, much of the detail has changed. Each process step has undergone – and still undergoes at present – intensive research and development work to meet economic, ecological, and quality requirements. All links in the chain between fiber and end user contribute to this progress. The chain does not only include the paper producing industry itself and its suppliers such as the machine and chemical industry but also the paper industry's customers and related industries, for example, printing houses, printing ink and printing machine suppliers, the manufacturers of corrugated board, and other converters.

R&D focus in papermaking is and has been on economic and environmental aspects such as

- reduction in consumption of raw material, energy, and water (Figure 1.1) as well as noise reduction;
- high machine runnability and long lifetime of machinery and its components;
- improvement in paper and board quality with respect to improvement in converting quality.

This has led to results of high practical value such as

- better understanding and consequent control of the whole process and quality parameters in a narrow band;
- reduction in fiber consumption by reducing basis weight at the same quality level and practical value;
- increased ratio of recycled fibers in graphic paper production, with up to 100% for newsprint and a growing ratio in high grades such as supercalendered (SC) and lightweight coated (LWC) papers;

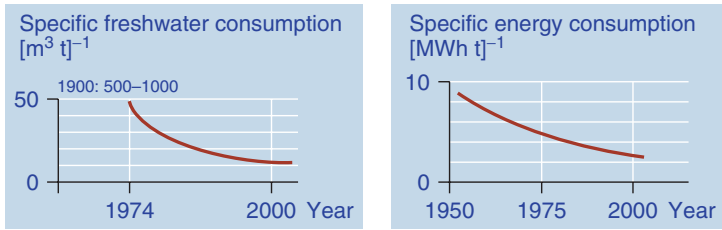


Figure 1.1 Reduction in specific energy and freshwater consumption in the last decades (Germany) [1].

- fillers and coatings replacing part of the expensive fiber material and improving quality;
- new coating and calendering technologies;
- higher safety in Yankee dryer and suction press roll operations;
- new methods of material design for fighting wear of machine components;
- further closing of water circuits;
- energetical use of waste;
- minimum number of personnel involved in the paper and board production process.

R&D work has been supported by modern tools and sciences in many areas, such as

- process analysis and simulation as well as advanced measuring, visualization, and control techniques;
- chemistry and materials sciences;
- finite element method (FEM) and computational fluid dynamics (CFD).

The papermaking process (Figure 1.2) starts with the delivery of the raw material of the stock components. These are

- fibers such as
 - recovered paper in bales or as loose material;
 - virgin pulps (chemical or mechanical), which are usually supplied in bales or, in special cases, as a suspension when both pulp and paper are manufactured at the same location (integrated mill).
- fillers and pigments
- chemical additives
- coating colors when coated paper is produced.

All these components have to be adequately prepared for optimum use in the papermaking process steps. The additives may be delivered ready for use or may have to be finally prepared according to the requirements in the mill.

Fiber stock preparation includes several unit operations depending on the furnish and the purpose. Stock preparation of virgin fiber pulp needs less machinery and energy than the preparation of recovered paper which, however, is the cheaper raw material. Virgin pulp preparation mainly needs disintegration and refining.

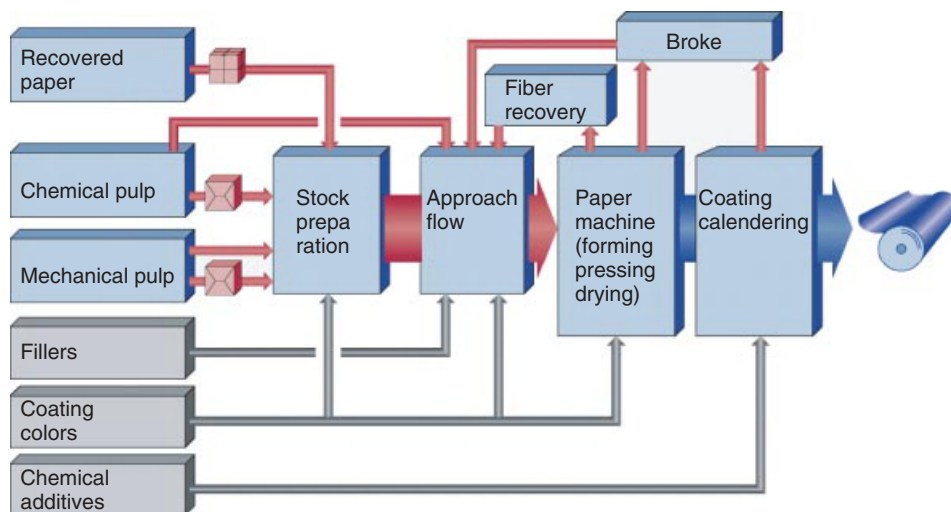


Figure 1.2 Overview of the papermaking process.

Processing of recovered paper afford more expenditure including several steps to separate undesired components from the fiber suspension.

The main objectives and the corresponding equipment in stock preparation are

- **Disintegration (also called slushing or repulping):** to obtain a suspension of individual fibers from fiber raw material; to do so, vat or drum pulpers, deflakers, and dispersers are used.
- **Separation:** to remove contaminants from the fiber suspension; this is done by screens, hydrocyclones, and flotation cells.
- **Treatment of fibers:** to change fiber properties by use of refiners and by bleaching.
- **Treatment of residual contaminants:** to change their size and shape to reduce or prevent their negative effect.

Fiber stock preparation ends at the paper machine chest. Here stock of high consistency is preferred to minimize carryover of chemicals and contaminants from stock preparation to the paper machine.

Water handling, wastewater purification, and waste processing are of high importance especially in recovered paper usage. An increasing number of mills make use of the thermal value of the waste, which formerly had been landfilled at high costs or supplied to external use. Owing to CEPI, landfilling has been reduced from 76.7 kg t^{-1} of produced paper or board in 1990 down to 17.8 kg t^{-1} in 2008 in Europe.¹⁾

Stock preparation is followed by the approach flow system connecting stock preparation with the paper machine and ending at the distributor of the headbox. Its main tasks are

1) CEPI statistics.

- to dose exactly and mix uniformly all the different components of the final suspension to be delivered to the paper machine;
- to supply a continuous suspension flow of constant consistency, quality, and flow rate at constant pressure to the headbox of the paper machine.

The task of the paper machine is to produce paper or board of the quality required by the end user – or by the intermediate process steps such as converting or printing. The paper and board properties have to be uniform in machine direction (MD) as well as in cross machine direction (CD). Further, the paper machine has to make the best use of the quality potential of the entering stock. The paper machine includes

- the headbox distributing the suspension across the machine width onto the wire;
- the wire section where the suspension is formed into an endless web by dewatering;
- the press section pressing water out of the web by mechanical means;
- the dryer section where the residual water is evaporated by heat;
- often, a sizing unit where starch or pigments are transferred onto the web;
- sometimes, a coating section where coating color is applied to the web;
- the calender to finally smooth the paper or board surface.

The paper manufacturing process ends with the paper web being reeled at the reeler at full width.

By tradition and technical feasibility, coating and supercalendering for surface quality improvement have been off-line processes in the past. At present both are increasingly integrated into the paper machine. The final activities in paper and board production are finishing, which means slitting of the full width reels into smaller rolls at the winder, followed by packaging the rolls for shipment.

Paper broke from the manufacturing process has to be recycled, and fibers are recovered from the white water of the paper machine in a save-all. White water is fed back from the paper machine to the approach flow system and stock preparation. Freshwater is supplied to the paper machine.

Along the paper production line, stock consistency varies according to the requirements of the unit operations. Unfortunately the terms low, medium, and high consistency relate to different consistency numbers depending on the actual unit operation (Table 1.2). It is also important to note whether the number gives the overall consistency including fibers and fillers or just fibers.

As paper is now a commodity, high cost pressure is put on paper and board production. The relative production costs listed in Table 1.3 show the high contribution of raw material and energy to the overall costs. The wide range of the figures indicates that the cost situation varies largely depending on the product, the kind of raw material, the machine and mill output, or the energy supply, as well as on the country and area.

Figure 1.3 shows the view of a paper mill for newsprint production in Central Europe. A new paper machine was embedded in the existing infrastructure and it started up late in 2010. The machine replaced one of the existing paper machines.

Table 1.2 Different naming of consistency ranges in the various unit operations in papermaking.

Unit operation	Actual consistency		
	LC (%) (low consistency)	MC (%) (medium consistency)	HC (%) (high consistency)
Repulping	<6	<12	12–28
Screening	<1.5	<4.5	–
Centrifugal cleaning	<1.5	<2.5	2.5–6
Bleaching	–	10–15	25–35
Refining	3–6	10–13	28–35
Web forming (headbox)	<2.0	–	>2.5

Table 1.3 Sources of production costs and typical ratio distribution.

Cost source	Range of cost ratio (%)
Fibers	40–70
Minerals and chemicals	1–18
Labor	4–13
Energy	12–22
Maintenance	4–10

Based on CEPI statistics and Section 26.2.

**Figure 1.3** View of a paper mill. (Source: Voith.)

It has been planned and built, and is operated based on the main ideas of ecological and economic paper production such as use of recovered paper, high yield in stock preparation, lower freshwater consumption, less electrical and thermal energy demand, reduced amount of additives – and, as a precondition, the produced paper has to meet the required quality level.

1.3 Economic Aspects

*Thomas Moldenhauer and Gert-Heinz Rentrop**

In 2010, the world production of paper and board was about 394×10^6 t. Although paper and board are used in some form or other in all parts of the inhabited world, the production is left to a limited number of countries. Nearly 5000 paper machines are responsible for production in 104 of the approximately 194 countries in the world, whereby the 15 largest producer countries alone account for 83% of total world production (Table 1.4).

The various requirements for the production of paper are not met everywhere. For instance, suitable raw materials must be available, including water, energy, and trained personnel. Furthermore, the construction of paper mills requires a very high investment, and a sufficiently large market and a favorable location are both essential prerequisites for economic papermaking. For these reasons, the modern paper industry is based mainly in the coniferous forest zone of the Northern Hemisphere, with centers in Europe, North America, and Japan.

World paper production has increased ninefold since 1950 when production was about 44×10^6 t (Table 1.5). During this time, the regions that did not belong to the classical paper-producing countries – above all China – have come to the fore, and their share of world production grew from about 3% in 1950 to 13% in 1980

Table 1.4 Production of paper and board by country, 2010.

Country	Production (10^6 t)	Share (%)
China	92.6	24
United States	75.8	19
Japan	27.3	7
Germany	23.1	6
Canada	12.8	3
Finland	11.8	3
Sweden	11.4	3
South Korea	11.1	3
Indonesia	9.9	3
Brazil	9.8	2
India	9.2	2
Italy	9.1	2
France	8.8	2
Russia	7.6	2
Spain	6.2	2
Other countries	67.3	17
World total	393.9	100

Source: RISI, VDP (Verband deutscher Papierfabriken) and Federal Statistical Office of Germany.

* Contributed to the First Edition.

Table 1.5 World production of paper and board (10⁶ t).

	1950	1960	1970	1980	1990	2000	2010
Europe	13.194	25.826	45.377	59.495	65.873	100.065	109.455
East	2.840	5.765	10.560	14.103	3.538	11.257	22.317
West	10.354	20.061	34.817	45.392	62.335	88.808	87.138
North America	28.286	39.393	56.323	71.179	87.985	106.603	88.636
United States	22.108	31.255	45.186	57.789	71.519	85.832	75.849
Canada	6.178	8.138	11.137	13.390	16.466	20.771	12.787
Japan	0.873	4.513	12.973	18.087	28.086	31.828	27.288
China	0.511	1.914	3.750	5.100	13.719	30.900	92.599
Others	0.876	3.279	11.264	18.257	43.142	54.585	75.921
World	43.740	74.925	129.687	172.118	238.805	323.981	393.899

Source: RISI, VDP (Verband deutscher Papierfabriken) and Federal Statistical Office of Germany.

Table 1.6 World production of paper and board by region (%).

	1950	1960	1970	1980	1990	2000	2010
Europe	30.1	34.5	35.0	34.6	27.6	30.9	27.8
East	6.5	7.7	8.1	8.2	1.5	3.5	5.7
West	23.6	26.8	26.9	26.4	26.1	27.4	22.1
North America	64.7	52.6	43.4	41.3	36.8	32.9	22.5
United States	50.5	41.7	34.8	33.6	29.9	26.5	19.3
Canada	14.2	10.9	8.6	7.7	6.9	6.4	3.2
Japan	2.0	6.0	10.0	10.5	11.8	9.8	6.9
China	1.1	2.6	2.9	3.0	5.7	9.5	23.5
Others	2.1	4.3	8.7	10.6	18.1	16.9	19.3
World	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Source: RISI, VDP (Verband deutscher Papierfabriken) and Federal Statistical Office of Germany.

and to 43% in 2010. At the same time, the circle of paper-producing countries has widened considerably from 61 to 111 and now includes a large number of developing countries. In these countries, the tendency toward self sufficiency is influenced by national economic considerations and the need to save foreign exchange for paper imports (Table 1.4).

In 2010, Europe, North America, Japan, and China accounted for 80% of the total world production (Table 1.5). However, the development in these regions has varied considerably. China's paper production has had a more than 18-fold increase since 1980 and it is now the largest paper producer in the world. In Japan, the paper industry has developed from a low during the postwar years to make the country the third largest paper producer. In the last four or five decades, Western Europe has more or less been able to maintain its share of world production. North America has had to accept large losses of its share of production (Table 1.6).

Table 1.7 World production of paper and board, arranged according to main types (2010).

Paper and board type	Production (10 ⁶ t)	Share (%)
Newsprint	33	8
Other printing and writing papers	110	28
Packaging papers and boards	204	52
Sanitary and household	29	7
Other papers and boards	18	5
Total	394	100

Source: RISI, VDP (Verband deutscher Papierfabriken) and Federal Statistical Office of Germany.

In 2010, graphic papers accounted for 36% of total paper production. This included newsprint (33×10^6 t) and other printing and writing papers (110×10^6 t). The production of packaging papers was 204×10^6 t, sanitary and household papers 29×10^6 t, and that of the remaining paper and board grades was 18×10^6 t (Table 1.7).

At present, nearly one-third ($112:394$) of the world production of paper and board is sold across borders. In 2010, exports and imports accounted for about 112×10^6 t.

The net exports to the United States, that is, exports minus imports, amount to 0.6×10^6 t. In contrast, Canada with its comparatively low population, has net exports amounting to 6.5×10^6 t, which is 50% of its paper production. The major part of Canadian exports goes to the United States. Western Europe with 12.7×10^6 t, a quota of 14% (based on the internal production) is a net exporter as well.

In China, the amounts imported and exported balance out at about 0.9×10^6 t. Japan is a net importer with 0.6×10^6 t. Of the remaining regions, the countries in Africa and Asia are the largest net importers. The imports and exports of South and Central America are roughly balanced.

World consumption of paper and board in 2010 was 395×10^6 t. China has by far the highest consumption of all countries, followed by United States and Japan. Germany is the fourth largest consumer, above Italy (Table 1.8).

Looking at the world paper consumption from a geographical point of view, it is apparent that the industrial countries of Western Europe, North America, and Japan not only produce but also consume a substantial part of the paper (Table 1.9).

There is also a relatively rapid increase in the consumption of paper in the remaining regions, especially in Asian countries such as India, South Korea, and Indonesia, which are becoming increasingly important for the international paper market. In the past 40 years, countries in South and Central America as well as in Eastern Europe and Africa have increased their share of world paper consumption annually. Improvements in the living conditions in these regions have been accompanied by a corresponding increase in the consumption of paper. The rise in both the standard of living and the individual income is as important a prerequisite as the spread of literacy for the consumption of writing paper and

Table 1.8 World paper and board consumption by country, 2010.

Country	Consumption (10 ⁶ t)	Share (%)
China	91.6	23
United States	75.2	19
Japan	27.9	7
Germany	20.2	5
Italy	10.8	3
India	10.8	3
UK	10.5	3
France	9.9	3
Brazil	9.5	2
South Korea	9.4	2
Russia	6.6	2
Spain	6.5	2
Canada	6.3	2
Indonesia	6.1	1
Turkey	5.0	1
Other countries	88.2	22
World total	394.7	100

Source: RISI, VDP (Verband deutscher Papierfabriken) and Federal Statistical Office of Germany.

Table 1.9 World paper and board consumption by region (%).

Region	1950	1960	1970	1980	1990	2000	2010
Europe	27.3	33.6	34.7	33.9	26.4	28.3	25.5
East	6.3	7.7	8.3	8.5	1.4	3.1	6.6
West	21.0	25.9	26.4	25.4	25.0	25.2	18.9
North America	64.2	50.9	43.4	38.4	35.2	31.0	20.7
United States	60.6	47.7	40.7	35.8	32.8	28.6	19.1
Canada	3.6	3.2	2.7	2.6	2.4	2.4	1.6
Japan	2.0	5.8	9.8	10.5	11.9	9.8	7.1
China	1.1	2.4	2.6	2.9	6.1	11.4	23.2
Others	5.4	7.3	9.5	14.3	20.4	19.5	23.5
World	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Source: RISI, VDP (Verband deutscher Papierfabriken) and Federal Statistical Office of Germany.

printing products. Another important factor is the buildup of exports and consumer industries with their demand for packaging materials.

The amount of paper consumed, however, is not an adequate measure of the standard of living of a country. The relative per capita consumption can only give a very rough indication of the living standard because other factors such as the average income, way of life, and consumer patterns must also be taken into consideration. In terms of paper consumption, the countries can be grouped according to their

Table 1.10 Population and paper consumption by region (2010).

Region	Population		Paper consumption	
	$\times 10^6$	%	10^6 t	%
Europe	814	12	100	25
Africa	1028	15	8	2
North America	347	5	82	21
Central and South America	597	8	27	7
Asia	4108	59	173	44
Australia/Oceania	34	1	5	1
World	6928	100	395	100

Source: RISI, VDP (Verband deutscher Papierfabriken) and Federal Statistical Office of Germany.

per capita consumption. For example, while the average consumption in Western Europe is 186 kg and in North America 235 kg, the per capita consumption in Eastern European countries is 63 kg, in Latin America 45 kg, and in Africa only 8 kg. Paper consumption per inhabitant is less than 1 kg in about 16 developing countries.

A comparison between population and paper consumption in different regions shows that Asia, which represents 59% of the world population, accounted for only 44% of world paper consumption. Conversely, North America has 5% of the world's population but a consumption of 21% (Table 1.10). An important indicator for the development of paper consumption is not only the gross national product but also the population growth (Table 1.9).

World population has more than doubled from 2.5×10^9 in 1950 to 6.9×10^9 in 2010. The per capita consumption of paper worldwide was 18 kg in 1950 and 57 kg in 2010, an increase of 316%. Thus the relative consumption of paper per capita has increased considerably faster than the world population. It is obvious that these average global values do not reflect the substantial regional differences.

In summary, the largest growth percentage potential for paper consumption is in the developing countries, especially in Asia and Eastern Europe, while industrialized countries such as the United States, Japan, and the Western European countries have relatively low growth rates, but still represent, in absolute terms, a considerable market potential.

1.4

Historical Background and General Aspects

Peter F. Tschudin

1.4.1

Introduction

Paper is defined internationally as a thin layer of mostly cellulosic plant fibers, produced on a screen by dewatering a slurry of fibers in water [2, 3]. The slurry is called *pulp*. Despite recent developments (proteinic or synthetic fibers,



Figure 1.4 Decorated bark cloth (tapa), of finest quality. Hawaii, eighteenth century. The impressed grooves of the beating mallet are markedly perceptible.

chemical additives, coating, etc.) the “cellulosic plant fiber” will be the main, not exclusive, component of paper, and water will be used in preparing the pulp and in forming the paper web also in the future. The difference between paper and other modern, sheetlike materials (plastic films; technical textiles; nonwovens), consisting also in the formation technology, is dwindling. More and more compounds and sandwiched materials include paper, either natural or treated, or paperlike materials.

1.4.2

Precursors of Paper

1.4.2.1 Tapa (Bark cloth)

Bark cloth, made since prehistoric times, is found widely along the Equator belt in nearly all cultures, used mainly for decorating and clothing [4]. It is produced by beating or pressing the inner bark (*liber*, bast) of trees and shrubs such as paper mulberry, lime tree, fig, or daphne, and is known by the generic term *tapa* derived from the Polynesian language. Tapa (Figure 1.4) is a feltlike material, similar to thick woven paper, showing in most cases traces of the beating mallets. Technically speaking, it is a kind of nonwoven paper. There are three different techniques to be observed in tapa making. The first consists of peeling off big pieces of the inner bark and beating them with a mallet. In the second, peeled pieces of bast are beaten together to form a larger and/or thicker piece. The most sophisticated method consists of three steps. In the first, small strips of bast are cut and cooked for several hours in suds of wood ash. This cooking is very similar to the basic operation of our alkaline pulping. Then the strips are rinsed, placed together on a wooden board, and beaten with a mallet, thus forming a small sheet on the board. The third step consists of drying and smoothing.

1.4.2.2 Felt

Felting techniques go back into prehistory [5]. Plant fibers or animal hair are separated from their original linking as much as possible and spread in thick layers



Figure 1.5 Felting: rolling up the mat covered with wetted layers of multicolored wool. Hotan (China), 1993.

onto a cloth or mat (Figure 1.5). Then they are covered by another cloth, rolled up, and beaten by foot stamping or with heavy wooden sticks to entangle them and stick them together. In another way, the ground mat bearing the fibers is rolled up and the roll is beaten. The mat is unrolled and rolled again several times. In wet felting, water is used to soak the fibers and help felting, generating hydrogen bonds.

1.4.2.3 Papyrus

Papyrus, the most commonly used writing material of Ancient Egypt and Classical Antiquity, was made in Egypt from the beginning of the third millennium BC. The triangulated stem of the papyrus plant is peeled and the pith cut into thin, small strips. A first layer of wet strips placed vertically side by side with a slight overlap is laid onto a board. Then, a similar layer of horizontally oriented stripes is laid above it. Beating with wooden sticks and pressing the still wet layers leads to a sheet of entangled fibers, most remaining in the original linking of the pith (Figure 1.6). After drying and smoothing several sheets are glued together to form a roll, ready to be written on. Gluing of several papyrus sheet fragments, usually



Figure 1.6 Transparency photograph of a papyrus sheet.

recycled material, results in board or papier-mâché. New papyrus rolls are very strong and flexible, an ideal writing material. They were exported in large quantities to the Mediterranean area until the eighth century AD. Parchment, made from hides, replaced the dwindling supply from Egypt. When paper was imported from the East, it was given the name of the Egyptian writing material because of its resemblance to papyrus.

1.4.3

Paper

1.4.3.1 Invention of Paper

The oldest papermaking technique, pouring pulp into a primitive mold, is still in use at a few locations in the Himalayas, in some remote spots of China, and in Southeast Asia. It shows clearly the descent from tapa and felting techniques (Figure 1.7). From recent findings of the oldest papers in Chinese tombs or in refuse heaps of military posts, it must be concluded that some kind of paper was produced in China since the final centuries BC. Nevertheless, the Chinese chronicles state that in 105 AD in Loyang, the court official Cai Lun invented papermaking from textile waste, that is, from linen or hemp rags, and propagated paper as a writing material [6]. This was the birth of paper as we know it now.

1.4.3.2 Chinese Paper

Chinese papermakers improved the effectiveness of the production, replacing the pouring technique by dipping the bamboo screen into a vat filled with diluted



Figure 1.7 Beating mulberry bark to make pulp. Hotan (China), 1993.

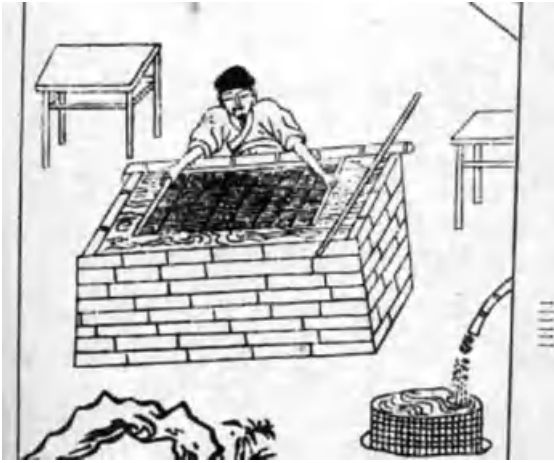


Figure 1.8 Chinese papermaker, dipping the mold. (From: Tiangong Kaiwu, 1637.)

pulp (Figure 1.8). After lifting the mold out of the vat and dewatering, the newly formed sheet of paper was immediately couched on a wooden board or a plastered wall to let it dry. The flexible bamboo screen was rolled off and could be reused with the vat. Thus, the handicap of waiting until a sheet dried on the mold was surmounted. Because of rag and paper mulberry shortages, they chose bamboo as a further source of fiber [7], the pulping of which took several weeks. China developed many kinds of specialty papers (sized, coated and dyed paper; anti-moth paper; waterproof paper); oversize sheets were made by couching the wet borders of smaller sheets together, and decoration watermarks were added by putting leather or board figures on the screen before pouring the pulp. Paper served for almost everything: writing, drawing, wrapping, clothing, protection from wind and rain, decoration, windows, even for making balloons and kites, and, last but not least, for making paper money or special currency to be burned in honor of the ancestors.

1.4.3.3 The Eastern Spread of Papermaking

Chinese papermaking techniques were introduced into Korea at an early date, and reached Japan in 610 AD. In both countries, fibers of the paper mulberry were mainly used. In Japan, splash dipping was developed, using a big mold suspended on a teetering twig [8]. Japanese papermakers were fond of art papers for decoration purposes. The ultimate in Japanese papermaking was the production of Shifu, paper yarn woven into heavy, beautiful fabric.

1.4.3.4 The Spread of Papermaking into Central and Southern Asia

At an early date (fourth to sixth centuries AD), it is attested that there were Chinese papermakers in Central Asia along the Silk Road, using the very old technique and local fiber plants such as black mulberry. There, Tibetans learned the papermaking craft and transferred the knowledge into the high valleys of the Himalayas where they used local plants such as the roots of *Stellera chamaejasme*. From Southern



Figure 1.9 Transparency photograph of an Arab paper sheet. Creases in coating are markedly perceptible. Fourteenth century AD. (Photo: Library of the University, Basel.)

China, the old-fashioned pouring technique spread into the emerging kingdoms of South Eastern Asia. India kept its traditional use of bark, textile cloth, and palm leaves as writing materials for a long time. Only at a later period (eleventh century AD, perhaps), was papermaking introduced from the north through contacts with Central Asia and Persia [9].

1.4.3.5 Arab Paper

The Arabs, in the course of their eastern expansion, became acquainted with the production of the new writing material reaching Samarkand. Subsequently, paper mills were set up in Baghdad, Damascus, Cairo, and later in the Maghreb. Having no paper mulberry trees and using screens made of reed, the Arabs made thin sheets of poorly beaten rag pulp and coated them on both sides with starch paste (from wheat or rice) which could be colored (Figure 1.9). This gave Arab paper its good writing properties and its fine appearance but also made it prone to damage because of humidity, crumbling, or insects. They also pressed two newly formed sheets together (wet couching), in order to obtain more strength. In the eleventh century AD, Arab papermaking knowledge spread into the Byzantine world and into medieval Europe, especially Spain (Xativa, Cordoba) and Italy (Amalfi, Genoa).

1.4.3.6 Medieval European Paper

Papermakers from Genoa and Fabriano tried to improve the Arab technique. They still exploited linen or hemp rags to get pulp, but improved the beating. Water

power was used to drive heavy stamping mills, huge oak trunks comprising four to six large troughs with three or four heavy wooden stampers, each beating the rags in fresh circulating water. The rags were transferred from trough to trough every 6 h to ensure a better degree of refining. Further improvements were stiff molds consisting of a wooden frame with inlaid copper or brass wire, which had to be couched on felts, heavy screw presses, and the replacement of starch sizing by dip sizing in animal glue.

This is the origin of the division of labor leading to a considerable increase in production: work at the vat normally involved four people – the vatman, who made the sheet using the mold; the couchman working alongside the vatman, placing the sheet on felt; the layman, who removed the moist sheets from the felts, and the apprentice, who had to feed pulp to the vat and provide vat heating. The press was operated jointly by this team. Depending on the format, up to nine reams (4500 sheets) of paper were made during a working day averaging 13–15 h. The paper was dried by women, hanging it on ropes in the drying loft. Apart from different sizes, three main sorts of paper were produced: writing paper (for letter and chancery use), printing paper (mostly unsized), and cheap wrapping paper (also broke, screenings), used also for drafts. As a further consequence of the change in mold construction, watermarking was invented in medieval Italy. Figure 1.10a–h show the separate steps in hand papermaking, from the work in the rag cellar to sorting and packaging.

1.4.3.7 Mechanization and Industrialization

In Europe, technical progress continued. In the sixteenth century, glazing the sheets by hand using a glass or stone burnisher was supplemented by the use of the glazing hammer, similar to a forging hammer. Toward the end of the seventeenth century, a most efficient tool, the so-called “Hollander” beater, supplemented or even replaced the stamping mill (Figure 1.11). As the rotating knives of the Hollander beater cut and shortened the fibers more than a stamper, the aging of paper was accelerated. This phenomenon is true also for the change in sizing. To improve the solubility and the penetration of the animal glue solution, alum was added, leading to acidic deterioration of paper. Further development of printing during the eighteenth and nineteenth centuries led to a steeply rising demand for paper, especially for new printing grades. This and the tremendous upsurge in papermaking soon led to a serious shortage of raw material and to regulations governing the trade in rags, to ensure the local production of paper for administrative purposes. Rags of minor quality, even cotton and wool were used, together with fillers such as starch or kaolin. So systematic search for rag fiber substitutes was needed [12]. From the seventeenth century, there was some concentration of handicraft activities in big factories, consisting of several mills, which still depended on skilled papermakers organized in open guilds. The efforts made to improve paper quality (woven wire molds since 1738) and to step up production as much as possible employing local people and developing auxiliary mechanical means (rag cutter, rag digester, Hollander beater, vat paddles, strainers, couching press, hydraulic press, glazing



(a)



(b)



(c)



(d)



(e)



(f)



(g)



(h)

table, glazing hammer, and calender) culminated in the design and construction of paper machines.

1.4.3.8 Paper Machines

A Frenchman, J.N.L. Robert, built the first paper machine, patented in 1799. It was driven by one worker using a crank. The diluted pulp contained in a large vat was hurled into a wooden chest by a rotating paddle wheel and directed onto an endless wire screen of laid type. The screen bearing the forming paper web was moved forward, horizontally shaken, and passed between a pair of couch rolls equipped with felts (Figure 1.12). The web, still moist, was then taken by a worker and cut into large pieces, which were hung on ropes to dry.

This machine was further developed in England by Bryan Donkin and by the Fourdrinier brothers. Soon, other types were developed, for example, the cylinder machine (Bramah, 1805; Dickinson, 1809) in which a cylinder with a mounted wire screen rotates in a vat filled with pulp. Other types were the mold-chain machine (Fourdrinier, 1806) and the twin-wire machine. Flat-type and cylinder machines gained ground in the nineteenth century and were extended to include a dryer section (Crompton, 1820) and a reeler, and somewhat later (1850), also a calender section (Figure 1.13a,b). Steady improvements led to a considerable increase in production. The paper machine heralded industrialization. In this new situation, the small operators who were unable or unwilling to afford machines tried to survive with piece work or by producing special grades and cardboard, but they were sooner or later compelled to discontinue their activities. Others had to adapt their existing buildings or set up new mills elsewhere. The decisive step in developing the US paper industry was initiated by Joshua Gilpin (1815). Special paper machines were successfully built (e.g., the so-called “Yankee” cylinder machine), and soon the US paper production became the largest in the world.

1.4.3.9 Pulping and Sizing

In European medieval papermaking, the rags were moistened and exposed to air in order to rot for weeks before beating (fermentation). This helped to dissolve dirt, yarn knots, or knit links and was equivalent to a modern enzymatic fiber treatment. During beating, slaked lime was added to the slurry, which resulted in fiber swelling, fiber bleaching, and improved fiber separation and quality [13].

Figure 1.10 Processing steps in European papermaking. (From: Chr. Ludwig Seebass: *Die Papiermacher-Kunst in ihrem ganzen Umfang: aus dem französischen Original des Herrn Desmarest . . . bearbeitet*. Lipsia, 1803 [10].) (a) The rag cellar: weighing, sorting, rotting, and washing the rags. (b) Rag cutting (work done by women or boys). (c) Stamping mill. (d) Main room: (to the left) dipping and couching; (to the right) pressing

and laying off. (e) Drying loft: suspending the sheets. (f) Sizing hangar: (to the right) size boiling; (to the left) dip sizing, pressing. (g) Glazing hammer. (Extracted from: J.S. Halle, *Werkstätte der heutigen Künste*, vol. 2, Brandenburg/Lipsia 1762 [11].) (h) The Salle: (to the right) dry pressing; (middle and left) cleaning, sorting, glazing by hand, format cutting, counting, and packaging.



Figure 1.11 Hollander beater, cast iron tub, Papeteries de Vaux, Payzac (France), about 1860.



Figure 1.12 The Robert paper machine (reconstruction, University of Grenoble).



(a)



(b)

Figure 1.13 Cylinder machine, Papeteries de Vaux, Payzac (France), about 1860. (a) Breast box with pulp cleaning and sorting cascade. (b) Cylinder with couch roll and board felt.

Even after washing and beating, particles of calcium carbonate and magnesium carbonate remained sticking to the fibers and got into the vat and into the paper sheet. There, they acted as a buffer, neutralizing acids and thus inhibiting the aging of old handmade papers. In the eighteenth and nineteenth centuries, efforts were made to improve the efficiency of rag pulping. Rag cutting machines and rag digesters replaced old-fashioned breaking and boiling. The stampers were replaced by the Hollander beater and later by refiners. To obtain rag substitutes on an industrial scale, in 1774, Claproth in Leipzig promoted deinking, using a kind of bentonite. Straw was propagated as a raw material but failed because of poor paper quality (Koops, 1800). Only the invention of the stone groundwood process (Keller, 1843) and of chemical pulping (soda process: first patents, 1851: Watt, 1854: Mellier; sulfate process: Dahl 1884; sulfite process: Tilghman 1866) solved the problem of getting large fiber quantities. Dip sizing of paper bundles in a solution of animal glue was replaced by pulp sizing, using rosin and alum (Illig, 1807). The resulting acid conditions in papermaking are in a large part responsible for the poor aging behavior of machine-made paper until the 1980s, especially of wood-containing grades in which lignin reactions are triggered.

1.4.3.10 From Industrialization to Automation and Globalization: Technical and Economic Trends of the Nineteenth and Twentieth Centuries

Several partly overlapping periods may be distinguished, each marked by definite trends. Rising capital investment was needed to mechanize papermaking, and the lack of rag supply was a problem for the papermakers. In consequence, the introduction of a pulping section in a paper mill or the construction of independent pulp mills became a priority task.

The evolution of the paper machine depended on progress in engineering and metallurgy. Until turbines replaced the venerable waterwheels, water energy was too slow and too poor to drive an improved paper machine. Even the introduction of steam engines did not help much; only when the steel quality available allowed the use of high-pressure or superheated steam, did progress in papermaking begin. But the problem of power transmission to the different parts of the paper machine remained. Here the introduction of electricity, permitting the installation of individual drives to every part of the machine, triggered a leap into the future: The web width was enlarged, working speed increased considerably and machines designed specifically for the production of particular paper and board grades (e.g., multicylinder machines) were developed. Alongside the development of printing in the nineteenth century, new paper grades were created, together with some kind of paper specialties such as punch cards, stand-up collars, tube papers, flong, pergamyn, ammunition papers, envelopes, tobacco paper, and toilet paper. The size of the pulping plant and of the paper machine grew to such an extent, that new factory complexes had to be erected, and there were also changes in research and development, marketing, controlling, and transportation. In most cases, this evolution led to commercial group building and mergers. Since the 1980s, the use of new materials (thermomechanical pulp, deinked recycled fibers, new fillers, process chemicals, and dyes) and new web forming principles (e.g., twin-wire or

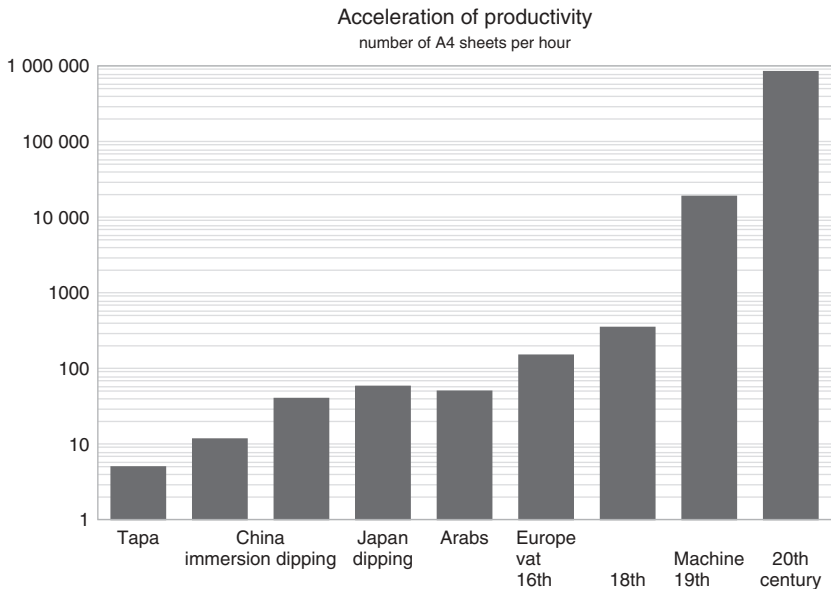


Figure 1.14 Productivity development until 2000.

gap formers), neutral sizing and – the most effective change – automation have brought further progress. This led to further specialization in specific paper types, and development of new paper grades (e.g., LWC papers and technical papers). In consequence, corporate mergers and international company groups came up with raw material supply and trading organizations of their own and unprofitable operations were shut down. Environmental problems, already documented in the nineteenth century, also triggered changes. New forestry principles have been introduced; fiber recycling covers more than half the fiber demand; heat recovery, closed water loops, and the replacement of aggressive chemical treatments in pulping have helped to improve the poor ecological image of the paper and pulp industry.

Paper production and consumption increased from medieval times to the end of the eighteenth century by a factor of 50 (Figure 1.14). Since then, paper and board have become a worldwide, large-scale commodity with exponential growth. In 2010, about 400 million metric tons were produced, of which about two-fifths in the fastest growing industrial market, Asia.

1.4.4

Historical Watermarking and Security

The real watermark, a bright figure in the paper sheet, is seen by the naked eye. In hand papermaking, it is formed by a curved wire which is sewn onto the screen of the mold; the wire reduces the thickness of the sheet, thus making the figure transparent (Figure 1.15). The watermark serves as a trademark and provides the historian with an unsurpassed dating and authenticating tool. By comparing a



Figure 1.15 Watermark of the Basel Paper Mill.



Figure 1.16 Dandy roll with soldered watermarks.

watermark with others of a certain date or origin, the paper historian will be able to determine the age and origin of a document or print. Shadow watermarks have been produced since the eighteenth century on a mold bearing a fine, embossed, woven wire, showing an image such as a black-and-white photograph [14]. On the flat-wire machine, real (line) watermarks are made by passing the newly formed web under the dandy roll on which watermark figures are mounted (Figure 1.16). On the cylinder machine, watermark figures are mounted onto the forming cylinder. To



Figure 1.17 Assignat (Bank note of the French Revolutionary Government), transparency photograph. Paper security devices: combined line and shadow watermark, signature print, and embossed stamp.

ensure uniformity, wire figures are replaced by casts. Besides the art form, real watermarking remains one of the most effective security measures.

Security and application aspects of watermarking, also publicity, influenced the development of other methods. Combined line/shadow watermarks (Figure 1.17) were supplemented by embossing, impressing (e.g., using molettes), and printing techniques (e.g., with engraved patterns or with a white or colorless ink) [15].

1.5

A Philosophy of Papermaking: Life Lessons on the Formation of Paper and People

Wilhelm Kufferath von Kendenich

In papermaking, both the manufacturing process and one of the primary properties of the finished sheet are referred to as *formation*, a concept that embodies all the design features of the interior and exterior of the sheet. Those attributes and processes that apply to the making of a sheet of paper may also apply – analogously – to the formation of a person. In life, a person’s formation depends on upbringing, training, education, design – all those things that contribute to one’s personality and overall makeup. These aspects also translate to the bigger picture of society’s fundamental interactions and interdependencies. Therefore, it might not seem so far-fetched to attempt to apply the fundamental rules for sheet forming from its basic scientific foundations toward man and society.

1.5.1

Fibers as Individuals

Fibers have various fundamental characteristics: diameter, length, stiffness, and so on. They are the basic building material of a sheet of paper, and each fiber has

its own individual character; as with snowflakes, no two fibers are identical, not even when they are all taken from the same wood and woven into the same sheet. Fibers are made – born, really – from wood by mechanical or chemical processes that give “birth” to the fibers. After liberation from the wood, the fibers are put into a water suspension and fines and fillers are added; these contribute to a smoother and better final sheet. One could imagine equivalent fines and fillers for people to be those things that make societal life more bearable and enjoyable: education, ambition, compassion, and civility.

1.5.2

Paper as a Social Construct

A sheet of paper is really nothing more than a collection of many fibers, fines, and fillers. In comparison to a community or society as a collection of many people, a sheet of paper is a microcosmic manifestation, a miniature society in its own right, each individual a sentient being, each one prepared for and taking its proper place, each fiber an equal member of that society. Sometimes, people find themselves grouped together and proclaim, “We are the people!” Given the opportunity, fibers could be reasonably expected also to exclaim, “We are the paper!”

1.5.3

Fiber Preformation and Human Training

The fundamental quality of the final sheet of paper is locked in place during the preformation, called stock preparation. In the stock preparation process, all fibers experience superficially the same treatment (for example, all are subjected to refining), but the effect is not the same for all the fibers as some may differ in their physical properties; each is, after all, an individual. But all are of equal value, equally useful for the paper being produced, equally valued, and equally important. All become part of the paper sheet by their interconnection. This is the basic tenet of the papermaker’s wisdom: the quality of paper is set in the stock preparation process. Thus, the foundation established in the preformation of fibers applies to analogous processes for people as well: recognize the nature of your individuality and your natural gifts as soon as you are able; protect and nurture them no matter what anyone says; follow them to the future they can provide. Making the leap from paper to human society and assessing the quality of the raw material at the end of the preparation period, we say to each individual, “You are unique and unlike any other but you have the same value as everyone else; now go out and make your unique and valuable contribution to society!”

1.5.4

Into the World of Turbulence

As the stock preparation was the nursery for those essential properties that determine the quality of a sheet of paper, so basic maturation and professional

training begin in the headbox. The suspension is transported from the nursery to the headbox, as young people are fledged from home at 18 or so. Bursting from the feed pipes into the vastly larger open volume of the headbox, we now see how the qualities imbued in the preformation process express themselves in this larger and far more turbulent world. How will young people behave and react when they find themselves on this long journey into and through the unknown? What kind of joy, fears, and anxieties will they develop? What new things will they experience? Will they be freed from old constraints, making and exploring new contacts? Properly formed in their earlier lives, it is to be expected that they will absorb and digest their new stimuli and grow accordingly.

1.5.5

Flocs and Vicissitudes

Fibers exhibit an annoying behavior as they travel from the stock preparation stage into the headbox, namely, the formation of unwanted clumps of fibers. The papermaker calls these groups *flocs*; incredibly, within the extremely short time span of only tenths of a second, they bind together very tightly and proceed through the pipes to the headbox. The papermaker cannot change this phenomenon; it is a behavior that interferes with the fibers' normal free state and is to be prevented if at all possible. Correspondingly, young people are quite often anxious about the unknowns they will face on their outward journey and may wish to remain closer to relatives, friends, and acquaintances, safe in their familiar circles, not forced out into the world. The desire to create buffers against inevitable vicissitudes or even life's shocks that await them can cause a social flocculation that can prove hard to break. But it almost always does.

1.5.6

Fibers Ready for the World, Part 1

Well prepared in the preformation process and suitably buffeted in the turbulent headbox, the fibers reach the lip of the headbox, ready for their placement in the world of the sheet. This is the moment of truth for the quality of the fibers and thus the eventual quality of the final sheet. On exit from the headbox, the fibers must have acquired the right amount of kinetic energy to achieve the proper throwing length and the compact shape of the free jet, and enough turbulent energy to maintain the mobility required to avoid renewed flocculation. Only then will the sheet form properly. The equivalent for young people is at the end of their training when they will have acquired three basic essentials: knowledge, values, and desires. These they take out into the world, into their social and professional lives. Now comes their first landing in reality – a true reality check – but hopefully one as gentle as possible.

1.5.7

Sheet Formation as the Basis of the Fiber's Society

With the grand moment of impact of the fiber jet on the forming fabric, everything is suddenly different. Water is not the natural environment for wood fibers; they like it dry, and now they can finally get the water out. As water is drained through the fabric, everything moves quickly as each fiber must soon find and settle into its final position because of this rapid drainage. There is a delicate balance between the kinetic energy to keep flocs from forming and the final placement of fibers through drainage, just as there are always things that people want to do and things they have to do.

Simultaneously with the rapid drainage, energetic pulses will be generated in the suspension above the first layer of fibers by the elements of the formation table. This helps to equalize the fibers' distribution in the undrained suspension and improve the nascent sheet's formation. This application of energy needs attention and care not to disrupt the fibers already laid in place. Additional energy is imparted to the fiber suspension from the difference in speed between the wire and the jet. There is an aligning of fibers in the incoming suspension along the direction of the machine, a final adjustment of the sheet in its transition from individual fibers to an interconnected society. This characteristic is expressed as the ratio of alignment of the fibers in the MD/CD ratio. One might interpret the degree of alignment in the MD to be those things that you are obligated to do and the degree of alignment across the machine to be those things you would like to do. Finding and maintaining the right balance between these two is the critical path that fibers and people alike must achieve. Without doubt, the journey along the forming section is a complex process laden with chaotic features.

There is, however, a conceptual divergence at the end of the forming process: the fiber's position and function are effectively locked in permanently while people have (hopefully) only begun their lifelong formation processes. A proper foundation of formation must be laid down as the person continues this formation development throughout his life.

1.5.8

Fibers Ready for the World, Part 2

When the sheet has left the forming section, and completed its trip through the presses to reach the dry end, it is fully formed and ready to embark on its career as a newspaper, a page in a book, a poster, or any of a number of other possibilities. So it is with young people: they are full of energy and potential, their hopes and dreams intact and undiminished by failure or the possibly unrealistic nature of their desires. Their sheet is not folded, spindled, or mutilated by the vicissitudes of life. But as one ages, it can happen that desires, visions, and goals have often proven to be dreams, a reality to which the properly formed person will adjust accordingly. It begins to dawn on a sheet of paper that it is not here forever. In the later phases of life, a sheet serene and standing apart from adversity, perhaps

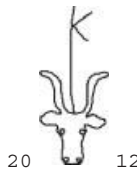
honored to be a page in a Shakespeare folio – a most suitable stance from which to enjoy its stature – and perhaps the equivalent is to be the honorable chairman of the choral society in Posematuckel village.

1.5.9

In Summary – Toward the End

Paper gives us pause to dwell on these matters; and for some, it leads to an analogy with the world that one may have been seeking for a long time, a world that one is more inclined to say does not exist or that one will never find. The author must admit that, whenever he holds a piece of paper in his hands, he is astonished that such a thin sheet of paper is actually such a large book that can teach one so much about the universe. The reader will now hopefully understand why, for this author, formation stands at the center of his worldview: a sheet of paper is a silent philosopher if you look and listen closely enough.

Mit Gruß von wegen's Handwerk
(traditional German fellow papermakers greeting)



*Dedicated to Dr Otto Kallmes, a masterful wet-end scientist and a true friend.
With translation assistance from Paul Kallmes.*

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2

Fibrous Materials for Paper and Board Manufacture

2.1

Overview

Jürgen Blechschmidt and Sabine Heinemann

Paper production is based mainly on fibrous raw material, which may consist of virgin or so-called secondary fibers. Virgin fibers are obtained from different pulping processes directly from plant raw materials, mainly from wood and annual nonwood plants. Industrially, mostly thinnings and sawmill residues are used. Secondary fibers are produced from recovered paper and board. Before the inventions of mechanical and chemical pulping processes in the nineteenth century, rags, that is, used textiles, were the only fiber source for paper and board manufacture. Nowadays, rags are only used in very small amounts for special paper grades. Synthetic and mineral fibers do not play an important role.

As its name indicates, *chemical pulp* is the term for fibrous material obtained from wood or annual nonwood plants by chemical processes, compared to *mechanical pulp*, which is produced by mechanical defibration of wood.

Approximately 90% of the raw material used in paper and board production in the world is wood. Annual nonwood plants are suitable for regions with low wood resources, larger areas that are not used for agriculture, and larger surpluses of agricultural residues (e.g., straw). Fiber manufacturing from nonwood plants is more expensive and causes more environmental pollution than that from wood. Chemical pulp from jute, flax, hemp, sisal, and bagasse, and others, is suitable for special paper grades such as filter papers or lightweight printing papers. In tropical and subtropical regions, fiber wood grows mainly in plantations.

In chemical pulp production, yields of 45–55% are common, whereas in mechanical pulping, it is ~80–95% and thus provides approximately twice as much fibrous material from the same amount of wood than one obtains from chemical pulping. Additionally, in chemical pulping processes, the water circuits and effluents are loaded with many more dissolved substances and therefore require a more intensive and thus more expensive treatment. Mechanical pulping is an energy-intensive process with specific energy consumptions of 1.3–3MWh t⁻¹, depending on the product (paper or board grade) and on the process design.

During chemical pulping, the required energy is produced by burning of black liquor. A modern kraft mill can deliver a power surplus of ~ 30 MW.

Recovered paper is nowadays the most important raw material in the world. Fifty-five percent of recovered paper (return rate) is used to produce ~ 400 Mio t paper per year. With a utilization rate of 70% and a return rate of 78% (2010), the German paper industry is leading in the utilization of recovered paper. A further increase in the paper production worldwide is realized by increasing the proportion of recovered paper for the fibrous raw material. Thus, the paper industry contributes significantly to the environmental protection and the economy of resources. Because the paper manufacturing from recovered paper requires less energy compared to virgin fibers, the CO₂ balance is also affected positively.

The unproblematic application of recovered paper in packaging papers and boards raised the utilization rate to 95%. During the past decades, the development of the deinking technology has increased the utilization rate of recovered paper in printing paper grades remarkably. Today in Germany, newsprint is made from 100% recovered paper.

“Deinking” is the process of printing ink removal from recovered paper by two procedures – flotation and washing.

The economic importance of the recovered paper utilization is defined in the European Declaration on Paper Recycling 2011–2015, European Recovered Paper Council (ERPC): “Recycling has formed an increasing part of the paper manufacturing process, linking directly or indirectly to a large number of sectors in the European economy.” “Recycling” is every recovery procedure by which waste materials are transformed to products or materials for use either in their original form or in other forms.

The evolution of the worldwide use of fibrous raw material is shown in Table 2.1.

2.2

Chemical Pulp

Sabine Heinemann and Jürgen Blechschmidt

2.2.1

Introduction

Wood is the most important raw material for paper and board fibers. Because of its structure and composition, it has an extraordinary suitability for that purpose.

Softwood tracheids and the libriform fibers from hardwood are especially suitable for the paper production. Because of their aspect ratio, that is, slenderness, they can significantly contribute to the paper strength. The cross section of such a fiber is simply divided into fiber wall and lumen. Based on its chemical aspects, the fiber wall can be described as a bio composite polymer [1] with the components cellulose, hemicelluloses (polyoses), lignin, extractives, resins, fat, and waxes (Figure 2.1).

Target of the chemical treatment is the delimitation of intact wood cells from the wood matrix. This process is also called *delignification*, and can be carried out

Table 2.1 Development of the worldwide consumption of fibrous raw materials and paper (popyry world paper markets up to 2010).

Fibrous materials and paper/board grades	1980		1990		2000		2010	
	Mio t	%	Mio t	%	Mio t	%	Mio t	%
Recovered paper (commercial)	60	–	100	–	160	–	195	(49)
Recovered pulp	54	31	90	37	144	45	176	44
Chemical pulp	93	54	120	50	145	46	180	46
Mechanical pulp	25	15	30	13	30	9	40	10
Fibrous materials (total)	172	100	240	–	319	–	396	–
Paper and board (total)	171	–	240	–	320	–	422 ^a	–

^aThis table is based on earlier studies. According to statistical information, the total world consumption of paper and board was 393 Mio t in 2008, and 370 Mio t in 2009. For 2010, 394 Mio t are expected (FAO).

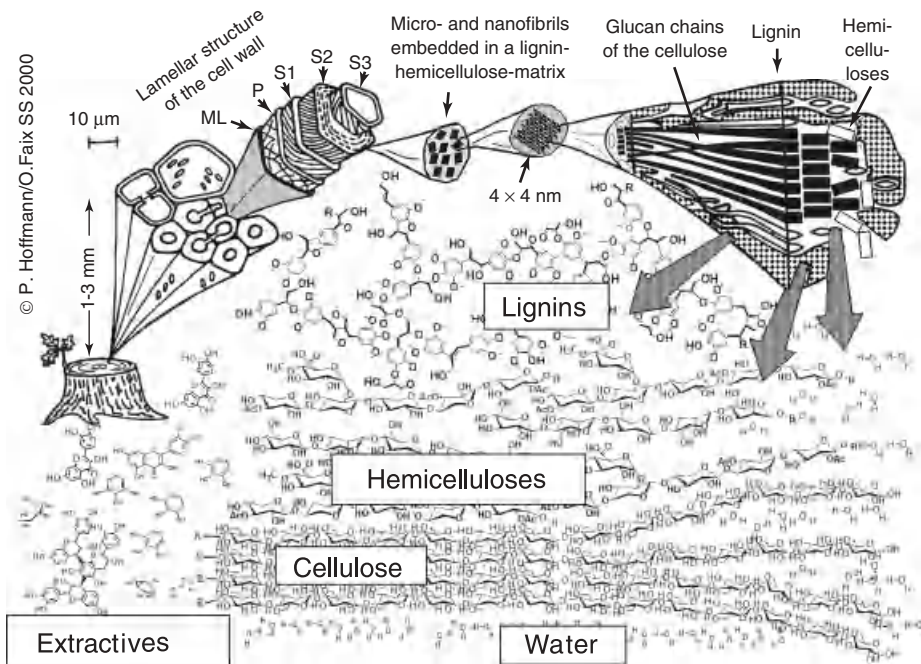


Figure 2.1 Wood as microcomposite and biocomposite polymer [1].

in alkaline, neutral, or acidic conditions. Depending on the applied chemicals, different processes are established, among which the sulfate or kraft processes and the sulfite processes are the most well known.

Today, the *sulfate process* or alkaline pulping is the dominant chemical pulping process for bleached and unbleached pulp for paper and board production. It can be applied to a wide range of lignocellulosic raw material and is very energy efficient. Drawbacks of the alkaline process are the comparatively low pulp yield and fibers difficult to bleach. On the other hand, recovery of cooking chemicals provides closed systems with minimal pollution [2]. Approximately 95% of the worldwide chemical pulp production is made by the sulfate or kraft process.

Acidic sulfite pulping for paper and board applications, among all pulping processes, has been on the decline in the past decades. Despite a better yield, better selectivity, and easier bleaching, it is being replaced by alkaline processes, especially due to the contemporary environmental regulations. There are still a few sulfite pulp mills running in Europe, but sulfite methods, which can be applied over a wide pH range, are mainly applied in the manufacture of specialty pulps such as dissolving pulps [3].

Most “high-yield” chemical pulping processes use neutral or mild alkaline sulfite semichemical cooking liquors. Semimechanical methods such as neutral sulfite semichemical (NSSC) pulping are used to manufacture pulp for certain packaging grades. The reactions between the active chemicals and lignin in the impregnation stage, for example, in processes such as chemithermomechanical pulping (CTMP), are chemically similar to the sulfite process, too [3].

2.2.2

Wood Preparation for Pulping Processes

Raw material for pulping processes is mainly saw mill residues (saw mill chips) or first thinnings. As seen from Figure 2.2, the main steps in the preparation of round wood logs from first thinnings are debarking, chipping, and storage of wood chips and bark [4].

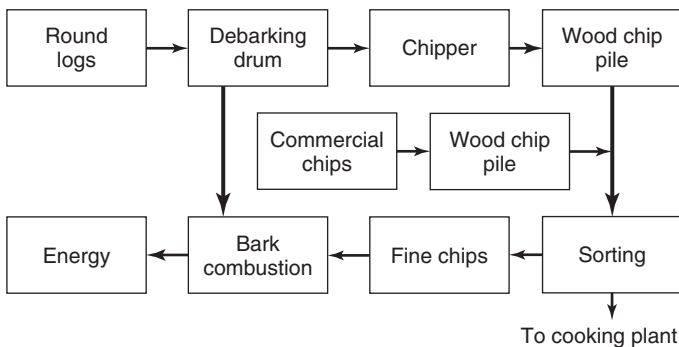


Figure 2.2 Scheme of wood handling in a pulp mill [4].

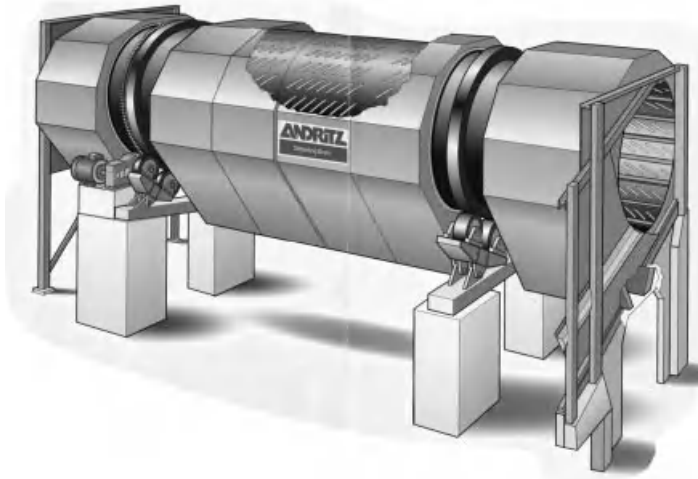


Figure 2.3 The Andritz drum debarker [5].

Debarking is mainly performed as dry process in debarking drums (Figure 2.3). The costs for wet debarking are higher than those for dry debarking. The working principle of the debarking drums is friction. The wood logs are rubbed together at their surfaces and at the inner wall of the debarking drum, resulting in the peeling off of the bark. Suitable trunk lengths are 2–6 m. The drum size ranges in length from 6 to 60 m, and the diameters range from 2 to 5.5 m, depending on capacity and production conditions [5]. After passing the debarking drum, the wood logs are washed.

For chemical pulping and refiner mechanical pulping, wood log chipping is performed in disc-chippers under defined conditions (Figure 2.4). The chippers have either a rotating steel disk with diameters of 2–4 m, centrally equipped with up to 15 knives, or a drum with length-oriented knives. The rotational speed is ~ 350 rpm. It is desirable that the wood chips are of uniform size and shape. Ideal chip lengths are ~ 20 – 35 mm, and chip thickness is usually 3–8 mm [6]. Thickness of the chips and thickness distribution, chip length and length distribution, dry-matter content, apparent density, packing density of the wood chips, and the proportion of bark residues are the wood chip parameters that later affect the quality of the resulting pulps.

Before storage, the wood chips are sorted, mainly in vibrations screens of cascade type or in conical screening drums. Too large chips are sorted out and diminished in disintegrators, and then fed back to the main line sorting. The accepted wood chips are stored in silos or piles until their use in the pulping processes.

The bark from drums and chip sorting and also other rejects from the sorting process such as branches, shives, and fine chips, are further diminished and burned for energy production.

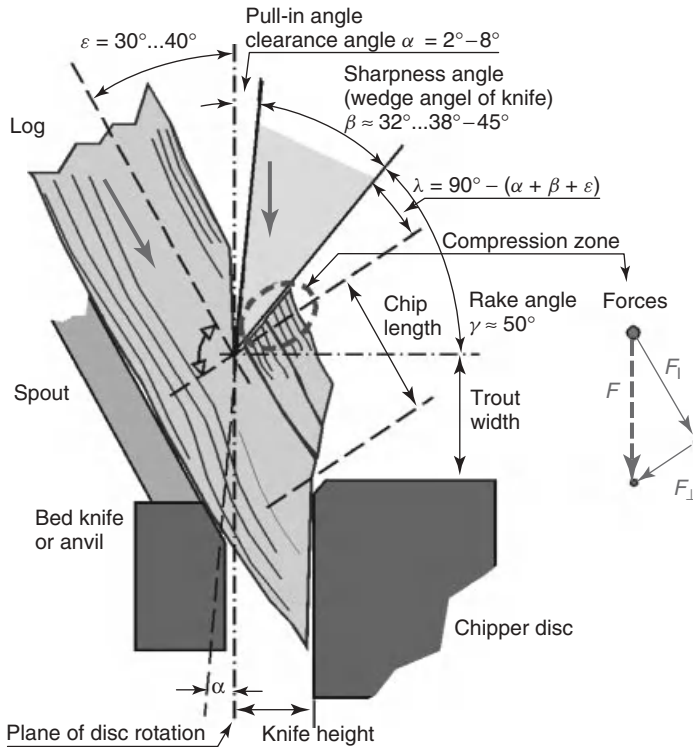


Figure 2.4 Cutting action of a wedge-shaped knife in a disc chipper – cross section through the disc and knife [6].

2.2.3

Sulfate Process

Sulfate pulp is a chemical pulp generated by cooking of plant raw material in an alkaline solution from caustic soda and sodium sulfide. Effective chemicals are NaOH and Na_2S .

This process is also known as alkaline pulping. Sodium sulfide is added to the process chemicals in the form of sodium sulfate Na_2SO_4 that can be recovered from the process chemicals and that is what the process is named after. Before the sulfate process, the soda process was introduced that worked only with sodium hydroxide and without sodium sulfide Na_2S . The resulting pulp was the so-called natron pulp. This name is alive even today.

Alkaline pulping requires the recovery of used chemicals. Recovery machines and plants are a significant part of the total pulp mill. The target of the pulping process is lignin dissolution, while cellulose and hardly hydrolysable hemicelluloses remain in the pulp. But in reality, some of these components are also dissolved and thus removed from the pulp, more in the alkaline process than in the acidic sulfite process, resulting in a lower yield compared to the sulfite process. The yield

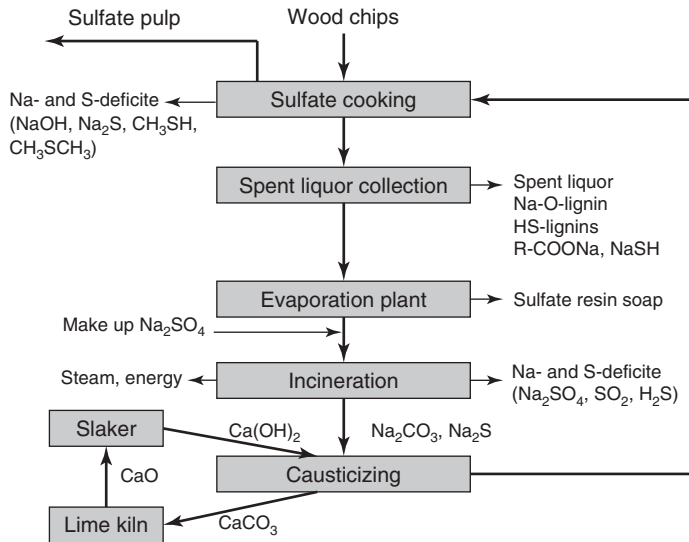


Figure 2.5 Sulfate pulping process steps [7].

of unbleached chemical pulp is 45–55% in the sulfate process and 50–60% in the sulfite process respectively. The process steps of the sulfate process are shown in Figure 2.5.

After wood chip treatment in the digesters, the recovery of the chemicals is performed in several steps.

2.2.3.1 Cooking

2.2.3.1.1 The Batch Process There are two cooking procedures available – the batch procedure and the continuous procedure. The batch process is performed in standing vessels with conical-shaped lower part having volumes of 200–400 m³ (batch digester) (Figure 2.6).

A typical displacement batch cooking cycle starts always with chip filling, followed by impregnation and hot displacement. Final heating with steam brings the digester content to the desired cooking temperature, and the cooking process itself is continued until the desired pH level is reached. Cold displacement stops the delignification process, and finally the pulp is discharged from the digester [4].

2.2.3.1.2 The Continuous Process To increase the production rate, several systems of continuous cooking have been developed. The outline of a single-vessel continuous cooking system is shown in Figure 2.7.

Wood chips are fed continuously together with white liquor and black liquor to the digester via dosage devices. At the same time, a particular amount of pulp and black liquor is released from the digester. Impregnation can be carried out at 60–70 °C with atmospheric pressure, or in pressurized mode at ~110 °C. During

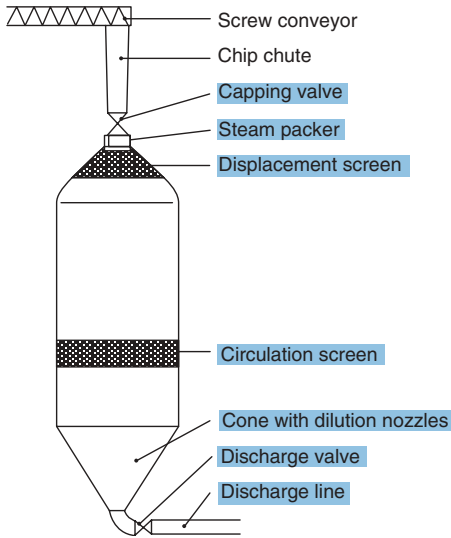


Figure 2.6 Typical batch digester for displacement cooking [6].

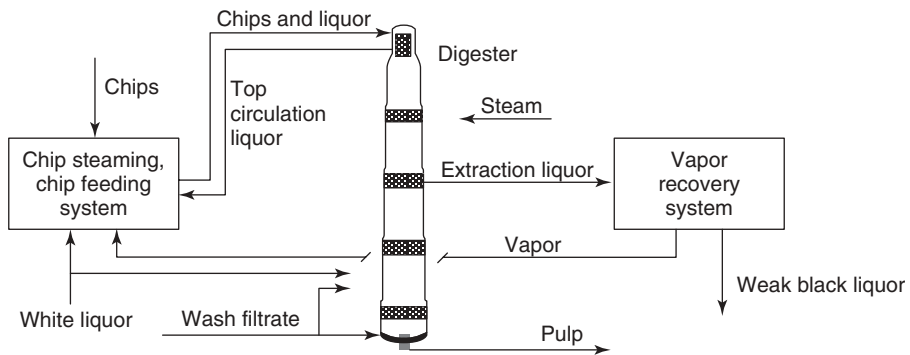


Figure 2.7 Outline of single-vessel continuous cooking system [6].

the impregnation time of 10–20 min, the cooking liquor penetrates into the wood chips. Common cooking conditions are 160–180 °C at 8–9 bar. For normal pulps, the cooking time is 0.5–2 h, for high-yield pulps ~1 h. A digester volume of 1.0–1.2 m³ per ton of pulp a day is assumed, corresponding to $1/10$ of the volume of batch digesters [8].

2.2.3.1.3 Batch Cooking versus Continuous Cooking One important advantage of the batch process is the higher process flexibility. Changing of wood grades, production rate, and pulping degree is easier in the batch process. In the continuous process, such changes produce a certain amount of pulp with lower quality. To

reduce the production rate, some batch digesters can just be taken out of the process line. It is not possible to run continuous digesters significantly below their designed production level [9]. Batch cooking has a higher reliability. In case of failure of one batch digester, the production rate is decreased, for example, by 10–15%. In case of failure of a continuous digester, the total pulp production is stopped. Further advantages of batch cooking are easier start-up and shut down, higher turpentine exploitation, and fewer problems with higher proportion of fine chips.

Advantages of the continuous cooking process are high productivity, resulting in more equal pulp quality, lower specific steam consumption, and lower specific energy costs. The space requirement is also smaller for compact designs. The process is convenient for automation and requires lesser personal care than that required for batch cooking processes.

2.2.3.2 Regeneration of Spent Cooking Liquor

Regeneration means recovery of chemicals from the black liquor and its transformation to fresh cooking liquor. In a sulfate pulp mill, approximately only one half of the technical equipment is used for pulping. The other part is used for liquor recovery owing to the high costs of the chemicals. Alkaline chemicals have to be recovered by almost 100%, which means an almost complete removal of cooking liquor from the ready pulp.

The water consumption to separate the liquor from the pulp has to be minimized. The lower the dilution of the spent liquor, the lesser water has to be vaporized.

2.2.3.2.1 Washing Process After cooking, the spent liquor is separated from the pulp in multistage washers.

Different equipment is used for this purpose – washing presses, pressurized diffusors, and drum displacers. The washing process in diffusors is rather time consuming but the rate of chemical recovery is higher than in washing presses. At the end of the washing procedures, the spent liquor has a dry-matter content of ~10%. Depending on the pulping degree, 9–12 m³ of spent liquor per ton chemical pulp are accrued. This spent liquor consists of 90% water, 5% organic substances, and 5% alkali chemicals.

2.2.3.2.2 Evaporation Plants The evaporation of the spent liquor to a dry-matter content of more than 60% is performed in evaporators with a minimum of hot steam.

Multistage evaporation plants are used (Figure 2.8), which reuse the created exhaust vapors for heating. Thus, the exhaust vapors, generated in the first evaporator which is heated with fresh vapor, are used for heating the second evaporator, which has a lower boiling temperature owing to lower pressure. Because each of the following evaporators operate with a lower pressure than the former one, the liquor is always pressed to the next evaporation column. Vacuum in the last evaporator allows evaporation at low temperature.

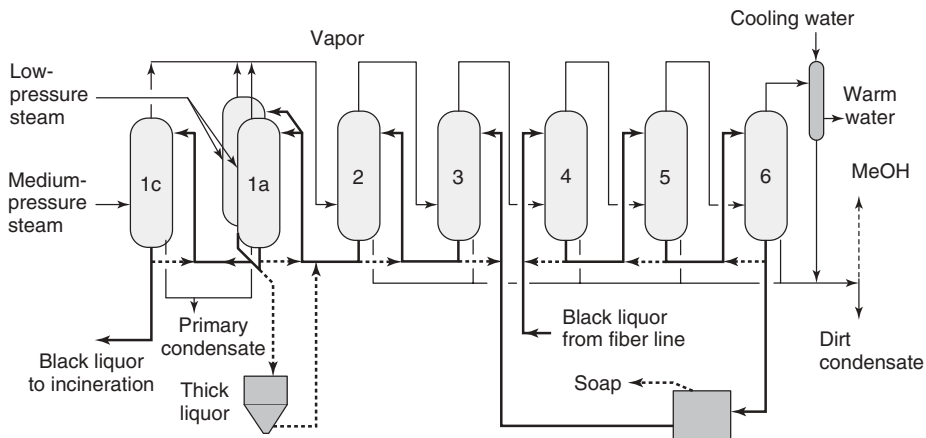


Figure 2.8 Black liquor evaporation plant [4].

The resulting thick liquor is burned in the recovery boiler (Figure 2.9), which is the most important and most expensive part of each sulfate pulp mill. In the recovery process, the remaining water is removed from the thick liquor. Organic compounds in the black liquor are burnt, and from the heat capacity of the combustion gases, steam is produced [9]. The steam vessel provides superheated steam of 4000–7000 kPa (40–70 bar).

The reduction of Na_2SO_4 to Na_2S occurs in the lower part of the combustion vessel. Combustion of organic compounds and transformation of sodium hydroxide to sodium carbonate occurs in the upper part. The so-called soda melt in the vessel is dissolved and consists of Na_2CO_3 and Na_2S .

2.2.3.2.3 Causticizing During the following causticizing (Figure 2.10), the melt reacts with lime milk $\text{Ca}(\text{OH})_2$, and sodium carbonate is transformed into sodium hydroxide. The resulting calcium carbonate is used to produce caustic lime CaO , which again is the basis for lime milk $\text{Ca}(\text{OH})_2$ in the causticizing process [7]).

2.2.4

Sulfite Pulp

Sulfite pulp is a chemical pulp generated by cooking of plant raw material in a sulfite containing cooking liquor in acidic, neutral, or alkaline environment. Presently, acidic magnesium bisulfite process is the most prevalent, because the components MgO and SO_2 can be recovered from the spent liquor by combustion. In an acidic magnesium bisulfite process, 6–10% total SO_2 is applied. Sulfite pulping is suitable only for selected wood grades, such as spruce, fir, and hemlock (softwood), and beech, eucalyptus, poplar, and birch (hardwood). Pine, larch, and Douglas fir, used mostly in sulfate pulping, are not suitable for sulfite pulping because of their phenolic compounds in the heartwood (e.g., pinosylvin), which

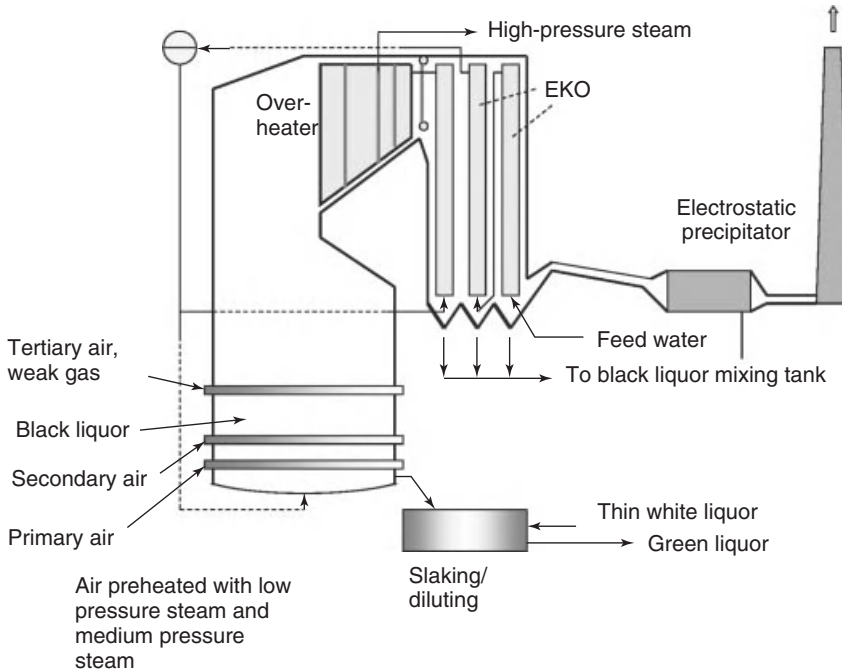


Figure 2.9 Recovery boiler for sulfate spent liquor [4].

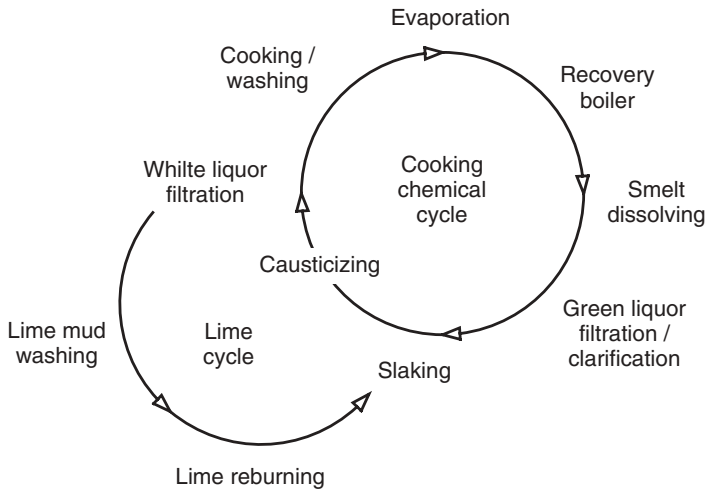


Figure 2.10 Major unit operations of causticizing and lime reburning in the context of the kraft chemical recovery cycle [10].

reacts with lignin in acidic conditions resulting in condensation products that cannot be dissolved [11].

2.2.5

Bleaching of Chemical Pulp

Bleaching of chemical pulp is performed after cooking to remove as much of the lignin and colored compounds as possible, which are retained in the pulp after washing and removal of spent cooking liquor. As a result, chemical pulp with a stable brightness ranging from 85 to 94% ISO brightness is obtained, depending on the target pulp application [12].

For special pulps with high purity, also the remaining extractives and hemicelluloses are removed in the bleaching process affecting the pulp viscosity.

Three to 5 mass% of the lignin in the unbleached pulp cannot be removed in the bleaching process. Depending on the cooking process, this lignin has been modified either by introduction of new conjugated carbon–carbon double bonds and quinone-type structures or condensation resulting in highly colored compounds (sulfate or kraft cooking) [13, 14]. The presence of covalent lignin–carbohydrate linkages is assumed to be responsible for the difficulties in removal from the pulp [15]. Sulfite pulp is easier to bleach because there are very few lignin modifications during the cooking process making the residual lignin brighter compared to that in sulfate pulp. Another reason for better bleachability of the sulfite pulp is the presence of sulfonate groups [16].

For a full delignification and bleaching of a chemical pulp, several bleaching stages are required in different sequences depending on the final product quality and end use. Oxidative chemicals such as chlorine dioxide, oxygen, hydrogen peroxide, ozone, and peracetic acid are used in a wide range of temperature, retention time, consistency, and pressure [12]. These bleaching chemicals react with lignin more or less selectively. Ozone and chlorine are the most powerful bleaching agents that are able to react with almost all types of lignin structure. Oxygen and chlorine dioxide react more selectively with free phenolic groups that are present after sulfate cooking depending on the kappa number [17, 18]. In conventional bleaching processes, hydrogen peroxide and hypochlorite are limited to carbonyl groups in general [12].

In certain cases, bleaching chemicals can also react with cellulose and hemicelluloses leading to some depolymerization and oxidation. This may affect the strength properties of the pulps and the brightness stability. The decreasing lignin content is characterized by a decreasing kappa number. The pulp viscosity is a measure for the bleaching effect on cellulose and hemicelluloses [12].

2.2.6

Semimechanical Pulp

The dominant process of semichemical pulping is the NSSC process, with sodium or ammonium sulfite as the digestion chemicals. The pulp yield is in the range

70–80% depending on the wood species, most commonly hardwood species such as birch, beech, maple, oak, and eucalyptus.

For NSSC pulping, conveyer-type or continuous-flow digesters are used. The wood chips for this process are shorter and thinner than in chemical pulping. They are preheated by steam and impregnated with a solution of sodium sulfite and carbonate or bicarbonate. After cooking – shorter at higher temperatures in the conveyer-type digester, and longer at lower temperatures in the continuous digesters respectively – the pulp undergoes a two-stage refining [3]. The yield of NSSC pulp is usually in the range of 75–85% on wood and depends on cooking time and temperature [19]. The subsequent mechanical treatment is performed to separate fibers as intact as possible from the wood matrix, which is softened during the chemical process. The generation of fines is not desired. The required refining energy depends on raw material, cooking yield, pressure, temperature, refining consistency, and refiner design [19].

2.2.7

Properties of Chemical Pulps

Sulfate or kraft pulps and sulfite pulps differ in their properties and behavior in further process steps such as refining because of different actions of the cooking liquor with regard to the fiber morphology.

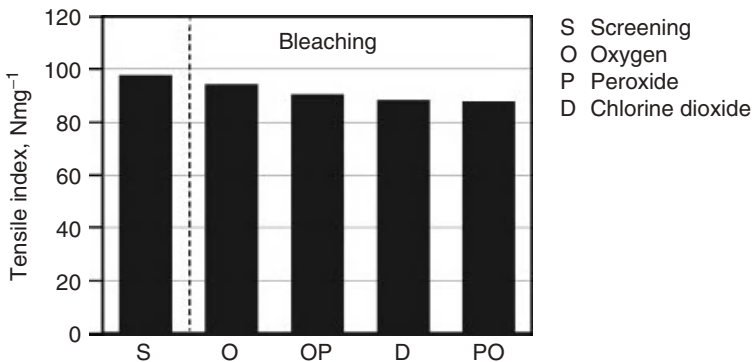
In sulfate cooking, the pulping process starts preferably from fiber lumen keeping the primary wall largely untouched. In the sulfite process instead, the cooking liquor penetrates into the fiber wall mainly from the middle lamella. This causes a partial or complete removal of the primary wall and the occurrence of pulping reactions preferably in the outer layers of the secondary fiber wall [20]. Properties of sulfate and sulfite pulps are compared in Table 2.2 [4].

The importance of the distribution of hemicelluloses in the outer fiber wall regions for the strength properties of the fibers could be approved by application of a special peeling procedure [20]. In these trials, pulps from alkaline pulping showed a high concentration of mannan and xylan in the outer fiber wall layers. Removal of these layers and thus decreasing the hemicellulose concentration in the remaining outer fiber wall regions resulted in lower tensile indexes. In sulfite pulping, the concentration of hemicelluloses in the outer fiber wall layers is significantly lower, which decreases the tensile index only marginally by peeling off these layers from the fiber wall. Both in sulfate and sulfite pulping, the tear index was nearly unchanged [4, 20].

Bleaching causes further degradation of hemicelluloses, depending on the bleaching chemicals and bleaching sequences [21]. This also affects the tensile strength, as seen in Figure 2.11.

Table 2.2 Properties of chemical pulps [4].

Properties and process behavior	Sulfate or kraft pulp	Sulfite pulp
Yield	Relatively low	Relatively high
Bleachability	More problems owing to high condensation level of the residual lignin	Good
Refining resistance	High	Low
Strength properties	High (especially dynamic properties such as tear strength)	Comparably low
		Yield, proportion of hemicelluloses and physical paper properties vary in a wide range by modification of the pulping process

**Figure 2.11** Development of tensile strength in the single sequences of a bleaching process. (Redrawn after [22].)

2.2.8

Properties of SemiMechanical Pulps

Semimechanical pulp NSSC is mainly used for fluting production, a material with high demand on sheet stiffness. Sheet stiffness is supported by a certain amount of fines. Excess proportions of fines instead are detrimental for the sheet stiffness and additionally cause dewatering problems in the corrugating medium machine [3]. Typical fractional composition data are shown in Table 2.3 [19].

Table 2.3 Typical fractional composition of NSSC (Bauer McNett) [19].

Fraction, mesh size ^a	After refining (%)	After final LC refining (%)
R14	3.5	1.0
P14/R28	17.0	6.8
P28/R48	52.5	40.5
P48/R100	16.0	12.6
P100	11.0	39.1

^aTyler series, R = retaining on the screen, P = passing through the screen.

2.3

Mechanical Pulp

Sabine Heinemann and Jürgen Blechschmidt

2.3.1

Introduction

Mechanical pulping is a thermomechanical process; but chemical processes can also play a role. Currently, two processes are relevant for mechanical defibration of wood – grinding and refining (Figure 2.12). The resulting products are groundwood and refiner mechanical pulp (RMP) [23].

Mechanical pulp is the common name for pulp received by mechanical defibration of wood independent of the applied mechanical process. *Groundwood* is the name for mechanical pulp received by mechanical defibration of round logs with a grinding stone. RMP is the common name for pulp received by mechanical defibration of wood chips in disc refiners.

During mechanical defibration, lignin is plasticized and remains in the pulp. This is the reason for the lower strength properties but higher light-scattering coefficient and opacity compared to chemical pulp. The residual lignin in mechanical pulps

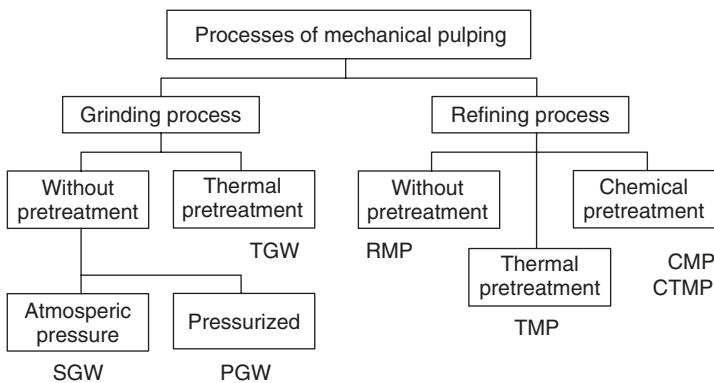


Figure 2.12 An overview of the basic mechanical pulping procedures [23].

results in a poorer and less stable brightness level. Mechanical pulps cannot be brightened by oxidative and reductive bleaching to the same extent as chemical pulps, as only negligible delignification takes place compared to the bleaching of chemical pulp.

Paper grades that contain more than 5% of pulp produced by mechanical or chemimechanical processes are referred to as *wood-containing papers*. Mechanical pulps are mainly used in short-life printing papers, hygienic papers, and board.

2.3.2

The Grinding Process

In the grinding process, round logs are pressed against a rotating pulp stone under certain pressure and temperature conditions. The pulp manufactured under atmospheric pressure is the so-called stone groundwood (SGW). Under high pressure, the so-called pressure groundwood (PGW) is produced. Depending on pressure and temperature conditions in the process, several working principles have been developed (Figure 2.13).

In the mechanical defibration of wood by grinding, numerous process parameters influence the final properties of the SGW significantly, such as

- moisture of the wood logs
- logs feeding rate or grinding pressure respectively

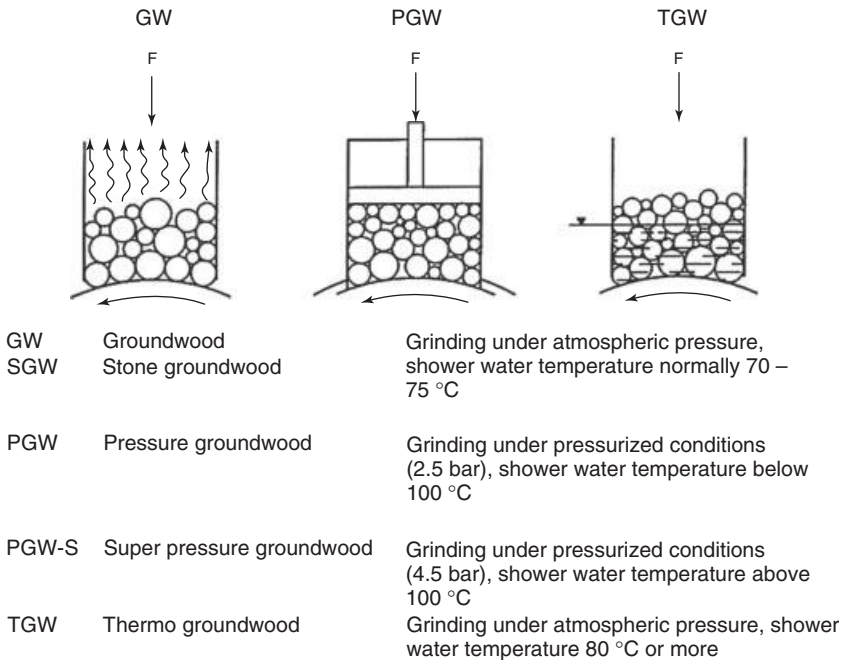


Figure 2.13 Principles of the grinding procedure [23].

- rotational speed of the pulp stone
- temperatures
- process consistency, pulp stone immersion depth
- macro and microsurface profile of the pulp stone
- specific grinding energy consumption.

Presently, grinding is done almost with only two different grinder types – atmospheric and pressurized two-pocket grinders and chain grinders. The pocket grinder is the oldest industrial grinder design, and this grinder type was essential for the development of pressurized grinding.

The grinding principle was invented by F.G. Keller in 1843 and has been practiced since then as atmospheric process for more than 100 years. A pressurized grinder has been developed by Tampella in Finland – known today as Metso Paper (Metso Corp.) – after 1970 (Figure 2.14). The pressurized grinder has higher temperatures in the grinding zone resulting in better results for the grinding of dry wood and hardwood [24].

The continuous chain grinder is widely distributed especially in Europe except Scandinavia. The first chain grinder was designed in 1921 by Voith, Heidenheim. Figure 2.15 shows a typical chain grinder.

Above the pulp stone is the log magazine. The logs are caught from the cams of the permanent moving chain elements and pressed down continuously with a certain pressure related to the feeding speed to the pulp stone.

The pulp stone is the most important part of the grinder. During the initial days of industrial grinding, natural stones were used. Artificial pulp stones have been used for more than 100 years. In Europe, there were cement-based concrete stones. In North America, the ceramic-based stones of today were developed. Artificial stones enabled tailor-made surface structures of the pulp stones.

Pressure grinding produces a pulp with higher long fiber content and higher strength than that by atmospheric grinding, and the properties are comparable to those from RMP (Section 2.3.3). One main advantage of pressure grinding is a better exploitation of the raw material without additional specific energy input and a pulp quality that enables saving of chemical pulp amounts in pulp blends.

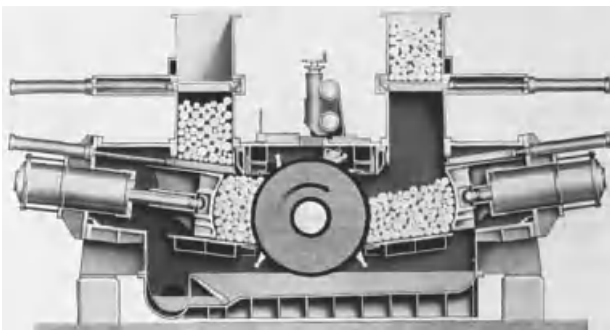


Figure 2.14 PGW grinder (Metso). (Courtesy of Metso.)

2.3.3

The Refiner Process**2.3.3.1 Refining Principles**

Fiber logs are cut down into wood chips. These chips are defibrated to mechanical pulp by means of disc refiners. Depending on the kind of chip pretreatment or chip posttreatment, several processes can be carried out and are specially defined [23, 25, 26].

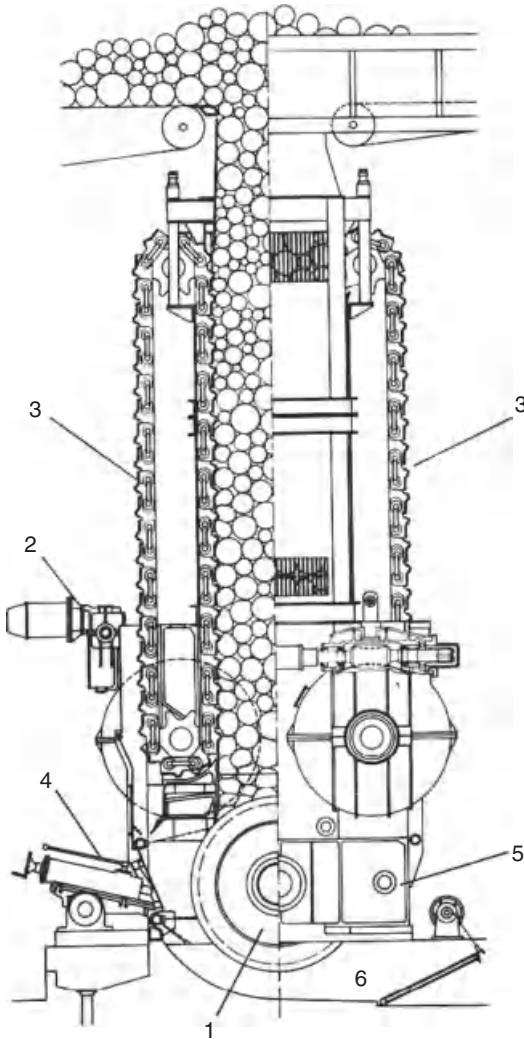


Figure 2.15 The chain grinder [30] (1) pulp stone, (2) feeding drive, (3) feeding chains, (4) stone sharpening equipment, (5) shower water pipe, and (6) grinding pit.

- **RMP (Refiner Mechanical Pulp)**

RMP is obtained by mechanical defibration of wood chips in a refiner and is carried out without pretreatment. Defibration takes place under atmospheric pressure. The wood chips are defibrated at temperatures of $\sim 100^\circ\text{C}$, mostly in two stages with consistencies of 20–30% in the second stage.

- **TMP (Thermomechanical pulp)**

In the refiner process with thermal pretreatment (TMP), wood chips are treated with steam at $140\text{--}155^\circ\text{C}$ for a short time at $300\text{--}500\text{ kPa}$ (3–5 bar) before they are defibrated under high pressure.

- **ThermopulpTM (Thermo pulp)**

Thermopulp differs from TMP in that the first-stage pulp is heated up to very high temperatures ($\sim 170^\circ\text{C}$) before entering the second refining stage.

- **RTSTM (Retention time, Temperature, Speed)**

Finnish pilot-scale research in the 1980s showed possibilities of substantial reduction of specific refining energy consumption by using high-speed refining at high temperatures in the first refining stage [27, 28]. According to this, Andritz has developed the RTS process. The RTS refiner operates usually at 2300 rpm with 550 kPa (5.5 bar) overpressure. The process includes atmospheric wood chip presteaming, and the retention time at high temperatures is 10–20 s. The RTS process is now part of the Andritz ATMP concept [29].

- **CTMP (Chemithermomechanical pulp), CMP (Chemimechanical pulp)**

In the refiner process with chemical pretreatment (CTMP/CMP), wood chips are impregnated with chemicals before they are mechanically defibrated in the refiner under high pressure of about 300 kPa (3 bar) or at atmospheric pressure, mainly in two stages. Impregnation chemicals are usually sodium sulfite and sodium hydroxide.

The CTMP and CMP processes differ in the intensity of the chemical treatment and the refining pressure. CMP is more heavily chemically treated, but refined under atmospheric pressure. In CTMP, the chemical dosage is lower, but the refining operates under pressure.

Wood chips as raw material enable the refiner processes to utilize wood qualities which are unsuitable for the grinding process, such as saw mill residues. Chemical pretreatment of wood chips opens the window also for the successful utilization of some hardwood species.

A typical flow sheet of a modern refining process is shown in Figure 2.16.

2.3.3.2 Mechanical, Thermal, and Chemical Impacts in the Refiner Process

Fiber delimitation from the wood fiber matrix occurs in the refiner process based on softening of the lignin in the middle lamella and in the primary wall of the wood fiber by pressure load frequencies in the refiner (mechanical softening), by thermal influences (thermal softening), and by chemical pretreatment (chemical softening) [23, 30].

There are numerous process parameters that are responsible for the character and the properties of the produced mechanical pulp, such as pressure and temperature during the thermal pretreatment and duration of the thermal pretreatment, the

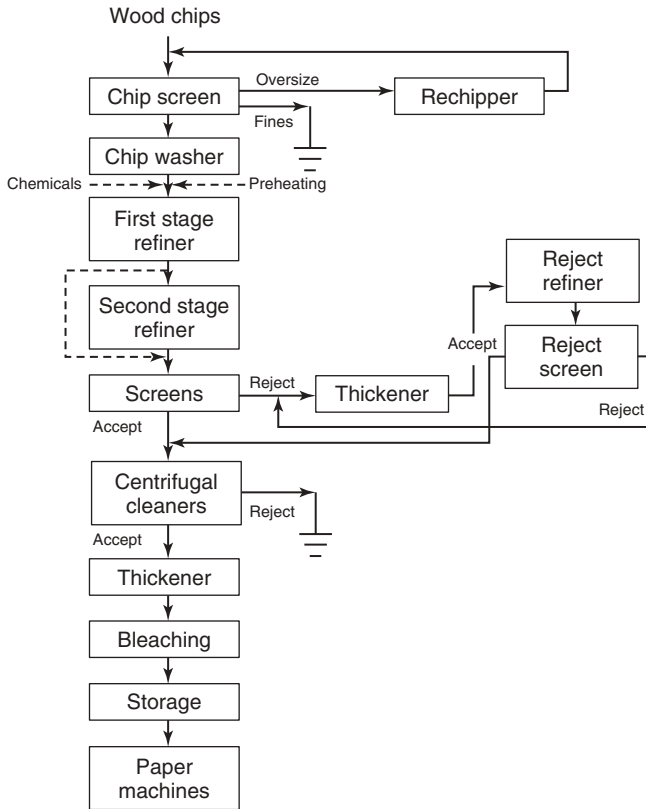


Figure 2.16 Typical flow sheet of a modern refining process [23].

addition of chemicals, the specific energy consumption, the energy distribution within the refining stages, the consistency in the refining zone of the first refining stage, the wood chip quality, and finally the refiner design [23].

The defibration temperature in the refining process is as important as for the grinding process and should be 100–130 °C. Raising the temperature to 140 °C leads to very strong lignin softening, and only little mechanical energy is required to liberate a fiber from the wood fiber matrix. But the resulting mechanical pulp has an unsuitable quality for papermaking; it is harsh and coarse. The softened lignin solidifies at the fiber surface to a hard substance; the pulp has a high refining resistance and low bonding ability. If the defibration temperature is lower than the softening temperature of the lignin, the mechanical pulp produced is coarse and has only a low level of strength properties. When the refining temperature is very close to the softening temperature, a high percentage of the fibers can be defibrated without being destroyed. The primary wall of these fibers can be damaged and allows the fibrillation of the secondary wall [23]. According to Giertz [31], the shearing frequency in a refiner is 10 kHz to 1 MHz. Following the fact that the softening temperature for high polymers increases by 7 °C when the frequency

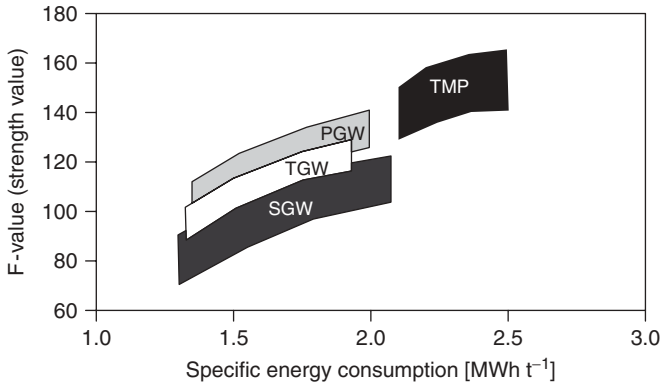


Figure 2.17 Strength value F depending on specific energy consumption. (Redrawn after [32].)

increases by $1/10$ it can be assumed that the lignin of moist chips will be softened in the refiner at 120–135 °C.

The specific energy consumption affects the property of mechanical pulps. It is at least 2 MWh t^{-1} oven-dry pulp for strongly fibrillated TMP and CTMP pulps from Norway spruce. The processing of Scots pine chips increases the specific energy consumption by 15–20%. Figure 2.17 shows how strength properties depend on the specific energy consumption. The so-called F -value in Figure 2.17 is a strength value that combines tensile strength and tear strength according to the following equation:

$$F\text{-value} = 10 \times \text{breaking length (km)} + 0.1 \times \text{tear strength (mJ m}^{-1}\text{)}$$

2.3.3.3 Machines and Aggregates for the Refiner Process

Disc refiners of different construction are widely used machines in the refiner procedure, mostly as single-disc refiners or double-disc refiners (Figure 2.18). The wood chips – pretreated if the respective process requires – enter the refiner in the center at the shaft and pass the discs from center to edge. On the refiner discs, refining plates (segments) from high strength steel with different profiles are mounted. The refiner discs are pressed together hydraulically. The refining gap has an essential effect on the mechanical pulp quality [23].

2.3.4

Mechanical Pulp Processing

The aim of mechanical defibration of wood is the complete delimitation of fibers from the wood matrix without being destroyed. This is the ideal case. In reality, a mixture of different fiber components and debris is created immediately after defibration. These components are

- shives (unsuitable particles that have to be separated from the pulp)

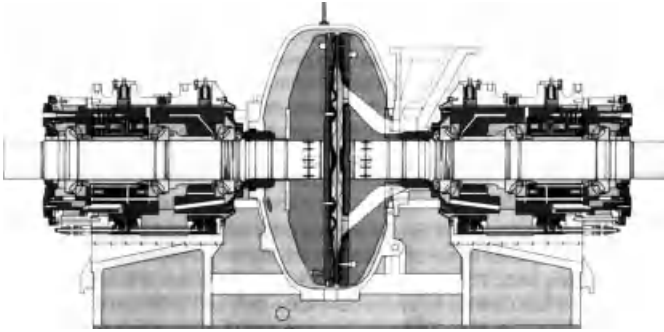


Figure 2.18 The double-disc refiner (Metso RGP 68 DD) [23].

- fibers, divided into
 - long fibers; length 800–4500 μm ; width 25–80 μm
 - short fibers; length 200–800 μm ; width 2.5–25 μm .
- fines, divided into
 - fibrillar fines (slime stuff); length up to 200 μm , width $\sim 1 \mu\text{m}$
 - flake-like fines (flour stuff); length 20–30 μm ; width 1–30 μm .

Additionally, wood pieces of different dimensions and shapes, sand, and other nonwood particles are found.

The pulp from the grinders or refiners has to be screened and washed. There are two process principles for screening in mechanical pulping:

- Pulp classification, that is, separation of the pulp into fractions of different particle sizes (applied for shives removal from the pulp)
- Separation according to particle density, that is, separation of pulp and minerals such as sand and other heavy material (applied for pulp cleaning).

Pressure screens are the most common equipment in screening and fractionation of mechanical pulp (Figure 2.19).

The pressure screen consists in a cylindrical screen basket as screening element and a concentric positioned rotor to keep the screen openings unplugged. The pulp suspension is fed from above axially or tangentially, the flow operates mainly centrifugal, and mainly the rotor rotates. Single-stage screens operate in low consistency or medium consistency. In multistage screens, several screening stages are run in one screening apparatus (Figure 2.19). Multistage screens are to replace the existing single-stage screens. Shives and stiff long fibers are removed as reject from below the screen. The filtrate moves very easily through the screen openings, which causes a thickening of the reject flow.

2.3.5

Mechanical Pulp Bleaching

The initial brightness of mechanical pulp from softwood is typically between 55 and 65% ISO, making this pulp applicable for newsprint without further bleaching

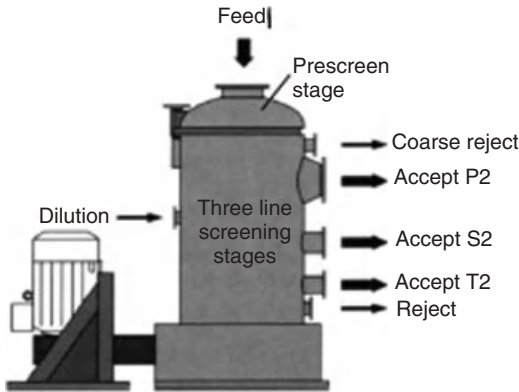


Figure 2.19 Multistage pressure screen (Metso) [23].

treatment. This initial brightness level is strongly affected by the intensity of bark removal, by the applied wood species, and by the storage time between wood harvesting and refining or grinding. The application of mechanical pulp in higher-quality paper grades such as SC paper or LWC paper requires a bleaching step [23].

Mechanical pulping processes keep most of the lignin compounds in the fibers. Applying the same aggressive chemicals such as those used in chemical pulp bleaching would result in an oxidation and removal of this lignin, decreasing the pulp yield dramatically. To maintain optical properties and the yield of the pulp as much as possible, bleaching of mechanical pulp has to be performed with chemicals of limited aggressiveness and under conditions, which keep the extraction of lower molecular weight carbohydrates and lignin compounds as moderate as possible [23]. The high temperature of the defibration process solubilizes polyoses and starts the hydrolysis of acetyl groups. Resins and lignins are partially dispersed and dissolved [33–35]. Higher pH and high temperature will intensify these effects, thus neutral or moderately acidic bleaching conditions are required to maintain the pulp yield.

Reductive bleaching with sodium dithionite is the simplest option because the available low and medium consistency after screening and latency chest can be applied. Besides an effective mixer and a tower or tube, no additional equipment is required.

Bleaching with dithionite typically is made at moderately acidic pH, between pH 4.5 and 6.5. Temperature in tower or tube bleaching is 60–80 °C. Higher temperature gives a faster response to the chemical addition. The reduction of chromophores is very fast, the time required is short: 15 min to 1 h is sufficient. The amounts of dithionite vary around about 10 kg t⁻¹ or 1% on fiber [23].

The application of the oxidative hydrogen peroxide in bleaching of mechanical pulp is by far older than its use in chemical pulp bleaching. Hydrogen peroxide will not react easily with the aromatic systems of lignin, that is why yield and optical properties such as opacity are only moderately affected by the bleaching process [23].

Pulp type		Mechanical pulp			CMP	Semi chemical pulp		Chemical pulp	
		SGW TMP	CTMP						
Yield	%	97	95	90		80	70	60	40
Biological oxygen demand (BOD)	kg t ⁻¹	10	20		50	100			200
Grinding or refining energy	kWh t ⁻¹	1200	2200	2500		1000	500	200	100
Freeness CSF	ml	100	120	200	400		600		800
Tensile index	Nm g ⁻¹	30	40	50	60		70	80	100
Light-scattering coefficient	m ² kg ⁻¹	65	60	50		40			30

Increase with refining
Decrease with refining

Figure 2.20 Characteristics of mechanical, semichemical, and chemical pulps [23, 25].

2.3.6

Properties of Mechanical Pulp

Figure 2.20 shows some of the main parameters for mechanical pulp, chemical and semimechanical pulps, sorted by yield: biological oxygen demand (BOD), grinding or refining energy (in the case of chemical pulp for final pulp preparation), freeness, tensile index, and light-scattering coefficient. The yield decreases from 97% for SGW to 40% for chemical pulp (kraft type) and the effluent impact increases, that is, the BOD increases. The specific energy consumption is lower for conventional chemical pulps than for CMPs but the consumption of chemicals is higher [23, 25].

Canadian Standard Freeness (CSF) is measured with ~100 ml for (fines-containing) SGW, and with 780 ml for chemical pulp with high long-fiber proportion.

Chemical pulps have a higher strength potential (tensile index) but lower light scattering ability. Light scattering values are given for the pulp before undergoing any additional mechanical treatment. Postrefining of mechanical pulp increases the light-scattering coefficient, whereas refining of chemical pulp decreases this parameter.

After screening and cleaning, final mechanical pulps have the following component proportions, depending on the process parameters during the defibration processes:

Shives	2–6% (extreme values up to 20%)
Fibers	50–80% (long fibers 25–55%, short fibers 25–40%)
Fines	20–50%

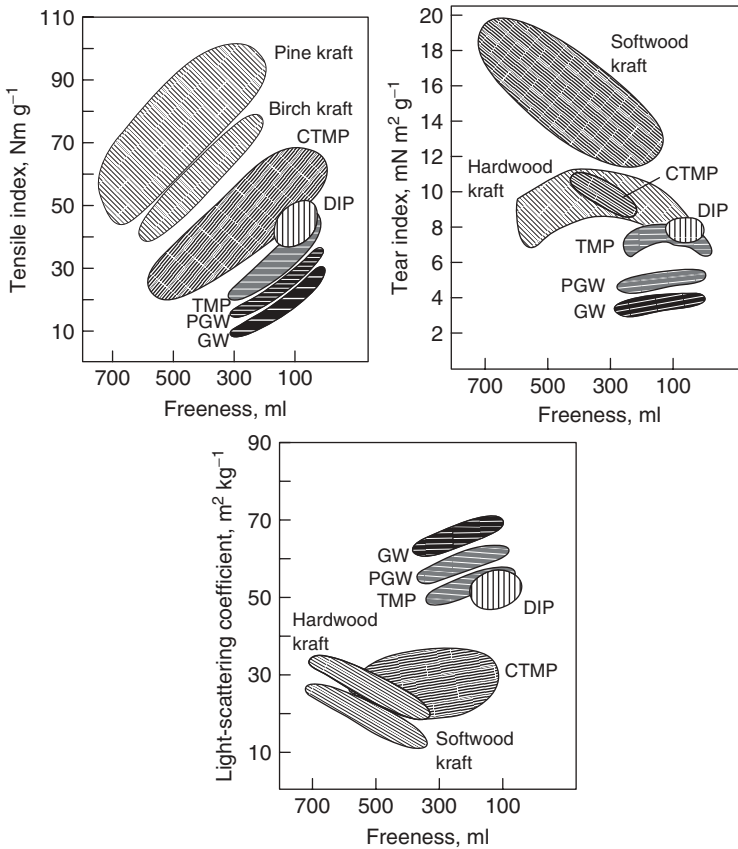


Figure 2.21 Tensile index, tear index, and light-scattering coefficient of different pulps depending on Canadian Standard Freeness (CSF). (Based on [36].)

Main parameters to characterize mechanical pulps are tensile index, tear index, and light-scattering coefficient depending on freeness (Figure 2.21). Mechanical pulps typically form bulky sheets with high light scattering. Thus, it is possible to make paper with acceptable stiffness and opacity at a considerably lower basis weight by using mechanical pulp than using chemical pulp. Compared at the same freeness level, TMP has normally the highest bulk and CTMP the lowest bulk of mechanical pulps. Regarding the mechanical pulps in Figure 2.21, groundwood pulps usually exhibit the best optical properties, whereas TMP and CTMP exhibit the best strength properties.

The yield of softwood CTMP is about 91–96%. CMP is more heavily chemically treated and therefore has more characters of a chemical pulp, that is, higher strength properties at the cost of lower light-scattering coefficient (Table 2.2). For hardwood, the yield of CMP can decrease to 80%.

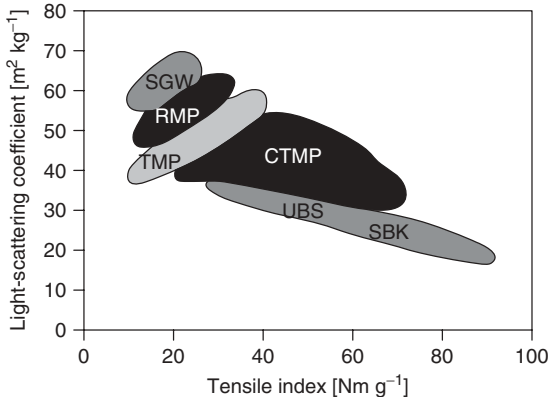


Figure 2.22 Light-scattering coefficient versus tensile index for various mechanical pulps compared with chemical pulps. (Redrawn after [37].)

Höglund *et al.* [37] compared mechanical pulps with chemical pulps according to their strength properties. The mechanical pulps were from Norway spruce wood (SGW, RMP, TMP, and CTMP), and the chemical pulps were from Scots pine (unbleached pulp USB, semibleached chemical pulp SBK). Figure 2.22 shows the respective possible property field for the tensile index and the light-scattering coefficient.

The mechanical pulping process in particular generates fiber fragments and other small particles called *fines*, which are essential for the formation of bonds between fibers, and, in addition to improving strength properties, mechanical pulp fines strongly increase the light-scattering coefficient and also improve other paper properties. The excellent properties of mechanical pulp fines are mainly considered to be a result of their small particle size and a large specific surface area in comparison with the fiber fraction [38].

Mechanical pulp fines generally deteriorate drainage less, and promote light scattering more and bonding less than chemical pulp fines. The filling of voids by mechanical pulp fines decreases air permeability and improves the smoothness of paper. Even the colloidal dissolved fines of mechanical pulp can improve bonding of unbleached pulps. In peroxide bleached pulps, the extractives in the colloidal fines can deposit on fiber surface deteriorating bonding [39].

Luukko has further distinguished mechanical pulp fines into fibrillar fines and nonfibrillar fines [38, 40]. Starting from a softwood TMP with given tensile index and light-scattering coefficient, both handsheet properties develop differently when fines are added. The higher the added proportion of fibrillar fines from chemical pulp the lower is the light scattering because of the high degree of bonding. With adding fines from mechanical pulp, light scattering increases with only gentle increase of tensile strength (Figure 2.23).

Table 2.4 displays a collection of the general quality requirements of mechanical pulps for their use in LWC and SCA printing paper grades.

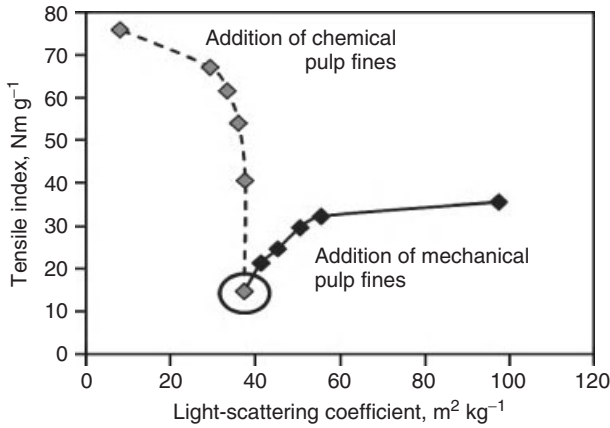


Figure 2.23 Effect of particle type on tensile index and light-scattering coefficient (circle = softwood TMP as base pulp). (Based on [40].)

Table 2.4 General quality requirements of mechanical pulp for use in LWC and SCA grades [23] SC = super calendered paper (SCA = SC grade A), LWC = light-weight coated paper.

Pulp grade	SGW	PGW	TMP	TMP
Paper grade	SC/LWC	SC/LWC	SC	LWC
Freeness (ml)	30–40	30–40	30–40	40–50
Shives content (%)	<0.05	<0.05	<0.05	<0.05
Coarse fibers (R14) (%)	<1.0	<1.0	<7.0	<3.0
Long fibers (P14/R28) (%)	10–15	14–20	28–33	22–27
Fines (P200) (%)	>36	>32	>28	>28
Apparent density (kg m^{-3})	450–500	440–500	450–520	450–500
Tensile index (Nm g^{-1})	>40	>45	>50	>50
Tear index ($\text{mNm}^2 \text{g}^{-1}$)	>3.5	>4.5	>7.0	>6.5
Light-scattering coefficient ($\text{m}^2 \text{kg}^{-1}$)	>70	>68	>58	>58

2.4

Recovered Paper, Recycled Fibers

Hans-Joachim Putz

2.4.1

Role of Recovered Paper in the Paper and Board Industry

In the past, chemical pulp was the most important raw material for paper production; but now this has been replaced by recovered paper. Two hundred and six million tons of this raw material were used globally in 2009 [41]. This volume

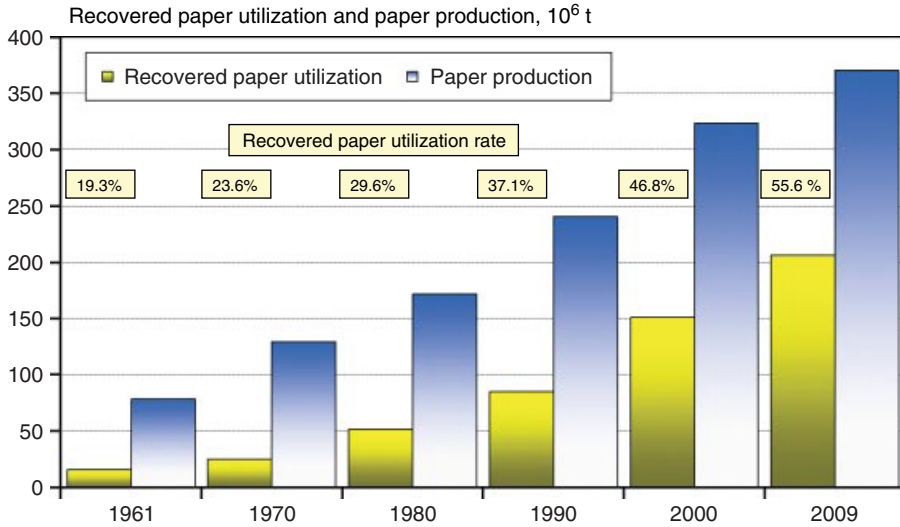


Figure 2.24 Global development of recovered paper utilization and paper production (1961–2009) [41–46].

exceeds the total volume of woodpulp, that is, chemical pulp (124 million tons) and mechanical pulp (31 million tons) [41]. These figures show that recycled fibers play a very important role today in the global paper industry as a substitute for virgin fiber pulps.

Figure 2.24 shows the global increase in recovered paper usage, compared to paper production since 1961 [41–46]. Globally, the use of recovered paper increased by ~5.5% annually, whereas annual paper production growth was only 3.3%.

The paper industry is the exclusive relevant user of recovered paper as a secondary raw material – at least in terms of material recycling. Various recovered paper processing systems with mechanical and chemical unit processes prepare recycled fibers for the production of paper and board grades. These processing systems use different recovered paper grades that contain either chemical or mechanical fibers or, mainly, an undefined mixture of both. Some paper and board grades can be made from recycled fibers exclusively. This includes paper grades such as corrugated medium and testliner or newsprint in Europe. For newsprint and other grades blends of recycled and virgin fibers are also used. The proportion of recycled fibers in the raw material furnish can vary from about 5% for fine papers to 100% depending on the paper grade or geographic region.

Figure 2.25 shows the largest recovered-paper-consuming countries. Far ahead of all others right at the top is China (62 million tons), followed by USA, Japan, and Germany (26–15 million tons each). The 12 countries listed used in total 160 million tons in 2009 corresponding to 78% of the global recovered paper consumption.

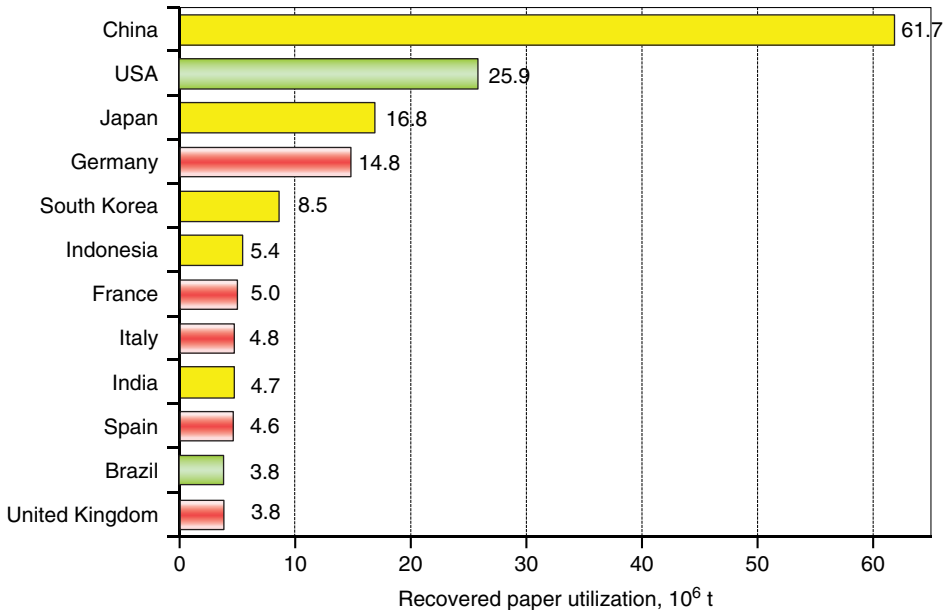


Figure 2.25 The 12 largest recovered-paper-consuming countries in the world (2009) [41].

2.4.2

Main Definitions for Statistics

Consideration of recovered paper use and recovery of used paper products requires definitions. Statistical definitions can be related to the world, a continent, a country or a certain region (e.g., Europe) or to a certain category of paper products (e.g., graphic papers or newsprint). Differentiation is given by three statistical parameters:

- Recovered paper utilization rate, in percentage, is the amount of recovered paper used as raw material in the paper industry, in tons, divided by paper production, in tons, on an annual basis, multiplied by 100.
- Recovery or collection rate, in percentage, is the amount of collected recovered paper for material recycling, in tons, divided by paper consumption, in tons, on an annual basis, multiplied by 100.
- Recycling rate, in percentage, is the amount of recovered paper used as raw material in the paper industry, in tons, divided by paper consumption, in tons, on an annual basis, multiplied by 100. Since a few years, the calculation for Europe comprises also the net trade of recovered paper.

From these definitions, it becomes obvious that the utilization rate is related to recovered paper usage in paper production, whereas the recovery rate is related to the amount of collected paper in consumption. Both rates can be affected directly either by the paper industry by the use of more or less recovered paper in paper production or by the waste management industry collecting partly recovered paper

from the paper consumed. The recycling rate has a more theoretical value based on recovered paper usage and net trade in paper consumption. A high level of recovered paper usage in paper production combined with strong net paper export rates will result in a high recycling rate, which has to be satisfied by recovered paper imports from abroad.

Recovered paper utilization rates globally and nationally may be used for comparison. Such statistics can, however, give a false impression of the recycling activities in different countries as the following discussion explains. The range of national utilization rates extends globally from 5% to more than 100%. Figure 2.26 shows the 12 largest papermaking countries, accounting for 77% of the global paper production in 2009 of 371 million tons. Simultaneously, they consumed about three quarters of the world's recovered paper volume. Heading the list are South Korea, Germany, China, and Japan with utilization rates above 64%. The lowest utilization rates are for Finland and Sweden. This is because about 90% of their paper production is exported owing to their low population figures. Owing to their low level of national paper consumption, only a small volume of recovered paper becomes available for collection.

Figure 2.27 shows the utilization rate for the three largest paper production regions in the world where the paper industry uses 85% of the global recovered paper volume: Asia, Europe, and North America. Paper production in these three regions is between 85 and 145 million tons each, resulting in recovered paper utilization rates of roughly 69% in Asia, 51% in Europe, and 35% in North America.

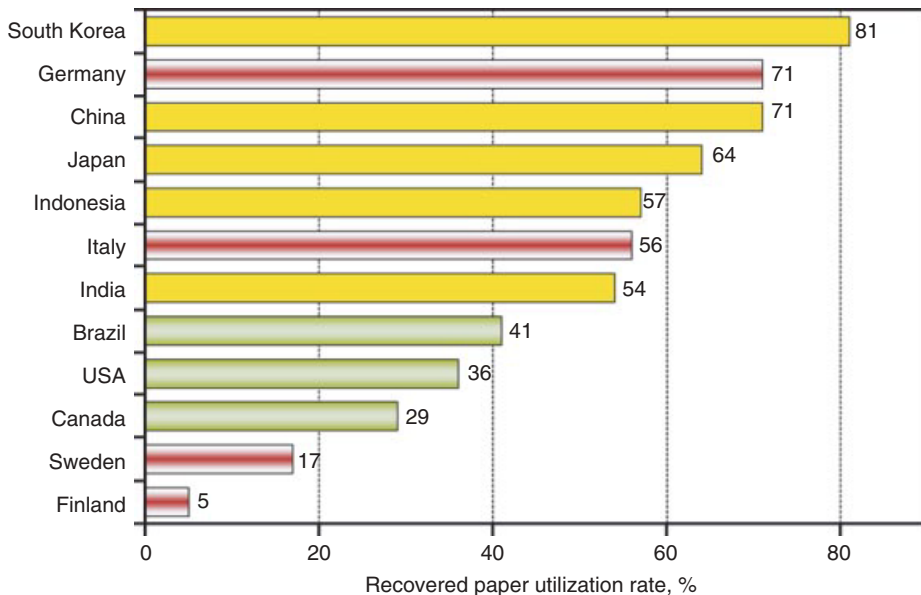


Figure 2.26 Utilization rates of recovered paper of the 12 largest papermaking countries in the world (2009) [41].

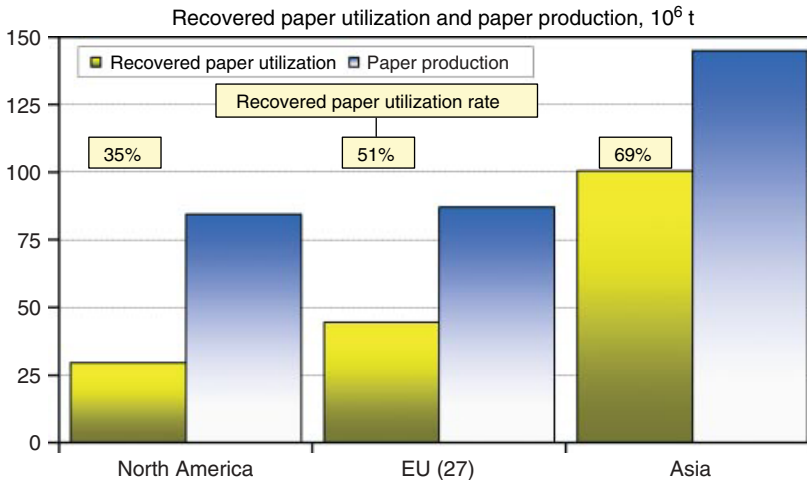


Figure 2.27 Recovered paper utilization rate and paper production in Asia, the EU countries and North America (2009) [41].

2.4.3

Utilization Rates for Different Paper Grades

Utilization rates for different countries should not be compared without further comment. It is important to know the structure of the production program of the different national paper industries in the main product categories of packaging papers and board, graphic papers, household, and hygiene papers as well as specialty papers because the utilization rates for these product segments differ significantly.

In Figure 2.28 the recovered paper utilization by the main paper categories for the CEPI countries (Austria, Belgium, Czech Republic, Finland, France, Germany, Hungary, Italy, The Netherlands, Norway, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, United Kingdom) is presented; additionally, the utilization rates are given [47]. The x-axis is a summarizing ordinate representing the total paper production in the CEPI countries of about 97 million tons, subdivided into the production of the various paper categories. The broader a single paper category, the larger the paper production (e.g., the biggest category, with 34 million tons, is other graphic papers). For each paper product category (e.g., newsprint) the used recovered paper volume is shown on the y-axis. In the circles the corresponding recovered paper utilization rate is given. It becomes obvious that the highest volume of recovered paper is used in the production of case materials (23.4 million tons) with a recovered paper utilization ratio of 94%. About the same recovered paper utilization rate of 93% is in newsprint, but with a significantly lower volume of 9.1 million tons. In the other paper categories between 1.7 and 4.2 million tons of recovered paper is used, resulting in recovered paper utilization

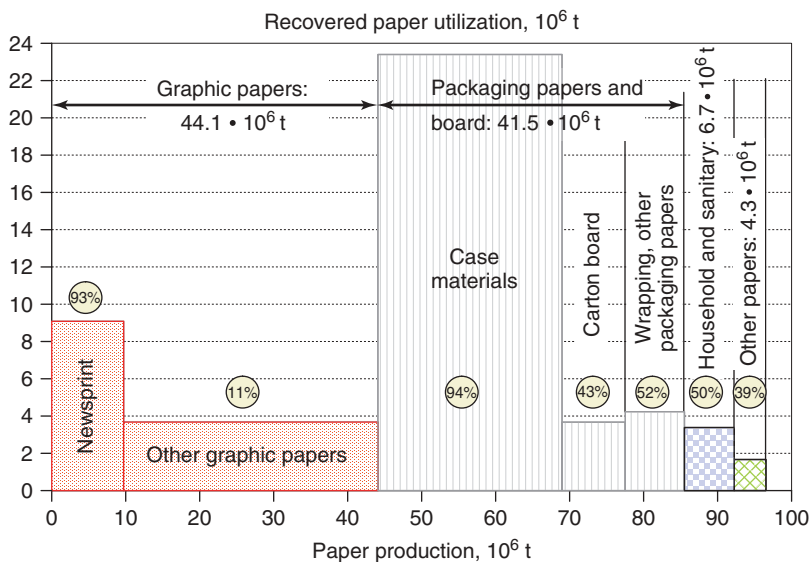


Figure 2.28 Recovered paper utilization by paper grades in the CEPI countries (2010) [47].

rates between 11% (other graphic papers) and 52% (wrapping and other packaging papers).

Traditionally, packaging papers and board have the highest recovered paper utilization rate. In the CEPI countries this ratio has reached 75% on average in categories of case materials, carton board, wrapping and other packaging papers. Demanding quality specifications have to be fulfilled by these recycled fiber-based paper and board grades to ensure trouble-free converting, for example, to corrugated board boxes or folding boxes and adequate functional characteristics of the finished products. Taking second place is the utilization rate of household and hygiene papers (50%). Owing to high yield losses in the flotation and washing steps, the proportion of recycled fibers in hygiene paper is not higher than 30% on average. The figure of 30% deinked pulp (DIP) comes from about 60% yield of 50% utilization rate. The group of other papers, comprising gypsum liners, special papers for waxing, insulating, and roofing, achieve a 39% utilization rate in the CEPI countries, but there are also many specialty paper grades such as cigarette paper, filter paper, or banknote paper for which no recycled fibers are used.

Finally, the level of the utilization rate for graphic papers is 29% of newsprint and other graphic papers on average. Owing to the wide spectrum of the paper grades produced, a distinction is necessary for this product segment because newsprint has reached a level of 93%, actually. The utilization rate of the other graphic papers is rising slowly but steadily and averages 11%. Included among these other graphic papers are wood-containing and woodfree papers that are coated or uncoated. Some use 100% recycled fiber furnish, for example, recycling copy papers.

2.4.4

Resources of Recovered Paper

Before using recovered paper for paper production, its recovery is necessary. Resources of recovered paper are in general a collection from industrial enterprises (e.g., printing houses), business operations (e.g., supermarkets) or offices, and from private households and small commercial enterprises. While the recovery of used paper from industry, business operations, and offices has a long history and can be easily managed, recovery of used paper from private households is more complex. Additional recovered paper resources cannot be expected in the first category, because these paper grades mainly belong to the so-called preconsumer grades, are of high quality, and are already recovered to almost 100%. Collected paper from private households is named “postconsumer” recovered paper, which consists usually of a mixture of different paper and board grades, which always requires a sorting process.

As far as national recycling activities are concerned, an assessment of the paper recovery rates of different countries is more relevant than a comparison between national recovered paper utilization rates. Figure 2.29 shows the collection rates versus the utilization rates of recovered paper in the CEPI countries. The bubble size is equivalent to the tonnage of paper consumption used in each country and therefore indicates the potential of paper waste to be recovered. Owing to intensified collection in each country, the average rose from 41% in 1991 to 67%, corresponding to a total volume of recovered paper of 57 million tons in 2010. It becomes obvious that the highest collection rates (>75%) in the CEPI countries are by Austria, United Kingdom, Germany, Switzerland, Norway, and the Netherlands, whereas the highest utilization rates (>70%) are in Germany, the Netherlands, Spain, United Kingdom, Romania, and Hungary. The largest tonnages of recovered

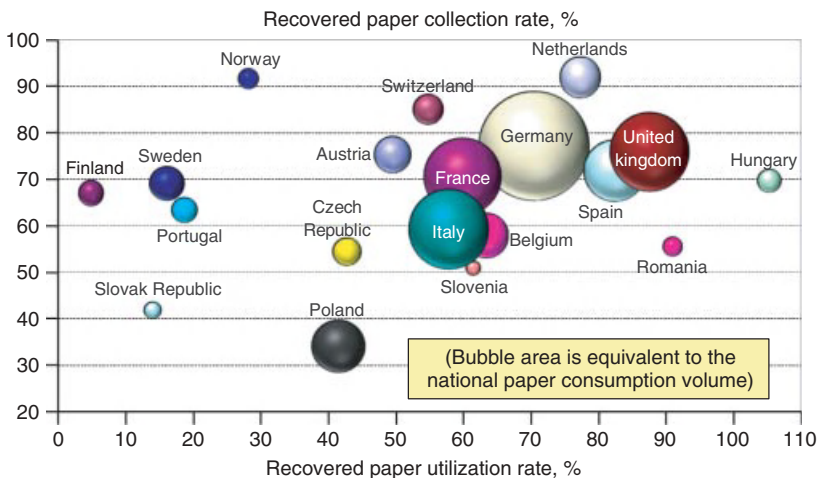


Figure 2.29 Recovered paper utilization and collection rates in the CEPI countries (2010) [47].

paper are used in the United Kingdom, Spain, Italy, France, and Germany where ~73% of the total utilized recovered paper (49 million tons) is used.

The maximum paper recovery rate in an industrialized country with a well-developed infrastructure is about 80% [48]. This theoretical limit of the recovery rate occurs as ~20% of the used paper products are not collectible, because they are contaminated, long living products or are destroyed by disposal or burning. This includes hygiene paper, specialty paper products, long-life paper products, papers used in industrial applications, and papers used for other purposes in private households such as fuel or compost material. Considering the theoretical recovery rate of 80%, the recovery rate of 77% already achieved in 2010 in Germany is equivalent to a paper collection efficiency of about 95%. Collecting additional used paper is probably not economically feasible.

At the global level, no data are available for the different sources of collection systems of recovered paper by tonnage. In Europe, CEPI has conducted recovered paper surveys, which found, for 2010, the following five sources of recovered paper:

- recovered paper from households: 38%
- recovered paper from trade and industry: 37%
- recovered paper from converting and printing: 12%
- recovered paper from offices: 10%
- recovered paper from unsold newspapers and magazines: 3%.

The recycling rate was introduced by CEPI for the first time as the relation between recovered paper utilization and paper and board consumption, and is now extended to net trade. On the basis of the consumption of paper and board, the figure indicates the internal material recycling of recovered paper in a country or a region as well as its net export of recovered paper for which a material recycling process is assumed. Nevertheless, recycling rates close to 100% indicate that either a large amount of recovered paper is imported or a high volume of produced paper and board is exported. Figure 2.30 shows the development of the recycling rates in the CEPI countries from 1991 with an increase of 2.8% p.a. until 2010, when it was approaching 69.3% where it should reach 66% ($\pm 1.5\%$) in 2010 according to the last European Declaration [49].

2.4.5

Lists for Recovered Paper Grades

Globally no common list of recovered paper grades exists. A European Standard was established in 2001 by CEN (European Committee for Standardization) as EN 643 for Europe [50]. All recovered paper grades are classified into the following five groups:

- Ordinary grades
- Medium grades
- High grades
- Kraft grades
- Special grades.

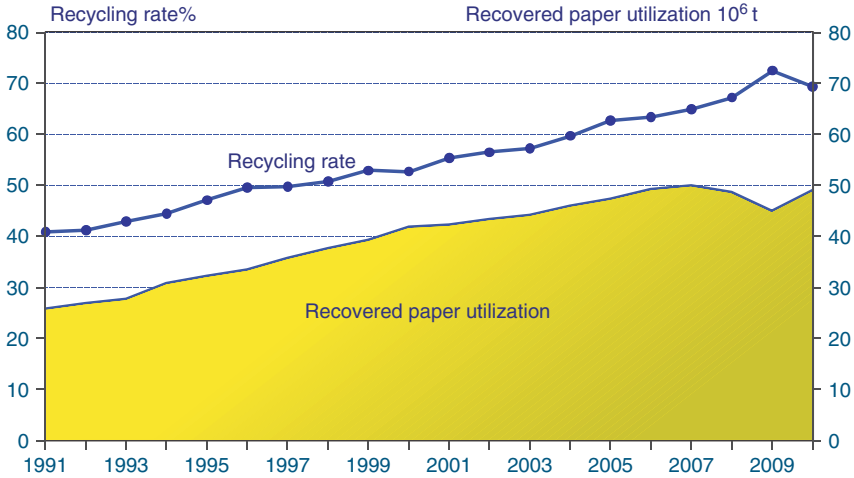


Figure 2.30 Development of recycling rate and recovered paper utilization in the CEPI countries [47].

Recovered paper grades are generally not defined by physically verifiable quality characteristics. Instead, the naming of recovered paper in the list uses one of the following criteria:

- Places of occurrence, such as supermarket corrugated paper and board (1.04)
- Former paper grades of the recovered paper, such as mixed magazines and newspapers (1.10)
- Mixed categories such as mixed sorted papers and boards (1.02).

In Europe, the use of DIP in newsprint dominates (48%), followed by printing and writing papers (18%) as well as hygiene papers (16%). Therefore, another very important paper grade in Europe describes a wood-containing recovered paper mix, commonly used for deinking. It is called *sorted graphic paper for deinking* (1.11) and originates primarily from household collections.

The complete list of recovered paper grades is available on the web site of GesPaRec under <http://www.gesparec.de/apsorten.html>.

Recovered paper grade lists are not comparable among Europe, USA, and Asia. Therefore recovered paper grades are summarized very often in the following four groups:

- **Mixed grades:** comprising always a mixture of various paper and board grades used for the production of packaging paper and board.
- **Corrugated and kraft grades:** comprising predominantly packaging paper and board grades used for the production of packaging paper and board. The term OCC is also very often used for this recovered paper grade and stands for “old corrugated containers.”

- **Deinking grades:** comprising exclusively graphic paper grades used – after a deinking process – predominantly for the production of graphic and tissue papers.
- **High grades:** comprising predominantly white, lightly printed graphic papers and board (very often woodfree), recovered by separate collection and therefore relatively clean.

2.4.6

Use of Recovered Paper Grades

Figure 2.31 shows that the use of recovered paper in paper production in the CEPI countries varies greatly by grade of recovered paper. In 2010, the consumption of recovered paper of all CEPI countries was as follows:

- 44% OCC grades
- 26% deinking grades
- 19% mixed grades
- 11% high grades.

While mixed grades and OCC grades (93% by weight) primarily find use in the production of packaging papers and board, the majority of all deinking grades (66% by weight) go for graphic paper production. These recovered paper grades are also used for household and sanitary papers with the addition of nearly three-quarter high grades. The production of other papers requires various proportions of all four recovered paper grade groups.

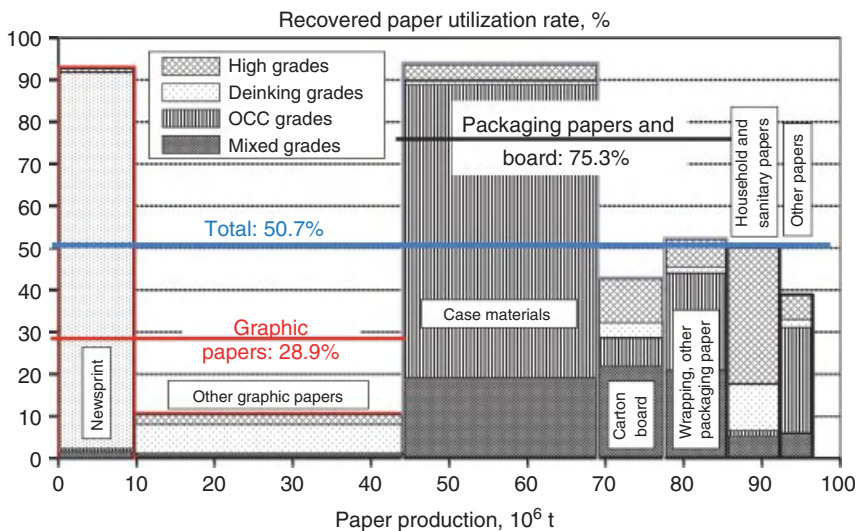


Figure 2.31 Recovered paper utilization by paper grades in the CEPI countries (2010) [47].

The total amount of 49 million tons of recovered paper was used:

- 48% for the production of case materials
- 19% for newsprint production
- 9% for wrappings and other packaging papers
- 7% for carton boards
- 7% for household and sanitary papers
- 7% for other graphic papers
- 3% for other paper grades.

The individual paper grades need specific recovered paper grades as raw materials. Thus collection and sorting of these resources has to be done in such a way as to satisfy the needs of the paper industry.

2.4.7

Requirements of Paper Products with Respect to Recyclability

Paper recycling is not an invention of the modern times. Processing of used rags in the eighteenth century for manufacturing of paper was already a form of recycling. By the invention of the production of mechanical and chemical pulp fibers from wood in the nineteenth century the use of rags was declining. Instead used papers became more favorable as raw material for paper production. In the beginning recovered paper was used only for manufacturing packaging paper or board (“brown” papers). But already in 1774 Justus Claproth [51], a professor in jurisprudence, published a small booklet with the translated title “An invention to make new papers from printed papers by washing out the printing ink completely from the pulp,” which can be considered the forerunner of a recovered paper process with ink removal, presently named deinking. Nowadays deinking is mainly performed as a flotation process to manufacture new graphic papers (“white” papers) such as newsprint or LWC from used recovered paper grades for deinking purposes.

The natural strength of paper is based on hydrogen bonds between the fibers. Because these bondings are easily dissolved in the presence of water with some mechanical action, paper is an ideal raw material for recycling. Initially, most papers produced are applicable for recycling. One exception, for example, are wet-strength paper grades, which are not completely disintegrated into single fibers in a typical recovered paper processing mill. Nevertheless, with more sophisticated operations such papers can also be defibered in a special process. But the majority of paper grades such as newsprint, LWC, and SC papers as well as folding boxboard or paper grades for corrugated board are predetermined for recycling. Fibers separated in water can easily form a new paper sheet, which develops its strength automatically during the dewatering and drying process of the paper by establishing new hydrogen bonds.

Recycling related problems arise typically not from the paper, but from the paper products produced. To come from the unprinted newsprint paper to a newspaper, ink has to be applied on the paper and this ink can later on create problems during the removal in a recycling plant. Another example is adhesive applications, utilized,

for example, to manufacture a magazine, a paperback as well as a cardboard box or a corrugated box. If the adhesive particles are not strong enough in wet conditions, they disintegrate in very small particles during pulping, becoming insufficiently removable by screening and cleaning and creating problems in terms of reduced runnability of paper machines, converting machines or quality problems of the manufactured paper. From this point of view, it has to be postulated that each paper product entering the business cycle should be manufactured as a recycling friendly (benign) paper product.

Despite the fact that industrial paper recycling has a very long history, requirements for recycling benign paper products are relatively young, but common methods are not very well known and sometimes also under discussion owing to misunderstandings. One reason for this is that the requirements to be achieved have always to be related to a single paper product, whereas paper mills usually treat recovered paper mixtures. These mixtures consist of a variety of paper products and it can be argued that the tested paper product is only a minor proportion of the recovered paper mixture. To recognize this argument the level of some parameters of a recycling benign paper product is significantly below the quality requirements of industrial manufactured paper.

The oldest method of testing recyclability is the PTS Method RH 021/95 for paper or board packaging materials or of print products on a laboratory scale [52]. While the test of packaging materials is still used, for example, to obtain the RESY symbol for corrugated boxes, the tests for printed paper products nowadays are performed according to INGEDE Methods described later on. The PTS test exclusively deals with individual paper products. Because the objective of paper recycling is not to recycle nonpaper materials, the materials examined must only satisfy the specification "suitable for recycling." For this purpose, the nonpaper components are not permitted to disturb recovered paper processing and paper production, place an unjustifiable stress on process water and effluent, or negatively influence the quality of the new paper produced from the recycled fiber pulp. A nonpaper material is suitable for recycling if it can be sufficiently separated from the pulped recovered paper by recognized technical processes and recycled or disposed without damage to the environment.

The method differentiates between packaging materials or print products intended for recycling into two classes:

- Category I (printed products) or
- Category II (packaging materials).

This subdivision does not constitute any quality evaluation. It simply considers the fact that the intended use of the new paper and board product containing recycled fibers puts different demands on the paper products used. Depending on the categorization of a paper product, the content of residues also has importance for the recyclability test by the PTS method [53].

- Category I include paper products from white or bleached fiber furnish that can be processed to DIP owing to their composition and character. They have use

primarily for production of graphic paper grades and hygiene paper. Owing to the fact that this test has been substituted by INGEDE Methods, it will not be further discussed here. Additional information can be found in literature [54].

- Category II includes all other products especially board and cardboard products including unbleached and brown papers that need not satisfy optical requirements such as brightness. They are not suitable to produce new white products but are suitable to make brown grades of board, testliner, or corrugating medium.

With Category II paper and board products that are usually collected in mixed recovered paper grades, the first step is to determine the residual mass after screening the repulped sample on a perforated plate with holes of 0.7 mm diameter as Figure 2.32 shows. With a residue mass of more than 50%, the paper or board product is classified as “not recyclable.” For 20–50%, the material is “recyclable but requires improvement in the product design” provided that the other test criteria are satisfied. If the residue mass is less than 20% and all other test criteria are satisfied, the product is categorically classified as “recyclable.”

When the rejected mass is below 50%, the test also includes screening using a 0.15 mm slotted plate and the production of a handsheet from the screen accepts. The test sheet should not adhere to the blotter board or the cover sheet used in the Rapid-Köthen device according to the German standard. The handsheets produced may contain only a small number of transparent spots or optical inhomogeneities (dirt specks). If adhesion occurs, the evaluation is “nonrecyclable due to tacky impurities.”

When transparent spots or optical inhomogeneities are observed, but no adhesion occurs, the product is classified as “recyclable with reservation due to optical inhomogeneities in the processed pulp” although the number and area of these defects are not numerically defined. Reduced quality caused by the dirt specks can possibly be reduced by an effective dispersion in industrial processing.

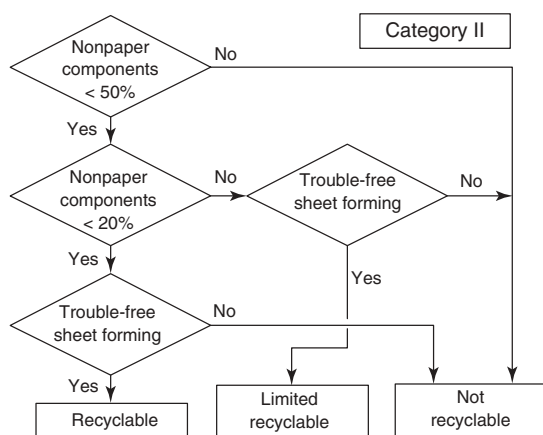


Figure 2.32 Evaluation scheme for board products of category II.

For paper products that have to be deinked, two test methods according to INGEDE have been very well established. They comprise a deinkability test on the one hand and a test on the fragmentation behavior of adhesive applications on the other. A print product has to pass both tests for overall positive recyclability with adhesive applications. If a print product contains no adhesive application, only INGEDE Method 11 is necessary to judge on the recyclability of a printed paper product, which then is reduced to the assessment on deinkability only. Two methods are valid for testing:

- **INGEDE Method 11:** “Assessment of Print Product Recyclability – Deinkability Test” [55] and
- **INGEDE Method 12:** “Assessment of the Recyclability of Printed Paper Products – Testing of the Fragmentation Behavior of Adhesive Applications” [56].

The test results of both methods are evaluated according to procedures published by the ERPC and give an easy-to-handle assessment result in one figure – the total score

- **ERPC document from March 2009:** “Assessment of Printed Product Recyclability – Deinkability Score” [57], and
- **ERPC document from July 2011:** “Assessment of the Recyclability of Printed Paper Products – Scorecard for the Removability of Adhesive Applications” [58].

2.4.7.1 Deinkability

The deinkability test according to INGEDE Method 11 is shown in a simplified sketch in Figure 2.33. It simulates at laboratory scale pulping and flotation, the two major process steps for ink removal. Before pulping all samples are artificially aged for three days to simulate typical natural aging of about three months. According to INGEDE Method 11 three quality parameters characterize the DIP in brightness,

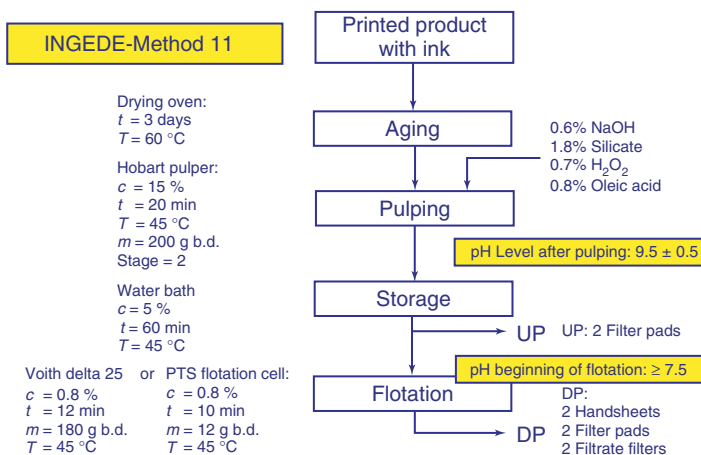


Figure 2.33 Deinkability test according to INGEDE Method 11.

color shade on the red–green axis and cleanliness (luminosity Y , a^* -value, dirt speck area A). Dirt speck area is determined in two size classes, comprising all visible specks above $50\ \mu\text{m}$ diameter and separately large specks with a diameter above $250\ \mu\text{m}$ for the most disturbing particles. The two last characteristics determined are the process parameters ink elimination (IE) and the discoloration of the filtrate (ΔY). The results of the single parameters give the experts an indication in which direction a print product has to be improved to pass the test or which problems are to be expected when large volumes of such a print product enter a commercial deinking line.

The assessment by the ERPC deinkability scoring system is based completely on the deinkability results according to INGEDE Method 11. The results of the deinkability tests are converted into deinkability scores. Therefore, one of the five print product categories has to be selected: newspapers, coated or uncoated magazines, and stationery. Stationery print products are subdivided below and above a luminosity level of 75 of the unprinted base paper and are defined as print products used for formal or personal correspondence, lottery tickets or one-side printed products mainly printed by digital printers. For further definition and examples of the print product categories, see the ERPC document [57] or the final report [59] on the COST action E48 “The Limits of Paper Recycling.” The scoring system allows to express the deinkability assessment in terms of one figure by weighing the parameters according to their importance. Additionally, the deinkability scores provide the opportunity for cross comparisons between different product categories. The maximum score is 100 points in all product categories.

To achieve a common point system, threshold as well as target values are defined. Depending on the type of threshold values, a lower threshold, an upper threshold, or a threshold corridor are fixed which have to be exceeded, undercut or met respectively. These threshold values which are independent of the print product categories are listed in Table 2.5. For a given print product, threshold values have to be fulfilled for each parameter. If one or more threshold levels are not reached, a print product is judged as “not suitable for deinking.”

According to Table 2.6 target values of the parameters color shade (a^* -value), dirt speck area (A_{50} and A_{250}), and filtrate darkening (ΔY) are equal for each print product category. The target values of the luminosity of the DIP (Y) and the IE have differing levels depending on the print product category.

If the target value of a parameter is met, the full score is given for this parameter. The scores of the six parameters in Table 2.7 have different values in order to reflect their importance. The DIP quality parameters have the largest impact on

Table 2.5 Threshold values of the ERPC deinkability score.

Parameter	Y points	a^*	$A_{50}(\text{mm}^2\ \text{m}^{-2})$	$A_{250}(\text{mm}^2\ \text{m}^{-2})$	IE (%)	ΔY points
Lower threshold	47	–3.0	–	–	40	–
Upper threshold	–	2.0	2000	600	–	18

Table 2.6 Target values of the ERPC deinkability score.

Category of print product	Y points	a^*	A_{50} ($\text{mm}^2 \text{m}^{-2}$)	A_{250} ($\text{mm}^2 \text{m}^{-2}$)	IE (%)	ΔY points
Newspapers	≥ 60	≥ -2.0 to $\leq +1.0$	≤ 600	≤ 180	≥ 70	≤ 6
Magazines, uncoated	≥ 65				≥ 70	
Magazines, coated	≥ 75				≥ 75	
Stationery (Y of base paper ≤ 75)	≥ 70				≥ 70	
Stationery (Y of base paper > 75)	≥ 90				≥ 80	

Table 2.7 Maximum score per parameter of the deinkability score.

Parameter	Y	a^*	A_{50}	A_{250}	IE	ΔY	Total
Maximum score	35	20	15	10	10	10	100

the total deinkability score with a proportion of 35% for the luminosity, followed by the dirt particle areas (25% as total of A_{50} and A_{250}) and color (20%). The process parameters IE and filtrate darkening each contributes to 10% only.

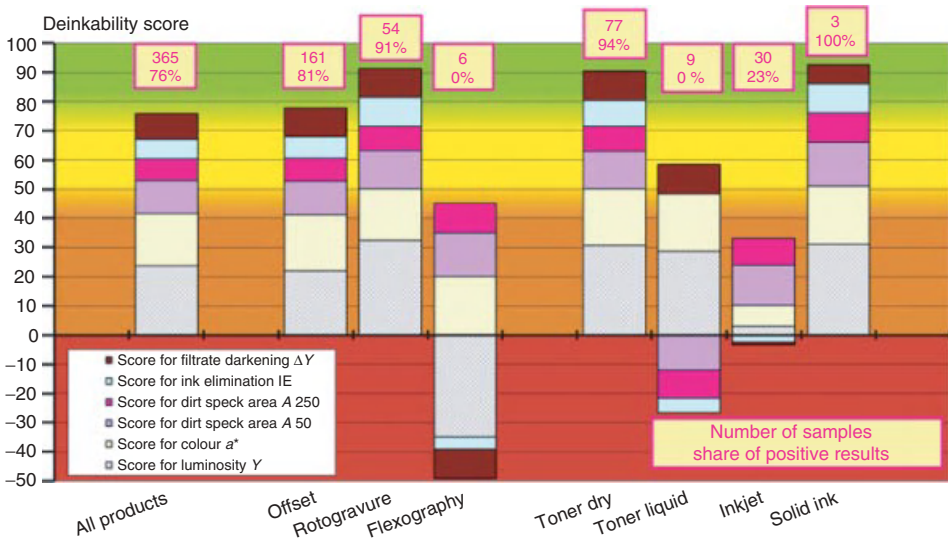
Between the threshold and the target value of each parameter, the score is linearly subdivided, resulting in a constant increment per parameter. Finally, the score of all five parameters is added up to provide a single number that corresponds to the total score for a particular print. This allows a simple overall assessment on the deinkability of a print product with one numerical value between 0 and 100 points comparable to test results of consumer goods (Table 2.8). If one or more threshold values fail, the print product is considered unsuitable for deinking. Anyhow, the product may be recyclable without deinking – for example, in a board mill. If all thresholds are reached the product is judged to be deinkable with three various gradations: poor, fair, and good. An easy-to-handle deinkability score calculator is available from the ERPC web site named “Assessment of Print Product Recyclability – Deinkability Score – Calculator” [60].

Figure 2.34 shows an overview on deinkability scores subdivided by printing technology. So far 365 print products are tested (left column) with an average total score of about 76 points. Seventy-six percent of all samples passed the test successfully. Most print products evaluated were printed in the traditional printing technologies offset and rotogravure. In these two categories the percentage of positive test results is much higher than in average: 81 and 91%, respectively. The average result of offset printed products is lower owing to the fact that the category offset comprises a large number of newspapers. The average score of rotogravure

Table 2.8 Rating of the deinkability scores.

Score	Evaluation of deinkability
71–100 points	Good deinkability
51–70 points	Fair deinkability
0–50 points	Poor deinkability
Negative (failed to meet at least one threshold)	Not suitable for deinking ^a

^aThe product may be well recyclable without deinking.

**Figure 2.34** Deinkability scores depending on printing processes.

printed products is significantly higher than the total average based on the higher luminosity of the DIP (see first lower part of the column) as a consequence of brighter and also coated papers. In contrast, the few tested flexographic newspapers never obtained a positive test result owing to hydrophilic and too small ink particles, which result in poor luminosity of the DIP, low IE, and high filtrate darkening.

By simulating a one loop deinking process the investigated liquid toner prints also never received a positive deinkability judgment. But from the figure (third column from right) it becomes obvious that the problems are related to another problem: too high ink speck areas (total area A_{50} and large particle area A_{250}) and too low IE. From inkjet prints until now only about one quarter obtained a positive deinking result. Those positive tests are either based on modified new formulated experimental inks or special coated papers. Typically inkjet inks fail the deinkability test owing to the same reasons as flexographic printed papers.

Digital print products manufactured by printing machines with dry toner or solid ink systems are typically not problematic in terms of deinkability.

2.4.7.2 Removability of Adhesives Applications from Graphic Paper Products

The evaluation of the fragmentation behavior of adhesive applications of graphic paper products is based on a macrosticky measurement described in INGEDE Method 4 [61]. This analysis is based on a laboratory screening procedure, where the reject is prepared after screening in such a way that adhesive impurities can be detected by a scanner based image analysis system. The method finds its application in mill control procedures as well as a part of assessment method for the removability of adhesive applications in INGEDE Method 12 [56]. This method simulates the screening ability of adhesive applications during recovered paper processing in a deinking mill. The two essential process steps are pulping with deinking chemicals and screening under defined physical conditions (Figure 2.35).

The particle size distribution of the macrostickies is measured (by area), thus allowing the assessment of the screening capability of the adhesives application in industry (Figure 2.36). Research work has proved that mechanical screening is the most effective tool for sticky removal in industrial processes. Sticky particles should be as large as possible in order to be screenable. It was found that macrostickies above 2000 μm diameter (determined by INGEDE Method 4) guarantee a complete removal in a state-of-the-art recycling process of recovered paper for deinking (Figure 2.37).

It is important to realize that the sticky result of a laboratory screening test depends not on the screening device used (Haindl classifier, Pulmac MasterScreen,

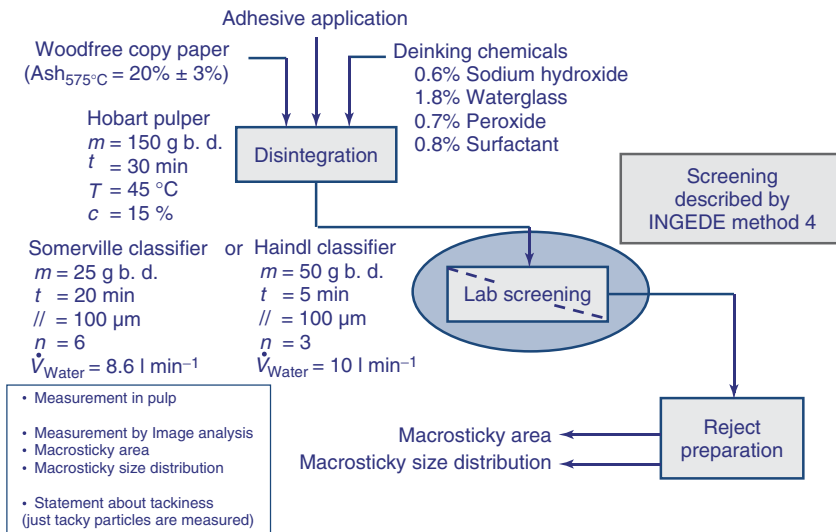


Figure 2.35 INGEDE Method 12: testing procedure of the fragmentation behavior of adhesive application.

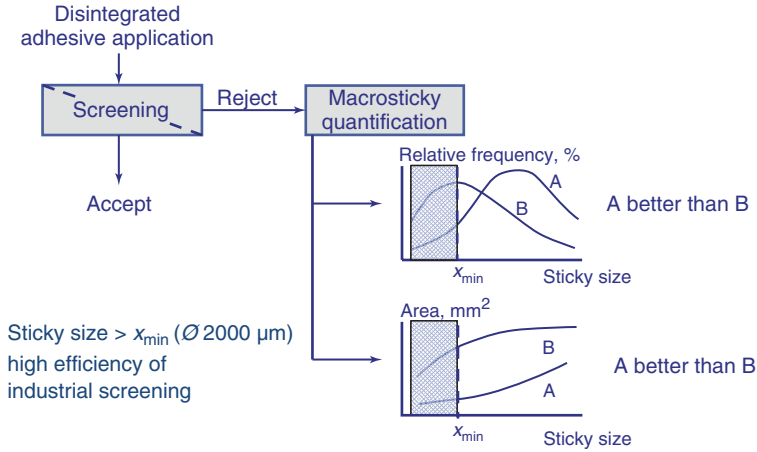


Figure 2.36 Assessment of sticky potential according to INGEDE Method 12.

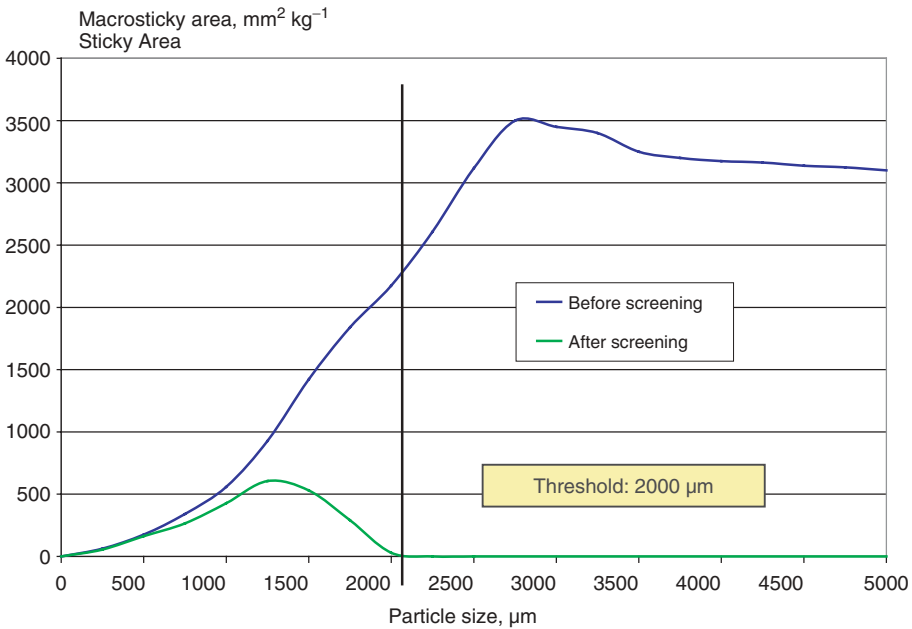


Figure 2.37 Macrostickiness area distribution before and after industrial screening.

or Somerville classifier), but on the largest slot width of the applied screen plate. The nominal slot width is not sufficient for characterizing a laboratory screen, because the width of the real slots always follows a frequency distribution and it is always the largest slot on the plate that finally affects the screening result (Figure 2.38) [62]. This is based on the fact that laboratory screening takes always a

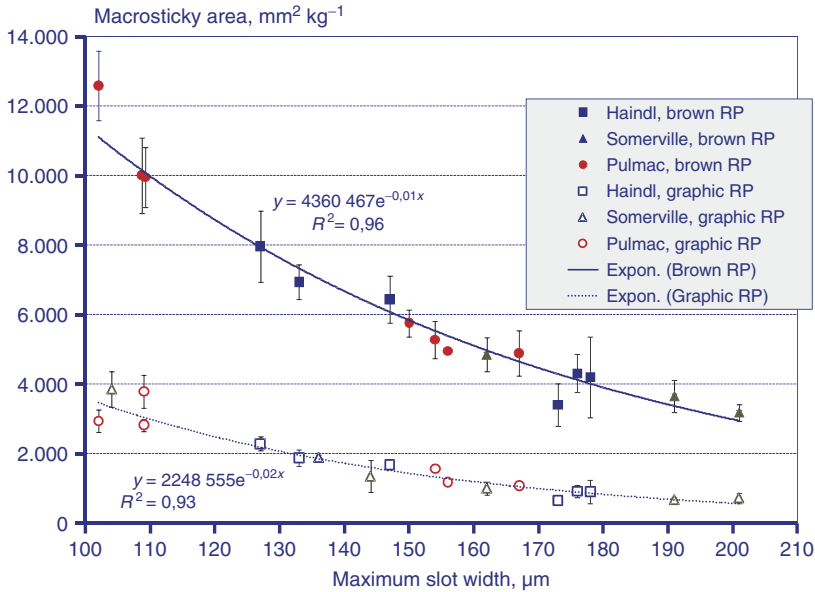


Figure 2.38 Correlation of sticky area versus maximum slot width (brown recovered paper and graphic recovered paper).

long time at high dilution, which increases the probability that all particles smaller than the widest slot will pass the plate.

The assessment of the removability of adhesive applications from graphic paper products is in principle adapted to the assessment of the deinkability score. A complete product is evaluated and the relevant parameters are the area and share of the sticky particles according to INGEDE Method 12 below $2000 \mu\text{m}$ diameter [63]. This particle size corresponds to the two dimensional sticky size after visualization and is not equivalent to the three dimensional real particle shape in the pulp. It has been verified in several mill scale examinations that after screening in a modern industrial process no particles above $2000 \mu\text{m}$ are existent in the recovered paper pulp. Actually there exists only one upper threshold of 50% for the share of macrostickies below $2000 \mu\text{m}$. If this threshold is exceeded an adhesive application is judged as “insufficiently removable.” For applications with a threshold below 50% a theoretical macrosticky area (A_t) after industrial screening is calculated based on mill data. The screening efficiencies for the removal of macrostickies are listed in Table 2.9. The sticky removal below $600 \mu\text{m}$ diameter is not considered because in this size class area, the removed stickies in industrial screening are compensated by fragmentation of larger sticky particles.

The theoretical total macrosticky area (A_t) calculated with the given efficiencies is characterized by a scoring limit of $5000 \text{mm}^2 \text{kg}^{-1}$ paper product. If this scoring limit is exceeded the adhesive application gets evaluated with zero points, but in contrast to the assessment of the share of the sticky area below $2000 \mu\text{m}$ the products gets no depreciation as “insufficiently removable.” Target values

Table 2.9 Screening efficiencies for calculation of the removability score.

Size class of macrostickies (equivalent circle diameter) (μm)	Removal efficiency (%)
<600	0
600–1000	20
1000–2000	80
>2000	100

according to Table 2.10 are given for the share of the macrosticky area below 2000 μm and the calculated theoretical total macrosticky area. Results below the target values of 10% for the share of the macrosticky area below 2000 μm and 500 $\text{mm}^2 \text{kg}^{-1}$ product for the calculated theoretical total macrosticky area lead to the full score of 80 points for A_t and 20 points for S_{2000} (Table 2.11). Results of target values and threshold values with respect to scoring limits are calculated by a linear allocation.

From both criteria the total score is calculated and the final assessment for the removability of an adhesive application is given according to Table 2.12. Owing to the fact that labels very often have to be tested not as a final product application but the label itself, a special procedure is described in the literature [58] to test the screenability of adhesive application on labels.

Figure 2.39 shows an evaluation performed according to the described procedure of different print products with back and side glue adhesives. It becomes evident that the products obtain different results. The differentiation between the print products with their applied adhesives allows to objectively assess the removability of the adhesives and to identify room for improvement. The products that failed

Table 2.10 Target values for calculation of the removability score.

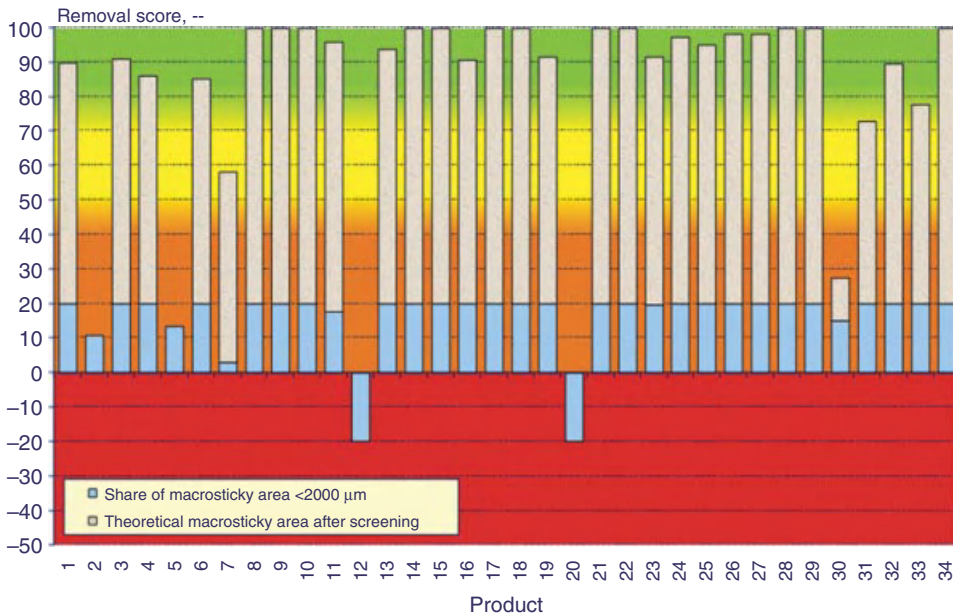
Parameter	T_s (%)	T_A $\text{mm}^2 \text{kg}^{-1}$ product
Target values	≤ 10	≤ 500

Table 2.11 Achievable scores.

Parameter	A_t points	S_{2000} points	Total points
Maximum score	80	20	100
Minimum score	0	-20	-20

Table 2.12 Rating of the removability score.

Score	Evaluation of removability
71–100 points	Good removability
51–70 points	Fair removability
0–50 points	Poor removability
Negative (failed to meet the threshold)	Insufficiently removable

**Figure 2.39** Removability score of adhesive applications of graphic paper products.

the test contained either a pressure sensitive adhesive or a dispersion adhesive. Hotmelts typically pass the test.

2.4.7.3 Removability of Adhesives Applications from Packaging Products

In an INFOR project a procedure was developed for testing the removability of adhesive applications from packaging products. This test method comprises low-consistency pulping without chemicals, coarse screening with 10 mm hole diameters, flake content determination with 0.7 mm hole diameter, and macrostickiness determination by flat screening with 0.1 mm slot width [64]. Actually the number of test results is not sufficient for setting threshold and target values for diverse packaging paper products. But further research projects are under progress.

2.4.8

Multiple Paper Recycling

During recycling treatments fibers undergo morphological and chemical changes affecting the dewatering behavior of the pulp as well as the sheet properties. In the 70th year of investigations by Stürmer and Götsching [65, 66], changes in different types of fibers during multiple recycling on laboratory scale are being tried. One particular concern is the development of the bonding ability of the fibers during multiple sheet forming and drying. This phenomenon has been described already by Jayme as “irreversible hornification” [67] and occurs in the cell wall matrix of chemical fibers. Hornification makes the cell wall microstructure more resistant to delaminating forces resulting in a stiffer and more brittle fiber [68, 69].

Figure 2.40 shows results of a simple laboratory experiment from Hunold and Götsching [70] in which mechanical (spruce TMP) and chemical (bleached pine sulfate) fibers are used for repeated slushing, handsheet forming, wet pressing, and Rapid-Köthen drying. It is evident that the behavior of the two types of fibers is quite different. Chemical pulp that is never dried has the highest breaking length and water retention values in the virgin stage of papermaking (generation 0) and loses its major proportion of strength and water retention ability during the first three cycles. Afterwards the properties of the mechanical and chemical pulp fibers stay on a more or less constant level over all nine recycling cycles. On comparing chemical and mechanical pulp during repeated recycling, it becomes obvious that the characteristics of both pulps converge. It has to be realized that all paper manufacturers buying chemical pulp on the market are using once dried fibers, which have lost a significant proportion of their strength and water retention ability during the first pulp drying stage.

These very simplified experiments of multiple paper recycling were enlarged in three test series performed by independent institutions or companies respectively, by integrating additional process treatments in the recycling process. After paper manufacturing, calendering and printing was introduced into the recycling cycles for a printed paper product with ink on the paper surface. Between slushing and

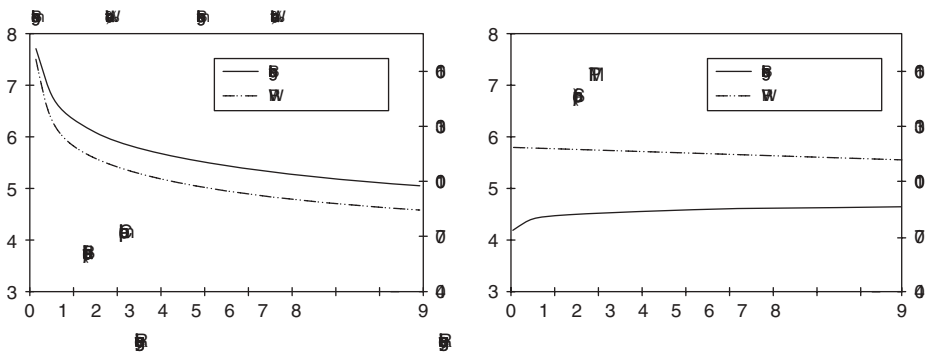


Figure 2.40 Changes of paper characteristics by multiple recycling [70].

before the next papermaking cycle a flotation process was integrated to remove as much ink as possible from the pulp slurry. The three test series differ in the scale of the experiments (laboratory, pilot plant, large-scale pilot study) and the possibilities of recovered paper processing with a single flotation stage on the one hand and a complete stock preparation line with double flotation and dispersion on the other. A team of researchers at SCA in Sundsvall and the Institute of Surface Chemistry in Stockholm [71] used TMP as raw material and worked on a laboratory scale. At the Institut für Papierfabrikation/Technische Hochschule Darmstadt [72] they worked in a pilot-scale investigation with a fiber mixture of 44% kraft pine chemical pulp and 44% spruce groundwood and a constant paper ash content of 12%. A company consortium of Holmen Paper AB, Norske Skog AS, Enso-Gutzeit Oy, and Bridgewater Co Ltd [73] performed a large-scale pilot study using a fiber furnish of 45% TMP, 23% PGW, 20% chemical kraft pulp, and 12% fillers. In both last experiments only fillers were added during the various cycles to keep the ash level of the produced paper on a constant level of 12%. To give an impression on the handled pulp volumes in the three test series it might be interesting to note that:

- in the lab-scale experiments only a few kilograms of raw material were necessary to perform five cycles with average losses of 5.2%,
- the pilot plant experiments started with 1 t of raw material to perform six cycles at average flotation losses of about 10% per cycle, and
- the large-scale experiment needed 1 t of paper in the final printing trial; it also had six cycles and deinking losses per cycle between 11 and 19%.

The target of all three projects was to simulate a paper recycling loop with additional process steps of calendering, printing as additional paper converting process, and flotation during stock preparation to evaluate more realistically the possible problems appearing on increasing recycling rates. Despite the fact that all studies had various focuses and were performed with different equipment the common results were quite similar. Even after the final recycling cycle all produced papers have sufficient strength characteristics and an acceptable printability. From the large-scale experiment Geistbeck and Weig [74] concluded in 2007 that the effects of multiple recycling are smaller than expected and that “the quality of newsprint produced from multiple recycled fibers is equal to newsprint made from virgin fiber.” The changes of the various properties in the experiments of different scale were summarized by Schabel [75] setting “+” for trends toward better characteristics, “o” for no changes, and “–” for worse characteristics according to Table 2.13.

But owing to what reason were all experiments stopped after six cycles? Each recovered paper processing is aligned with losses. If flotation is required for ink removal, a yield of 80–85% is typical. So with each recycling cycle the amount of usable fibers for paper production gets smaller. With 80% yield after six cycles only about 30% of the material is left. Additionally, samples of each cycle from different process stages have to be taken for analysis. Further material is lost in chests, pipes, and pumps and reduces the available material. Additionally, a certain minimum amount of paper is necessary to start recovered paper processing and paper manufacturing. Without input of virgin fibers at a certain point of paper

Table 2.13 Effect of multiple recycling on deinked pulp (DIP) and paper properties.

Property	Effect of multiple recycling
DIP: mechanical properties	Freeness – Long fiber share –
DIP: optical properties	Fines, WRV + Brightness ++ Dirt specks +
DIP: chemical characterization	Specific surface + Carboxyl groups + Lignin content + COD ++
Paper: mechanical properties	Strength + Elongation + Roughness – Stiffness – Porosity –
Paper: optical properties	S-value – K-value + Opacity o Brightness – Formation –
Printing	Water and oil absorption – Contact angle – Linting + Print through –

+: trend to better properties

o: no significant effect

–: trend to worse properties

++: trend to much better properties.

production recycling is not possible; however, globally in the long term such high losses cannot be avoided.

By modeling the age distribution of recycled fibers can be calculated depending on recovered paper used for any paper production. A first “one-parameter model” is a very simplified model which was introduced by Hunold and further developed to a “multiparameter model” [76]. This multiparameter model takes into account, for example, the manufacturing of newsprint, SC, and LWC paper for the national as well as international paper for newsprint production according to Figure 2.41.

This model was used by Putz and combined with updated mass flow balances to calculate the fiber age distribution of recovered paper for deinking for 2015 (Figure 2.42) [77]. The conclusion of this scenario makes clear that in the near future the average fiber in pulp for newsprint in Germany will not be more than about 2.4 times recycled. The consequences of this finding for the pulp quality are illustrated in Figure 2.43 [75]. The changes to be expected in important pulp properties owing to the estimated increasing average fiber age are not very

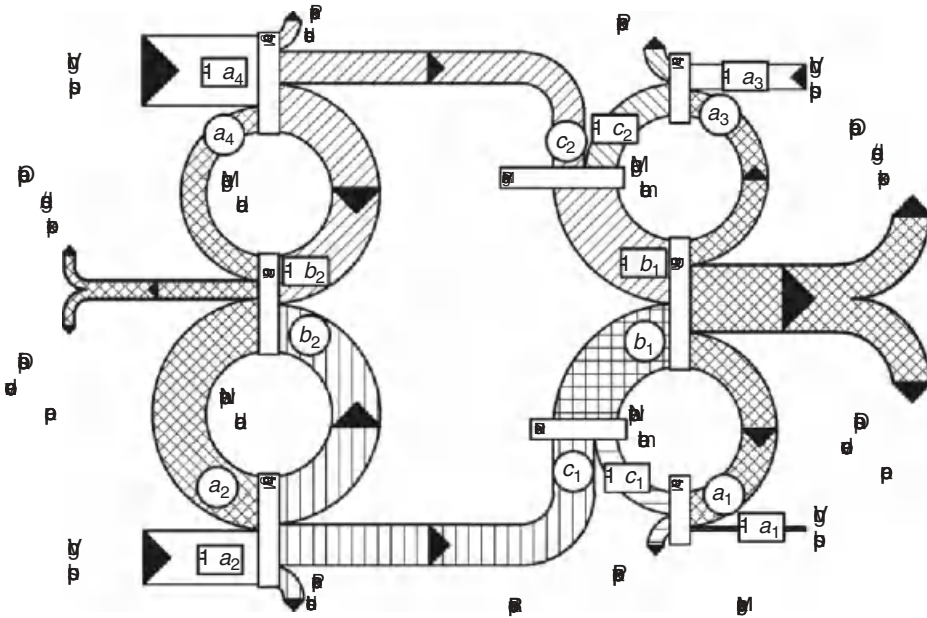


Figure 2.41 Multiparameter model according to Hunold [76].

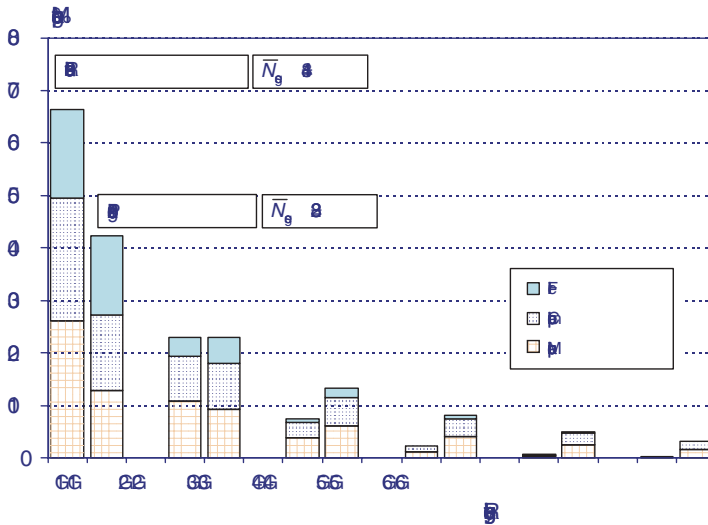


Figure 2.42 Fiber generations of recovered paper for deinking according to the modified multiparameter model [77].

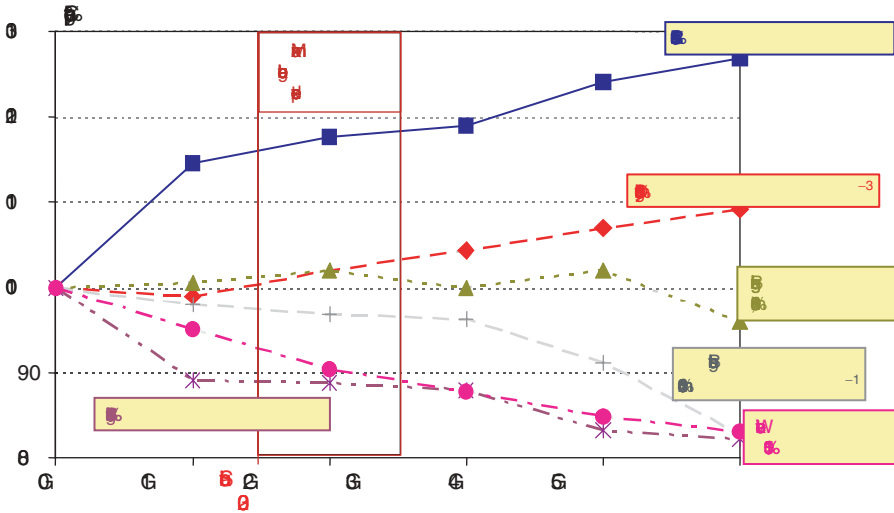


Figure 2.43 Development of important fiber properties acc. to average fiber age in RCF pulp for newsprint production [77].

big. These results are based on pilot-scale investigations which are in agreement with other laboratory and large-scale multiple recycling experiments. According to these findings there is still potential for more intensive recycling in the future. The average fiber age will not exceed critical values and the pulp properties are not affected too negatively. Therefore, a recycling collapse is not expected. Using recycled fibers as a raw material will be a sustainable way to save energy and resources. It will become more important in the future that all components to be used in manufacture of paper products result in recycling friendly designs of paper products to make it easier to recycle paper products without any problems. This is also valid for all harmful substances which are in public discussions from time to time within the context of paper recycling.

2.5 Wood Pulp Fiber Suspensions

Geoffrey G. Duffy

2.5.1 Introduction

Classical particulate solids dispersed in liquids produce slurries with flow characteristics quite different from the liquid itself. Particles denser than the fluid settle and turbulent flow forces are required to lift and keep them in suspension. Density, particle size, particle concentration, and flow velocity dictate the effectiveness of dispersion, and successful pipeline slurry applications depend on a wise selection

of these factors. When flowing, there are strong particle–particle collisions, but rarely are there any significant particle-binding forces. Hence, slurry rheology and the derived flow equations are based either on classical Newtonian fluid mechanics or non-Newtonian models. In special cases, where particles tend to settle, slide, or bounce along the bottom of the in pipe, other flow models have been developed based on the unique mechanisms of particle movement (dense-phase, sliding bed, and saltation flow models).

Fiber “particles” liberated from wood or other crops in a pulping process are long and thin (fiber length-to-diameter ratios often much greater than 30). Fibers are mostly elastic and flexible. However, because they are hollow, thin-walled, and rectangular in cross section, some may collapse in processing and become ribbon-like and more plastic in character. Consequently, when fiber suspensions are either mixed in a tank or flow in a pipeline, they collide, interact strongly, entangle, and form substructures that completely change the overall nature of the suspension. At very low fiber populations the entanglement is momentary, but as fiber concentration increases more coherent bundles (termed *flocs*) develop. These new *particles* have elastic and plastic properties different from the fibers themselves, as well as other particulate solid–liquid systems. When flowing in suspension the frictional resistance to flow is well above that for water by itself, but strangely enough, at higher flow velocities the flexible fibers and fiber bundles interact with turbulent liquid eddies and actually produce friction losses lower than the liquid by itself (termed *drag reduction*). Hence, in pulp and paper mills, fibers exist not so much as separate entities but as coherent bundles which “adhere” to each other to produce larger network structures. These suspension networks exist even at low fiber concentrations (as low as 0.4% for long-fiber softwood pulps) and they take the shape of the containing vessel.

2.5.2

Flocculation

Fibers as tracheids in a wood structure are beautifully ordered and aligned. Mechanical or chemical pulping, and subsequent pulp preparation processes individualize the fibers but they cannot remain as separate entities because of insufficient free volume in water suspension (typical for pulp and paper). Elastic fibers bend, fold, and rotate in a shear field, but when the fluid motion ceases (immediately after pulping, repulping, or slushing in a flow situation or in a mixer), the fibers are spatially inhibited, prevented from straightening, and come to rest in a strained state. Elastic fibers push against neighboring fibers which are also restrained, producing many active fiber–fiber stress sites. Other more plastic-like fibers conform and crowd the entangled bundle as many of their fiber–fiber contacts are passive. When these and some smaller “passive” fibers come into close contact they can become more actively involved in the bundle or floc structure.

The interlocking mechanism of strained and constrained fibers can be viewed essentially as energy stored in the suspension. Floc coherency and floc strength results as each elastic fiber contacts and interlocks with adjacent fibers under

stress. In essence the skeletal structures are held together by repulsion as the fibers force against each other, and they in turn force against neighboring fibers. Some less flexible or more plastic-like fibers conform to the neighboring fibers and floc bundles, but some are “activated” over small lengths on the fiber. Shorter fibers and fiber fragments also do this and thus they can partake actively or remain as crowding filler elements. The inbuilt coherency of fibers under stress produces floc “particles” that can withstand compressive, elongational, and rotary shear forces. They can be individually removed from a suspension with tweezers and still retain coherence. The physical properties of the flocs themselves characterize not only the fiber suspension, but also certain fiber properties (fiber length and thus fiber source, fiber type, degree of refining, or bleaching, etc.).

Network structures made up from the coherent flocs conform to the vessel shape. Intraflocular strength still dominates, but the interflocular strength is significant in processing as the mechanical forces causing floc–floc adhesion depend on floc “roughness,” crowding, and the ability of flocs to deform plastically and “invade” neighboring flocs [78–82]. Naturally these network structures strongly affect the flow behavior in pipelines, mixers, and processing equipment such as screens.

In essence then, the base fiber “particle” can produce three other different types of “particle.” Increasing fiber concentration slowly first produces loose, incoherent fiber bundles even at low suspension motion. These unstable “particles” easily disentangle to release fibers, and then reform again. Increasing fiber concentration further produces the floc coherency which in turn forms networks that dominate in most mill operations. The solid-like suspension networks move quite differently from liquids when flowing. It is therefore important to recognize that each “particle” has its own characteristics, and each produces some unique fluid–“particle” interactions that are far different from conventional particulate–solid slurries [78–82].

2.5.3

The Flow of Wood Pulp Fiber Suspensions

Independent, single fibers only exist either as free-moving “particles” at extremely low fiber concentrations, or momentarily, in intense shear fields. Laminar flow never occurs throughout suspension flow at concentrations above the sedimentation concentration (about 0.4%), although it may occur locally at the fiber suspension–solid surface interface [82, 83]. Flowing inhomogeneous fiber suspensions are controlled by the state of the suspension, which in turn depends on fiber concentration and population, fiber type, and on the process from which they were made. Network structures exist at low shear rates as large composite “particles” at concentrations above about 0.5–0.7%. Occupying the entire vessel volume, they can behave as large separate entities, flowing as an entire plug in a pipeline, for example. When this occurs the predominant shear resistance force is at the solid surface and is controlled, not so much by the liquid itself, but by the structure of the flocs and the interlocking flocs. Above about 1% fiber concentration for softwood pulps, there is virtually no settling and little phase separation. At low flows the bulk of the suspension is unsheared and undisturbed. Laminar shear flow can only

occur in very, very small shear gaps, small shear zones, or with heavily beaten pulps (quasicontinuum) [84]. In refiners for example, the fiber population is so high and the gap so small at the bar interfaces that solid–solid interactive mechanical shear occurs. In the grooves there is certainly more like fiber–fluid suspension motion, but still with the suspension structure dominating. Attempts have been made to employ classical non-Newtonian models [82, 85] to fiber suspension flow and these incorrect models have unfortunately led to much misunderstanding of the actual mechanisms of shear.

Pressure differentials are normally used in pipeline flow to obtain friction loss data for mill pipeline design and other information. As momentum and heat transfer in suspensions result from identical fiber–floc–turbulent eddy mechanisms, then heat transfer measurements can also be used [86]. Because fibers and flocs interact with liquid eddies, they modify the turbulence structure and flow measurements also provide insights into pulp fiber quality variations [87–89]. Model fibers [90] can also be used to determine how fiber length, diameter, and stiffness affect suspension flows.

Suspension flow behavior can be modified by “treating” the fibers (refining, drying, etc.) [85], changing the liquid properties (liquid viscosity) [91, 92], changing the shear rate (flow rate or impeller speed) [93], altering the wall surface condition (roughness, air injection, etc.) [94, 95], or modifying the driving pressure application rate (pulsing or cyclical forcing) [96]. A thorough understanding of the nature and structure of fiber suspensions is basic to understanding, improving, and controlling many industrial processes and process equipment such as pumps, mixers, washers, screens, cyclones, refiners, and raffinators.

2.5.4

The Mechanisms of Flow

The flow of wood pulp fiber suspensions is unique. Because the majority of flow situations are in pipelines with constant flow symmetry, and steady and uniform flow rate, the various mechanisms of flow are described here with reference to a typical pipe friction loss curve for a chemical pulp in Figure 2.44 [82, 85]. Other cases are considered separately.

Typical friction loss data are reported as the pressure drop per unit length $\Delta P/L$ versus flow velocity U as shown in Figure 2.44. A plot of friction factor f versus flow velocity U is also presented, but it is important to note that a Reynolds Number Re cannot be truly assigned as inhomogeneous fiber suspensions have no viscosity (water viscosity has sometimes been used in the past). The letter notations denote critical points and designate various flow subregimes [85].

Overall it can be seen that the level of friction loss for fiber suspensions is far higher than water from A to G. More notably and in contrast, friction loss is below water from G to K. From A to G there are various forms of plug flow with less than 5% of the total flow volume in shear. At about G and beyond, the plug diameter is progressively reduced as a turbulent fiber–water annulus develops (termed *Transition Flow G to J*, and *Fully Developed Turbulent Flow* at point J and beyond).

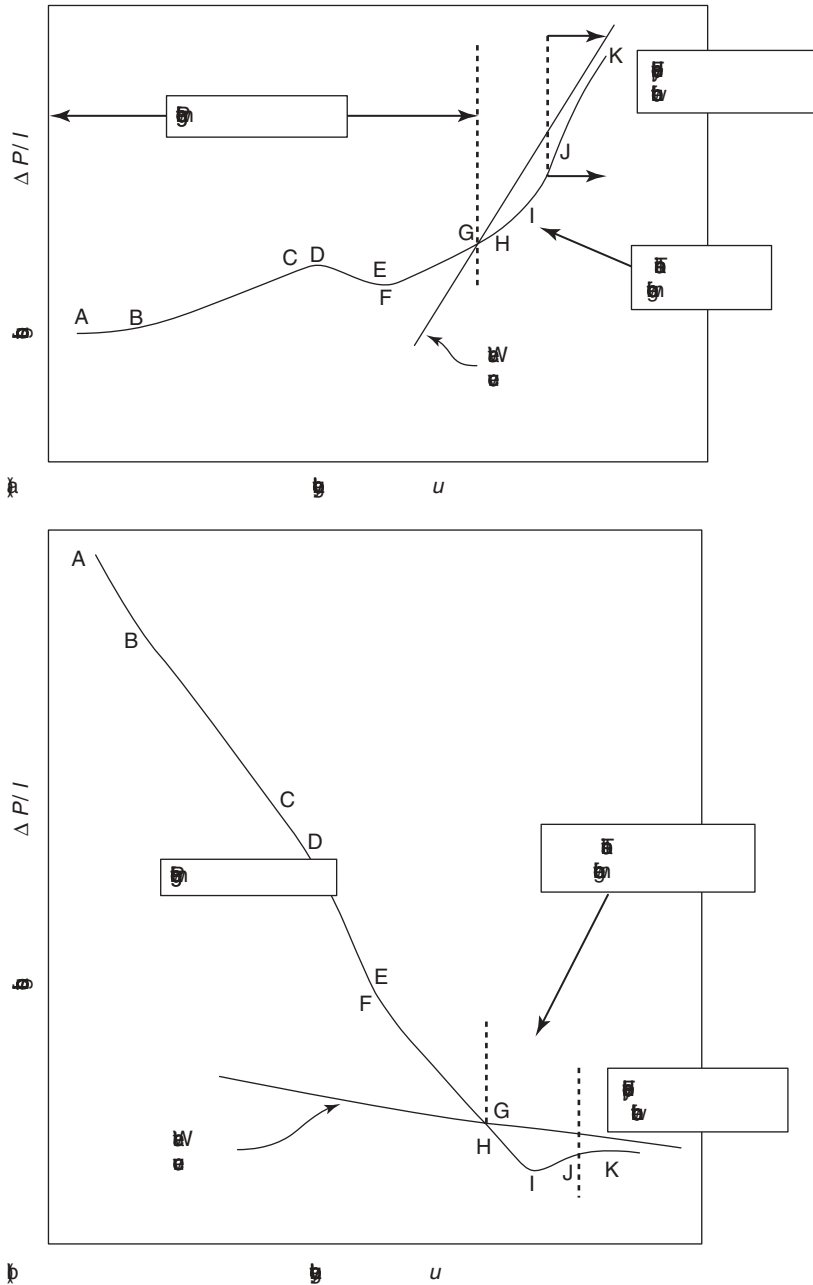


Figure 2.44 Typical friction loss curves for chemical pulps.

From point F the shape of the friction loss curve is governed by the turbulent nature of the initially thin boundary layer followed by the developing annular zone beyond G. The curve is at a maximum vertical distance below the water curve at point I, and then at higher velocities, moves back toward but remains below the water curve. Unlike any other flowing solid–liquid suspension, fully developed turbulent flow does not occur until the flow conditions are at point J on the curve. In contrast, fully developed turbulence for water would occur at a very low velocity corresponding to about B.

2.5.4.1 Sub-Regime Zero–A

If a transparent pipe section is used, the plug can easily be observed as a stable, interlocking, combination of flocs with the floc size (typically 4–7 mm) depending on fiber length (hardwood or softwood fiber). Then if a variable speed, pump motor drive is used and the rotary speed is slowly increased, the plug will begin to oscillate slightly back and forth without any bulk motion. It appears initially that the flocs are “sticking” to the pipe wall. The oscillation frequency increases until bulk flow begins very slowly at a specific pump motor speed. It is then possible to reduce the motor speed with the pulp plug still flowing at the same speed indicating that the peripheral flocs contacting the wall have been reset or folded back into the plug to a small extent to allow flow to proceed with less pump pressure. Some have also observed porous media flow near this point with water oozing from the network without the plug moving.

2.5.4.2 Sub-Regime A–B

The level of friction loss is almost constant as velocity increases in flow regime A–B. This condition in effect indicates solid–solid (boundary) friction, and can be verified by changing pipe roughness. The magnitude of friction loss increases with increasing fiber concentration, and the span of velocity over which the friction loss remains constant increases with increasing fiber concentration in this flow regime. At higher fiber concentrations, the flocs are denser and stronger, the network radial outward force higher, and the drag on the wall greater. Water pockets between the flocs protruding from the plug are clearly visible as the plug surface is not entirely smooth and does not contact the wall completely. Floc–wall drag simply dominates at this low shear rate. Some pulsing superimposed on the flow can also be observed indicating that the surface floc asperities are forced to “reorganize” momentarily in the plug to distribute the stress concentrations. There is a repeated sequence of flocs holding strongly against the pipe wall followed by release so that other flocs are forced to take the load. It is also thought that the slight stick-slip motion is linked to the centrifugal pump impeller frequency and number of impeller blades.

Subregime A–B is the main flow regime for MC flow (10–20%), where pipe friction is either independent of flow velocity, or only very slightly dependent on it [94, 95]. At 10% fiber concentration there are over 60 000 softwood fibers per cubic centimeter (over 560 000 fibers cm^{-3} for short hardwood pulp fibers). At these high fiber populations, the flocs are denser and stronger, and the peripheral flocs are forced harder against the pipe wall. This flat portion of the friction

loss curve covers a wider flow velocity range ($0.5\text{--}2\text{ m s}^{-1}$) also at these higher concentrations. Further evidence for the strong drag on the wall was found when pipes were removed from service after a reasonable operating life showing an almost mirror-like internal finish [94]. This was even more noticeable in the past when positive-displacement pumps were used as the pulsing motion coupled with the high frictional drag sometimes wore through the pipe wall.

2.5.4.2.1 Air The third-phase air also affects flow in two distinctly different ways. Air trapped inside the suspension network under pressure in the pipeline forces the plug radially outward against the pipe wall and increases pipe friction. These internal air pockets expand as the absolute pressure decreases along the pipeline. However, air bubbles trapped near the plug–wall interface actually force the flocs away from the wall and the frictional drag is reduced [94]. Hence it is not primarily the quantity but location of the air bubbles that is significant. Pipe–wall surface air lubrication has been used to good effect with very small amounts of air being injected into the plug–wall shear-zone interface. This has been used worldwide in improving flowability and reducing pump power in MC flows [94, 95].

2.5.4.3 Sub-Regime B–C

As flow increases beyond B, friction loss increases with increasing flow velocity. More peripheral flocs protruding from the plug begin to bend backward and some are dislodged. With a slight increase in shear rate (flow velocity) the number of flocs removed from the network surface increases and these flocs interact and combine to form large rolling flocs that rotate backward over the plug surface at a lower speed than the plug (Figure 2.45). In some cases it is observed that the large and more cylindrical-like rolling flocs pick out other flocs from the plug together with some fibers and fiber fragments. Toward the upper limit C at higher flow rates and just before the maximum, fewer and fewer flocs are removed from the plug surface and the plug surface becomes smoother and more uniform. Some secondary, rotating flow in the small water–fiber pockets between the flocs can be observed in this region B–C.



Figure 2.45 Plug flow with flocs rolling along the pipe wall at a lower velocity.

2.5.4.4 Sub-Regime D–F

The change from a positive slope in the curve of about $+1/3$ to a negative slope of about $-1/3$ with only a small increase in flow velocity near the maximum point D is unique, and really remarkable in fluid mechanics. It indicates that there is a very strong and definitive change in the mechanism of flow. Plug flow still exists. There is no visual or photographic evidence for any plug surface disturbance; hence the enormous change in shear must be right at the plug–wall interface. The shear rate is clearly sufficient to flatten the plug surface at or near the maximum point C to allow a very thin, essentially “fiber-free,” water boundary layer in laminar flow to develop and thicken between C and E. The location of maximum point C depends on the network strength which is affected by fiber refining, drying/reslurrying, or bleaching the pulp fibers [97]. These changes shift the onset of this subregime to lower velocities and lower friction loss levels. Increasing pipe roughness also moves point C to a lower velocity [98] indicating that the rough pipe-surface peaks are being water-lubricated at a lower shear rate. In contrast, when the fiber network strength is increased (e.g., by adding a small amount of chopped-wool fibers which have jagged surfaces), point C is translated to a higher velocity at a higher friction loss level. The onset of the plug smoothing therefore corresponds with the formation of a water annular layer in laminar shear at C.

2.5.4.5 Sub-Regime F–G

The distinct minimum E in the friction curve is again another unique occurrence in fluid mechanics. This time the change is opposite; from a negative slope of about $-1/3$ to a positive slope of about $+1/3$ as the flow velocity is increased only by a small amount from E through F. The plug surface itself is still visibly smooth at this point. The minimum point E, like the maximum point C, also shifts to a lower velocity with changing pulp conditions (refining, drying and reslurrying, bleaching), as well as increasing pipe roughness.

It is surprising that plug flow still exists at the minimum point E although high-speed video and photographic evidence reveal that a few fibers, fiber fragments, and crill now exist in the very thin annular layer which is in turbulent shear. From F to G the number of fibers in the thin annular layer progressively increase as the shear stresses are now large enough to tear more fibers from the flocs and plug periphery. The slope of the pulp curve from F to G (and up to I) is noticeably lower than the equivalent water curve at corresponding velocities, as the fibers in the thin annular layer interact and modify small turbulent eddies in a different way. Fiber–liquid interactions and the subsequent lowering of the turbulence intensity in the annular layer have been verified by the simple addition of a high-molecular weight polymer solution which separated the friction loss curves after the minimum point E, but had no effect on the pulp curve from the maximum C to the minimum E where the annular layer was laminar.

2.5.4.5.1 Point G Plug flow still exists at point G. Small fiber bundles and fibers dispersed in the very thin, turbulent annular layer around the plug are able to govern the flow characteristics from F to G. The turbulent eddy–fiber interaction is the

key shear mechanism and the central plug core at this condition could essentially be a solid cylindrical capsule. In Figure 2.44 the pulp curve crosses below the water curve at G, although the two systems are not directly physically related at that point. Water by itself would be in fully turbulent flow well before this point, but with fiber suspensions, the plug core still exists with more than 95% of the total flow volume unshredded. Thus the intersecting points of two separate curves is simply a physical fact, and the onset of drag reduction at G is not linked mechanistically, as “drag reduction” for the pulp suspensions actually starts in the boundary layer near the minimum point. Drag reduction although is reported as the fraction or percentage below the reference liquid-only curve. In other more homogeneous systems where drag reduction occurs, say with certain dilute polymer solutions, the onset of drag reduction develops at the onset of turbulence and at much lower velocities and where all the flow is already in turbulent shear. In startling contrast, there is no discontinuity at G in the fiber suspension curve and the slope from the minimum F to point G, and on to the point I, is almost constant and clearly lower than the slope of the water curve over the same range.

2.5.4.6 Sub-Regime H–I

The thin fiber–water annulus grows slowly in thickness from the minimum point E in the friction loss to the crossover point G. The shear stress level increases with increasing flow rate. From about G the turbulent fiber–floc annulus grows rapidly with the central fiber–plug simultaneously decreasing in size. At I a plug of ~20% of the pipe diameter exists [99–102]. Point I on the pulp curve is at the maximum (vertical) distance below the water curve. This point represents the maximum level of drag reduction (between 35 and 45% below the water curve depending on the pulp type) [99]. The plug diameter reduction has been tracked by velocity profile measurements as the flow rate was increased [101]. Extensive data have shown that there is a gradation in floc size and fiber fragments radially from the reduced solid plug to the wall in this region. Extrapolation of the linear reduced velocity profiles (log scale) all intersect at the same reduced coordinates that are identical for water (or any other liquid). This finding clearly shows that all the flow modifications (fiber–eddy interactions) are in the turbulent core and not in the water boundary sublayer. This is in contrast to certain drag-reducing polymers where the essential change of mechanism is in the boundary sublayer owing to the smaller molecular scale. It has been proposed that two competitive mechanisms are operating over this transition flow regime in the core: larger flocs and stiff fibers providing “solid-links” to transmit force or momentum, while flexible fibers interact with the turbulent eddies to absorb energy and reduce momentum.

2.5.4.7 Sub-Regime I–J and out to K

The friction loss curve for fiber suspensions increases in slope from I to J and the curve moves toward the water curve [82, 85]. The diameter of pulp plug continues to be reduced from I to J, until the plug no longer exists at point J (proven from velocity profile studies [82, 101]). This is the point of fully developed turbulence. Beyond J and out to K, the curve continues to shift toward the water curve, then moves

almost parallel but remains below the water curve at the very highest velocities. Clearly the fiber–eddy interactions are modified with increasing shear rate. At the highest flow velocities the level of drag reduction remains constant.

2.5.4.8 Some Differences with Mechanical Pulps

For mechanical pulps, the maxima and minima in the friction loss curves are often less well defined, or absent altogether. In some cases the initial curve slope increases to a maximum level and plateaus before the curve crosses over to fall below the water curve [98]. Some of the differences of these mechanical pulps can be associated with the lower strength of both flocs and the network itself. In a few cases, such as with high-yield mechanical pulps and a few recycled pulps, some longitudinal split-flow has been observed because of the lack of plug-network coherence. The top half of the suspension has been observed to travel faster than the bottom half with the horizontal cleavage being very noticeable at about mid-diameter.

2.5.4.9 Flow of Fiber Suspensions in Small Diameter Pipes, Holes, Slots, and Gaps

Experiments with fiber suspensions flowing in small diameter pipes with diameters of the same order of magnitude as the flocs (or less), have revealed some new phenomena and new mechanistic insights which could be applied to small holes and gaps [103]. Fiber suspensions at concentrations greater than 2% were able to be pumped into 3.77 mm diameter tubes from larger diameter pipes using a series of pipe “T” pieces, reducing sequentially in size. Data at the same fiber concentration were obtained simultaneously from pipes in series ranging in diameter from 28.8 to 3.77 mm. The pulp curve surprisingly changed from the characteristic “S” shaped curve, as shown in Figure 2.44, to one that was actually identical with the water curve, as shown in Figure 2.46. Visual observation and photographic evidence revealed that typical small-size coherent flocs do not exist in the small diameter tubes. Rather long cylindrical flocs were observed flowing end on end, each being between 200 and 500 mm long for chemical pulps. Floc lengths were much shorter for the weaker mechanical pulps (100–250 mm). The long cylindrical flocs are in stark contrast with the typical 5–7 mm “spherical”-sized flocs that flow side by side in larger industrial-size pipes. These “spherical”-type flocs actually existed just upstream in the 22.5 mm diameter pipe before the small diameter tubes. The data presented in Figure 2.46 highlight the enormous differences for the same pulp conditions [103] (concentration, temperature, etc.). The investigation showed that there was extrusion-like flow at the entrance to the small tubes resulting in the formation of these continuously long, cylindrical flocs. The cylindrical flocs were more compliant, and fibers at the edge of the “plug” were more directionally aligned, and hence could readily deflect, retract, and fold backward away from the wall as single entities. Network coherence was more in the axial direction than in the radial direction, as in larger pipes with the smaller flocs. Proportionately the water annulus was larger and the “network” radially weaker in the small pipe diameters [103]. The cylindrical floc structure meant that pulp friction loss was almost identical with water flowing alone in the same tube even though the

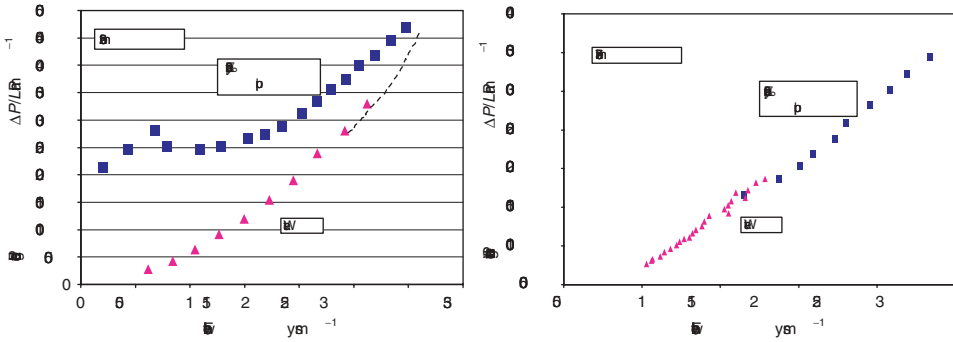


Figure 2.46 (a and b) Friction loss plots for a 2.0% bleached eucalypt kraft pulp flowing in a 22.5 and a 3.77 mm pipe simultaneously. The sharp contrast in flow behavior is clearly seen [103].

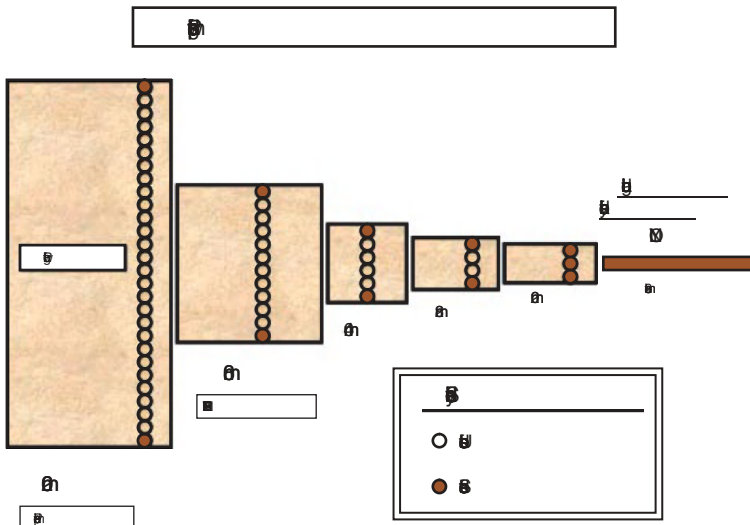


Figure 2.47 Diagram showing single flocs in the plug flow regime in large pipes, and single cylindrical flocs in very small diameter pipes. Severely shear-stressed and deformed flocs are shown in a darker color [103].

fiber concentration was 2% (Figure 2.46). An interpretation of the mechanisms is explained more graphically in Figure 2.47.

These insights are also important in understanding the flow through small holes, slots, and gaps, in process operations such as screening. If normal flocs or network structures exist before the orifice, and if the accelerating flow and associated shear stresses are able to break up the structures, then a different more-stretched and elongated fiber structure will result. This mechanism is visually illustrated in



Figure 2.48 Elongational flow of fibers through small screen holes showing how different fiber structures can form.

Figure 2.48 with fibers being “individualized” to align themselves momentarily in the flow direction.

2.5.4.10 The Effect of Increasing Liquid Viscosity on Fiber Suspension Flow

Increasing the liquid viscosity into which fibers are mixed gives fibers more time to relax after intense shear [91]. Fibers straighten slightly more before they collide so that the floc size and interlocking strength are lowered and the network integrity reduced. Consequently the flow behavior is affected across all flow regimes. This has been put to good use in pressure screening [92] as the more viscous liquid–fiber suspension lowers screen pressure drop, increases screen capacity, increases fiber passage, and lowers reject thickening. Naturally as the mean floc size is reduced in the more viscous liquid, the papersheet formation (uniformity) is also improved [92].

2.5.4.11 Nonsteady State Fiber Suspension Flow (Viscoelastic Suspension Behavior)

Some abnormal and inexplicable flow behavior has been observed in certain mill operations such as mixing [93]. Pulp suspensions have been seen to climb the rotating vertical shaft during agitation and mixing. Some pulp tank agitators have been found to rotate backward after the motor was switched off and the mixing impeller shaft initially stopped. It was also found that the torque–velocity curve when the mixer impeller rotor speed was increasing was different from the torque–velocity curve when rotor speed was decreasing. The two-curve separation or hysteresis is an indication of a suspension behaving both elastically and plastically (viscoelastic system) with the suspension being able to resist elastically to some degree before breaking down and yielding plastically at a slightly higher shear rate.

Indeed as shown in Figure 2.49, this phenomenon does exist with fiber suspensions [96]. Both pressure differential measurements and absolute pressure-at-a-point measurements produce hysteresis curves that depend on the type of fiber suspension (bleached or unbleached), fiber concentration, and acceleration/deceleration rates. The curves separate to different extents depending

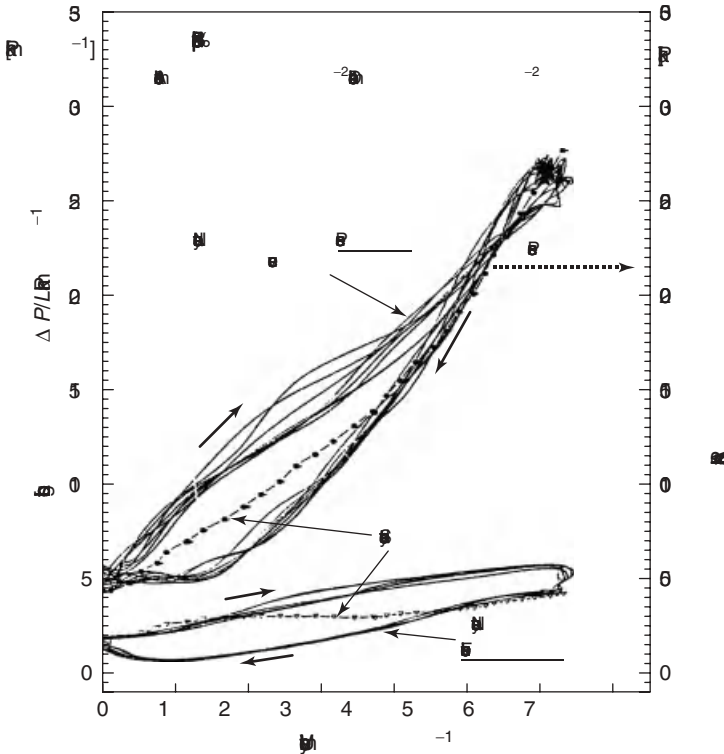


Figure 2.49 Typical dynamic friction loss data and absolute pressure-at-a-point data for a bleached kraft pine pulp (3.28% concentration, acceleration rate 1.81 m/s^2 and deceleration rate 1.4 m/s^2).

on the network strength when other conditions are the same, and this difference can be used to characterize various pulps [96]. In fact the hysteresis curves are actually a measure of the dynamic deflocculation and reflocculation of a specific pulp type. In accelerating flows, fibers and flocs have to be torn from the existing strong pulp plug. The energy required to achieve that in the plug flow regime is higher than the localized shear in steady state flows, and thus the dynamic friction loss curve is mostly higher than the steady state curve. Conversely, on deceleration from almost fully developed turbulence, the dynamic friction loss is much lower as fibers slowly interlock to form flocs, then floc structures, and finally the reformed plug (friction loss curve below the steady state curve).

This fairly rare phenomenon has also been applied to a fiber suspension pipeline pumping using a variable speed pump motor drive [96]. If the motor speed is programmed to vary over a short period around a mean velocity, then the average level of friction loss notably decreases owing to hysteresis. A similar effect is obtained by switching the pump on and off for short intervals (saw tooth profile). This unique viscoelastic effect may have wider potential use in the pulp industry.

Table 2.14 Time for fully-dispersed fibers to recombine and form flocs (reflocculation time), over a range of fiber concentrations.

Fiber concentration C (%)	Reflocculation time (s)
1	0.01–0.1
2	0.015–0.04
4	0.003
10	0.0000003

2.5.5

The Significance of Fiber Reflocculation after Dispersion

The state of a suspension at a particular flow velocity or shear rate governs the resistance to flow. Fiber crowding and the natural tendency for fibers to collide and lock up again after dispersion is very significant. The time to reflocculate has been determined for a wide range of conditions and is extremely short. These reflocculation times are presented in Table 2.14.

For a completely dispersed 10% fiber suspension the separated fibers would “lock” up again in less than 0.3 μ s from the impeller, which corresponds to only a few millimeters distance from the rotating impeller.

2.5.6

Medium Consistency MC Flow

Up until about 1950, the pumping of pulp suspensions at fiber concentrations above about 5% was unheard of. Rotary positive-displacement pumps came in the 1960s and the first MC pumps operated on this principle. The pump motor power however was very high and they imposed an intense pulsing motion on the flow owing to the low rotary speed and the stick-slip behavior of the pulp plug [85, 94]. The pulsing frequency matched the product of the number of impeller blades and pump rotary speed. Outlet pipes from the pump had to be either embedded in concrete or strongly fastened to the floor/wall as the intense vibrations often broke the pipes away from their mountings. The total frictional resistance was very high because the pump outlet pressure had to overcome acceleration/deceleration forces in addition to the normal steady state, solid–solid, sliding frictional forces. Many of the early design equations did not separate the actual friction loss component from the pulsing frictional component and should be used with caution. In addition the high-density HD rotary pump impellers, and often the inner casing, had to be rebuilt or replaced almost annually.

Open-impeller centrifugal pumps at that time could only handle pulp suspensions less than about 5% concentration. In the 1960s, the Allis–Chalmers Pump Company in the United States of America attached a protruding propeller as an extension to the centrifugal pump impeller and were able to pump pulp suspensions

up to about 7% concentration. Later in the 1970s, the Ahlstrom Pump Company in Finland pumped pulp at 8–12% fiber concentration using a similar device at the pump inlet. Theirs was a protruding, three-bladed rotor extending into the pulp tank and attached to the rotating impeller [104] to momentarily mobilize the flocs to allow them to reconfigure and flow into the pump inlet. Pumps were made more robust by continuous air removal from the suspension at the lowest pressure point in the pump. More recently the Swedish pump company, Scanpump AB, shortened the pump inlet casing length so that the open impeller was actually partly inside the tank. Today most open-impeller MC centrifugal pumps have similar components and are being used successfully worldwide.

Flow in a pump could not be observed so the earliest investigations into MC (8–20%) flow behavior were carried out with mixing vessels. The condition of a well-agitated, fully moving fiber suspension in a tank (flocs still present) was initially treated as the fully developed turbulent reference state (called *fluidization* at the time). In fact, the agitator simply mobilized the flocs to develop strong flow patterns that could be clearly observed and defined [96]. Fully developed turbulence did not exist however, as this would actually be the state where the fiber “particles” themselves were fully dispersed (no floc bundles present). The accepted condition for fully developed turbulent mixing in all slurry systems was defined when all the base “particles” were free to move and collide in the mixer. Flocs of course are made up of many base fiber “particles.” For fiber suspensions it was found that the impeller torque-rotational speed curves dipped below the corresponding water curve [93, 104] and then suddenly and steeply increased at slightly higher rotary speeds. It was thought at the time that this was similar to pipe flow, simply by curve comparison. However this was an unfortunate comparison and clearly not the case. In fact, the sudden dramatic change in the mixer curve slope was a result of “flow switching” (nonexistent in pipe flow). The already established rotary or swirling motion suddenly “switched” to a combined swirling (rotary)-radial flow, which then induced longitudinal suspension flow at the vessel walls, and thus the steep slope increase. The suspension flowing down the vessel walls collided with the base of the tank, and moved radially inward to the impeller (back mixing) to set up complete agitation of the tank and floc mixing [93]. Technically the entire tank full of pulp became agitated (but not mixed), and flocs were mostly undisrupted as they moved side by side and end on end in bulk motion.

Some experiments with premade bleached and unbleached fiber suspension both of the same 10% fiber concentration were located in different zones in a mixing tank. Both white and brown flocs continued to exist separately for quite a long period after agitation was fully developed. This confirmed that the agitation even at high impeller speeds was incapable of causing floc disintegration and produce fully developed turbulence of the fibers themselves. Good agitation without true mixing was thus confirmed. It was possible to eventually get some floc breakdown in a small vessel with a large impeller operating at or above 3000 rpm. However, if the tank had small longitudinal baffles at the wall, either white or brown flocs remained stationary there, the flow intensity being insufficient to mix these completely. These

observations were valuable for understanding what was happening inside a pump, even though there was no back mixing.

In the case of pumping at these high fiber concentrations, the first important issue is for stationary flocs in the tank to be mobilized at the pump casing inlet in order to get them to travel to the impeller. The second important issue has been the third-phase air. Sustained long-term pump operational performance has been achieved by extracting air continuously from inside the pump. This has prevented air buildup, air pocket growth, and subsequent pump air-binding. In addition, pump power has also been lowered by injecting small quantities of air at the plug–internal pipe wall interface immediately after the pump to “air lubricate” the wall, reduce friction loss, and thus lower pump power [94].

2.5.7

Pulp Flow in Open Channels

Open channels are sometimes used in pulp mills either in drainage systems or for storage tank overflows. The interlocking structure of fiber suspensions in gravity flows poses a problem as conventional open-channel flow equations for liquid flows do not apply. Some work on fiber suspensions flowing in open channels has given some fresh insights into the slope and flow requirements for structured fiber suspensions [105].

2.5.8

Practical Design Methods for Determining the Pipe Friction Loss of Industrial Piping Systems

The complex “S” shape of the friction loss curve (pressure drop vs flow velocity) for wood pulp fiber suspensions makes the design procedure difficult [99, 106–108]. Friction loss characteristics depend on the suspension properties which in turn depend on the wood source from which the fiber comes, the pulping process, the degree of fiber modification (bleaching, refining, and drying/reslurrying), as well as temperature and pipe roughness. For chemical pulps each curve at a particular fiber concentration has maximum and minimum points. If the pipe diameter is increased at a specific fiber concentration, the whole friction loss curve simply shifts vertically downward to lower pressure drop levels. Increasing fiber concentration in a specific diameter pipe shifts the curve both upward and to the right as both the maximum and minimum points move to higher flow velocities and thus higher friction loss levels. Creating a simple design procedure to cover all possibilities has therefore led to some compromises. Two main methods have emerged for designing pipeline systems. Both have been adopted and are now widely used:

- The stepwise approximation method for reexpressing the friction loss curve [97, 109, 110].
- The dimensional analysis single-curve method [111, 112].

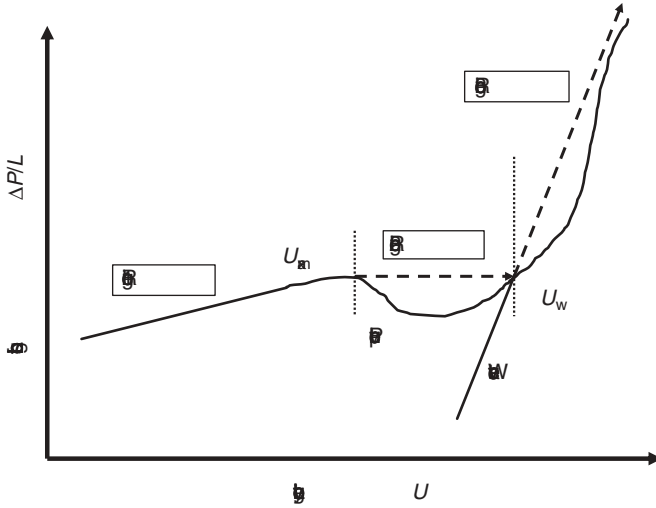


Figure 2.50 Stepwise procedure for the design of pipeline piping systems.

2.5.8.1 The Stepwise Approximation Method

This is presented graphically in Figure 2.50. The curve can be divided into three regions:

- **Region 1:** before the maximum in the friction loss curve,
- **Region 2:** between the maximum and the water curve, and
- **Region 3:** the water curve itself at higher flow rates.

The rationale is that the most frequently encountered flow regime in pulp and paper mill piping systems is the part of the plug flow regime before the maximum in the friction loss curve (Region 1). Fortunately data plotted on logarithmic coordinates as pressure loss versus flow velocity produce curves that are approximately linear and almost parallel over a wide range of fiber concentrations. At higher flow velocities beyond the maxima, the curves are nonlinear and less systematic. However, if the design velocity is greater than U_{\max} , any pumping system must at least be able to handle the conditions at the maximum point in the curve. Hence, the friction loss determined at the maximum is used when the design velocity lies between U_{\max} and the water curve U_w .

2.5.8.1.1 Region 1 Extensive friction loss data have been obtained for a wide range of chemical and mechanical pulps (bleached and unbleached, dried and never-dried) at concentrations ranging from about 0.5–5.5%. Least squares regression lines have been fitted and numerous correlations determined that take the following form for Region 1 (plug flow before the maximum):

$$\Delta P/L = KC^\alpha U^\beta D^\gamma \quad (2.1)$$

Data for the various coefficients may be obtained from the literature [97, 109, 110]. A selection is presented in Table 2.15.

Table 2.15 Values of parameters and exponents of Eq. (2.1) for some selected pulps (diameter D m, velocity U m s⁻¹, concentration C %).

Pulp type	Parameter K	Exponent α	Exponent β	Exponent γ
Long-fiber kraft never-dried CSF = 725	11.80	1.81	0.31	-1.34
Long-fiber kraft never-dried CSF = 260	17.00	1.81	0.31	-1.31
Long-fiber kraft dried-reslurried	9.40	1.81	0.31	-1.31
Short-fiber kraft birch dried-reslurried	5.20	1.78	0.27	-1.08
Short-fiber kraft aspen never-dried	5.30	2.14	0.36	-1.04
Newsprint broke CSF = 75	5.19	1.91	0.36	-0.82
NSSC hardwood CSF = 620	4.56	2.31	0.43	-1.20

For all chemical pulps, the fiber concentration coefficient α varies between 1.78 and 2.14 in this region, the velocity exponent β between 0.27 and 0.36, and the diameter exponent γ from -1.08 to -1.34. The mean values are 1.81, 0.31, and -1.31 respectively. The value of K is also specific for each pulp and K accounts for the effect of temperature, bleaching, drying, and internal pipe wall roughness.

The upper limit of Region 1 is at the maximum U_{\max} which is given by the equation:

$$U_{\max} = K' C^n \quad (2.2)$$

Where K' and n are specific to each pulp type and condition (K' ranges from 0.49 to 0.98 and n ranges from 1.3 to 1.9). Hence if the design velocity is lower than U_{\max} , the appropriate correlation of the form of Eq. (2.1) can be used for the specific pulp and pumping conditions.

2.5.8.1.2 Region 2 The friction loss at U_{\max} must be the basis for design when the expected flow velocity in practice would be above U_{\max} . Even though the actual friction loss curve goes down for chemical pulps and may plateau for certain mechanical pulps, the pump must at least supply the pressure at this maximum point, which is the “worst-case” situation. The friction loss estimate at the maximum can therefore be used while the design velocity of flow is between the maximum point U_{\max} and the corresponding point on the water curve U_w . In essence the friction loss estimate remains constant between U_{\max} and U_w . The design correlation in Region 2 is therefore:

$$\Delta P/L = KC^\alpha U_{\max}^\beta D^\gamma \quad (2.3)$$

Equations (2.2) and (2.3) can be combined to eliminate velocity U_{\max} in Region 2:

$$\Delta P/L = K.K'^\beta C^{\alpha+\beta n} D^\gamma \quad (2.4)$$

2.5.8.1.3 Region 3 At the end of Region 2, all pulp curves cross below the water curve (onset of drag reduction) at U_w . Although good design equations have been

developed for Regime 3 [113], a conservative but slight overestimate can easily be obtained by using the water curve in Region 3.

An equation for the end of the transition from Region 2 is:

$$U_w = 1.22 C^{1.4} \quad (2.5)$$

It has been recommended that the conventional friction factor f versus Reynolds number Re plot be used in Region 3 as the effect of pipe roughness can easily be included. A simple estimation can also be obtained from the Blasius equation for smooth pipes:

$$\frac{\Delta H}{L} = 264 U^{1.75} D^{-1.25} \quad (2.6)$$

The stepwise method is easy to use and has been applied successfully in designing many large pulp and paper mills worldwide.

2.5.8.2 Dimensional Analysis Single-Curve Method

This method is based on dimensional analysis [111, 112] and correlates two dimensionless groups in a manner similar to the Moody diagram for Newtonian fluids (friction factor vs Reynolds number). Dimensional analysis produces a single curve to represent all the various friction loss curves for a wide range of fiber concentrations, pipe diameters, and flow velocities. Dimensional analysis [111] showed that wall shear stress τ_w for the pulp suspensions (which incorporates friction loss $\Delta P/L$) could be normalized using the disruptive shear stress τ_d [114], (approximately the value of τ_w at U_w , the point where the pulp curve and water curve cross). The disruptive shear stress τ_d is also approximately equal to the shear stress at the maximum τ_{max} in the friction loss curve. The ratio of τ_w/τ_d was plotted against the other dimensionless group which includes τ_d , flow velocity U , pipe diameter D , and water properties, density ρ and viscosity μ :

$$\tau_w/\tau_d = \phi \left([U^5 \rho^2 \mu / \tau_d^3 D]^1 \right)^{1/6} \quad (2.7)$$

A typical example of a graph of data using this correlation form is presented in Figure 2.51. This procedure, known as the *Moller method* [111], has been adopted and used extensively [112]. There have been some concerns expressed over the ratio τ_w/τ_d (hence the magnitude of the frictional pressure drop $\Delta P/L$), as the ratio is sensitive to the value selected for τ_d .

2.5.9

Mechanistic-Based Models

Several flow models have been proposed that are based on both the known mechanisms of flow and theoretical considerations [82, 83, 85], rather than classical non-Newtonian models. These include

- 1) A plug-flow model before the maximum in the friction loss curve [82, 83] which theoretically matches the Empirical equation (Eq. (2.1)).

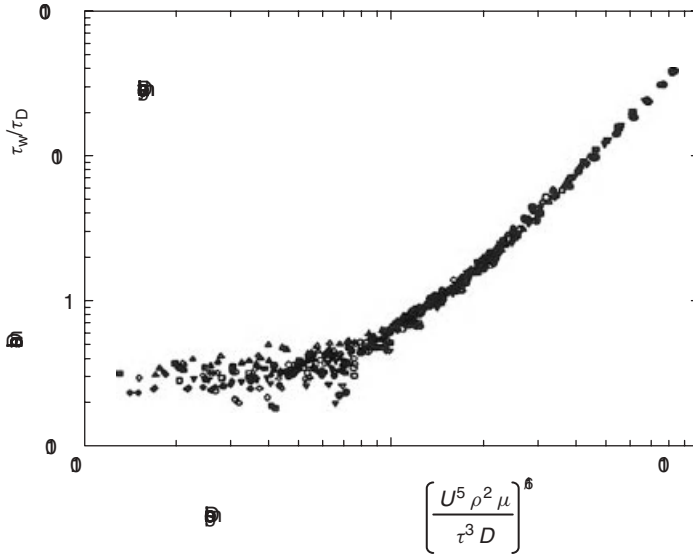


Figure 2.51 Typical friction loss data for a bleached softwood chemical pulp showing the relationship between two dimensionless groups for a wide range of fiber concentrations. (After Eq. (2.5).)

- 2) A wall-slip model [83] that has been derived for the regime of flow between the maximum and minimum points in the curve, that validates the development of the thin water layer in laminar shear in that region.
- 3) Two simple but erudite models that clearly and actually describe the Transition Flow Regime [100, 102], using a single parameter that is only a function of fiber concentration.
- 4) A simple and usable model that predicts friction loss from the minimum point in the friction loss curve to the point of fully developed turbulence [85, 115]. It is based simply on the fact that the cross sectional flow area of the sheared annulus in transition flow is approximately proportional to the magnitude of drag reduction. The model has been tested [114] using published mill data obtained independently from large diameter pipelines. Friction loss values were predicted within $\pm 8\%$ of the mill-data values.

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3

Mineral Fillers in Papermaking

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While mineral fillers can be found in different paper and board grades, printing and writing papers represent by far the most dominant area for their application. Today, there are many important functional reasons for the use of fillers in printing and writing papers and certain grades of board. Mineral fillers available for paper applications exhibit various chemistries, morphologies, refractive indices, brightnesses, particle size and particle size distributions, hardness, and solubilities.

3.1

History of the Use of Mineral Fillers in Papermaking

Mineral fillers have long been used in the art of papermaking. In China, already in the fifth to seventh centuries, calcium sulfate was added to the paper furnish together with starch powder. Additions of calcium sulfate, chalk, or talc have been found in Arabic papers, handmade in the eighth century. According to Dard Hunter, the first documented use of filler (china clay) in European papermaking took place in England in 1807 [1]. Data published by W.J. Barrow and T. Barrett strongly suggest that early European papers, made by hand according to the Italian method, contained calcium carbonate pigments as filler [2, 3]. The historical use of fillers in papermaking was also mentioned in the annals of philosophy in England, July 1823. *To increase the weight of printing papers, certain paper manufacturers have introduced monstrous quantities of gypsum (or kaolin) to the rags.* In the year 1871, Rudolf Wagner already acknowledged in his handbook of technology some of the functional advantages of applying fillers in papermaking. *The moderate addition of a suitable mineral body to paper is by no means disadvantageous, and it is useful in several ways. By his means, medium fine papers are given improved brightness and thin papers more opacity. Finally, through the addition of inorganic material, less expensive paper may be produced.*

3.2

Global Mineral Consumption in the Paper and Board Industry

For several decades now, the industry producing the mineral coating and filler pigment has enjoyed continuous growth through supplies to paper and board manufacturers. This growth has spanned all continents, and in particular to the expanded use of products based on calcium carbonate.

The global consumption in 2010 of such mineral pigments, as applied to paper and board, is presented in Figure 3.1. On a worldwide basis, the paper and board industry absorbed 31.7 million dmt (dry metric ton) of pigment for paper and board coating and filling. As also graphically indicated, for filling purposes alone, 13.6 million dmt of pigments were used.

Precipitated calcium carbonate (PCC) (43% or 5.9 million dmt) has become the most widely used filler in the paper and board industry, applied within the body of the paper, followed by natural ground calcium carbonate (GCC) (33.5% or 4.5 million dmt). About 12% or 1.6 million dmt of that total filler was represented by clay (kaolin). A 10% share, or 1.4 million dmt, is given for talc, which serves as a filler and as finely processed talc for pitch control. Other (specialty) filler pigments equaled about 1% or 140 000 dmt.

With the use of recovered paper in papermaking (e.g., for newsprint, magazine paper, various board grades, etc.), a substantial amount of secondary pigment is transferred back into the production of new paper or board. This recycled

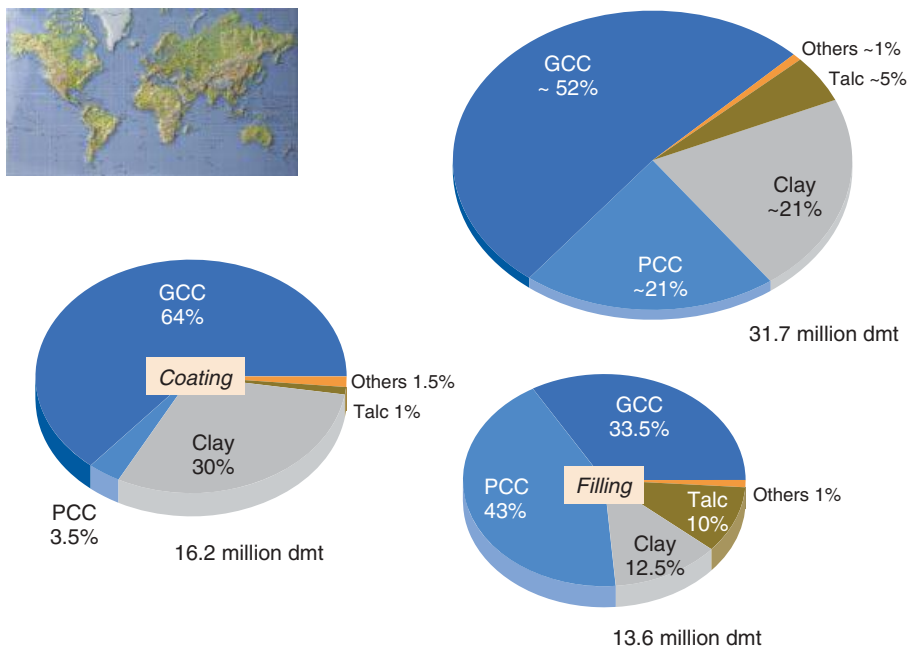


Figure 3.1 Global mineral consumption in paper and board, 2010. (Source: Omya.)

pigment also acts as filler. However, as the pigment is mostly agglomerated and the composition varies significantly by the nature of the pigment, the resulting impact on paper quality is also somewhat inconsistent. Recycled pigment cannot meet the quality and range of functionality provided by specifically designed virgin fillers.

3.3

Why Use Mineral Fillers in Paper and Board?

Fillers are applied in paper and some board grades mainly

- to improve the optical properties, such as brightness and opacity, or coverage in multilayer structures;
- to improve the smoothness of the sheet surface (i.e., decreased roughness after calendering);
- to deliver extra bulk to the sheet (structured fillers such as scalenohedral PCC);
- to improve the sheet microformation by filling the voids between the fiber matrix;
- to support the coating color hold-out in base papers used for coated grades;
- to enhance printability in the various printing processes through a more uniform paper surface, delivering higher opacity and better ink receptivity, the latter resulting in reduced printing ink penetration and less wicking, leading to less print-show and strike-through to the opposite side of the sheet;
- to improve the dimensional stability of the paper, as most fillers remain inert when wetted, unlike the natural fibers usually used in papermaking;
- to enhance drainage and drying by replacement of the hydrophilic fiber compact by the more permeable composite structure derived from the inclusion of mineral fillers, introducing additional pores in the matrix;
- to improve the permanence of the paper (alkaline papermaking, CaCO_3 filler)
- to reduce cost, as regular (main) mineral fillers are, in general, lower in price than typical papermaking fibers; replacing fiber by regular mineral fillers usually provides significantly better papermaking economics. Therefore, efforts are made to include as much filler in the paper and certain boards as the technological and quality demands can support.

The amount of filler (loading) in the paper has of course a strong impact on the sheet properties obtained. Figure 3.2 documents the influence of increased filler loading on some important paper properties. The results shown are based on a pilot paper machine study, using natural GCC as filler in a typical woodfree uncoated fiber furnish. The basis weight of the paper produced was 80 g m^{-2} . In general, the influence of the filler is magnified with increased loading in both directions, desired and undesired. Also, the main location and distribution of the filler in the sheet has a major influence on the end performance. Fillers, in the presence of chemical additives, can interact with the fibers and fines through various deposition and flocculation mechanisms. In the final sheet, the effect of the filler is dependent not only on the intrinsic properties of the filler particles and particle clusters but

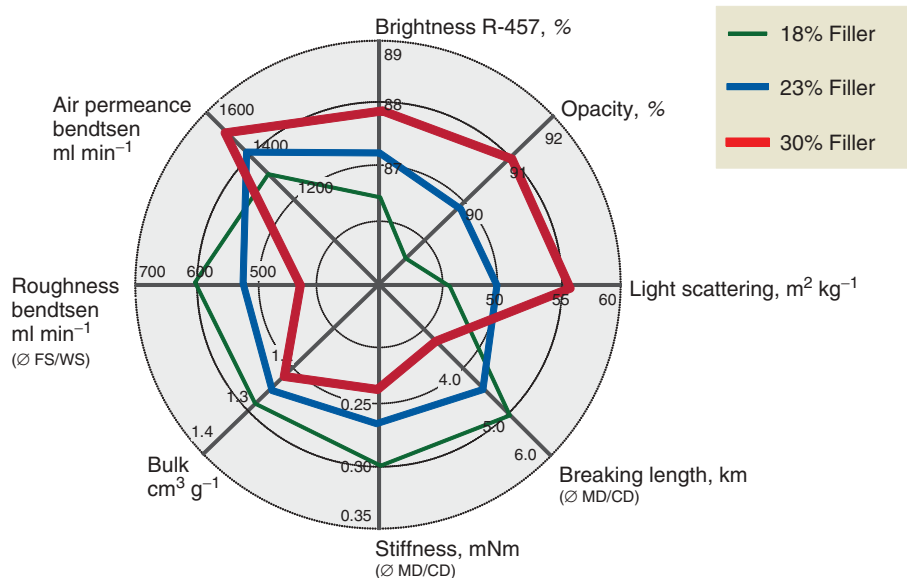


Figure 3.2 Impact of filler loading on some important paper properties. (Source: Omya.)

also on the extrinsic influence of the filler on the fiber network. This includes, for example, the disruption of the fiber network by the filler.

As demonstrated, brightness and opacity/light scattering are significantly improved with increased natural GCC filler loading. The higher porosity, derives from an increased number of pores with higher loading, supporting also drainage and drying. In addition, less quantity of fiber needs to be processed and dried. The limits in terms of filler loading are set primarily by an accompanying reduction in stiffness and decreased strength (tensile strength, tear resistance, internal bond, and surface strength). Sufficient surface strength is particularly important in offset printing or in copier machines. Inadequately fixed filler on the paper surface can result in dust accumulation (blanket piling) in the offset printing process or contamination of the copying machine. Also, the initial wet web strength can represent a limitation to the filler loading level, as this characteristic is linked to paper machine runnability. The initial wet web strength strongly depends on the dryness of the paper web. The addition of fillers to the sheet tends to decrease initial wet web strength. According to the literature, new polymer solutions can provide extra wet strength to the never-dried paper web [4].

The overall filler loading level can be also limited by operating a traditional Fourdrinier wire section, which is due to the usually very pronounced two-sidedness of the sheet. Of course, in general, the very important impact of the fiber source (strength potential) available and the machine configuration installed (former, press configuration, first open draw position, etc.) should not be overlooked.

Typical mineral pigment loading levels (determined on oven-dried paper) in different European paper grades are documented in Table 3.1. Overall, the typical

Table 3.1 Filler loading (on oven-dry paper) in printing and writing papers, Europe.

Woodfree uncoated	20–27%
Copy, stationery, offset	PCC, GCC, chalk, blends
Woodfree coating base	12–25%
Single, double, triple coated	Secondary, GCC, PCC, chalk
Wood-containing uncoated	30–37%
Supercalendered, magazine, and so on	Secondary, clay, GCC, PCC, talc, blends
Wood-containing base	8–16%
Light/medium/high	Secondary, GCC, PCC, talc
Weight coated	–
Newsprint	8–24%
Recycled/virgin fiber	Secondary, chalk, GCC

Source: Omya.

woodfree uncoated paper grades are loaded mostly with primary (fresh) filler only. The type of fillers applied is usually PCC or natural GCC or sometimes a combination thereof. Also known is the combination of PCC with some chalk or the use of sole chalk in tinted paper. The coating base papers are filled with the coating (secondary) pigment coming from the coated paper broke plus some primary filler. The primary filler can be GCC, PCC, clay, or, in certain cases, talc. The wood-containing uncoated papers contain 100% primary filler but can also carry a secondary pigment from recycled paper and fresh filler. The primary fillers used in typical supercalendered papers [5] are either all clay, combinations of clay with GCC or PCC, or even triple compositions such as clay/PCC/GCC. Today, newsprint is mostly made from recycled fiber, sometimes combined with some virgin fibers (thermo mechanical pulp (TMP) or stone ground wood (SGW)). Newsprint made from recycled fiber contains substantial amounts of recycled pigment, and, if technically possible, additionally some fresh filler, reaching up to 24% of total pigment loading. The primary filler applied in newsprint is usually chalk (dry- or wet-ground) or wet-ground limestone or marble-based GCC. Newsprint paper based on virgin fiber contains about up to 12% chalk as filler in response to the strong efforts to maximize the loading level further.

The results of a global copy paper survey, in terms of mineral filler loading, are illustrated in Figure 3.3. In this study, 52 copy paper samples from around the globe were randomly collected and analyzed in detail [6]. Basically, all papers evaluated contained calcium carbonate-based fillers (exception: talc in paper from India). Interestingly, while in Europe as well in North and South America PCC is predominantly applied as filler in such paper grades next to GCC, by far most of the new production capacities installed in China have chosen GCC as filler. India is presently moving away from the traditional use of talc toward the application of PCC, GCC, or combinations thereof. Overall, the filler loading levels found reflect also the quality of the fibers available locally (eucalyptus, birch, pine, straw,

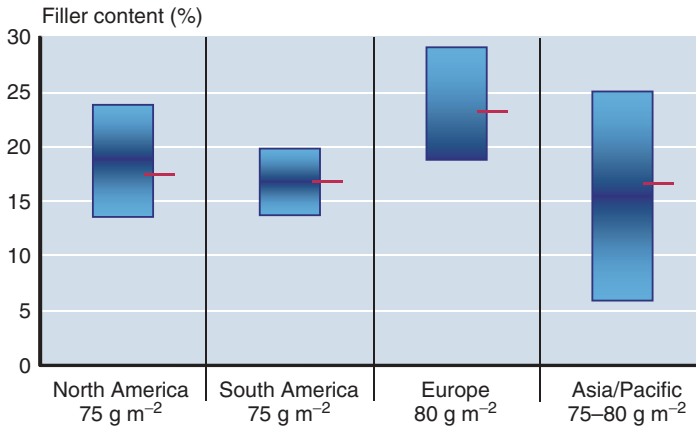


Figure 3.3 Mineral content (on oven-dry paper) in multipurpose office paper, worldwide. (Source: Omya.)

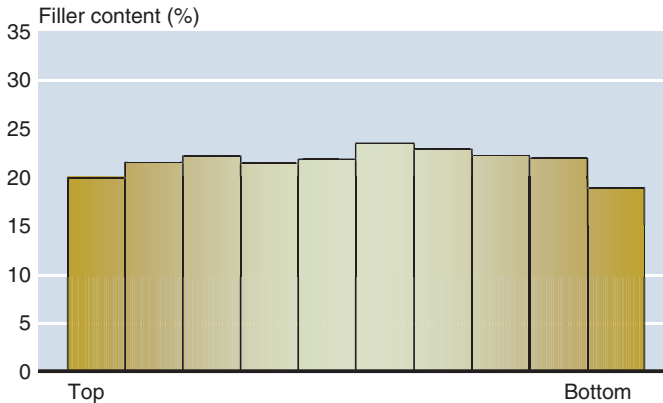


Figure 3.4 Filler distribution in the z-direction, woodfree uncoated paper; copy paper, basis weight 80 g m^{-2} ; filler loading 25%. (Source: Omya.)

bagasse, bamboo, etc.), the existing technology (machinery and process), as well as the individual (local or export) needs in respect of paper quality.

Figure 3.4 depicts the filler distribution in the z-direction of a woodfree, uncoated copy paper with a basis weight of 80 g m^{-2} and 22% PCC filler loading. This paper sample was produced on one of the most modern paper production units. The very uniform filler distribution in the z-direction and the somewhat reduced filler concentration close to the surface demonstrate impressively how much the technology has advanced.

The development of manufacturing concepts in which the filler in graphical papers can be preferentially positioned at specific locations in the z-direction of the sheet “layering” is still going on. Turning such concepts into practice, however, will require new technologies and quite significant investments [7].

3.4 Filler Loading Increase via Surface Application

Particularly in woodfree, uncoated paper production, in addition to regular internal filling, preferably fine-ground GCC pigment can be applied via the sheet surface. This method, classified as “surface filling,” is frequently adopted in various countries around the globe, and represents a very cost-effective method to maximize the total filler loading. Figure 3.5 shows the results of adding two units of extra filler through the paper surface versus the nonsurface-filled reference.

Finely ground natural calcium carbonate filler is added to the film-press or size-press starch solution, and penetrates together with the starch into the depth of the sheet without getting concentrated on the sheet surface. No additional additives, such as synthetic binders, and rheological modifiers are required. There is no impact on the wet-end system, and at moderate loading increase (typically 1–2%) paper stiffness and strength are also not affected. This latter phenomenon can be explained by the fact that the fiber matrix is already built before entering the film press, and the additional pigment is only filling up the larger voids between the fibers rather than disrupting fiber–fiber contact during sheet formation. This can be confirmed by comparing the mercury pore size distributions of such papers without surface filling. Paper caliper and bulk can become slightly reduced as would occur in conventional internal filler loading increase (replacement of lower density fiber by higher density pigment). Surface filling reduces the sheet porosity and permeability dramatically, allowing potentially also for some reduction in fiber refining, thereby regaining some bulk and saving energy [8].

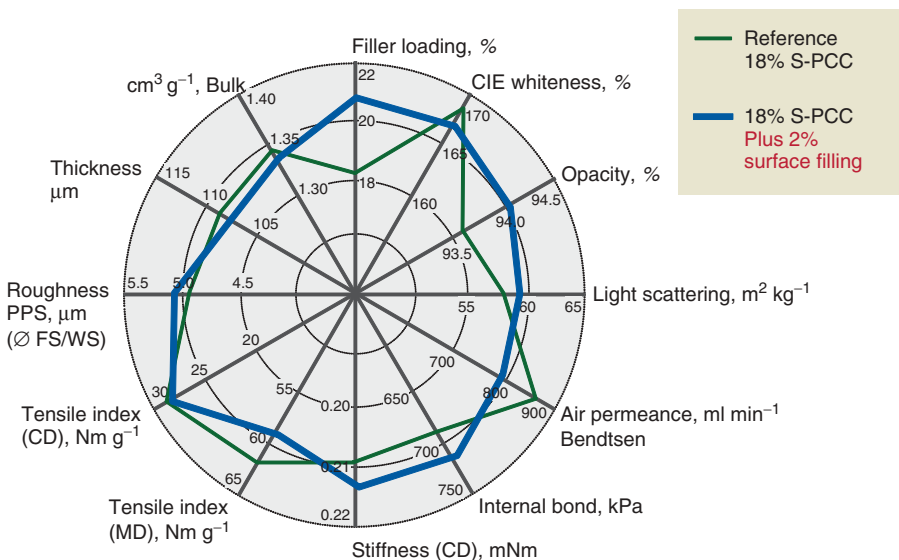


Figure 3.5 Results of surface filling woodfree uncoated paper with fine GCC, copy paper 80 g m⁻², commercial experience. (Source: Omya.)

3.5 Choice of Fillers

The choice of fillers usually takes into consideration primarily the desired performance in a specific paper or board grade, the internal situation in the mill, the general availability of the product, and the cost, including the external and internal logistics. In times of dramatically increased cost pressure on the paper industry (excess production capacity, competition from electronic media, etc.), the filler cost, like all other furnished components, clearly gains in importance when considering the choice of filler. This can, within limits, even lead to some downgrading. Optimizing cost with respect to the type of filler for a specific paper grade usually results in a compromise concerning the attainable properties when using a single filler. In cases where one single pigment does not meet all the requirements, filler combinations are applied. There is a continuous trend toward fully or partially replacing specialty pigments by regular or low-cost, modified fillers. Table 3.2 provides an overview of the range of regular fillers and specialty pigments applied in the production of certain paper grades and white top liner.

Of great importance are the potential interactions of the fillers with wet-end furnish components such as retention aids, starch, sizing agents, and dyes. Therefore, the selection of the filler type and grade needs also to be made in the light of these possible interactions. Finally, also sustainability considerations are gaining importance in terms of which grade of filler to choose for a specific application.

Table 3.2 Paper grades, range of fillers, and/or specialty pigments applied.

Woodfree uncoated Copy, stationery, offset	PCC, GCC, PCC/GCC, talc/GCC (Asia) –
Woodfree coating base Single, double, triple coated	GCC, PCC, chalk –
Wood-containing uncoated Supercalendered, magazine, and so on	Clay, clay/GCC, clay/PCC, secondary pigment, calcined clay
Wood-containing base LWC, MWC, HWC	GCC, talc, PCC, chalk –
Newsprint, directory	Secondary pigment, chalk, GCC, PCC, calcined clay, amorphous silicate, (TiO ₂), amorphous PCC
High opaques (thin print)	TiO ₂ , zinc sulfide, PCC, calcined clay, amorphous silicate
Decoration paper	TiO ₂ , Talc/TiO ₂ , calcined clay, or silicate/TiO ₂
Cigarette paper	PCC
White top liner	GCC, PCC, chalk, calcined clay

Source: Omya.

3.6 Characterization of Fillers

Chemical composition, particle morphology, particle size (also particle size distribution), brightness, refractive index, specific surface area, particle charge, and abrasiveness are commonly used to characterize papermaking fillers. In addition, measuring the intrinsic pore size distribution of (specialty) fillers via mercury intrusion has proven to represent a very valuable tool for indicating the absorption potential. Table 3.3 summarizes some chemical and physical data of fillers and specialty pigments.

CaCO_3 is soluble under acidic conditions, and therefore requires a near-neutral or slightly alkaline pH papermaking environment [9, 10]. Figure 3.6 depicts the general solubility of CaCO_3 depending of the pH of the environment.

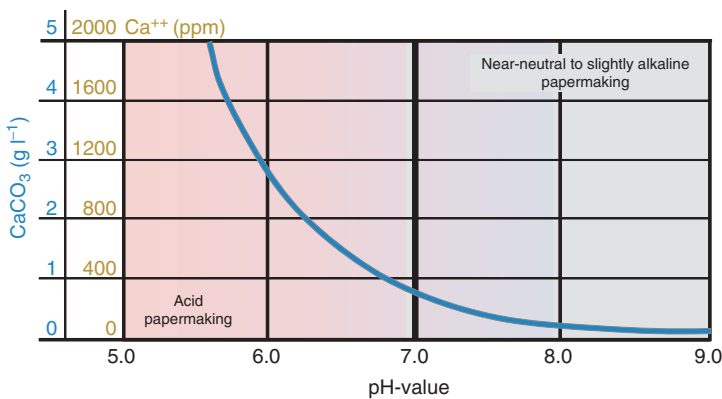


Figure 3.6 Solubility of CaCO_3 versus pH environment. (Source: Omya.)

To be able to use CaCO_3 as a filler and/or as a coating pigment, numerous paper and board mills around the globe have converted their wet-end systems from acidic to neutral and slightly alkaline pH. Historically, paper was mostly produced at a distinctly acidic pH. Paper produced in such a manner decomposes relatively quickly, and therefore presents a serious problem for the conservation of documents in libraries and so on. Complicated and expensive measures are applied to save valuable documentation printed, unfortunately, on acid-made paper. Woodfree paper, produced in the slightly alkaline mode and containing some CaCO_3 filler for buffering, exhibits a dramatically improved permanence and can be stored for hundreds of years under regular conditions.

3.6.1

Brightness

The widely used Tappi brightness (BaSO_4 standard) is measured at a wavelength of 457 nm. The indication of the yellowness index as well as the CIELAB L^* , a^* , and b^* values provide additional valuable information for the manufacturer and the

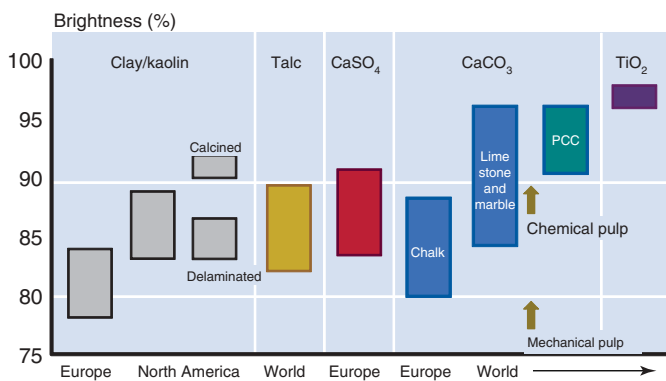


Figure 3.7 Brightness (Tappi R-457) of various regular paper fillers and some specialty pigments. (Source: Omya.)

customer. Fillers exhibiting high pigment brightness, such as natural ground or precipitated CaCO_3 , are in demand for the production of high quality printing and writing papers. Figure 3.7 compares the Tappi brightness of various fillers of different geographical origins, including some specialty pigments, as well as, for comparison, some highly bleached chemical and mechanical pulps. The brightness range of the different types of filler depends on the raw material quality used and the various processes (mechanical classification, magnetic separation, flotation, grinding, bleaching, precipitation, etc.) applied in their extraction, purification, and production.

3.6.2

Refractive Index

The refractive index indicates the extent to which a light beam is deflected when passing from vacuum into a given substance. The refractive index is determined by the filler's chemical composition and molecular structure. Powders are usually measured in an index-matching liquid. The material, ground into a fine powder, is immersed in a series of liquids until scattering and reflectance disappear, that is, the material becomes invisible. Of course, the powder should not be soluble in the liquid. It can be tested either using a laser beam or by studying the turbidity with the eye or a turbidimetric method. The more the particles differ from the medium (i.e., the more their refractive indices differ), the more light will be scattered by the particles. If there is no difference at all, no light will be scattered. However, as calcium carbonate is birefringent (doubly refracting), the method described is not ideally suitable for this specific mineral. The higher the refractive index developed in the paper, the higher the amount of reflected and/or scattered light, and the higher the increase in paper opacity. Titanium dioxide TiO_2 shows an extraordinarily high refractive index (rutile 2.75, anatase 2.55), while other common fillers exhibit indices of around 1.55–1.65 (zinc sulfide 2.39). For comparison, the refractive index of cellulose, as used in papermaking, is about 1.60.

Table 3.3 Characteristic chemical and physical data of regular fillers and specialty pigments.

Filler	Chemical composition	Crystal habit	Morphology	ISO brightness (%)	Refractive index	Density (g cm^{-3})	Specific surface ($\text{m}^2 \text{g}^{-1}$)
Kaolin hydrous	$\text{Al}_4(\text{OH})_8(\text{Si}_4\text{O}_{10})$	Hexagonal (1:1 layer silicate)	Hexagonal platelets	70–90	1.56	2.8	10–2
Calcium carbonate	CaCO_3	Trigonal	Rhombohedral	80–96	1.58	2.7	2–12
Natural Precipitated							
			Scalenohedral, aragonite, rhombohedral, prismatic all forms can occur discretely, clustered or agglomerated	92–97	1.56	2.7	4–12
Talc	$\text{Mg}_3(\text{OH})_2(\text{Si}_4\text{O}_{10})$	Hexagonal (2:1 layer silicate)	Hexagonal platelets	70–88	1.57	2.7	5–20
Gypsum	CaSO_4	Monoclinic	Needles	88–98	1.54	2.8	2–5
Titanium dioxide rutile, anatase	TiO_2	Tetragonal	Isomorphic (round particles)	97–99	2.76/2.55	4.2/3.8	8–12
Calcined clay	$\text{Al}_2\text{O}_3/\text{SiO}_2$	Hexagonal (1:1 layer silicate)	Fused platelets	89–93	1.56	2.7	15–25
Synthetic, precipitated silicate, silica	mostly Al or Mg/Ca-silicates	Mostly amorphous	Irregular composite	93–96	1.55	2.1	40–70
Aluminum trihydrate, hydrated alumina	$\text{Al}(\text{OH})_3/\text{Al}_2\text{O}_3 \cdot x\text{H}_2\text{O}$	Gel, pseudo-hexagonal (pseudo boehmite)	Irregular composite, hexagonal platelets	96–98	1.58	2.4	5–9
Cellulose	–	–	–	90	1.60	–	–
Air	–	–	–	–	1.00	–	–
Fibers	–	–	–	–	–	About 0.7	1–2
Fiber fines	–	–	–	–	–	–	6–8

Source: Various and Omya.

3.6.3

Particle Morphology

The structure of fillers can be observed and characterized best by scanning electron microscopy (SEM). The particle morphology has an influence on light scattering via the number and size of air microvoids in the sheet. For different morphologies, there is a different optimum for light scattering in terms of particle size. The particle morphology has an impact also on the packing of the filler particles in the flocculates usually formed during the papermaking process. The results are morphology-related differences in sheet drainage, drying behavior, and in paper properties such as bulk, porosity, ink receptivity, strength, and dusting. The sheet surface roughness as well as paper gloss after calendering and the sheet compressibility (important in rotogravure printing) are also influenced by the morphology of the filler or specialty pigment applied. Papers filled with platy fillers (clay) and originally bulky fillers (scalenohedral PCC) require less calender impact for obtaining a certain smoothness and/or gloss than papers loaded with rhombohedral or prismatic shaped fillers.

3.6.4

Particle Size and Particle Size Distribution

There are different methods (sedimentation, laser scattering/diffraction, etc.) to determine the particle size distribution of a filler. However, the results obtained by the different methods are usually not directly comparable. For example, even the regularly followed procedure of comparing pigments with very different morphologies by just one single particle sizing method, by adopting the equivalent hydrodynamic sphere, fails to provide correctly comparable particle size distribution curves. The sample preparation (state of dispersion) also has a great influence on the outcome of the individual measurement. Nonetheless, for convenience, the most widely used equipment for measuring particle size distribution of filler and coating pigments is the sedigraph unit (manufacturer: Micromeritics).

It covers a wide range, from coarse filler (30 wt% smaller than 2 μm) products to very fine fillers, coating pigments, and structured fillers. Laser diffraction methods are preferably applied for coarser products (<30 wt% <2 μm) and for structured (bulky) fillers. Figure 3.8 shows some typical particle size distribution curves (measured by the sedigraph method) of natural chalk.

Figure 3.9 illustrates the size relation between the GCC filler particles and filler clusters as well as the fibers in the sheet. As is clearly demonstrated, the filler particles are much finer than the fiber, and, in particular, much smaller than the voids between the fibers.

In the papermaking process, most of the original filler particles form clusters, in the form of flocculates, also supported by the addition of different flocculating wet-end additives. The degree of flocculation can be optimized by careful handling of the wet-end chemistry. To obtain a highly uniform sheet, any excessive

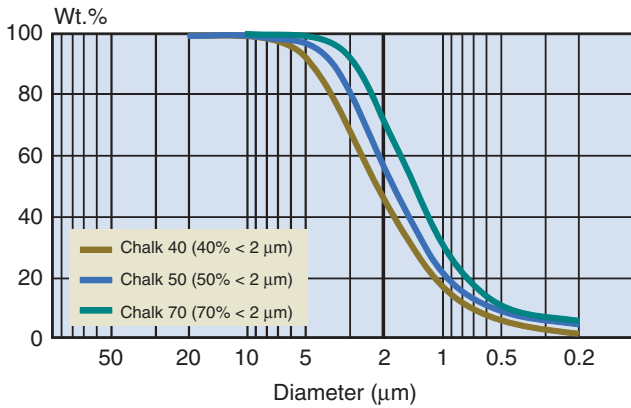


Figure 3.8 Typical particle size distribution curves of selected chalk slurry fillers, sedigraph method. (Source: Omya.)

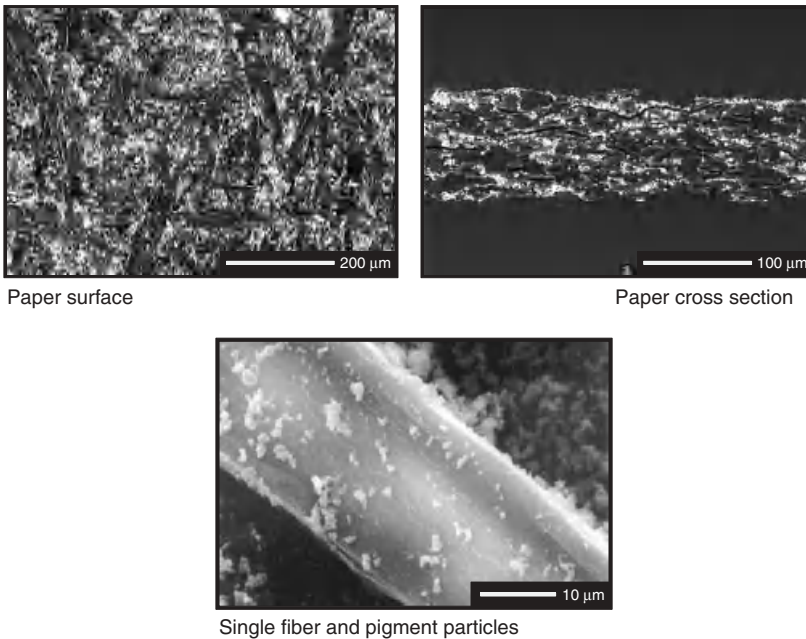


Figure 3.9 Size relation of typical GCC filler particles versus fiber/fiber matrix. (Source: Omya.)

flocculation, of course, should be avoided, as this disturbs the uniformity of formation of the sheet.

In general, the optical properties provided by a filler are also strongly influenced by its particle size and particle size distribution. Finer fillers, within limits, as well as a steeper particle size distribution (more particles of similar optimum size)

Table 3.4 Typical light scattering value ranges of major mineral fillers and some virgin fibers for paper and board.

	Light scattering ($\text{m}^2 \text{kg}^{-1}$)
Calcium carbonate	
GCC	140–190
PCC	210–270
Clay/kaolin	
Hydrous	70–120
Calcined	200–300
Titanium dioxide	450–650
Silicates/silica	280–340
Fibers (pulp)	
Chemical	20–45
Mechanical	50–70

Source: Omya.

produces more light scattering, and hence more opacity. Table 3.4 gives some typical light scattering ranges for major fillers, for specialty pigments, and, also for comparison, for some virgin pulps.

However, finer fillers have a more negative impact on the paper strength than coarse pigments of the same weight proportion. Non-platy, large particles tend to be released out of the paper surface more easily than smaller particles, resulting in, for example, more blanket piling in offset printing or increased contamination of a copying machine.

3.6.5

Specific Surface Area

Usually, the specific surface area is measured by the nitrogen adsorption method (BET: Brunauer, Emmet, Teller). The particle fineness, the particle size distribution, and the particle morphology are, depending on the structure, indirectly reflected in the specific surface area of the filler. Finer, nonstructured fillers exhibit a higher specific surface than coarser ones. There is, in general, a direct correlation between the specific surface area of a filler and, for example, the internal sizing agent demand. An internal sizing agent is applied to the wet end in order to make the paper more hydrophobic. The specific surface area of regular paper fillers ranges between 2.5 and $14 \text{ m}^2 \text{ g}^{-1}$. Typical papermaking fibers exhibit a specific surface area between 1 and $2 \text{ m}^2 \text{ g}^{-1}$, while fiber fines show specific surface areas of 6 – $8 \text{ m}^2 \text{ g}^{-1}$. As one consequence, increasing the filler loading level usually increases the additive demand: that is, the sizing agent, dyes, and so on. Specialty pigments applied as filler can reach specific surface areas as high as 70 – $80 \text{ m}^2 \text{ g}^{-1}$.

3.6.6

Particle Charge

The fillers applied in the paper and board production process need to be understood also as part of the rather complex wet-end chemistry. The electrostatic charge (zeta potential) that surrounds the pigment can be anionic or cationic. Depending on the type of filler, its origin, and the specific chemicals applied in the filler production process (grinding aids, dispersant, flotation, biocides), the charge density can be on different levels. To obtain a good charge-related stabilization of a negatively charged filler slurry at high concentration, the dispersant applied needs to be highly anionic. Typically, the salts of poly(acrylic acid) are applied for this purpose of electrostatic stabilization, as these provide the pigment surface with a distinct anionic charge. Similarly, low molecular weight and high charge density polyadmac, modified polyethylenimine or polyvinylamine, and so on can be used, for example, to develop distinctly cationic slurry stabilization.

The charge density of a filler slurry is of particular importance in the context of selecting the most suitable retention aid system. Today, there are many retention systems available, and the most suitable one has to be found for each individual filler application. The ordered addition of multipolymer retention aid systems and, in particular, the so-called microparticle systems offers efficient tools to retain anionically stabilized filler pigments at high production speeds effectively. Distinct cationic charged fillers are no longer in use, one reason being the potential for quenching the commonly applied negatively charged optical brightening agents (OBAs). It should be mentioned that the very mild cationic charge by nature on certain dry-ground GCC fillers does not show any negative impact on OBA efficiency.

3.6.7

Abrasiveness

There are many different and important factors that can have a significant impact on wire abrasion [11]. The abrasion potential of fillers is influenced by the particle structure, the particle fineness, and the particle hardness. Relatively coarse plate-shaped pigments tend to be less abrasive than non-platy ones of similar size. Increasing the filler fineness decreases the wire abrasion potential significantly. This is particularly pronounced when changing from very coarse, dry-ground, marble-based GCC fillers to finer GCC qualities. Large size, non-platy impurities such as quartz increase the wire abrasion excessively. Any pigment that is harder than the synthetic wire, which is commonly installed in the paper machine, potentially initiates wear on the wire.

There are different laboratory methods for determining the potential abrasiveness of a filler. The most modern unit is the Einlehner AT 2000 abrasion tester. This instrument works by using a cylindrical ceramic body with specific slots and a wire made of a synthetic filament. In order to obtain reliable and comparable results, maintaining the correct measuring conditions is absolutely mandatory.

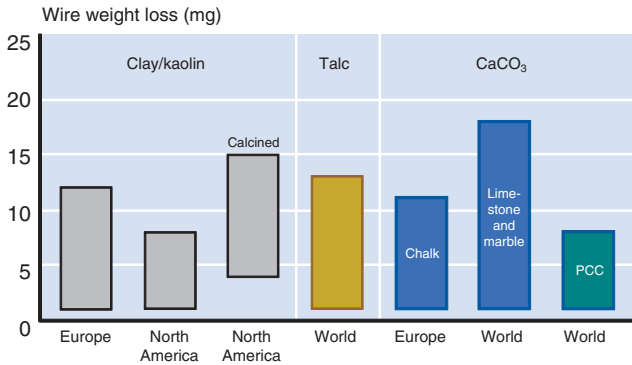


Figure 3.10 Abrasion of various paper fillers, measured by the laboratory method AT 2000. (Source: Omya.)

In particular, the quality of the ceramic body installed has a major influence on reliability of the abrasion results obtained. Figure 3.10 compares the different paper fillers on a global basis by this specific method. Again, because of the differences in the raw material used, the processes applied, and the differences in particle fineness, the abrasion ranges presented are only indicative.

Practical experience gained in recent years has shown that wire abrasion is greatly influenced also by the conditions on the paper machine. In general, lower filler retention potentially increases wire wear. The wire drag load should be minimized, for example, by a small number of stationary drainage elements and optimized low vacuum loads. The dry suction box ceramic surfaces should display low surface porosity and should be well maintained.

3.7

Main Mineral Fillers

As indicated under Section 3.2, the main fillers (in terms of quantity applied) are kaolin (hydrous), natural GCC, and PCC. Although comparatively much less sold in volume, talc still plays some role as a filler and more so as a pitch control mineral.

3.7.1

Kaolin (Hydrous)

Hydrous kaolin, or commonly named *clay*, is used today predominantly in wood-containing (mechanical) uncoated papers (supercalendered magazine papers, catalogs, etc.) [12]. Kaolin is formed by the decomposition of granite under special conditions (water, pressure, temperature, and pH). Kaolin deposits can be found at a number of major sites around the globe as a result of metamorphosis within granite outcrops. The largest ones from which paper filler and coating

pigments are extracted are located on the southeast coast of the United States and Brazil, in the Capim Basin (mainly secondary deposits), in Cornwall in the southwest of the United Kingdom (primary deposit, today filler only), and in Germany (primary deposit). Primary kaolins are those that are found at the places where they were originally formed, and are accompanied by the original matrix including partially altered and residual materials. Secondary kaolins have been transported by surface water from their place of origin, and, by progressive sedimentation, become deposited at a different location. Other kaolin deposits of commercial interest occur in Russia, Central Europe (Czech Republic, France, Spain), Ukraine (all primary), Australia (secondary), and China (primary, secondary). Because of the presence of a very high ratio of kaolin, exploiting a secondary deposit source requires significantly less processing than drawing from a primary deposit. Of the 12 million tons/year of clay used in the paper and board industry, 75% is for coating and 25% for filler application.

Kaolin processing involves the purification of the kaolin-containing raw material by several techniques including mechanical classification, grinding, bleaching, magnetic separation, and flotation. Kaolin is supplied as a slurry or dried in powder form (spray-dried or in crumbles). Figure 3.11 shows a generalized flow sheet for the wet processing of kaolin, based on secondary deposits.

The aspect ratio, or platyness, of kaolin is strongly dependent on the geophysical nature of the deposit. The aspect ratio expresses the relationship of the major diameter to the platelet caliper. Secondary kaolins tend to be of lower aspect ratio; some Brazilian examples, however, are exceptions to this rule. Primary Cornish kaolin,

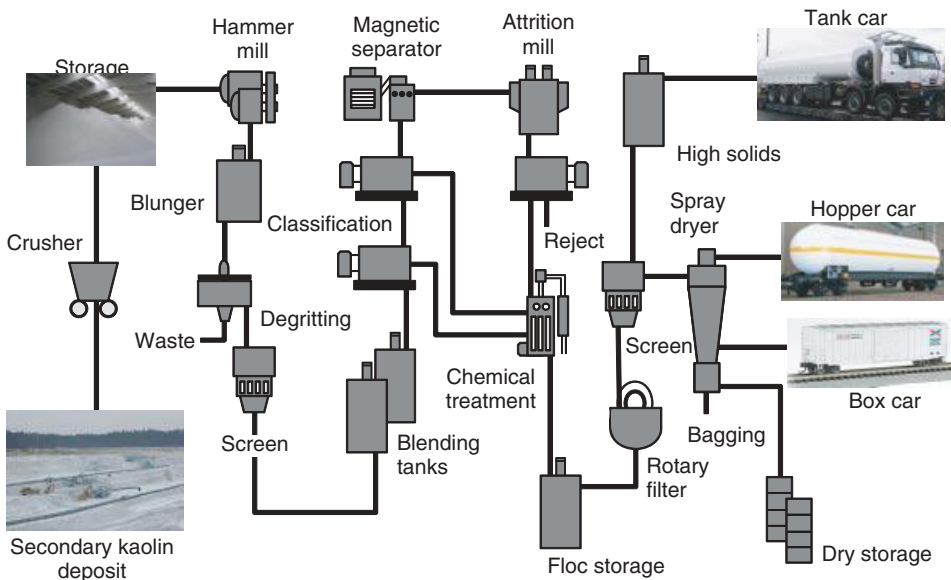


Figure 3.11 Flow sheet on the processing of water-washed kaolin, secondary deposit. (Source: Burgess, Thiele Kaolin.)

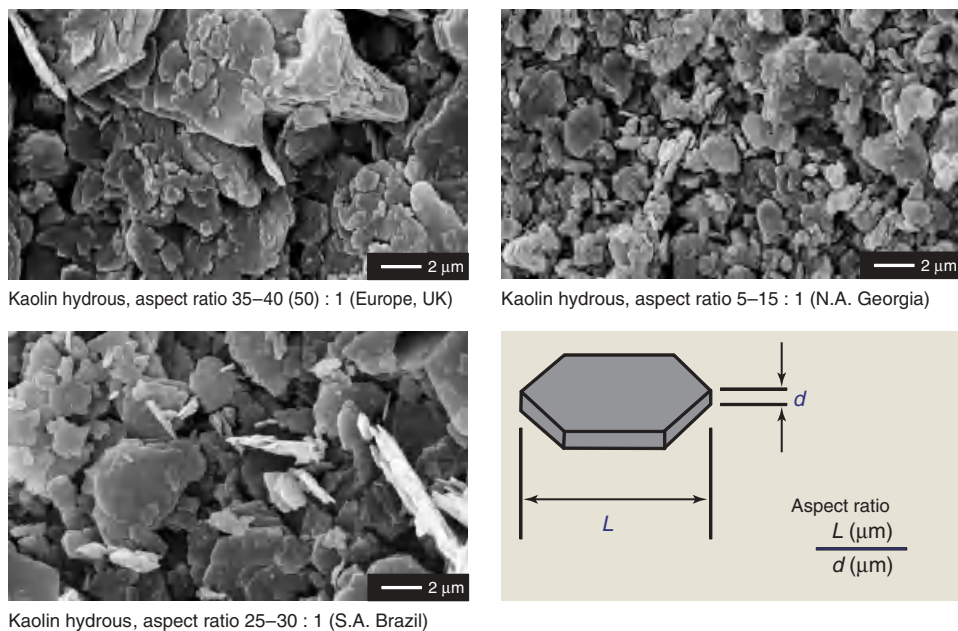


Figure 3.12 SEM pictures of typical kaolin fillers of different origins. (Source: Omya.)

for instance, has an aspect ratio of 25–40 : 1, compared to Georgian kaolin with an aspect ratio of 12–25 : 1 (Figure 3.12). The aspect ratio distribution throughout the various size ranges is also an important attribute of kaolin (Table 3.5), with the presence of bentonite or montmorillonite at the fine end of the particle size distribution being a particular feature of some clays, raising the aspect ratio of the fine

Table 3.5 Pigment data of typical clay kaolin (hydrous) fillers of different origin.

		European	North American	Brazilian
Specific surface BET	$\text{m}^2 \text{g}^{-1}$	9.0	14.0	6.5
Sedigraph 5120				
<5 μm	%	85	90	85
<2 μm	%	55	65	40
<1 μm	%	35	55	20
<0.5 μm	%	20	25	10
APS d_{50}	μm	1.8	0.7	2.4
Brightness R-457	%	81	83	87
Solids content	%	Crumbles	60–65	Dry
Aspect ratio		35	25	25

APS, Average particle size.
Source: Omya.

fraction to as high as 100:1. The hexagonal crystalline platelets of kaolin produce a high gloss of the finished paper after calendering. This gloss development also depends on the degree of delamination, that is, the extent to which the platelet agglomerates or stacks are broken into individual platelets. Filling of paper with a higher aspect ratio clay produces (after paper calendering) lower sheet porosity and higher paper gloss. Because of its chemical composition, clay can be used as a filler in both acidic and alkaline papermaking environments.

3.7.2

Natural Ground Calcium Carbonate (GCC)

Natural GCC (chalk, limestone, marble) filler is predominantly applied in woodfree uncoated paper, mechanical uncoated papers (usually in combination with kaolin), coating base papers, newsprint, white top liner, and folding box board.

Natural CaCO_3 constitutes the most frequently occurring type of sedimentary rock on our planet. It covers about 4% of the earth's crust. Calcium carbonate was and is formed in the oceans through biomineralization and reactions of calcium salts with CO_2 and other atmospheric gases (Figure 3.13). Natural CaCO_3 occurs in three major geological modifications. Chalk is the mostly crushed but not yet fossilized remains of the shells of tiny marine animals. Most chalk deposits were laid down during the cretaceous period, about 150 million years ago. By geological transformation (pressure) and thermal metamorphosis (heat and pressure), it is transformed into limestone and marble [13].

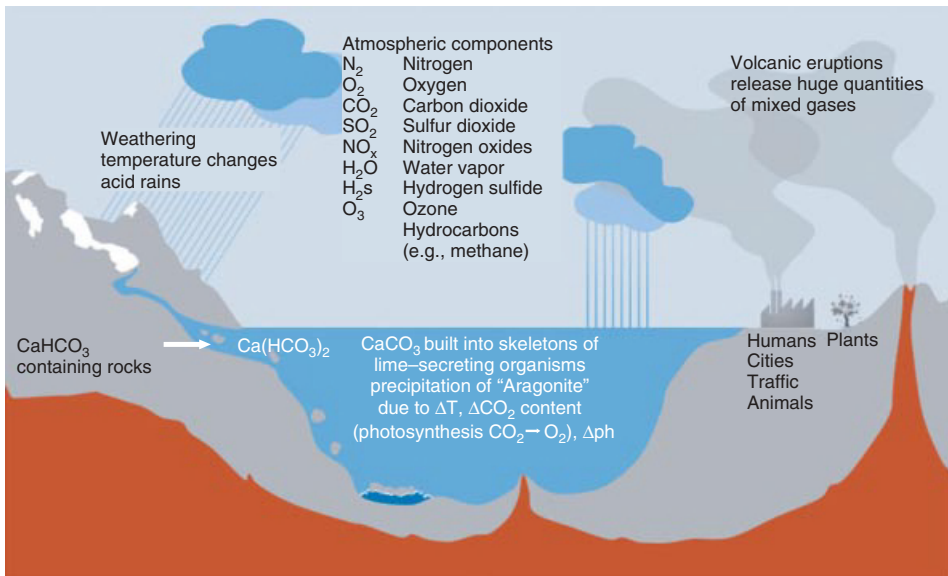


Figure 3.13 The carbonate cycle. (Source: national geographic.)

Natural calcium carbonate (limestone, marble) for the paper and board industry is processed at numerous locations around the globe: for example, in North America (Vermont, Canada, British Columbia, Alabama), in Europe (Norway, Finland, France, Spain, Portugal, Germany, Austria, Italy, Turkey), in Russia, in the Middle East (Egypt, Jordan), in the Far East (South Korea, China, Taiwan, Indonesia), in Australia, and in New Zealand. In addition, there are active plants located in Latin America (Mexico, Chile, Columbia, Brazil) and South Africa. Natural GCC in the form of chalk products for the paper and board industry is processed in Denmark, Belgium, France, Germany, and Russia. Chalk is a material of soft texture and requires relatively low energy for processing. Natural GCC fillers based on limestone or marble are produced by prewashing the raw material, followed by grinding, fine grinding, and screening the product. In case of undesired impurities in the raw material, these are removed by magnetic separation and flotation. Figure 3.14 shows a typical production process flowchart for GCC fillers, based on limestone or marble raw material.

The production, shipping, and application of GCC fillers in the wet (slurry) form have become by far the most preferred practice. GCC filler slurries exhibit a solids content of 65–74% (by weight) and are usually stabilized by using an anionic

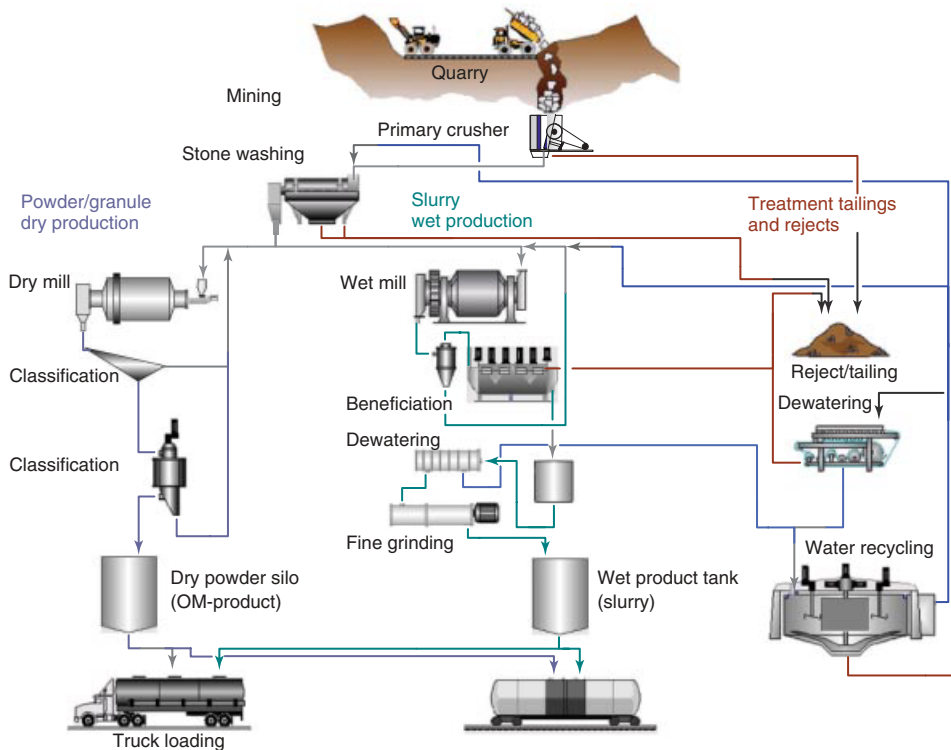
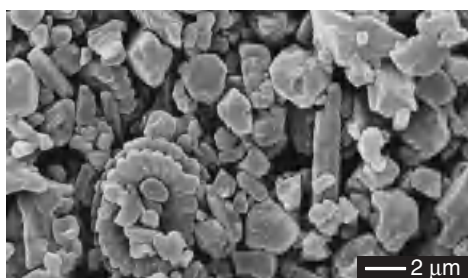


Figure 3.14 Process flow sheet natural ground calcium carbonate, marble. (Source: Omya.)

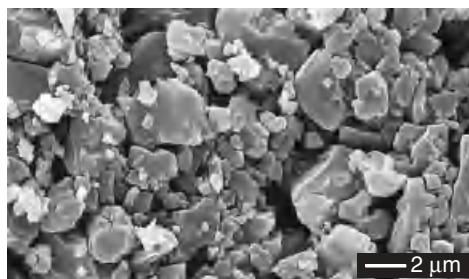
grinding and dispersing agent. Modern multicomponent retention aid systems and wide practical experience have made it possible to retain also highly concentrated dispersed filler slurries efficiently at good formation. Cationic stabilized GCC filler slurry products are technically possible but not much in use anymore commercially.

Next to wet-ground GCC, there is still a significant volume of dry-ground GCC produced and applied in the paper and board industry of certain countries. The range of fineness of such products is about 30–55 wt% below 2 μm , as measured on a sedigraph. Issues related to the use of very coarse products include excessive clothing wear and dusting in paper printing and general end use.

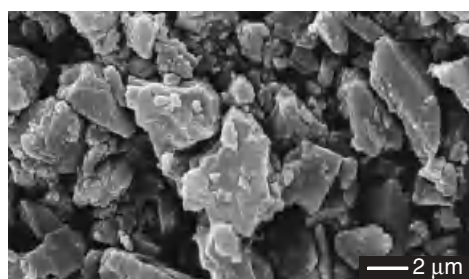
The crystallite habit of natural ground CaCO_3 filler is rhombohedral (Figure 3.15). For high brightness demand, GCC fillers based on limestone and marble are preferred by the paper industry [14]. Lower brightness chalk is used as filler in the production of regular newsprint, where there is less demand for brightness, next to their application as primary filler in coating base papers. The fineness of GCC fillers for paper is generally much greater than for kaolin-based fillers, particularly those sourced from primary kaolin deposits (Table 3.6). This is required, for example, for obtaining high light scattering, low abrasiveness, and low dusting out of the paper surface in the printing process.



Chalk 80–110 million years



Limestone 110–150 million years



Marble 300–500 million years

Figure 3.15 SEM pictures of typical filler chalk and GCCs. (Source: Omya.)

Table 3.6 Pigment data of typical natural ground calcium carbonate fillers, chalk, and GCC.

		Chalk dry-ground	Chalk wet-ground	GCC 60 wet-ground	GCC 75 wet-ground
Specific surface BET	m ² g ⁻¹	2.5	5.0	8.0	9.0
Sedigraph 5120					
<5 μm	%	85	95	90	95
<2 μm	%	45	70	60	75
<1 μm	%	15	30	40	30
<0.5 μm	%	<5	10	25	25
APS d ₅₀	μm	2.1	1.5	1.6	1.4
Brightness R-457	%	84	84	95	95
Solids content	%	Crumbles	65	65	72

APS, Average particle size.

Source: Omya.

3.7.3

Precipitated Calcium Carbonate (PCC)

PCC filler is predominantly applied in woodfree uncoated paper but also in wood-containing uncoated paper (combined with clay), woodfree coating base paper, directory paper, and white top linerboard [15]. In order to control the porosity and burning rate, PCC is also widely used as filler in the manufacture of cigarette paper.

One very important raw material for the production of PCC is a suitable deposit of natural CaCO₃. Only a few limestone deposits meet the stringent demands for the production of high quality PCC. Carefully selected limestone is calcined at 800–900 °C to obtain calcium oxide (CaO or quicklime), requiring energy and releasing CO₂ release. The quality and uniformity in quality of the lime used has an immense influence on the quality of the final PCC product. The addition of water (exothermic reaction) produces calcium hydroxide Ca (OH)₂ or slaked milk of lime. The usually applied carbonation process consists of bubbling CO₂ through the milk of lime. At the end of the process, there exists once again CaCO₃, now in the form of PCC. The process can be manipulated, within limits, to influence particle shape and fineness. PCC is often produced in plants located onsite at the paper mill, but there are also several large so-called offsite production units. A generalized flow sheet for the production of PCC is presented in Figure 3.16.

The morphologies of PCC used as fillers are commonly scalenohedral (rosette-shaped), rhombohedral (cubic-shaped), or aragonitic (needle-shaped). The morphology is defined by process parameters such as temperature, pressure, reaction speed, and additives. The particles can be arranged as individual discrete, clustered, or agglomerated. These different arrangements represent an additional tool to influence the overall pigment performance (Figure 3.17 and Table 3.7).

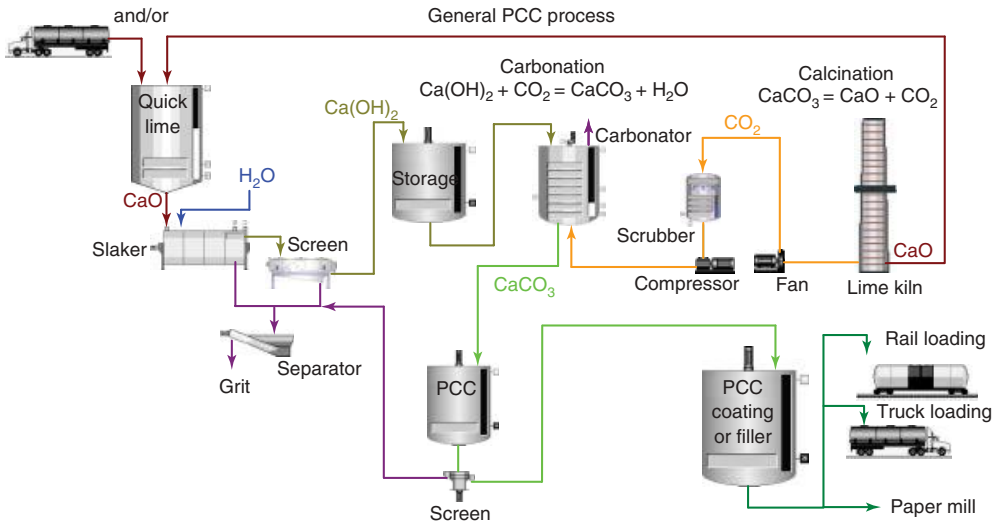


Figure 3.16 Process flow sheet for the production of precipitated calcium carbonate. (Source: Omya.)

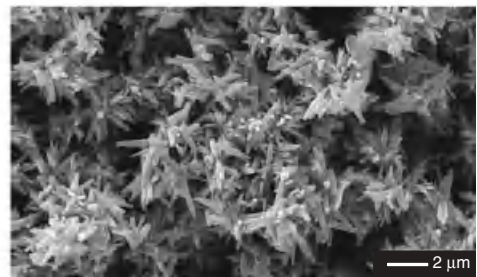
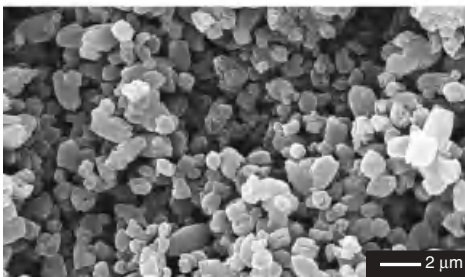
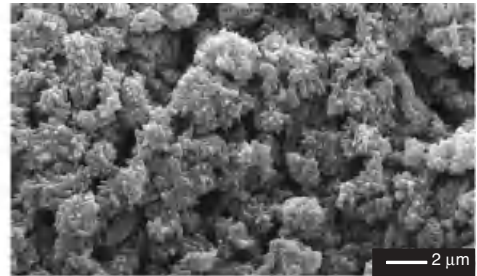
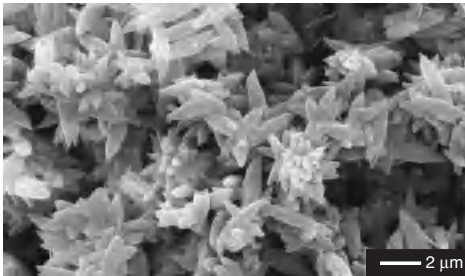


Figure 3.17 SEM pictures of typical PCC fillers. (Source: Omya.)

Table 3.7 Pigment data of typical precipitated calcium carbonate fillers.

		S-PCC coarse	S-PCC fine	R-PCC fine	A-PCC fine
Specific surface BET	m ² g ⁻¹	4.5	12.0	5.5	10.0
Sedigraph 5120					
<5 μm	%	95	100	100	100
<2 μm	%	30	90	95	75
<1 μm	%	5	20	60	20
<0.5 μm	%	< 5	5	10	5
APS d ₅₀	μm	2.5	1.5	0.9	1.5
Brightness R-457	%	96	96	96	96
Solids content	%	20	20/50	20/50	20

APS, Average particle size.

Source: Omya.

Currently, the most common PCC morphology applied around the globe is the clustered scalenohedral one. This rosette-shaped type of PCC (S-PCC) provides increased caliper and bulk to the paper (compared to kaolin or GCC). However, as a consequence of this higher bulk, the strength properties are reduced and the sheet becomes distinctly more open and permeable. Also, somewhat hindered drainage compared to GCC or prism-shaped PCC has been reported. A PCC providing extra high bulk, in general, tends also to exhibit a lower light scattering potential. Combining different carefully selected morphologies assists in the optimization of specific paper properties. Although particle morphology and fineness can be influenced largely in the PCC production process, in the end a suitable compromise addressing the different properties desired by the papermaker has to be found.

Figure 3.18 portrays the impact of scalenohedral PCC versus GCC on the properties in the case of a woodfree uncoated paper. The study was carried out on a commercial paper machine on the basis of 80:20% eucalyptus/pine, basis weight 80 g m⁻², and 21% loading [16]. No adjustment in terms of refining and so on was made. As documented, the most significant difference originating from the fillers applied is the higher bulk with the use of PCC.

CaCO₃ in the form of PCC, as is true for GCC, is naturally soluble under acidic conditions and therefore requires a near-neutral to slightly alkaline pH environment. Residual calcium hydroxide Ca(OH)₂ in the PCC can require extra measures for pH control of the final product and the paper mill wet-end system.

Various development work has been carried out by various manufacturers trying to produce PCC fiber fibril composites directly in, for example, a high consistency fiber stock. Also the so-called fiber lumen loading concept was investigated in depth. However, so far there has been no major breakthrough in the commercialization of such processes [17, 18]. In addition, the possibility of producing such composites inline is being explored [19]. One major drawback of all these concepts is, for example, that the pigment structure cannot be controlled like in a regular

PCC process. The predominant PCC pigment crystal habit adopted is colloidal rhombohedral.

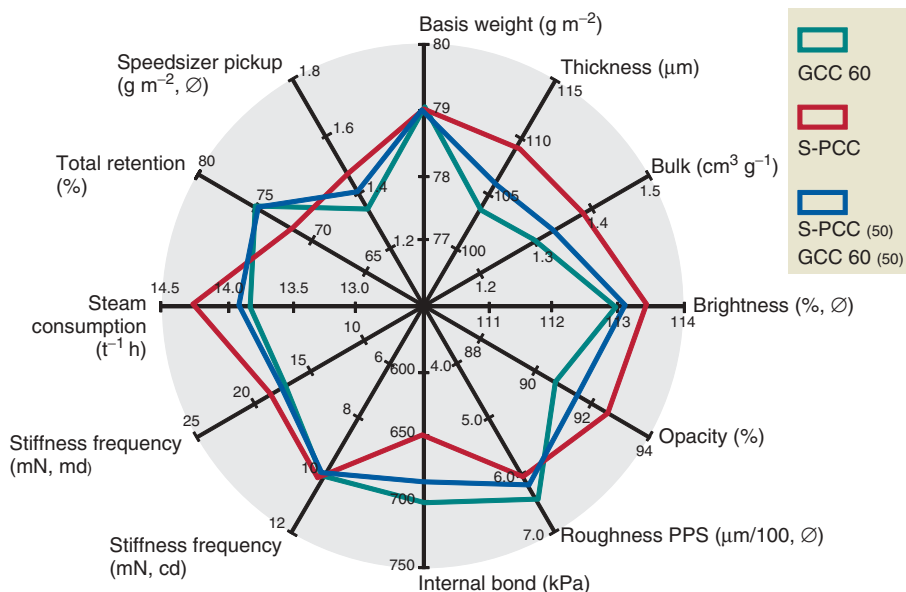


Figure 3.18 Scalenohedral PCC versus GCC in woodfree uncoated paper, commercial trial. (Source: Omya.)

3.7.4

Talc

Talc as filler is applied in woodfree uncoated paper in Asia Pacific, often combined with natural GCC. There is a current strong trend, for example, in India, to replace talc by either PCC or GCC or combinations thereof. In Europe, it is used only in a very few cases as primary filler in wood-containing coating base paper and wood-containing uncoated paper, in the latter case in combination with clay and calcium carbonate. Talc reduces the permeability of the base sheet and can improve rotogravure printability. Talc as filler is also applied in wall paper manufacture.

Talc is found naturally throughout the world within an assembly of various minerals and as a secondary pigment. Major talc producing countries are China, India, USA, Russia, Finland, France, Australia, Austria, Spain, Italy, Mexico, and North Korea. China represents by far the largest producer and exporter of talc in the world. In Figure 3.19, a schematic of the talc production process is shown.

Micronized talc is applied to control pitch originating from the use of chemical pulp and white pitch coming from the coated broke. Typically in the case of softwood, about 2–8 kg t⁻¹ pitch control talc is added. Micronized talc (10–40 kg t⁻¹) is added to render harmless the stickies present in the deinking process and in the production of new paper based on recycled fiber (Mondo Minerals, Finntalc in

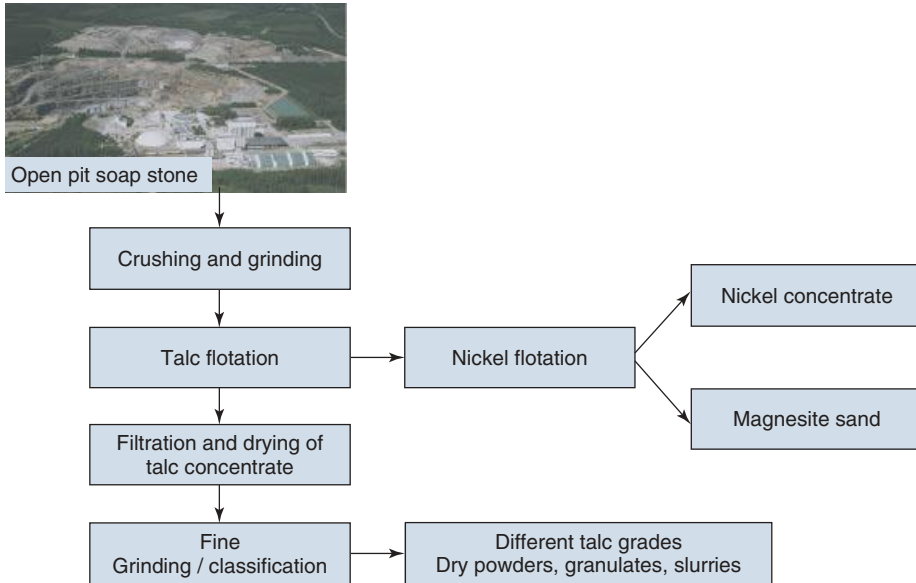
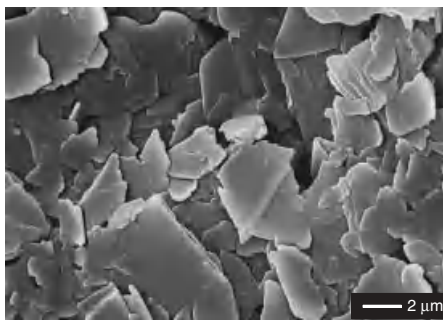
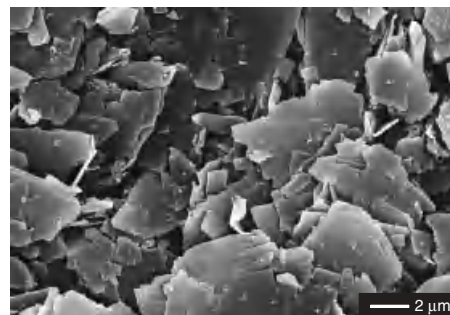


Figure 3.19 Talc production process, Finland. (Source: mondo minerals.)

Pitch and Sticky Control Brochure). Talc particles are stably adsorbed on the surface of the resin or on the sticky component and render these interfering substances harmless by covering them or being incorporated into them. The performance of talc depends on its purity (low chlorite and dolomite content desired), the fineness, and specific surface area. In Figure 3.20, SEM pictures of talc as fillers and for pitch control are shown.



Filler talc



Pitch control talc

Figure 3.20 SEM picture of talc filler and talc for pitch control. (Source: Omya.)

Pyrophyllite, a layered aluminum silicate hydroxide mineral $\text{Al}_2\text{Si}_4\text{O}_{10}(\text{OH})_2$, is similar to talc in appearance and crystal structure. Pyrophyllite is successfully applied as a filler and for pitch control in South Africa. Interestingly, some paper mills have recently replaced the function of micronized talc as sticky control by applying bentonite (adsorbent aluminum phyllosilicate, intrinsic specific surface area $400\text{--}600\text{ m}^2\text{ g}^{-1}$) instead. There are indications that also calcium carbonate-based filler pigments carry the ability of adsorbing wood extractives. One condition is that such pigments be free of anionic dispersants. By specific selection and/or modification of calcium carbonate-based mineral pigment, the potential to be used as pitch and sticky control can be enhanced. Experience shows that the real effectiveness of adding minerals for the purpose rendering pitch and stickies harmless can only be proven over long periods of practical application in the specific paper or board production line.

3.7.5

Gypsum (Calcium Sulfate)

Calcium sulfate is used only on a very small scale as filler in printing and writing papers (Figure 3.21). In recent years, gypsum as filler has been widely replaced by GCC at various locations. Gypsum, on the other hand, is largely applied in the manufacturing of gypsum board. Gypsum board is made up with a high percentage of calcium sulfate material and lined with reinforcing sheets of paper. It is used in the construction industry for walls and ceilings.

Gypsum can be sourced from either natural deposits or as a by-product, for example, in the production of fertilizer or citric acid. Another gypsum by-product originates from the desulfurization of flue gases emitted by power plants based on fossil fuels. Although available in huge amounts, so far all attempts to make this by-product technically and economically usable as paper filler have been unsuccessful. Gypsum may exist as different chemical structures ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$

		Calcium sulphate dihydrate	Crystal water-free
Chemical formula		$\text{CaSO}_4/2\text{H}_2\text{O}$	CaSO_4
Density	g cm^{-3}	2.3	2.9
Hardness	Mohs	1–2	3–4
Solubility water 23 °C	g l^{-1}	2.1	2.7
pH value		6.0	6.0

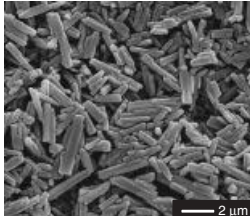


Figure 3.21 SEM picture of calcium sulfate filler and chemical data. (Source: Omya.)

(dehydrate), $\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$ (hemihydrate), CaSO_4 (anhydrite)) and in general exhibits a high solubility, more or less independent of the pH environment [20].

3.8

Specialty Filler Pigments

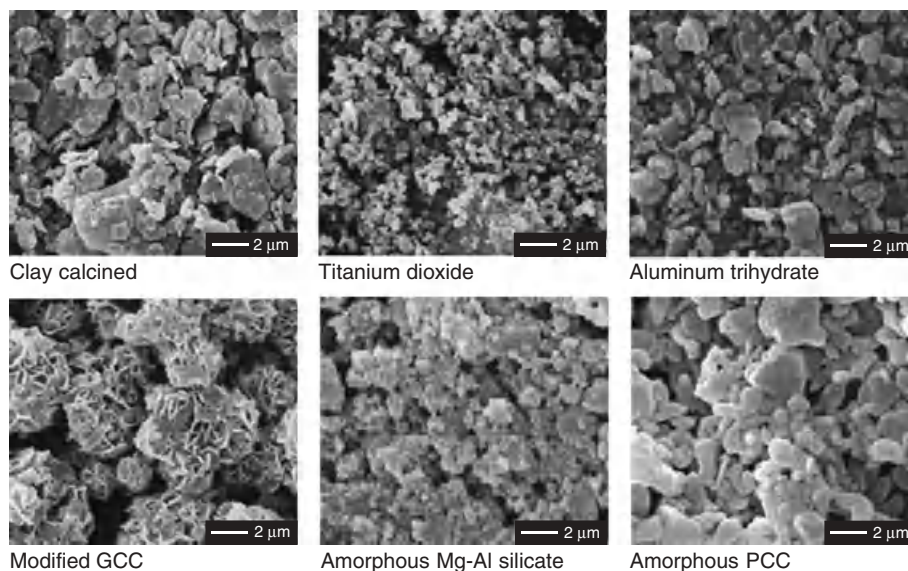


Figure 3.22 Specialty filler pigments for paper and board: Clay calcined, titanium dioxide, aluminium trihydrate, modified natural ground calcium carbonate, amorphous magnesium aluminium silicate, amorphous precipitated calcium carbonate. (Source: Omya.)

3.8.1

Calcined Clay

Calcined clay is a specialty filler applied to the sheet mainly in order to increase light scattering/opacity and to reduce the ink print-through potential. Typical areas for the application of calcined clay are lower basis weight uncoated wood-containing papers (i.e., telephone directories, low basis weight newsprint, supercalendered paper, etc.). It can be found also as a filler in white top liner, folding box board, and liquid packaging board.

In the calcination process of kaolin, the water of hydroxylation (14 wt%) is first driven off at temperatures of 500–700 °C. On continued heating up to 900–1000 °C, the particles begin to fuse together into secondary particle aggregates, accompanied by an increase in brightness. Further agglomeration results in tertiary particles. The final result is a large number of kaolin–air interfaces and relatively high internal pore volume, leading to increased light scattering and opacifying properties (Figure 3.22).

3.8.2

Titanium Dioxide

Titanium dioxide is a specialty and particularly effective filler. It is applied in specialty papers, often at low basis weights, with particularly high demand in dry and wet opacity and sheet brightness. TiO_2 can be found in thin print paper, for example, Bible paper, as well as in highly opaque grades. As it provides excellent wet opacity due to its high refractive index, it is used widely in the production of label paper and decor base paper.

Titanium is the fourth most abundant chemical element found on earth. In nature, titanium occurs only in the form of oxides or mixed oxides with other elements. Mineable deposits are generally of volcanic origin. The titanium dioxide pigment industry uses between 90 and 95% of the global titania ore extracted.

Titanium dioxide is a synthetic material commercially produced by the sulfate or the chloride process. It exists in three modifications with different crystal lattice structures and therefore different physical properties. The modifications are rutile, anatase, and brookite. However, of technical importance are only rutile (hexagonal close packing of the oxygen atoms) and anatase (cubic close packing of the oxygen atoms), which differ from each other in some of their physical properties. The typical refractive index for rutile is 2.75 and for anatase 2.55. In comparison to other pigments, TiO_2 exhibits also an extraordinarily high density (3.9 g cm^{-3} anatase, 4.2 g cm^{-3} rutile). Rutile gives higher brightness (but less blue whiteness) and opacity, while anatase supports OBAs better as it absorbs less ultraviolet light. Compared to the rutile form, anatase has a lower Moh's hardness of 5.5–6.0 instead of 6.5–7 [21].

Even at only low addition levels, TiO_2 has a remarkable effect on paper opacity due to its unmatched high refractive index and high light scattering potential. Because of its high refractive index, TiO_2 is the only pigment that provides high opacity even when the paper is wet (label paper). The extra high refractive index is also important for providing opacity in the manufacturing of decoration paper. In the production process of this specialty paper, resin penetrates completely throughout the sheet structure, thereby filling up the voids and diminishing pore structure volume, resulting in reduced light scattering. Because of the extreme fineness (average particle size $0.2\text{--}0.25 \mu\text{m}$ (Figure 3.22) and the complex chemistry in applications (e.g., high amounts of cationic wet strength agent, etc.), TiO_2 filler pigments can be difficult to retain in the paper web.

Because of its high cost, TiO_2 is often used in combination with extenders. These extenders are other less costly minerals (e.g., $\text{Al}(\text{OH})_3$, synthetic silicate, silica, barium sulfate), which are capable of replacing TiO_2 to a limited extent while producing similar results. The effect of providing wet opacity to the sheet by TiO_2 , however, cannot be reached by using extenders alone. No extender matches the extra high refractive index of TiO_2 . The closest to TiO_2 in terms of refractive index is zinc sulfide with a value of 2.37.

3.8.3

Amorphous Silicates and Silica

Amorphous silicates and silica are also specialty pigments, mostly used in lower basis weight newsprint and directory paper. These pigments are added in small percentages (sometimes applied in combination with regular paper fillers) to enhance paper brightness and opacity as well as absorption properties, for example, reduction of print-through.

Amorphous silicates are produced by the destabilization of soluble silicates to yield amorphous discrete particles in varying degrees of aggregation. The high specific surface area in combination with an organophilic surface is responsible for the excellent ink adsorption characteristics. Amorphous silicate also has the potential to increase somewhat the bulk of the paper sheet (Figure 3.22).

Magnesium aluminum silicate has been also coprecipitated with a rhombohedral-shaped PCC as core, as one single product, and has found its way into commercial application. The target was to reduce the ink print-through in lower basis weight newsprint or directory paper at lower cost than regular amorphous silicate alone [22].

3.8.4

Aluminum Trihydrate ATH (Hydrated Alumina)

Aluminum trihydrate (ATH) (Figure 3.22) represents a specialty filler pigment that contributes to paper brightness and ink receptivity, and acts as a flame retardant. The effect on flame retardance can be explained by the 35 wt% bound water based on material weight. The bound water is released at temperatures above 150 °C. The raw material source for the production of ATH is bauxite. Bauxite is a blend of Al_2O_3 , Fe_2O_3 , SiO_2 , H_2O , TiO_2 , and other minerals. To produce ATH it is necessary to stabilize the alumina content and to separate out the other minerals. This is done by the so-called Bayer process. After the final filtration, the clear liquor of sodium aluminate is seeded with specially prepared fine crystals of ATH. This seeding causes the sodium aluminate to decompose to ATH or $\text{Al}(\text{OH})_3$, which forms a precipitate.

Some bauxite ore deposits exhibit a rather high purity and brightness. Such material can be converted directly into filler grades. The physical difference between a fine precipitated ATH and a fine-ground ATH is small.

3.8.5

Modified Natural Ground Calcium Carbonate MCC

Natural GCC has been specifically modified into a pigment with a completely different morphology and consequently with different properties [23]. Figure 3.22 shows modified GCC particles in their original state. Modified GCC is easily compressible, for example, in the paper calendering process [5]. It should be mentioned that the modified GCC also exhibits an extraordinarily high specific

surface area of up to $80 \text{ m}^2 \text{ g}^{-1}$ BET or more, and provides particular absorption and adsorption properties.

3.8.6

Amorphous Precipitated Calcium Carbonate

In commercial trials, a new amorphous PCC composite specialty pigment has been successfully applied in newsprint [24]. The primary target of this specific development was to hinder the low viscosity ink fraction of the cold-set ink from migration to the back side of the printed sheet. Although the addition rate is usually very low (about 1–2%), the effect on print-through is quite significant. Figure 3.23 illustrates the effect of applying such an amorphous PCC or magnesium aluminum silicate on a modern high speed newsprint machine, using 100% recycled fiber base with a total pigment content of 20% in the new paper.

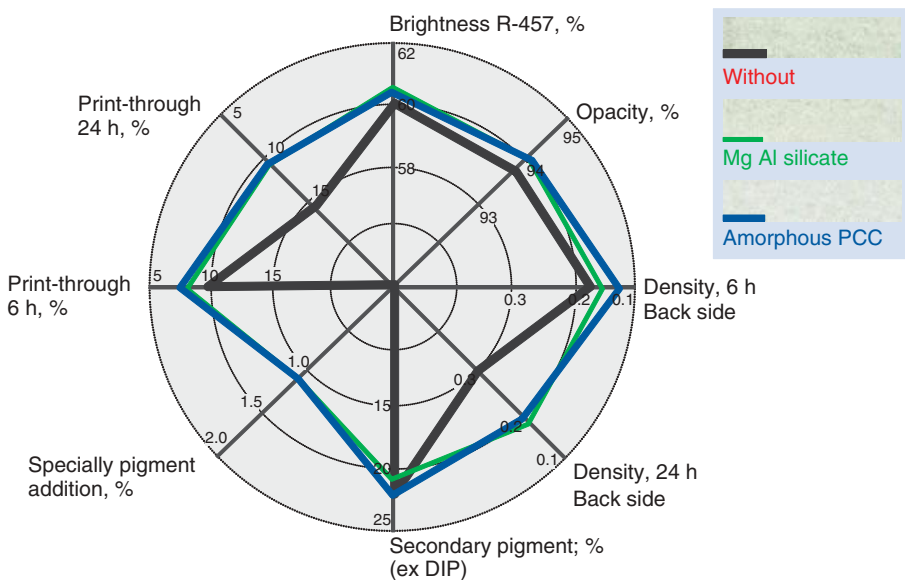


Figure 3.23 Effect of applying 1% specialty pigments on print-through reduction, commercial experience. (Source: Omya.)

3.8.7

Other Fillers or Specialty Pigments

It must be mentioned that there are several other industrial minerals being used directly or indirectly as paper fillers. These materials include barites, barium sulfate, calcium sulfite, zinc oxide, zinc sulfide, diatomaceous earth, mica, bentonite, and pyrophyllite.

Bentonite, which is an adsorbent aluminum phyllosilicate (60–80% montmorillonite next to quartz, mica, feldspar, etc.), shows an intrinsic specific surface area of 400–600 m² g⁻¹ and strong swelling when exposed to water in the presence of sodium ions. This mineral has been successfully used for many years as part of a retention and drainage system or sticky control.

Synthetic organic fillers are, for example, based on polystyrene or urea formaldehyde. Local availability, cost, and the need for obtaining certain special properties are the deciding factors in the selection of these materials. However, the total volume is very small in comparison to the major fillers and specialty pigments, as described above.

3.9

Preservation of Pigment Slurries

Silvia Hubschmid

CaCO₃, clay, and talc slurries (white mineral dispersions, pigment slurries) are natural products produced under industrial conditions. They contain water and are therefore susceptible to bacterial contamination [25–27].

These white mineral dispersions are either stored in silos, where the product is continuously removed and new product is filled in, or are transported through various pipelines into trucks, railcars, and ships. Because of the fact that bacteria are omnipresent in the air and on surfaces, all these stages can act as sources of contamination.

Bacterial growth can affect quality parameters such as the pH and, therefore, the viscosity of a pigment slurry. Furthermore, brightness and even smell can be negatively affected. Therefore, white mineral dispersions are commonly treated with biocides in order to hold down the level of bacterial growth for as long as possible.

Preservatives (biocides) and disinfectants are defined chemical substances or mixtures of substances that destroy microorganisms or inhibit their development at low concentrations, usually in the range of 0.1–5000 µg ml⁻¹ or g⁻¹.

In regard to white mineral dispersions, there are technical as well as regulatory factors restricting the number of biocides that can be used. For example, a biocide must be effective without negatively influencing the pigment slurry characteristics. It must be stable to a certain extent in the white mineral dispersion but should not be found in the final products. Therefore, the biocides commonly used for the preservation of white mineral dispersions decompose over time once added into an alkaline system. The rate of decomposition depends on many different factors, including the chemical itself, the temperature at which the biocide was added, the storage temperature of the white mineral dispersion, the level of bacteria present initially and during storage and transport, the system pH, and so on.

Neither the magnitude of contamination taking place throughout production, storage, and transport nor the rate of biocide decomposition can be predicted.

Therefore, posttreatment of stored white mineral slurries with biocide may become necessary over time.

Common biocidal substances that are applied in white mineral dispersions nowadays are combinations of formaldehyde-releasing compounds (O-, N-formals), isothiazolines (MIT 2-methyl-4-isothiazoline-3-one, CMIT 5-chloro-2-methyl-4-isothiazoline-3-one, BIT 1,2-benzisothiazoline-3-one), bronopol (2-bromo-2-nitropropane-1,3-diol), 2, DBNPA (2-dibromo-3-nitrilopropionamide), aldehydes (e.g., glutaraldehyde), and others.

The amount of biocide to be dosed, as well as the compatibility of specific biocidal trade products, must be tested specifically for each application. The amount of biocide to be dosed must be carefully evaluated in order to prevent the formation of resistant bacteria over time. This is very important because modification of known substances or the development of new active agents is rarely found these days due to strong restrictions and limitations resulting from legislation as well as health and safety considerations.

3.10

Outlook

Maximilian Laufmann

There is a continuous demand for technical and presently even more pronounced economical development in the various paper and board grades. In this context, the quality and choice of the filler is also under continuous review. Brightness, opacity, and surface properties, such as smoothness, uniformity, surface strength, and printability, will continue to be of great importance. To address these demands, further specific pigment developments and the combined application of different filler grades can be expected. Replacing the more expensive specialty pigment applications by regular fillers is always of interest. Calcium carbonate-based fillers will penetrate the paper and board market even further. Interestingly, there are even some examples of tissue paper filled with a small quantity of GCC.

The global consumption of wood in the paper and board industry equals about 40% (200 million tons/year) of the total wood harvest. Growing competition coming from biofuel will make the fibers even more valuable in the future. Also for this reason, investigations on how to increase the filler loading in various paper (and board) grades even further are constantly going on. Maintaining stiffness and strength properties and runnability at increased loading and cost effectiveness are some of the challenges. At the already very high filler loading levels as practiced in Europe, each percentage point of further increase represents a significant success. High filler loading principles include preflocculating the filler by applying certain polymers and forming flexible flocculates in a size of about 30–50 μm . Also systems such as applying a novel dry-strength agent combined with a modified calcium carbonate filler and an advanced retention aid programs are offered [28]. Treating the onsite-produced PCC with acrylic resin polymer increases in particular the internal bond. New polymers can support retention, drainage, and initial wet web

strength [4]. As has been observed, the performance of such principles seems to be more promising for woodfree papers rather than for magazine papers or newsprint. Covering fine-ground GCC by a synthetic polymer shell has been shown to carry some technical potential in commercial trials [29]. Combining biopolymers in a smart way could be one route to allow for higher filler loading. The use of nanofibrillized cellulose (NFC) as strength agent does hold some technical potential, but its addition simply to the wet end may at the end not be economical. Although reduced significantly, the specific energy consumption needed to produce NFC is still quite high [30, 31]. Developing filling through the surface of the sheet further in combination with NFC could be an additional tool for completely new solutions [32]. One new alternative route being investigated is polyelectrolyte multilayering (polycation plus polyanion) onto the fiber surface. The claimed advantages include no sheet densification, less shrinkage, and higher dry content compared to refining fibers for strength. However, the development of this idea is at an early stage [33, 34].

Acknowledgment

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4

Functional Chemicals

4.1

Overview

Roland Pelzer

Chemical additives for paper manufacturing are generally divided into the following:

- 1) Commodities:
This group includes inorganic acids, caustic, bleaches and similar products. These chemistries are not dealt with in this book with one exception, the aluminum compounds, which are included in *Process Chemicals*, Section 6.2.
- 2) Specialty chemicals, which are
 - a. functional chemicals used in paper manufacturing to improve or to change particular properties of paper, for instance, to change the hydrophilic paper surface to hydrophobic to a certain extent
 - b. process chemicals used to ensure a proper run on the paper machine to produce desired paper quality at maximum output
 - c. utility treatment chemicals that do not relate to the papermaking process itself. They are needed to run utilities such as boilers, cooling towers, and energy plants. Fresh water, process water, and effluent treatment, on the other hand, are normally seen as an essential part of papermaking; related chemical additives are included in *Process Chemicals*, Section 6.11.

Paper coating needs functional chemicals and process chemicals, as well. Owing to the particular process of paper coating, these have been reserved for discussion in Chapter 5.

The amount of specialty chemicals used in paper manufacturing is estimated at 1.1% in average without starch and modified starches, which sum up to another 1.6%. Global paper production, estimated at 400 million tonnes in 2011, allows drawing conclusions on the global demand of specialty chemicals being 4.5 million tonnes, from which 60% is estimated as coating additives. Finally, the market for functional chemicals and process chemicals for paper manufacturing and the smaller share of utility treatment chemicals remains as some 1.8 million tonnes (active matter) or 7 billion euro [1]. The demand for chemical additives varies a

great deal, of course, depending on the raw material mix and the paper grades to be produced. The growth rate of chemical additives for paper manufacturing in total can be expected to be above the growth rate of paper production, since the global mega-trends of

- increasing utilization of recycled fibers
- increasing machine speeds
- increasing filler levels
- reducing specific water consumption are boosting the demand for appropriate chemical additives.

4.2

Starches in Papermaking

Johan Schrijver

4.2.1

General Remarks

Papermaking is the largest nonfood application for starches globally, consuming approximately 5 million metric tons annually [2]. The quantity and quality of the applied starches vary in a wide range and depend on the end use of the paper and board grade and the applied production process. In a typical sheet of copy paper, for instance, the starch content may be as high as 10%. Both chemically modified and unmodified starches are used in papermaking. The application of starch is shown in Figure 4.1. Starch is applied in the wet end, by spraying in the forming section, by surface sizing in the dryer section, as well as in coating.

In the wet part of the papermaking process, starches used are mostly cationic, having a positive charge bound to the starch polymer. These starch derivatives

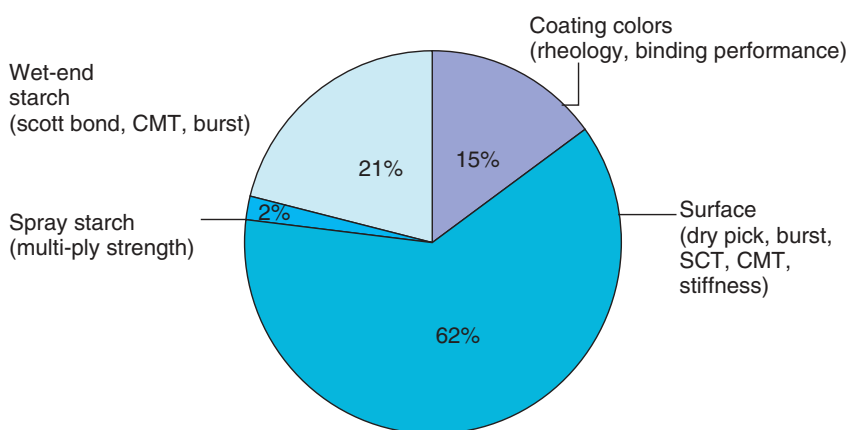


Figure 4.1 Starch in papermaking by application [2].

associate with anionic or negatively charged paper fibers/*cellulose* and inorganic fillers and fines. Cationic starches together with other retention and internal *sizing* agents help give the necessary properties to the suspension and paper web being formed in the papermaking process and provide the required dry strength to the final paper sheet. Cationic starch is fully cooked and added to the paper pulp usually at 1% solids, and with dosage rates of 2%.

Owing to lower basis weights and higher filler and recovered paper levels, there is a growing need to use higher amounts of starch in the wet end. This is mainly to compensate for the lower strength properties of the smaller fibers. The dosage level is limited because of the input of positive molecules. The maximum dosage of cationic starch is 2% (at a degree of substitution (DS) of 0.02 mol/mol). Otherwise, the zeta potential will be around zero. New developments combine anionic and cationic natural or synthetic polymers. Table 4.1 shows the trend of starch use in different paper grades.

In the dry end of the paper machine, the paper is rewetted with a starch-based solution. This process is called *surface sizing*. These starches (native and cationic) have been chemically or enzymatically depolymerized at the paper mill or by the starch industry (oxidized or acid thinned starch). The size press starch solutions are applied to the paper by size press or film press at a consistency of 6–10% solids. Further development is seen with the increase in the solids and use of the size press application as a coater. The surface sizing also contains other additives such as defoamers, fillers, sizing agents, and optical bleachers. All this gives the final paper additional strength and provides further water hold out or “size” for superior printing properties.

Starch is a low-cost functional additive derived from renewable, sustainable sources, much like the trees themselves. With the growth in recycled fiber application, modified starches will continue to help papermakers meet the required strength properties. Further effort will be placed on developing modified starches in order to achieve even more functionality compared to the more costly synthetic chemicals. Starch is a unique backbone for addition to and combinations with several new chemicals. The combinations add value (performance vs costs) to the end product.

Table 4.1 Trend of starch use in paper making in the European Union.

Paper grade	Trend	Starch level (%)	Type of starch
Wood-free uncoated	↓	4	Commodity
Coated (w'f and w'c)	↓	2.5	Commodity/value added
SC Paper	↑	0.75	Commodity
Board	↑	2.5	Commodity/value added
Kraftliner	→	1	Commodity
Newsprint	↓↓	0.5	Commodity
Fluting/liner	↑↑	5	Commodity
Tissue	↑↑	0.4	Value added

4.2.2

Sources of Starch

Starch is the major carbohydrate reserve in plant tubers and seed endosperm where it is found as granules, each typically containing several million amylopectin molecules accompanied by a much larger number of smaller amylose molecules. By far the largest source of starch is corn (maize), with other commonly used sources being wheat, potato, tapioca, and rice (Figure 4.2). Starch with 100% amylopectin (without amylose) can be isolated (as a hybrid of dent corn), which is called *waxy* maize starch. Waxy maize starch is a functional papermaking starch that is extremely large in molecular weight compared to dent corn. This larger size allows for more cationic contact points that can be formed between the anionic paper fibers and the starch, and, therefore, more reactivity in creating the desired paper properties. Recently, a waxy potato starch has been developed, and the first trials for paper applications are promising. The costs of these starches are very high and finding the right niche is bound to be difficult.

The kind of starch used has also varied a great deal by source. Figure 4.3 shows that potato starch, in particular, lost a large market share mainly due to the huge price variations caused by harvest losses.

Potato starch, a root starch grown mostly in Europe and the Northern United States, is the second most popular functional starch used in papermaking. Potato starch has a breakdown similar to that of amylose and amylopectin content, yet it is a larger molecule with inherent anionic properties from the phosphorus found in the soil from which the potato grows. Such a high amount is not found in cereal starches. Potato starch is also a stable product when cooked, which can remain

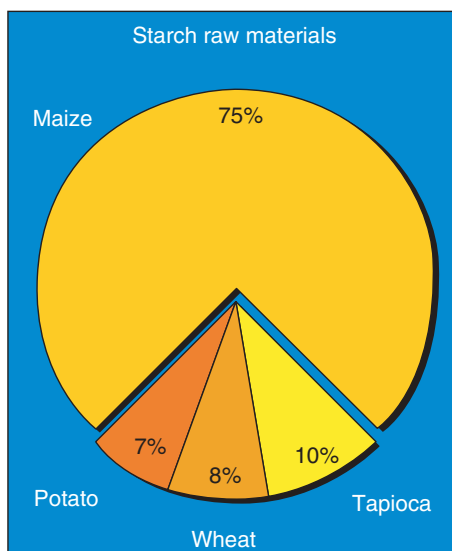


Figure 4.2 Starch raw materials [2].

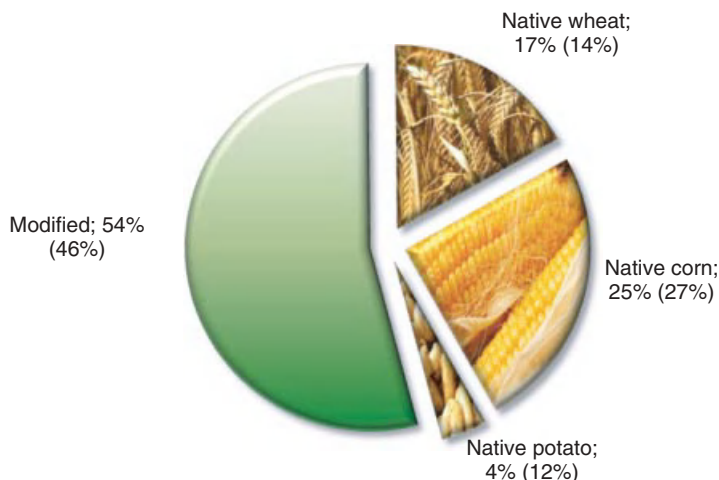


Figure 4.3 Variation of the raw material source in starch for papermaking from 2005 to 2008.

stable in solution for many hours, similar to waxy maize. With the reduction of the subsidies in Europe, it is expected that potato starch will be supplied to the paper industry only if the functionality gives it value.

Tapioca starch is likewise a root starch, but mainly grown in Asia and South America. Tapioca has stability properties similar to that of potato and waxy maize and is the third most common functional starch used in papermaking.

Wheat starch is mainly used in Europe and Australia. The use is based on low price levels of wheat starch, which strongly depend on a combination of wheat raw material price and the value of the co-product vital wheat gluten (protein). The high price level of this protein results in a low starch price. Rice, pea, and banana are typically not used for starch production (in paper application) unless dictated by economic conditions, such as an existing low-cost source or plant is located close to a paper mill. Typically, these starches have much more lucrative options within the food market than in papermaking.

The selection of the starch to be used depends on both the total cost structure and the functional goal. The starch costs are also strongly dependent on the revenue of its co-products when surely considering a cereal starch. The revenues of the co-products can vary by time and geographical situation. Cost-in-use is typically the decision point from where mills choose their best option.

4.2.3

Structural Unit and Starch Processing

Starch consists of two types of molecules (Figure 4.4), amylose (normally 20–30%) and amylopectin (normally 70–80%). Both consist of polymers of D-glucose units linked in α -1,4-formation. In amylose, this results in a linear chain, whereas in amylopectin about one residue (in every 20 or so molecules) is also linked in the C-6

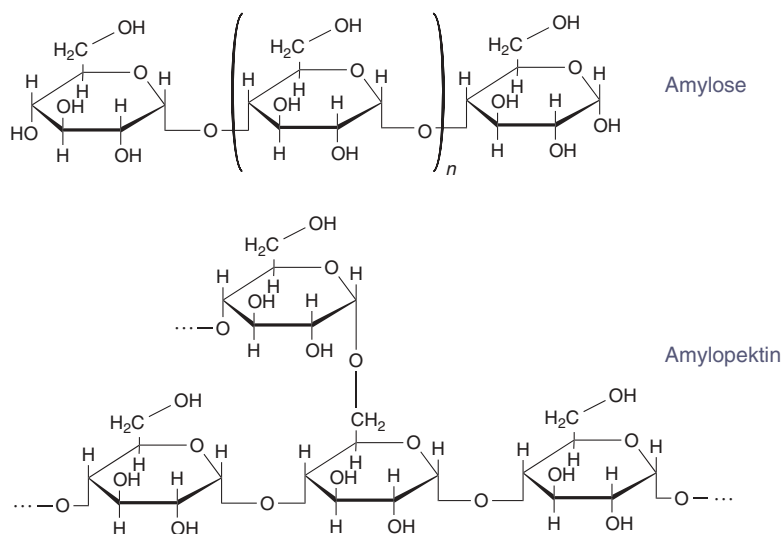


Figure 4.4 Chemical structure of starch components.

position, forming branch-points. The relative proportions of amylose to amylopectin and branch-points depend on the source of the starch, for example, amylomaizes contain over 50% amylose, whereas “waxy” maize has almost none (~3%).

Starch molecules arrange themselves in the plant in semicrystalline granules. Each plant species has a unique starch granular size: *rice starch* is relatively small (about 2 μm) while *potato starches* have larger granules (up to 100 μm). Microscopic shots of different starch corns are shown in Figure 4.5.

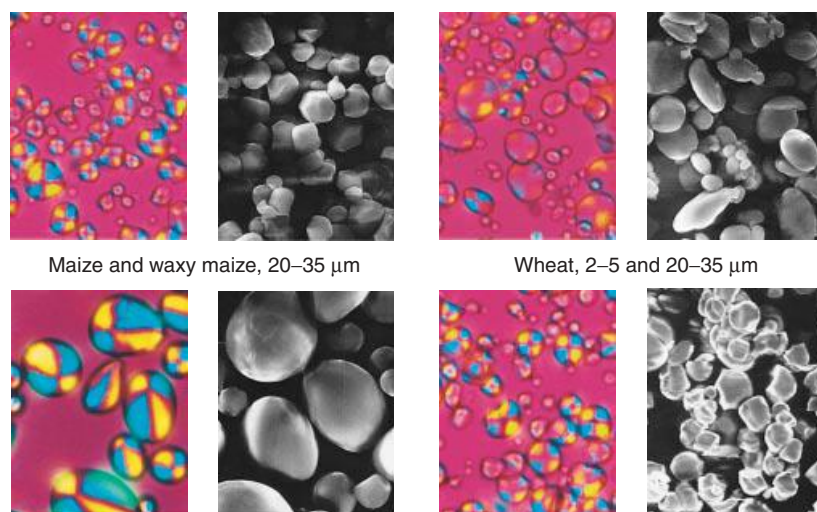


Figure 4.5 Microscopic shots of starch corns.

Although in absolute mass only about a quarter of the starch granules in plants consists of amylose, there are about 150 times more amylose molecules than amylopectin molecules. The reason is that amylose is a much smaller molecule than amylopectin.

Industrial starch preparation is carried out either continuously or batchwise, as shown in Figure 4.6a–c.

Starch becomes soluble in water when heated. The granules swell and burst, the semicrystalline structure is lost, and the smaller amylose molecules leach out of the granule, forming a network that holds water and increases the *viscosity* of the mixture. This process is called *starch gelatinization*. As shown in Figure 4.7, with increasing temperature the starch becomes a paste during cooking and

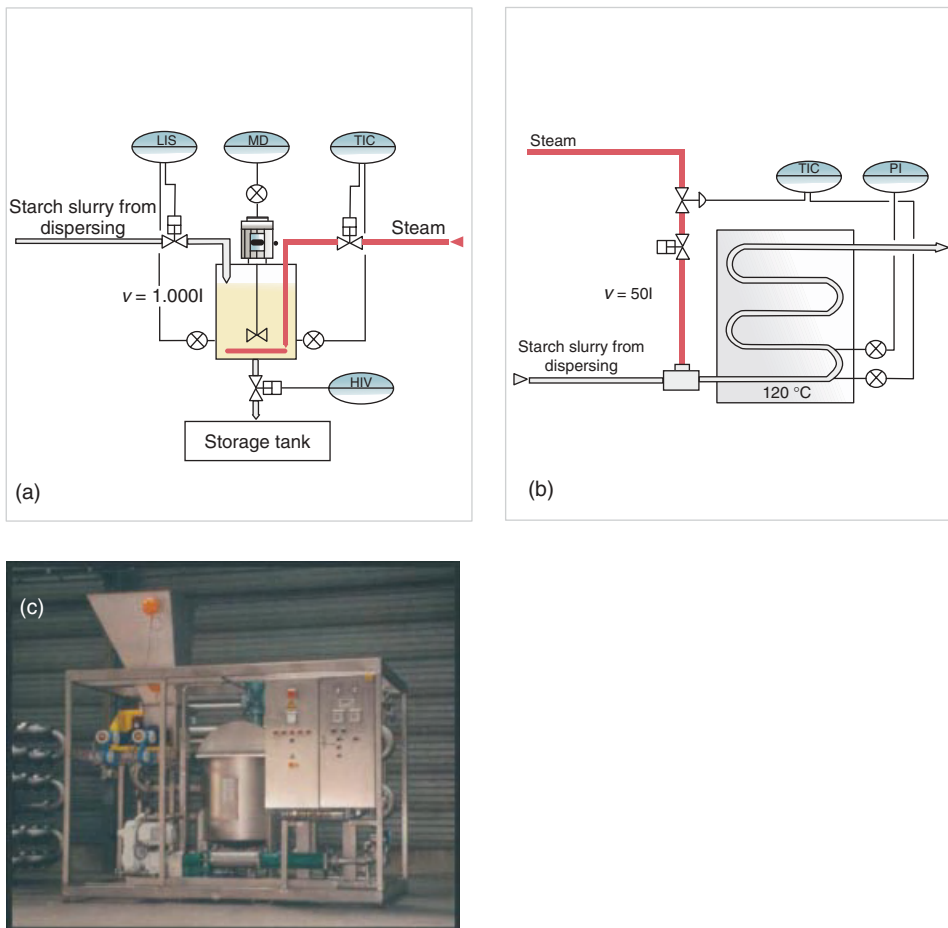


Figure 4.6 (a) Batch cooking process, (b) continuous cooking process, and (c) industrial jet cooker.

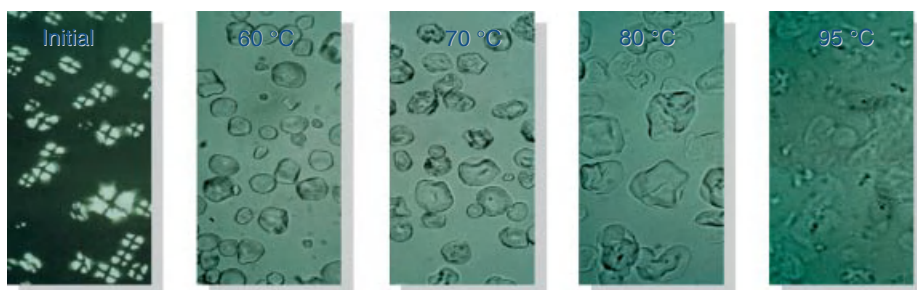


Figure 4.7 Starch granules during dissolving at different temperatures.

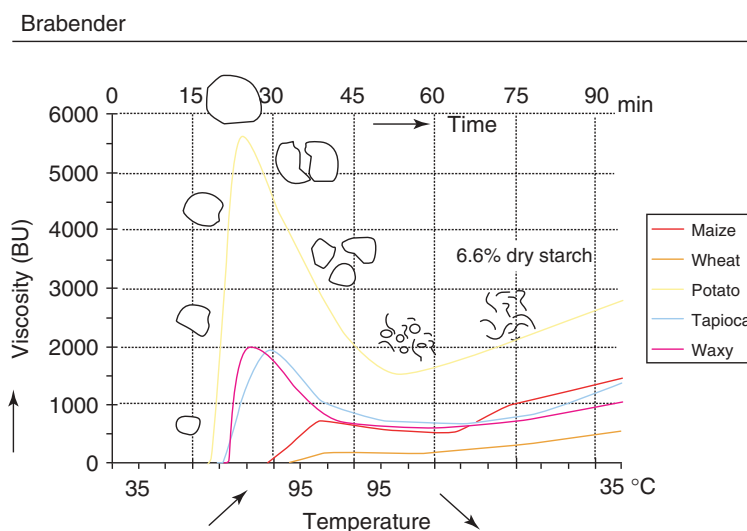


Figure 4.8 Starch cooking viscosity development (gelatinization) during heating up and cooling down.

increases further in viscosity. During cooling or prolonged storage of the paste, the semicrystalline structure partially recovers and the starch paste thickens, expelling water (Figure 4.8). This is mainly caused by the *retrogradation* of the amylose. This process is responsible, for example, for the hardening of bread or *staling*, and for the water layer on top of a starch gel (*syneresis*).

Some hybrid plant varieties have pure amylopectin starch without amylose, known as *waxy starches*. The most used is *waxy maize*, others are *glutinous rice* and *waxy potato starch*. Waxy starches have no retrogradation, resulting in a more stable paste. High amylose starch, *amylomaize*, is cultivated for the use of its gel strength.

Table 4.2 Chemical composition of different starches.

	Unit	Potato	Corn	Wheat	Tapioca
Starch grain diameter	μm	5–100	3–25	2–35	5–35
Amylose content	%	20	28 ²	28	17
DP ³ amylose	–	3000	800	800	3000
Amylopectin content	%	80	71	71	83
DP amylopectin	–	2 × 10 ⁶	2 × 10 ⁶	2 × 10 ⁶	2 × 10 ⁶
Phosphorus content	%	0.08	0.01	0.04	0.01
Lipids	%	<0.05	0.5–0.6	0.5–0.8	<0.1
Protein	%	<0.6	0.3–0.4	0.4	0.8
Moisture	%	18.1	12.7	12.8	12.0
Gel temperature	%	60–65	75–80	80–85	65–70
Ash	%	0.4	0.2	<0.2	<0.1

4.2.4

Chemical Composition of Starches

Starch properties depend a lot on the plant sources. Table 4.2 shows the chemical composition of starches from different sources, which has major impact on starch properties.

4.2.5

Chemistry, Modification, and Conversion Technology

For efficient usage of starch in papermaking, the native starch has to be modified. Unmodified starches, which differ in properties such as amylopectin to amylose ratio, granule dimensions, gelatinization temperature, and the molecular weights of the component fractions, are available. In addition to these variables, modified starches greatly extend the number of potential wet-end starch additives available for a given application. Much research has been carried out that has resulted in the development of new applications for starch in papermaking. Physical, chemical, and genetic modifications and combinations have further improved the starch application potential. The following modification methods are practiced:

- physical modification
- fractionation into amylose and amylopectin components
- thermomechanical conversion
- acid hydrolysis
- chemical modification
- oxidation
- derivatization
- enzyme conversion.

Thermomechanical conversion, acid hydrolysis, and enzyme conversion all lead to a decrease in the molecular weight of the starch and a corresponding decrease in the solution viscosity. This makes the starch more manageable, for instance, for its application onto the paper surface in a size press or film press. For that, a certain low viscosity of the starch solution is necessary. On the other hand a reduction in the molecular weight of the starch means a loss in its potential for improvement of paper strength. This means that maximum strength improvement by surface application requires the optimal ratio between the viscosity and the pick-up of the starch solution in sizing. Improvement of up to 30–60% in paper strength properties is reached by surface treatment of paper. This explains why 62% of all starches used in the paper industry are for surface sizing.

Native starch, as such, is not suitable for wet-end usage because of its very low retention in the paper sheet (<30%), which is undesirable from both economic and environmental standpoints. To obtain good starch retention on papermaking stock, it is necessary to attach cationic substituents to the starch molecule. Starches are cationized with either tertiary (diethylamine ethyl chloride hypochloride) or quaternary (epoxy propyl trimethyl ammonium chloride) amine groups. The cationic charge of the tertiary group depends on pH, with decreasing charge at higher pH values above 6. Quaternary cationic groups retain their complete charge at all pH levels. Typical commercial wet-end cationic starches have a DS of cationic groups ranging from 0.01 to 0.05. In other words, 1–5 of 100 anhydroglucose units contain one cationic group. For example, a starch of molecular weight 4×10^6 Da and a DS of 0.01 will have approximately 250 cationic charges per molecule. These cationic starches are produced by the starch manufacturers. Owing to the ionic reaction with the paper stock, addition rates above 1.5% lead to an undesirable change in the charge of the stock suspension, causing problems during paper production and leading to a high COD load in the circuit water system and in the untreated waste water.

Alternatives to these covalently bonded cationic charges are cationic polymers, which react with native or slightly anionic starches by fixation and/or precipitation. Such polymers can be used in the paper mill during or just after cooking of the starch. A very effective polymer is polyvinylamine (PVA). It forms, for example, with native potato starch or mildly anionic corn starches and the paper fibers, a very stable complex, which results in very good retention up to an addition level of 5% starch. Figure 4.9 shows a model of such an on-site process. This wet-end application allows much greater improvements in paper strength than with cationic starches and gives results very close to those obtained with surface application of starch. The mechanism of dry strength improvement by wet-end starch is based on interfiber bonding. Here, its free glucose hydroxy groups participate in hydrogen bonding with fiber surface cellulose molecules, which means a “chemical hydration” of the fiber compound system. In addition, wet-end starch improves sheet formation by improved retention of fines and fillers and also provides more uniformly distributed fiber–fiber bonds by hydrogen bonding.

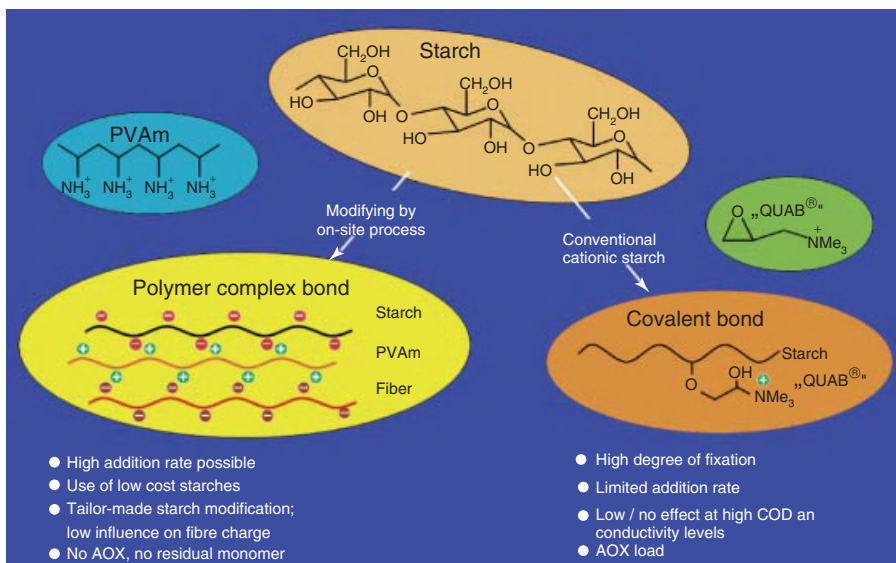


Figure 4.9 Modification of starch for wet-end purposes.

4.2.6

Applications

4.2.6.1 Wet End

4.2.6.1.1 Strength Additive The strength properties of paper can be measured in three ways: in the X, Y, and Z direction. Tensile, stiffness, and Mullen are typical tests papermakers do when optimizing their production and as quality control to meet the demands of their customers. The goal is to obtain the required strength values at optimal machine speed at lowest cost-in-use. Starches are key players in meeting these goals. Cationic starches will form hydrogen bonds with anionic paper fibers in order to strengthen the sheet web and allow less wood fiber addition.

There are several variables to consider when adding cationic starch to the wet end, such as the following:

- How much cationic charge can be used? This is highly dependent on the amount of anionic charge that exists within both the pulp and other functional chemicals added.
- Can the cationic starch be cross-linked to gain even more strength? Typically, a cross-linked starch will further enhance the strength of the final paper at less addition rates than non-cross-linked starches.
- Can anionic starch be added to the cationic starch to create an amphoteric starch? This is typically done when papermakers can gain maximum advantage of starch addition with minimal disturbance to wet-end chemistry. When mere

cationic starches are added at high addition rates, there is a risk of upsetting the chemical balance, which can cause dramatic issues in the wet end such as over-cationization that will cause severe foaming in the drained water. Control of wet-end chemistry is vital to ensure that a uniform paper product is manufactured. Amphoteric starches were developed to allow more starch addition such that up to 20% starch can now be added in certain paper grades for maximum strength achievement.

- Should a potato or waxy maize cationic starch be considered instead of a dent cationic starch? In most cases, the waxy variety will (i) give more strength to the final paper sheet and (ii) remain in a cooked state for much longer without becoming unstable.
- At which position in the wet end should the cationic starches be added? This decision can dramatically change the strength properties. Early dosage (close to the pulper) will give proper mixing and adequate dwell time and assure maximum strength improvement. The dosage of the cationic starch closer to the headbox will have more effect on retention and dewatering.

4.2.6.1.2 Dewatering and Retention Cationic starches can be vital in retaining maximum fines, fillers, and pulp and aiding in sheet dewatering. Most fines and fillers are anionic and are attracted through hydrogen bonding to the cationic receptors that act as a “fish net” in grabbing those particles. Again, a potato and waxy maize starch with its higher molecular weight has proved to be the superior functional starch for retention.

For maximum performance of cationic starches, the starches have to be added prior to synthetic retention aid products so that the starch is given reaction time to bond the fillers and fines to the fibers.

Modified starch is by far the most economical additive for retention and drainage improvement and should be maximized prior to any consideration of adding synthetic products.



Figure 4.10 Pilot machine used for starch application trials.

Last but not the least, the efficiency of cationic starch is very much impacted by other chemical additives in the furnish. Investigations, preferably on pilot scale systems (Figure 4.10) using process water from the mill intended for the scale-up, have to be carried out beforehand. Still, the complexity to imitate the practical situation is high. This is mainly caused by the difficulty in reaching stable conditions in the primary circuit of the wet end of the pilot paper plant. The levels of fines, charge, fillers, anionic trash, and conductivity in such pilot plants fluctuate a great deal and make the interpretation of the results difficult. The pilot work can help to develop a model and a guideline for the preparation of a practical trial.

4.2.7

Spraying Starch

On some paper machines, spraying unmodified and uncooked starches to the Fourdrinier wire can be advantageous as regards costs and performance. The starch will at first act as a filler and be retained on the surface of the sheet or between layers. It will typically gel or cook while the sheet dries throughout the drying sections.

In such applications, starch can be added at high rates – up to 20% of the final product. In some cases, the starch can be less expensive than the wood fiber, thus lowering the manufacturing costs. Also, and more importantly, the starch increases the strength of the final paper.

Besides these considerations, the major reason for spraying is still the improvement of the bonding strength between the layers in multiply paper and board.

4.2.8

Surface Sizing

Most of the starch in papermaking is applied on the surface in size press or film press applications. This is done to increase the strength and higher water resistance of the paper surface. The surface application ensures a maximum of starch utilization, since there is no loss by dewatering. The only issue is that a part of this starch can come into the wet end by the brokes. This might be the reason for some paper plants using low cationic starch in the size press. A disadvantage is that for the size press application, the paper is rewetted again and needs to be dried once more. This has an important impact on the speed of the paper machine.

Often, the surface sizing solution contains other hydrocolloids, such as *gelatin*, or surface sizing agents such as alkyl ketene dimer (AKD) or *acrylic copolymers*. Surface sizing agents are *amphipathic* molecules, having both *hydrophilic* and *hydrophobic* ends. The sizing agent covers the cellulose and forms a film, with the hydrophilic tail facing the fiber and the hydrophobic tail facing outwards. This creates a water-repellent situation. Sizing improves the surface strength (X, Y, and

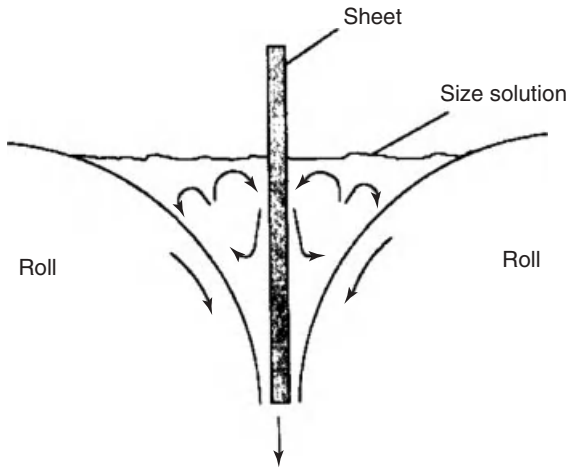


Figure 4.11 Conventional size press.

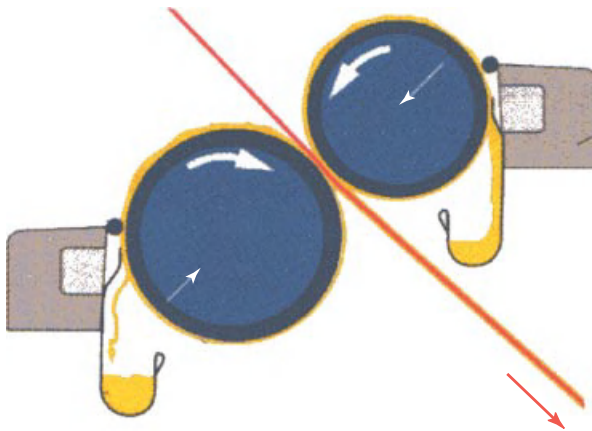


Figure 4.12 Film press. (Source: Voith paper.)

Z direction), printability, and water resistance of the paper surface. In the sizing solution, *optical brightening agents* (OBAs) may also be added to improve the opacity and whiteness of the paper surface. Figures 4.11 and 4.12 show devices for surface sizing, a conventional size press with size pond and a film press with pre-metered size application on the application rolls.

Also, for sizing, trials on pilot paper or coater machines are often used in order to predetermine the most efficient formulation for the mill trial (Figure 4.13). But these trials can only give hints regarding the direction to go. The complexity due to



Figure 4.13 Pilot scale size press.

rewetting the paper and adjusting the right temperature and moisture control will be always different in practice.

4.2.9

Coating

Many paper grades are coated with suitable pigment-rich formulations to improve gloss, slickness, color, printing detail, and brilliance. The coating color can be applied either on-machine or off-machine, depending on product requirements and operating goals.

The coating processes are either pigment based or meant to give special properties to the paper. Without qualification, the term *coating* usually refers to pigment coating. Functional or barrier coatings (e.g., lacquer, varnish, waxes, resins) are more often applied off-machine as part of a converting operation.

Starch application is strictly a functional coating process. The pigments are blended with a binder system (typically starch and latex) to hold the pigment onto the sheet and provide suitable finish and rub resistance. Also, water retention and rheology are influenced, which are important parameters during the processing of the coating onto the paper.

The variety of coating formulations is large. They may contain as many as 10 ingredients. There are typically three types of ingredients: pigments, binders, and additives.

Coating binders can be either starches, proteins (caseins), or synthetics (typically latex). Starch is by far the least costly binder; therefore, coating formulations strive to add as much modified starch as possible while meeting end use requirements.

The natural binder used in paper coating is all modified. Some are modified at the plant, as in enzymatical or thermochemical conversion of the starches. More often, highly modified starches such as dextrins, etherified starches, and biolates

are found. As starch is a sustainable material for coating color formulation, it may replace fossil-based synthetic binders in the future.

4.3

Colorants

Klaus-Peter Kreuzer

4.3.1

General

Historically, alongside sizing agents and fillers, colorants can be considered as one of the oldest chemical additives used in papermaking.

The earliest information regarding colored paper is from the Far East. In China, colored silk paper was used for making lanterns and hand fans. As far back as the eleventh century, aqueous extracts of sycamore and saffron were used in the Middle East for coloration of their handmade paper. By the sixteenth and seventeenth centuries, paper was being tinted with indigo and logwood (*Haematoxylum campechianum*) [3]. The expression “stock dyeing” first appeared in print in the early 1700s.

After the discovery of synthetic dyes such as Perkin’s mauve in 1856, the versatility of dyes rapidly came to be realized.

Initially, new synthetic dyes were developed solely for use in the textile industry, and a large range of colors soon became available. The paper industry found that many of these textile dyes could also be used for paper. Acid dyes and, increasingly, the direct dyes used for dyeing cotton found use in paper. It is only relatively recently, from the 1950s onwards, that dyes specifically designed for use in paper have been developed. Progress since then has been swift, alongside the development of new anionic direct dyes; the first cationic direct dyes started appearing in the 1960s. It is not just the development of the new dyes but the fact that manufacturers started to produce stable liquid forms that could be added continuously that changed the use of dyes in the paper mill.

At the same time, the first organic pigment dispersions appeared and were used for coloration of papers in the new laminate industry. With more modern kitchens using laminate work surfaces and the recent increase in laminate flooring, the importance of these colored decor papers increased.

Research on new and improved paper dyes continues and the main trend in the past 20 years has been the development of new cleaner dye formulations. This resulted in a large improvement in the environmental profile of the dyes themselves and especially in the effluent.

The trend for colored papers is growing. Today, color is not just an aesthetic choice; it is also a vehicle for imparting information, to gain attention, and to instill a feeling of quality. The correct choice of color can impart both an artistic and functional meaning.

4.3.2

Origin of Color

Visible light, what our eyes can detect, is only a small part of the whole electromagnetic radiation spectrum. As shown in Figure 4.14, the visible region consists of light with wavelengths of approximately 400–700 nm.

If all incident light is reflected by a surface, this will appear white. If nearly all light is absorbed, then the surface looks black. Surfaces appear colored if they absorb and reflect unevenly different parts of the visible spectra [4] as can be seen from the reflection curves in Figure 4.15.

The absorbance of light of particular wavelengths is largely linked to the extent of the resonance (mesomeric) system of the dye molecule. Light falling on the molecule is absorbed when an electron moves from its ground state to an excited state. These transitions have a discrete energy, and if this energy corresponds to wavelengths in the visible region then the molecule appears colored.

If the number of delocalized electrons and conjugated part of the dye molecule is small, the oscillation frequency of the system is high, the corresponding stimulus energy is high, and the molecule absorbs higher energy light at shorter wavelengths such as in the UV region. If the number of delocalized electrons and conjugated part of the dye molecule is large, the molecule absorbs energy from the lower energy visible part of the spectra. Dye chromophores consequently tend to be large molecules with extensive delocalized electron structures.

The optimized overlapping of the π -orbitals throughout the delocalized structure is crucial and can only be fully achieved if the whole chromophore is coplanar. Consequently, all direct dyes have a coplanar molecule structure and align with the flat cellulosic structure. The same mechanism occurs whether UV or visible light is absorbed.

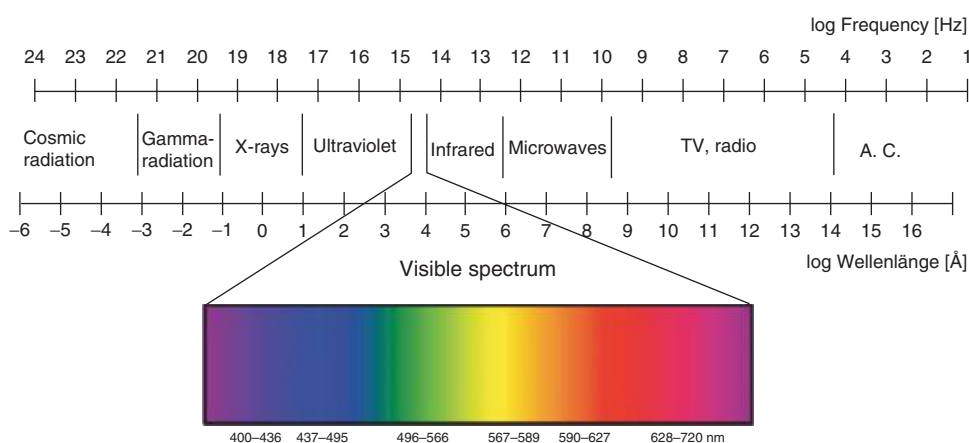


Figure 4.14 Electromagnetic spectrum.

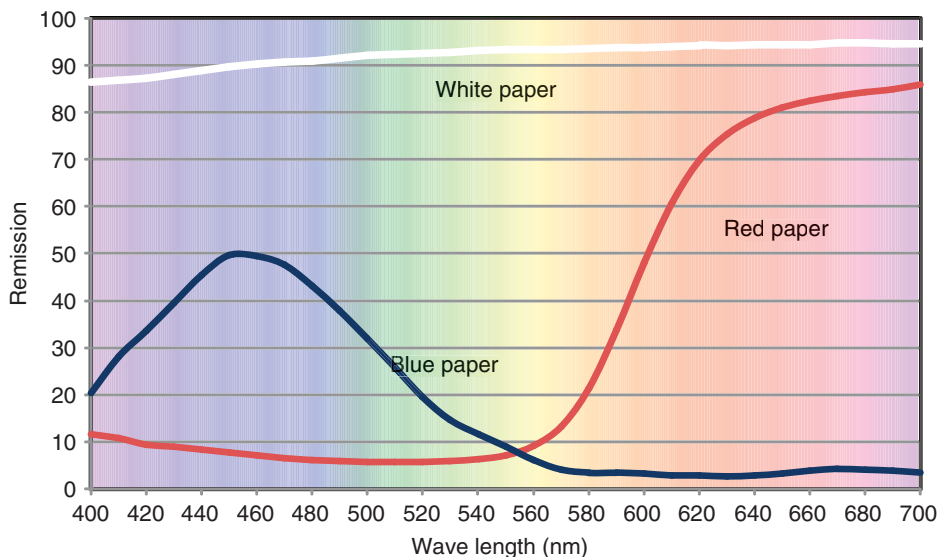


Figure 4.15 Reflection curves of white and colored paper.

4.3.3

Colorant Classes

Colorant is the collective name for all coloring substances. All colorants are divided by DIN 55944 into inorganic and organic colorants (Figure 4.16). Excluding the large volume of inorganic white “filler” pigments, only carbon black and iron oxides are used in large quantities in the paper industry. By far the predominant class of colorants for paper coloration are the synthetic organic compounds. Dyes are colorants that are soluble in the application media (water in case of paper coloration). Pigments, in contrast, are insoluble in water and must be dispersed before use [5].

4.3.4

Dyeing Mechanism

The chemical constitution of the water-soluble dyes is often very similar. Subtle differences in structure, for example, by exchanging substituent groups, can result in significantly different properties such as shade, substantivity, light fastness, or solubility. Knowledge about the chemical structure of the single components in paper coloration helps to understand the electrostatic interactions between the cellulose and dye.

Typically, the chemical structure of a synthetic organic dye is a system of conjugated double bonds. The π -electrons of such double bonds are not fixed and

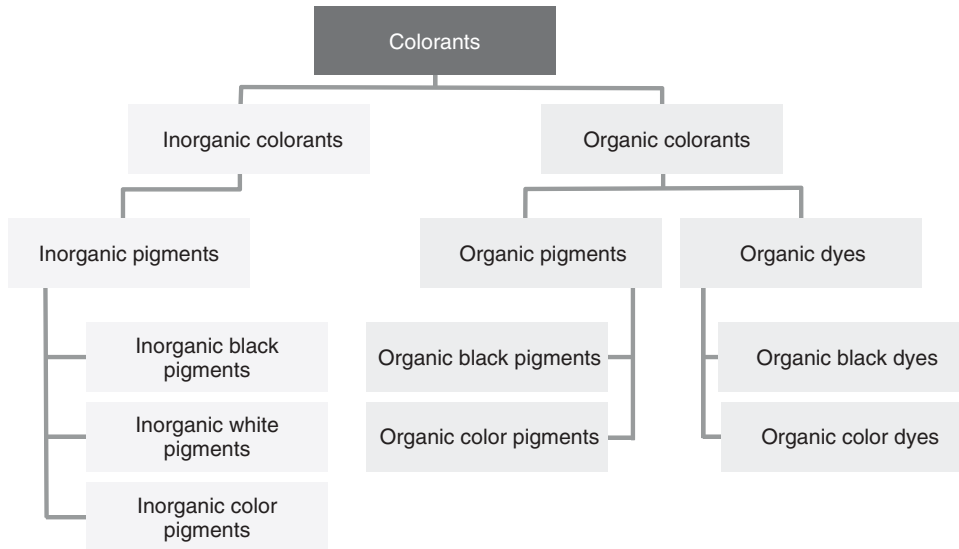


Figure 4.16 Colorant classes by DIN 55944.

are relocatable over the whole conjugated system. Chemical structures that provide the freedom of these delocalized π -electrons and have an extensive resonance system that produces color are called “*chromophores*.” Substituent groups such as $-\text{NH}_2$, $-\text{OH}$, $-\text{SO}_3\text{H}$, and $-\text{COOH}$ consolidate color strength and substantivity and improve the solubility of the dye. They are called “*auxochromes*” [6].

Another important property of paper dyes, apart from the structure imparting color, is the ability of the dye molecule to build associations with the substrate to be dyed – the cellulose fiber. These interactions between the dye molecules and the fiber strongly influence the substantivity and affinity of the dye, that is, the backwater coloration and bleeding tendency.

To get the best dyeing results, the physical and chemical properties of a dye molecule must interact strongly with cellulosic fibers.

These kinetic process steps are important (Figure 4.17)

- Dilution and quick equal distribution of the dye in water
- Molecular diffusion through the hydrodynamic boundary layer
- Adsorption of the dye molecule to the cellulosic fiber
- Molecular diffusion of the dye molecule into the capillary and hollow space of the fiber
- Adsorption of the dye molecule at the inner surface of the fiber
- Association of the molecules on the fiber surface

All of these reactions are reversible processes that need a certain time to find equilibrium.

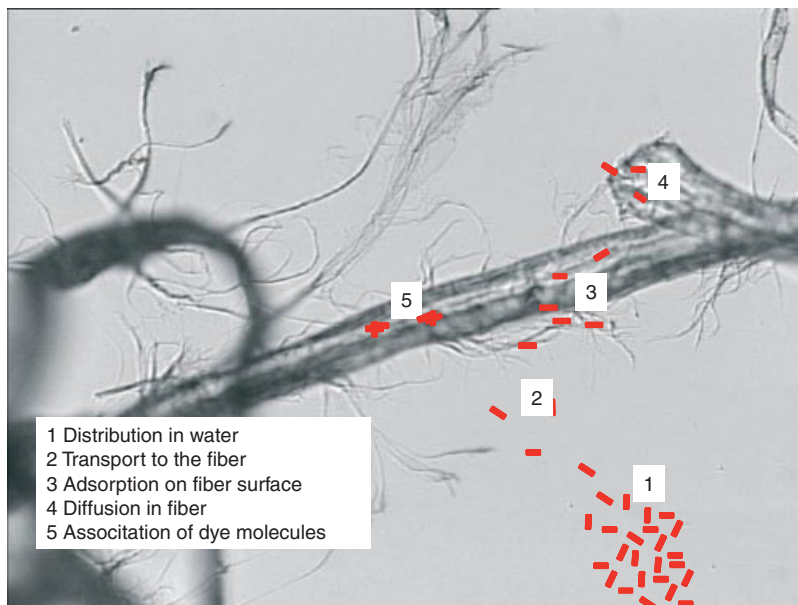


Figure 4.17 Kinetic process steps of direct dye coloration.

The important effective binding forces are electrostatic attraction, hydrogen bonding, and van der Waals forces.

4.3.4.1 Substantivity and Affinity

The terms *substantivity* and *affinity* described by Wegmann [7] are two different properties of dyes.

Substantivity is the ability of a dye to be adsorbed from an aqueous solution onto the cellulosic fiber and is associated with the backwater.

Affinity is the capability of the dye to stay attached on the fiber and is closely linked with the bleed fastness.

4.3.5

Direct Dyes

Owing to their easy application, the large range of shades available, and their generally good technical properties and moderate pricing, direct dyes represent the largest colorant class used in paper coloration. Today, approximately 60% of all paper dyes are anionic or cationic direct dyes. The dosage quantities can range from 0.005% dye (for shading of white paper) up to more than 10% dye (for deep dyed tissue). Figure 4.18 shows some application examples of direct dyes.

Direct dyes are a class of dyes with good substantivity to cellulosic fibers and therefore show a good water fastness in paper coloration. From a chemical point of view, direct dyes are typically lithium or sodium salts of azo and polyazo

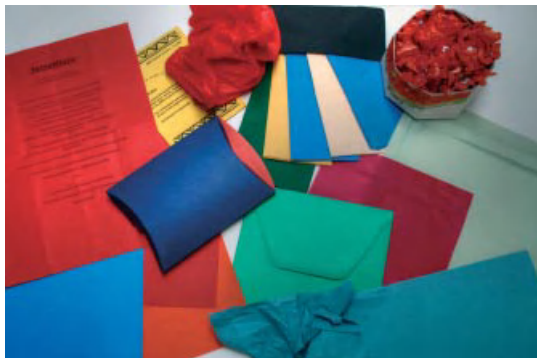
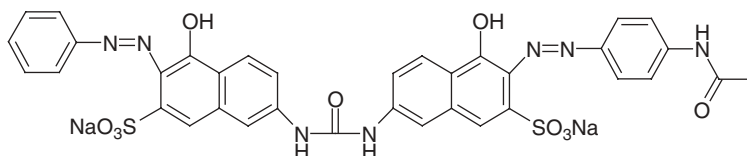


Figure 4.18 Application examples of direct dyes.



Direct Red 23

Figure 4.19 Chemical structure of an anionic direct dye.

dyes containing sulfonic acid or carboxylic acid groups to make them soluble (Figure 4.19). Lightfast turquoise dyes are commonly based on partly sulfonated copper phthalocyanine. Auxiliaries such as urea were often added to liquid dye formulations, in order to improve the stability, but nowadays the trend is to minimize or even eliminate these auxiliaries altogether.

The ultimate goal for modern direct dye manufacturers is a stable liquid product that contains only the active substance and water. For ecological and economical reasons, auxiliaries in dyes are minimized.

4.3.5.1 Anionic Direct Dyes

Anionic direct dyes show a high affinity to all bleached-wood-free cellulosic fibers. Yield on wood-containing fibers is somewhat lower.

Normally, direct dyes do not require a fixing agent. Only for the deepest shades or if there are particular requirements for bleed fastness is the use of a fixing agent necessary.

All fixing agents have a negative influence on the brilliance and light fastness of the dyeing, but the extent they affect the shade depends on the dye used and also on the chemistry of the fixative. Therefore, careful choice of an appropriate fixing agent and avoiding overuse is important.

To avoid the danger of mottling, anionic direct dyes with high substantivity must be added at dosage points with very high turbulence, for example, directly before a pump.

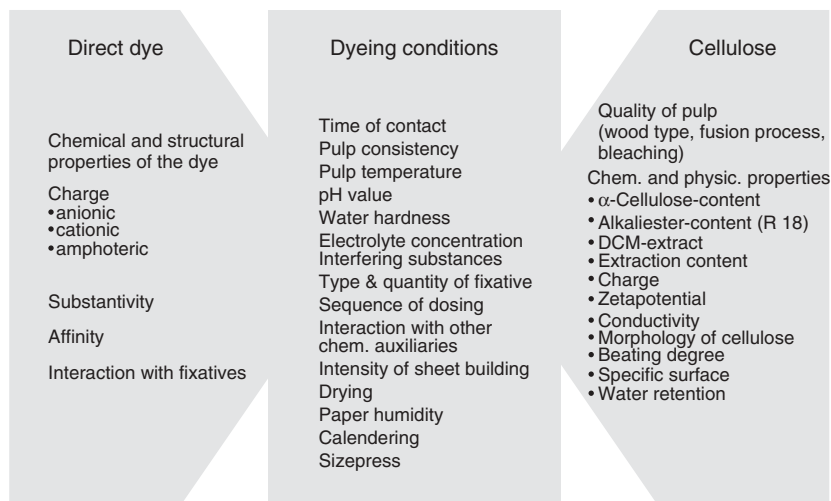


Figure 4.20 Interaction between direct dyes and cellulose.

The interaction between direct dye and cellulosic fiber is influenced by a large number of factors (Figure 4.20).

4.3.5.1.1 Cellulosic Fibers The type and mix of chemical pulp used affects not only the physical properties of the paper but also the color intensity, shade, and the two-sidedness of dyeing. The type and ratio of hard and softwood as well as the bleaching process used will influence the coloration results. Therefore, it is important for the best results when shade matching in the laboratory, to use the actual pulp used in production.

Particular attention must be paid if a broke is used, whether a colored or an uncolored broke is used. Additives such as fillers or cationic polymers can influence the shade and color yield significantly.

4.3.5.1.2 Stock Freeness The color strength achieved increases with the beating degree of the stock since fibers are more accessible to the dye after refining. Refining results in a larger fiber surface area by defibrillation.

4.3.5.1.3 Contact Time A conventional anionic direct dye needs a few minutes contact time for complete exhaustion on the cellulosic fiber. Under ideal conditions, after just 10 s the adsorption of the dye is finished. The diffusion of the dye molecule into fiber capillaries and the association of the dye to a balance of adsorption/desorption requires more time. Such a long contact time is only available by batchwise coloration (addition to the pulper), but not with continuous dyeing. In order to reduce the contact time needed, dye retention fixatives can be used.

Another method is the use of a combination of anionic and cationic direct dyes. In this case, the anionic dye is “fixed” by the cationic direct dye.

4.3.5.1.4 Stock Consistency Stock consistency below 2.5% can lead to reduced color yields. At very high consistencies stock circulation can be poor; mottling can occur under these conditions when highly substantive direct dyes are used.

4.3.5.1.5 pH-Value and Sizing Dyes can show large variations in strength and shade when the pH changes. In general, neutral sizing conditions have little or no effect on the shade of anionic and cationic direct dyes compared to unsized conditions, although where cationic promoter resins are used, bigger changes can be observed. Acid sizing typically can have a larger effect on shade.

4.3.5.1.6 Water Anionic direct dyes require the presence of electrolytes in order to dye cellulose. These electrolytes are present in most cases as the hardness salts present in the water. Ideal conditions for anionic direct dyes are German hardness values between 5 and 15. Here, higher affinity dyes show a maximum yield. Under soft water conditions, the addition of magnesium sulfate may be required to obtain full color yield. The presence of interfering substances (“anionic trash”) can also negatively influence dye yield. Definitions for different water hardness values are given in Table 4.3.

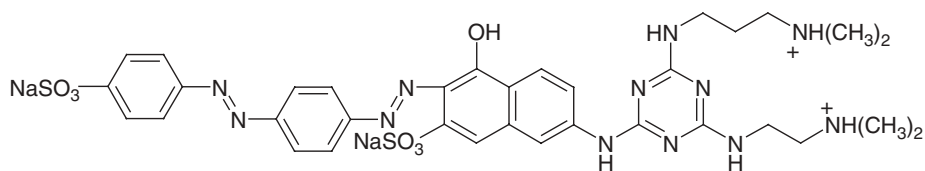
4.3.5.1.7 Order of Addition When using cationic and anionic direct dyes in combination, the cationic component should always be added first, to achieve maximum color yield. When using other cationic additives, the anionic direct dye should be added first. The dosing points of cationic additives must be far enough apart from the anionic direct dye in order to avoid the danger of precipitation. Two-sidedness can be greatly affected by the order of addition of dye, filler, and other auxiliaries.

4.3.5.1.8 Fillers Owing to their white color and high surface area, the addition of fillers will cause a loss in color strength. Generally for the addition of 1% filler, 3% more dyestuff is required to get the original color strength.

When fillers are used, two-sidedness can be a problem since in the case of anionic dyes they are left largely uncolored. Each filler type and grade will have a different effect on the dyeing result depending on its shade, particle size, and the amount used.

Table 4.3 Different water hardness definitions.

1 German Hardness (dH) = 1 mg CaO/100 g water (11 water of 1 dH contains 10 mg CaO or 7.13 mg MgO)
1 French Hardness = 1 mg CaCO ₃ /100 g water
1 British Hardness = 1 grain CaCO ₃ /gallon water



Basic Red 111

Figure 4.21 Chemical structure of a cationic direct dye.

4.3.5.2 Cationic Direct Dyes

Like the anionic direct dyes, the cationic direct dyes possess a coplanar molecular structure (Figure 4.21). In contrast to the anionic direct dyes, these molecules incorporate one or two cationic substituent groups. These dyes appear in the color index as basic dyes, but this is strictly incorrect as they differ from the classical basic dyes in being larger and more linear and planar in much the same way as anionic direct dyes.

The positive charge gives cationic dyes a very high substantivity to both wood-free and wood-containing cellulosic fibers. Where there is a pendant cationic group attached to a direct dye molecule, the substantivity for cellulose is so greatly increased that paper can be dyed with very short contact times [8]. In some cases, anionic direct dyes can be fixed with cationic direct dyes. Those color combinations cause uncolored backwater and good bleeding fastness.

Cationic direct dyes are not sensitive to water hardness. So they are appropriate in systems with low or variable water hardness. Owing to their high substantivity to all negatively charged substances, cationic direct dyes react quickly with anionic interfering substances such as fines, carboxymethyl cellulose (CMC), or dissolved starch. This results in a lower color yield and deposits in the wet end. A small pre-addition of a cationic polymer to quench this anionic trash will restore the full efficiency of the cationic direct dye.

4.3.6

Basic Dyes

In principle, basic dyes are simply cationic dyes. But in reality they are very different from the cationic direct dyes. Basic dye molecules are not coplanar, and, as the mesomeric (resonance) structure in Figure 4.22 shows, the positive charge is not fixed to an ammonium or a carbenium ion.

Basic dyes are not used for bleached cellulose as their structures are neither planar nor large enough for sufficient substantivity or affinity. On paper, which contains lignin and which is more anionic, the older basic dyes are applied.

Consequently, basic dyes have a high affinity to all lignin containing fibers such as ground wood, TMP, CTMP, and unbleached cellulose. Secondary fiber pulp often contains wood-free beside wood-containing fibers. Here, the preferential dyeing of wood-containing fibers can cause mottling.

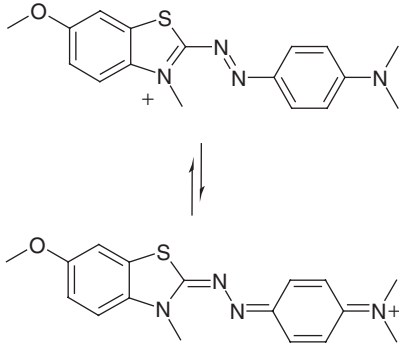


Figure 4.22 Mesomeric (resonance) structure of a basic dye.

Basic dyes offer bright, strong colors at low cost. Their main applications are coloration of all kinds of packaging grades such as fluting, corrugating medium, and testliner. Also, directories such as yellow pages, egg boxes, and newspapers are often colored or tinted with basic dyes.

As the fastness properties, especially the light fastness, are poor, the basic dyes are only suited to short-lived papers or low-quality papers. Figure 4.23 shows some application examples for basic dyes.



Figure 4.23 Application examples for basic dyes.

4.3.7

Sulfur Dyes

Sulfur dyes have been used for dyeing cellulose fibers since their discovery over 100 years ago. Dyeing cotton and blends thereof with synthetic fibers remains their main application. Sulfur dyes are also used for paper, but to a much lesser extent. For paper coloration, mainly liquid qualities of Leuco Sulfur Black 1 are used [9].

From their dyeing performance, sulfur dyes are somewhat similar to vat dyes. However, unlike vat dyes, which can generally only be dissolved in water with strong reducing agents such as sodium dithionite/sodium hydroxide, sulfur dyes are preferably dissolved with weak reducing agents, especially sodium sulfide or the combination glucose and sodium hydroxide.

The reduced sulfur dye becomes attached to the cellulose fiber from alkaline aqueous solutions because of their pronounced substantivity. Similar to the reduced vat dyes, they are fixed onto the fiber in their insoluble oxidized form by the action of air or oxidizing agents.

Sulfur dyes are normally used to dye paper in a batch process – by addition to the pulper. After addition, the pH is gradually adjusted with acid until a pH < 6.5 is reached. This precipitates the reduced sulfur dye onto the fiber.

Compared with other classes of dye, the sulfur dyes mainly color cellulose fibers in dull muted shades. Their advantage lies in the inexpensive production of very deep colorations with excellent fastness properties, in particular for navy and black shades.

Common textile grades of sulfur dyes are not suitable for paper coloration as they contain high amounts of sodium sulfide. Under the acidic conditions needed to precipitate the dye, the sulfide present produces the strongly smelling and toxic hydrogen sulfide. For safety reasons, special grades of sulfur dyes suitable for paper needed to be developed. These formulations contain only traces of sodium sulfide.

Sulfur dyes are particularly suitable for intensive deep black stock dyeing. At dosing rates of up to 40%, the back water is colorless as long as the correct procedure is used. High opacity and excellent light fastness (rating 7) are further benefits of paper colorations with sulfur dyes.

Application examples are decorative paper, envelope linings, passe-partout, roofing felt board, board for ring binder and folders, mottle fibers, packaging paper, and wrapping silk paper as well as loudspeaker membranes and car panel board (Figure 4.24).



Figure 4.24 Application examples for sulfur dyes.

4.3.8

Acid Dyes

Acid dyes were developed for the dyeing of wool, synthetic polyamides, and silk in aqueous media. They are of limited use in the paper industry. They possess as a common feature a very high solubility in water (due to their content of carboxyl groups), and are not able to build associates or hydrogen bridge bonding. So, acid dyes have a poor affinity to cellulosic fiber. Also, the bleed- and light fastness of the acid dyes on cellulosic fiber are very poor (Figure 4.25). The application of acid dyes is thus limited to the small area of flower crepe and similar paper qualities.

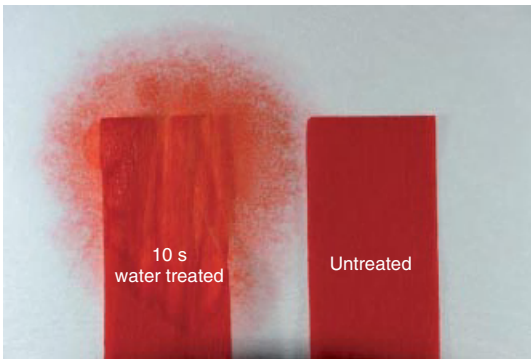


Figure 4.25 Poor bleed fastness of an acid-dyed crepe.

4.3.9

Pigments

With approximately 15% of the market (by value), organic pigments are the third most important colorant for paper coloration. The reason for their growing importance is their high fastnesses in comparison with dyes. Pigments show an excellent light fastness, high temperature stability and are inert to pH-variations, water hardness, and common chemical additives such as bleaching agents. By definition and in contrast to dyes, pigments are water insoluble. Figure 4.26 shows some application examples of organic pigments.

4.3.9.1 Inorganic Pigments

In the paper industry, inorganic pigments such as chalk and china clay are used in large amounts as fillers. Apart from carbon black and iron oxides, inorganic pigments are rarely used for coloration. This is mainly because inorganic pigments typically have dull shades, weak color strength, and often contain heavy metals (Table 4.4).

Inorganic pigments are hydrophilic. Therefore, they can be incorporated as a powder into the aqueous paper production.

Table 4.4 Examples of inorganic pigments.

Chemical classification	Type	Color index
Chemical elements Oxides/ oxidehydrates	C (furnace-, channel-carbon black)	P.Black 7
	TiO ₂ (titanium dioxide)	P.White 6
	ZnO (zinc oxide)	P.White 4
	Fe ₂ O ₃ (iron oxide, red)	P.Red 101
	Fe ₃ O ₄ (iron oxide, black)	P.Black 6
	FeOOH (iron oxide, yellow)	P.Yellow 42
Silicate	Na ₆ Al ₆ Si ₆ O ₂₄ * (NaS _n) (ultramarine blue)	P.Blue 29
Carbonate	CaCO ₃ /MgCO ₃	P.White 18

4.3.9.2 Organic Pigments

Organic pigments are typically used when the fastness properties of dyes are insufficient.

As examples, applications where pigments are preferred include laminate paper coloration, the tinting of white paper, banknotes, document base papers, passe-partout, label papers, and laundry papers.

**Figure 4.26** Application examples for paper grades colored with pigments.

The disadvantage of all organic pigments is that they are hydrophobic. They cannot be added directly in powder form to the aqueous paper production.

Organic pigments must first be converted into aqueous pigment dispersions.

In beadmills, the organic pigment is milled with anionic dispersants and other auxiliaries to form stable pigment dispersions. All the important technical properties of the pigment dispersion depend on the efficiency of this milling process.

During this process, the particle size of the pigment is reduced to 100–600 nm. Depending on the dispersant used, the pigment dispersion is stabilized by steric hindering or electrostatic repulsion [10].

Anionic organic pigment dispersions have no affinity to the cellulosic fiber. In stock dyeing, they must be fixed (retained) by cationic polymers or alum ions (aluminum sulfate, polyaluminum hydroxy chloride (PAC)). A pigment dispersed in a nonionic dispersion cannot be fixed. The fixation can be increased by adding the pigment to the pulper before refining.

Owing to their water insolubility, all kinds of pigments are particularly suitable for surface application in coatings.

For the tinting of white paper grades, both in stock as well as in coatings, P.Blue 15, P.Blue 15 : 1 are often used in combination with P.Violet 23. All these pigments have an excellent light fastness.

For paper grades that do not require such high properties, P.Violet 3, P.Violet 27, and P.Blue 14 (not registered in Europe) are sometimes used. These types of organic pigments are named lakes. They are produced by precipitating basic dyes with metal ions such as barium, iron, copper, tungsten, and molybdenum to form water-insoluble salts (= lakes). By definition, these water-insoluble salts are pigments [11]. Laked pigments do not have the high performance of true pigments – their technical properties such as light fastness or solvent solubility are much closer to their corresponding basic dye. Owing to equilibrium conditions, a small amount of the free basic dye used in the lake will be found. This can cause technical problems in the use of these laked pigments. Table 4.5 summarizes the main properties of paper colorants.

4.3.10

Dosing of Dyes and Pigments

While more than 30 years ago colorants were handled and dosed manually in the color kitchens of many mills, today their handling is a much cleaner and safer process thanks to modern dosing techniques.

Liquid colorants are added diluted or undiluted to the pulp using dosing pumps. The addition point can be the pulper, the mixing chest, or in front of a pump (Figure 4.27). The dosing pump types used are typically peristaltic pumps, helical rotor pumps, or piston pumps.

Powder dyes are added pre-weighed in water-soluble paper or polyvinylalcohol (PVOH) bags. The bags can be added directly to the pulper without the need to weigh the loose powder. This eliminates the danger of dust being breathed in by operators. For many industries such as deep dyed tissue production, combinations of powder added early to the pulp and liquids added late for fine control of shade give optimum economics and shade control.

Manual color correction to achieve the desired shade requires a highly experienced color man on the machine for good results.

Online color control can save production costs by reducing the amount of off-shade paper (broke) produced. The adjustment of color is done in a closed loop color control (CLCC) by online measurement of the color point and computer-controlled colorant dosing depending on how the current shade compares to the target range.

Table 4.5 Main paper colorant properties.

Charge	Direct dyes		Basic dyes	Organic pigment dispersions
	Anionic	Cationic	Cationic	Anionic
Fibre affinity				
Wood-free cellulose	+++	+++	+	None
Wood-containing cellulose	++	+++	+++	None
TMP, CTMP, GW	++	+++	+++	None
Mixed recycled fibres	++	+++	+++	None
Backwater				
Wood-free cellulose	+++	+++	+	–
Wood-containing cellulose	++	+++	+++	–
Light fastness	2–4	1–3	1	4–8 (1–2 lakes)
Fixation	Normally not necessary only for special fastness requirement or deep shades		Wood-free necessary	In every case necessary
Application	Graphic paper (writing, printing paper) transparency paper liner (packaging paper) tissue, towels		Packaging grades newsprint,	Laminate paper Graphic paper (tinting) Banknotes Laundry paper Sterilization paper

With the online measurement of the colorimetric values (L^* , a^* , b^*), the computer calculates the color differences (dL^* , da^* , db^*) and correctly adjusts the discharge of the dosing pumps.

4.3.10.1 Stock Dyeing

Stock dyeing is the most common process for coloring paper. About 95% of dyes are applied to the stock. Pulp can be colored batchwise or continuously. Pale shades are normally colored continuously, whereas for deep shades both procedures are normally used together for economic and technical reasons. A main part of the colorant (60–80%) is added to the pulper. The final shade correction is done continuously by the addition of the colorant later in the wet end. Batchwise addition to the pulper has the advantage of giving a long contact time for the colorant and fiber. This results in a high color yield and good bleeding fastness. Continuous coloration allows quick color corrections to be made.

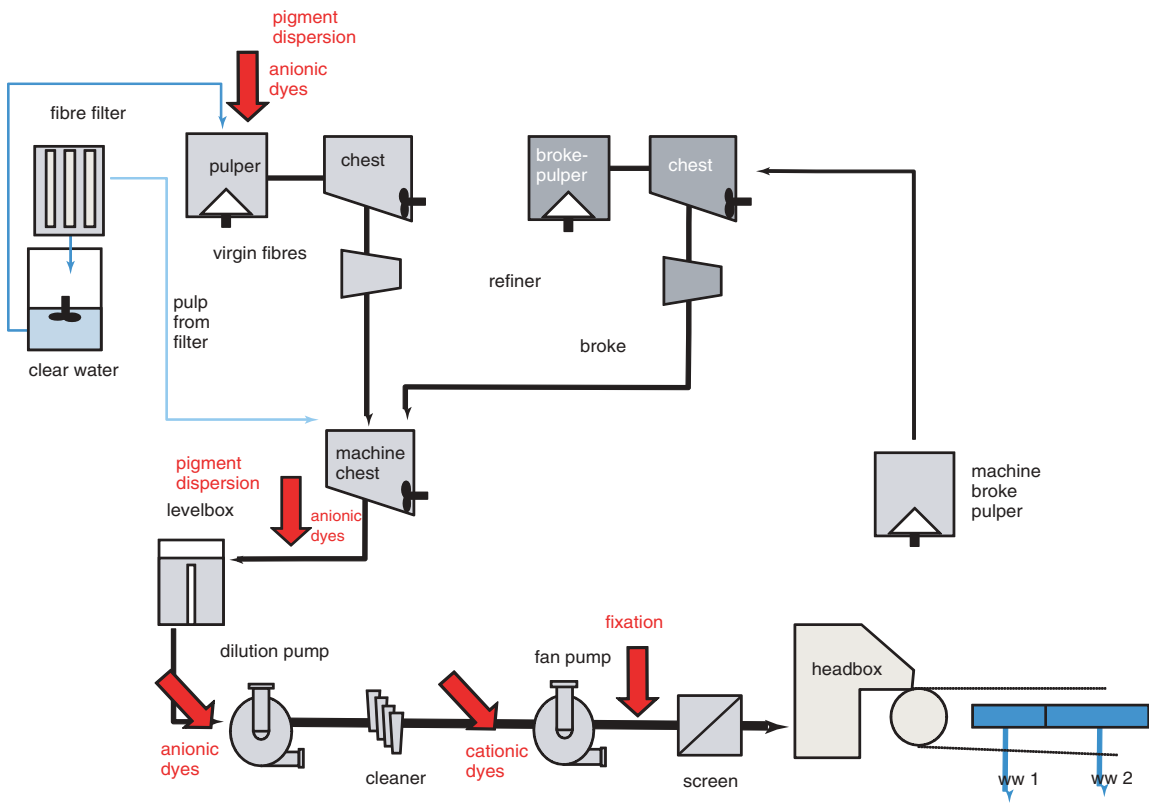


Figure 4.27 Addition points for colorants in wet end.

4.3.10.2 Surface Coloration

For high basis weight board, stock coloration might be uneconomical. In this case, the board can be colored at the surface. The charge of the dyes should match the charge of the other additives. This will mean anionic dyes are used with anionic surface size and cationic dyes used with cationic surface size. Often, a light stock coloration is combined with surface coloration at the size press.

The light stock coloration makes it less likely that an uneven appearance will result owing to uneven surface dyeing. Surface coloration, often together with surface sizing, generates the target color strength with a minimum of cost as the internal fibers are not colored.

Unfortunately, surface colorations, especially colorations with anionic dyes, give much lower bleeding fastness than stock colorations. For this reason, cationic direct dyes or basic dyes are often preferred.

Owing to the water insolubility of pigments, these are often used in combination with a co-binder such as starch or PVOH for size press or film press coloration. For linerboard and testliner, the starch application system can be modified to allow dyeing on only one side to further improve economics.

4.3.10.3 Coating Coloration

Coating colors are mainly tinted with organic pigments. Here, anionic or nonionic pigment dispersions are suitable. They are added as the last component to the coating color, to minimize the shear forces acting on the pigment. High shear forces can damage the physical bond between organic pigment particle and dispersant. The hydrophobic pigment particles then agglomerate and cause colored spots in the coating.

4.3.11

Technical Properties of Coloration

The requirements of colored paper depend on the end use of the paper. In many cases, this is a balance of all the desired properties of the end user.

4.3.11.1 Colorimetry

Color is a sensory impression of the human brain. The target of colorimetry is to quantify this subjective sensation by objective values. The most widely adopted system of objective color description is the CIE system.

In the three-dimensional CIELAB-colorimetric space with the values L^* (lightness), a^* (red/green axis), and b^* (yellow/blue axis) every color can be described (Figure 4.28).

These values are used for description of colors and as the central control parameter for color control in paper production. For more information regarding colorimetry, extensive technical literature is available [11–13].

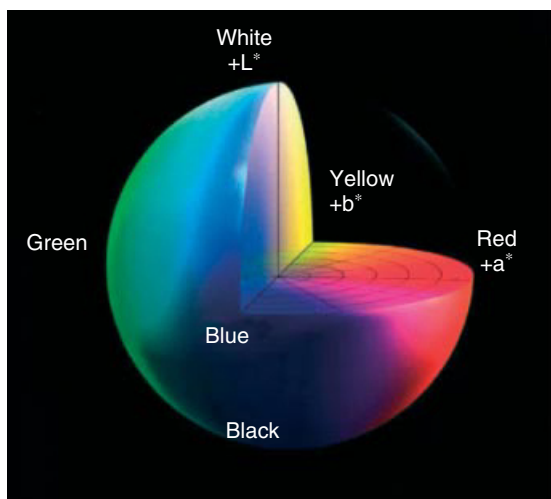


Figure 4.28 CIELAB color space.

4.3.11.2 Light Fastness

This is defined as the fastness of a colored paper to the action of light. It is dependent on both the colorant used and also the raw materials of the paper. The grading of light fastness is specified by a test method according to DIN 54004 and ISO 105 B02, which is also used in the textile industry. Originally light fastness was tested by exposing the colored paper to sunlight under defined conditions. Today, artificial light with a radiation spectrum similar to sun light is used. The light fastness cannot be given as an absolute value, but can only be expressed in relation to a standard that is exposed simultaneously. In the textile and paper industries, the Blue Wool Scale is used as a standard for comparison. It consists of blue dyeings with eight different light fastnesses. Rating 1 signifies the lowest and rating 8 the highest light fastness [14].

4.3.11.3 Bleed Fastness

The standard testing of bleed fastness for colored papers is described in the international standard DIN EN 646.

Bleed fastness of paper and board is required for all food contact papers as well as for tissue papers. According to DIN EN 646, the test must be carried out in each case to determine whether and to what extent the dye can migrate from a colored paper onto the packed foodstuff or to human skin. In DIN EN 646 the colored paper is tested in contact with water, diluted acidic acid, synthetic saliva, olive oil, or iso-octane.

A test specimen is placed between two uncolored glass fiber filter papers moistened by dipping into the test solution. This sandwich is placed between two glass plates and loaded with a certain weight. The specimen is kept in this condition for 10 min (B) or 24 h (A) at 20 °C.

After drying, the coloration of the glass fiber paper is compared with the Grey Scale for staining. A rating of 1 signifies a very poor bleeding fastness and a rating of 5 signifies no bleeding.

4.3.11.4 Other Properties

Rub resistance is required for album and wrapping paper as well as for cover board, while acid resistance is required for parchment and vulcanized fiber base paper. Solvent resistance is required for labeling paper (packaging of perfumes and spirits) and laundry papers. Special organic and inorganic pigments are suitable for this purpose.

Heat resistance is required for cable and laminate paper, for which organic and inorganic pigments are suitable [14].

4.3.12

Ecology/Toxicology

During the past decade the number of laws and regulations providing health and environmental protection during the transport, storage, and use of colorants in paper manufacturing has again risen worldwide.

Colored papers for food contact have to fulfill international regulations like FDA 21 CFR § 176.170 and 21 CFR § 176.180 or 2003/53/EG as well as national regulations such as Recommendation XXXVI of BfR and German LMBG.

Beside these regulations, a number of eco labels for paper try to guarantee that green claims have been controlled and certified by an independent body. The demand of eco labels such as Nordic Swan, EU-Eco label (EU-flower, EU/66/2010), and Blue Angel distinguish on the basis of the different paper grades.

For these different labels, many factors such as heavy metal content, lack of specific azo-chemistry capable of being cleaved to give banned amines, and hazard labeling of the paper colorants are regimented.

4.4

Optical Brightening Agents (OBA), Fluorescent Whitening Agents (FWAs)

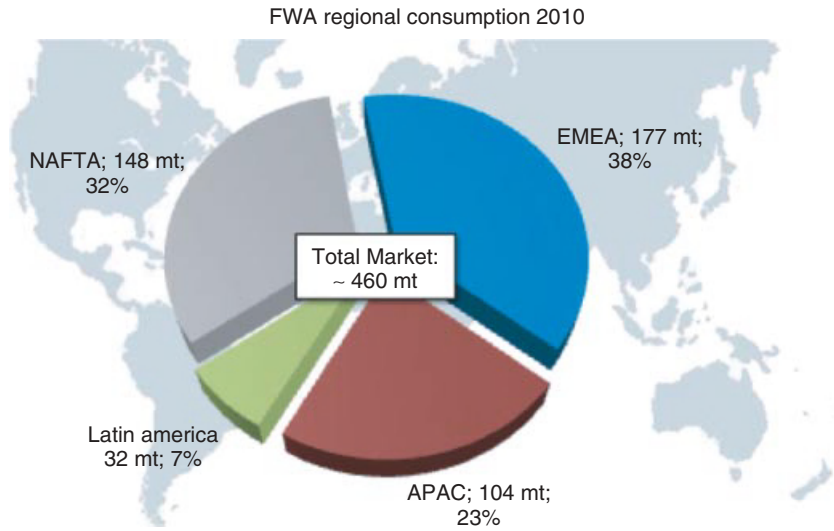
Bernhard Hunke and Günter Klug

4.4.1

Introduction

For the past 60 years fluorescent whitening agents (FWAs) have played an important role in enhancing the whiteness and brightness of paper. They do it by transforming UV light into visible blue light. FWAs were discovered between 1930 and 1940. However, widespread use of FWAs did not commence until after the end of World War II. Today, large quantities of FWAs are being used in the paper, detergent, and textile industries and are employed more or less as a matter of course.

The regional consumption of FWAs for paper in 2010 is shown in Figure 4.29.



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Figure 4.29 Regional consumption of FWAs in 2010.

The highest consumption is still in Europe because of the high whiteness levels in printing and writing grades and the world's leading requirement for efficient and effective whitening programs. Western Europe accounts for 75% of the EMEA (Europe, the Middle East and Africa) consumption – with Eastern Europe being the growth driver in consumption over the past years.

North America has caught up in consumption since the early 2000s, and now accounts for a consumption of 104 000 or 104 000 tons/year, which equals 32% of the global market. The step-up in whiteness level around 2005 has since stabilized and the market is decreasing in line with the decreasing paper production, but also facilitated especially in FWA demand as the market for highest white papers is satisfied by imported A+ grade papers. Asia is still behind Europe and the Americas, but with the strongest growth trend by virtue of high growth rates in fine paper production. Its consumption was 104 000 or 104 000 tons/year, more than 50% of which is used in Chinese paper production. Global whiteness trends, which finally determine the requirements for white papers and for the whitening additives, are summarized in Table 4.6.

4.4.2

Basics about Whiteness

The color of an object can only be seen when it is exposed to a light source and the color itself depends very much on the light source. Our most important light source

Table 4.6 Global trends for whitening of paper.**White paper – global trends**

Higher whiteness for improving print quality (contrast) and appearance
 Higher whiteness both in wood-free and wood-containing paper grades
 Cost efficient and high performing products are required
 Products providing only a small contribution to anionic load in the wet end (e.g., recycling of broke)
 Higher ratio in surface applications, lower amount added in wet end
 Tailormade whiteness concepts for maximizing machine efficiency together with the option to use lower quality raw materials (cost)
 Optimal combination of FWAs, shading dyes, and fillers/coating pigments for maximum cost savings

Source: Ref. [15].

is the visible white daylight of the sun. A perfect-white standard has a reflectance of 100% at every wavelength of the visible spectrum. The reflectance of barium sulfate, in the form of a pressed powder, is often used to represent a perfect-white and has a reflectance of approximately 98.5% across the visible spectrum.

TAPPI brightness and ISO brightness were developed to measure the bleaching extent of chemical pulps. Both these brightness procedures have a blue filter and measure light in a bandwidth centered at a wavelength of 457 nm. While both relay realistic assessments of pulp bleaching, the actual numerical values generated by these procedures are different and difficult to compare.

Once the pulp is converted into paper, the addition of fillers, shading colorants, FWAs, and so on changes the reflectance curve to such an extent that the measurement of brightness at a single wavelength does not accurately interpret what our eyes see. For example, a blue shading colorant improves the perceived whiteness of the sheet but the TAPPI brightness remains unchanged or even decreases. Nevertheless, TAPPI brightness remains the primary means by which the effect of FWAs on paper is evaluated in North America. In Europe, whiteness is the primary meaning by which the effect of FWAs on paper is evaluated. Whiteness measurements interpret more accurately what the eye prefers as white than brightness measurements do.

4.4.3

The CIE Whiteness

In 1983, the CIE introduced a whiteness formula that was also adopted by the ISO TC 38 Textile. The CIE whiteness formula is widely used today for evaluations:

$$W = Y + 800 (x_n - x) + 1700 (y_n - y) \quad (4.1)$$

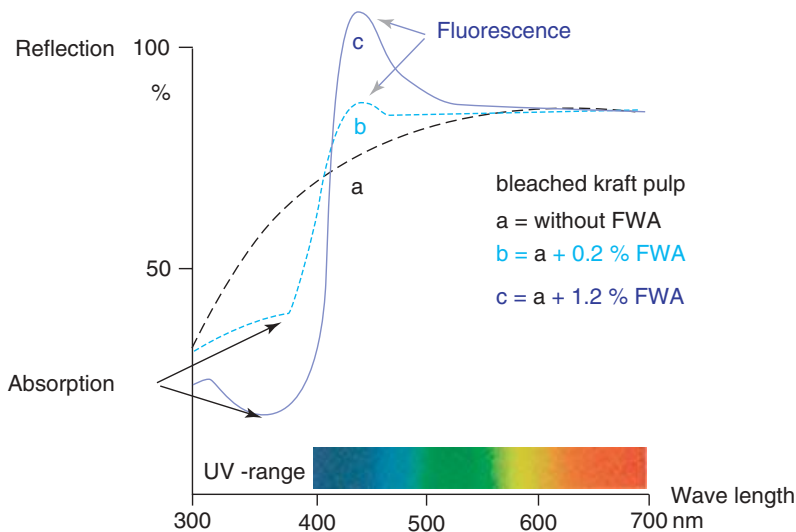
This formula includes the lightness, Y , the other numbers indicate the degree of bluish tint. The higher the lightness and the bluer the tint, the whiter the paper sample appears.

4.4.4

Fluorescent Whitening Agents

FWAs are used to reduce the yellowish tint of bleached pulp. They enhance the reflection in the blue region of the visible spectrum and increase the brightness of the paper. These FWAs are fluorescent dyes that absorb UV radiation and then emit visible blue light. Figure 4.30 shows the reflectance curve of a paper without a FWA and two reflectance curves of papers containing different quantities of the FWA. It also includes the reflectance between 300 and 400 nm, the primary range of UV radiation. The paper samples with FWA show a very distinct reduction in reflectance (increased absorption) in the UV range (300–400 nm) and an increased reflectance in the blue range of the visible spectrum (400–500 nm) due to fluorescence. In the long wavelength part of the spectrum (500–700 nm), the reflectance curves remain constant. FWAs change the appearance of paper in two ways: first, they increase the reflectance, resulting in an increased L^* -value, and second, and even more important, they lower the b^* -value (making the paper bluer). As mentioned earlier, this color change makes the paper look even whiter and brighter.

Reflection curve (incl. UV- range 300–400 nm) of papers with and without FWA



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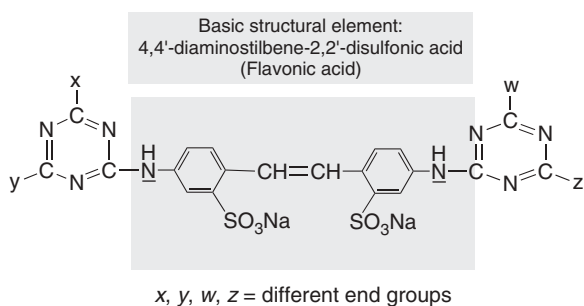
Figure 4.30 Reflection curve of papers with different volumes of FWA.

4.4.4.1 Structural Formula

FWAs are widely used in the paper, textile, and detergent industries. A number of suitable chemical groups are available. In the paper industry, the derivatives of the 4,4'-diaminostilbene-2,2'-disulfonic acid are used (Figure 4.31). They are anionic and are similar in fiber affinity to direct dyestuffs.

One special feature of FWAs is their cis–trans isomerism, illustrated in Figure 4.32.

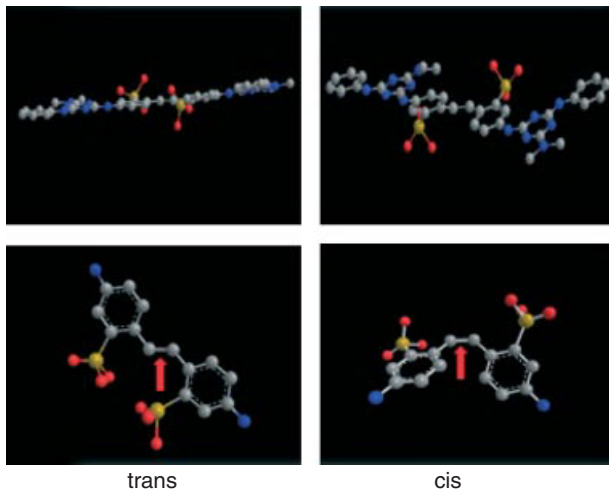
Only the planar trans-form of the FWA molecule produces fluorescence. And it exhausts much stronger onto the cellulose fiber just as a direct dyestuff does. As



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Figure 4.31 Structural formula of flavonic acid based FWAs.

Trans- and cis form of FWAs



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Figure 4.32 Cis–trans isomerism of FWAs.

light radiation can change the active trans-form into the inactive cis-form, diluted FWA solutions should not be exposed to light. Highly concentrated liquid FWAs remain fairly stable under the influence of UV-containing light.

4.4.4.2 Types of Fluorescent Whitening Agents

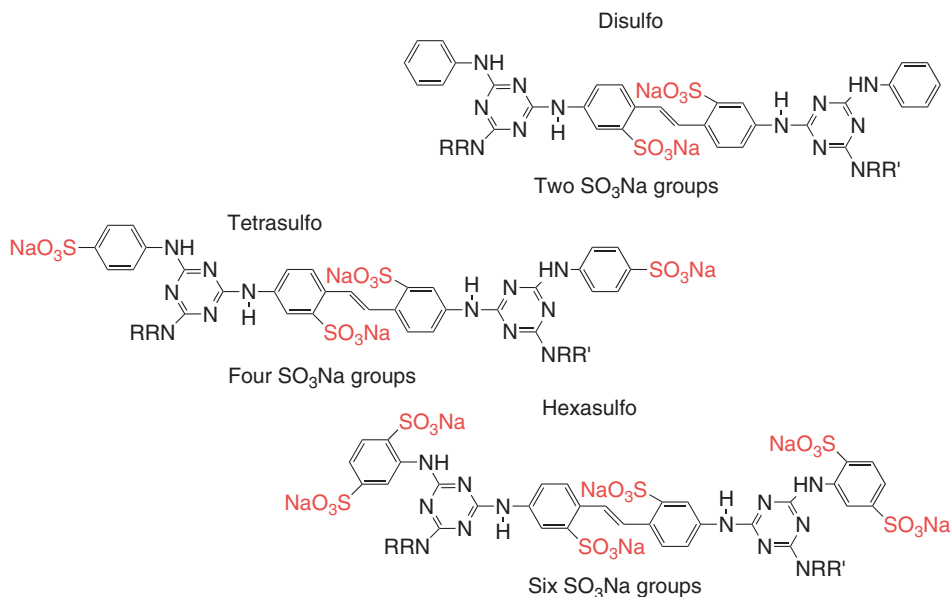
Paper FWAs can be classified into three groups (Table 4.7):

Universal types usually have four solubilizing sulfo groups, substantive types have only two. The special types FWA types have six sulfo groups (Figure 4.33).

Table 4.7 FWA-types and their characteristics.

FWA type	Characteristics
Disulfo (two sulfo groups) substantive type	Very good fiber affinity, little acid/alum/cationic stability, low compatibility with starch
Tetrasulfo (four sulfo groups) universal type	Sufficient fiber affinity, good acid/alum/cationic stability, good compatibility with starch
Hexsulfo (six sulfo groups) special type	Poor fiber affinity, excellent acid/alum/cationic stability, good compatibility with starch, very high whiteness levels are achieved

Source: Ref. [15].



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Figure 4.33 Basic structures of the main FWA types.

The hexasulfo types are not appropriate for stock addition because of their poor fiber affinity. The hexasulfo types are designed mainly for surface applications and achieving highest whiteness levels.

4.4.4.3 Hue of Fluorescence

FWAs produce fluorescence by absorbing UV radiation and emitting visible blue light. The maximum absorption of UV radiation for the usual paper FWAs is around 350 nm. Their maximum reflectance is in the blue range of the visible light at approximately 430 nm (Figure 4.33). The fluorescent hue of paper FWAs varies only slightly. In most cases, shade variations in FWA-containing papers result from the actual manufacturing conditions, that is, pH value, FWA addition rate, alum concentration, and, to a lesser extent, from the FWA hue. If it is necessary to change the shade of a white paper, one should not look for an FWA with a different hue, but investigate the following two possibilities:

- Optimization of the ratio of internal stock addition and surface addition of FWA
- Shading of the paper by adding very small amounts of blue and/or violet colorants

4.4.5

Factors Influencing the Performance of FWAs

As mentioned above, the FWA fluorescence is a matter of two phenomena occurring more or less at the same time: absorption of invisible UV radiation and re-emission of blue light to compensate for the yellow tint of paper. Anything that interferes with these two procedures reduces the performance of FWAs. Being aware of the factors that can influence FWA performance, their use can be optimized. FWAs in paper can only be effective when they are exposed to a light source with an efficient amount of UV radiation. Besides the illuminant, other factors relating to the fiber and paper manufacturing processes can limit the FWA's performance.

The factors that influence the performance of FWAs are the specific mill water, the fiber materials, and the filler used in the manufacturing process. In addition, the acidity of the furnish and the use of alum, sizing agents, or cationic additives are important for the effectiveness of FWAs because they have a strong impact on the greening or graying limit. Fixation on the fibers and the use of carriers in the coating determine the light fastness. All these factors are discussed in detail here.

4.4.5.1 Mill Water

Larger amounts of iron ions in the mill water can diminish the level of whiteness or brightness. Even more damaging are the so-called humic acids, which are high molecular weight, water-soluble substances occurring mainly in areas with peat and bituminous coal. Humic acids are especially prevalent during periods of very wet weather. Their ability to absorb UV radiation limits the performance of the FWAs. Humic acids in mill water can be detected by measuring absorption levels within the shorter wavelength UV range. Owing to stricter effluent regulations,

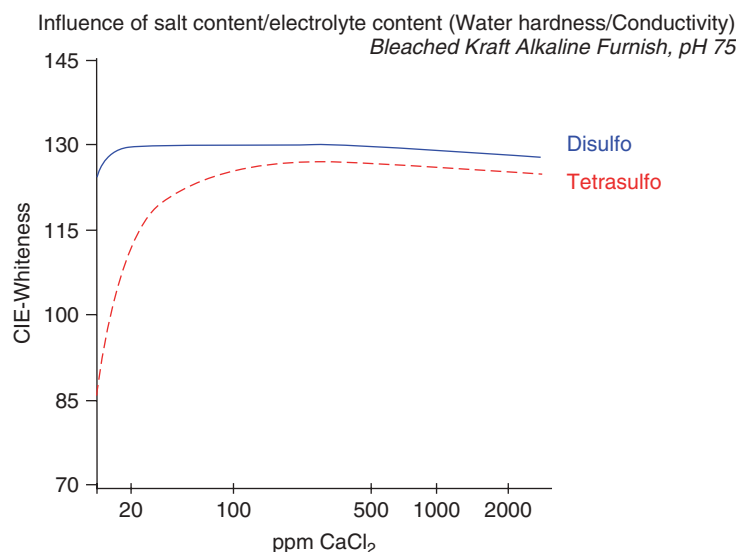
closed white water systems are becoming increasingly popular, but this has resulted in higher white water salt concentrations. The effect of calcium chloride has been investigated under laboratory conditions. As illustrated in Figure 4.34, universal FWAs exhaust poorly on cellulose fibers when deionized water is used, whereas substantive FWAs perform better in deionized water. A certain salt concentration or water hardness is actually necessary to obtain the best exhaustion of FWAs onto cellulose.

In the given example, this concentration is 20 mg/l CaCl_2 for the disulfo-type and 100 mg/l for the standard tetrasulfo type. For this reason, the substantive type is the most appropriate FWA for use in soft water systems. Once salt concentrations exceed 0.3% CaCl_2 in the water, the whiteness values decrease.

The concentration of anionic impurities from wastewater and mechanical pulp can build up in the system. These impurities do not directly impair the performance of the FWAs, which are also anionic. However, if the impurity is slightly yellowish, it may affect the whiteness and brightness of the paper even when FWAs are not present. A build up of cationic products in the white water system can reduce the whiteness and brightness of the paper because of their negative influence on FWAs, which will be explained later.

4.4.5.2 Fiber Materials

The strongest influence on the efficiency of FWAs certainly comes from the pulp. FWAs perform best on fully bleached chemical pulps, but not on mixed waste paper and unbleached pulps. The following three points are essential for ensuring a high gain in whiteness and brightness:



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Figure 4.34 Salt/electrolytes – influence on whiteness.

- lowest possible UV radiation absorption, as UV radiation must be available to activate the FWAs
- lowest possible yellow tint, which the FWAs have to overcome
- highest possible total reflectance in the visible light range, that is, highest possible initial whiteness or brightness level of the raw materials.

Figure 4.35 shows the gain in brightness with pulp of different bleaching grades. While pulp with a low base brightness of 67 TAPPI could only be brightened 18 points up to 85 TAPPI, a high base brightness pulp of 83 TAPPI is brightened with the same amount of FWA up to 114 TAPPI. This is a difference of 31 points.

4.4.5.3 Fillers (White Pigments)

Fillers are used in combination with FWAs in stock as well as in coating mixtures. As with fibrous materials, the filler should have the lowest possible yellow tint and low absorption of UV radiation in order to obtain the maximum whitening and brightening benefit from the FWAs. Titanium dioxide is a pigment having a high whiteness level. It is used in specialty paper grades because of its excellent brightening and opacifying capabilities. TiO_2 has a high base whiteness in the

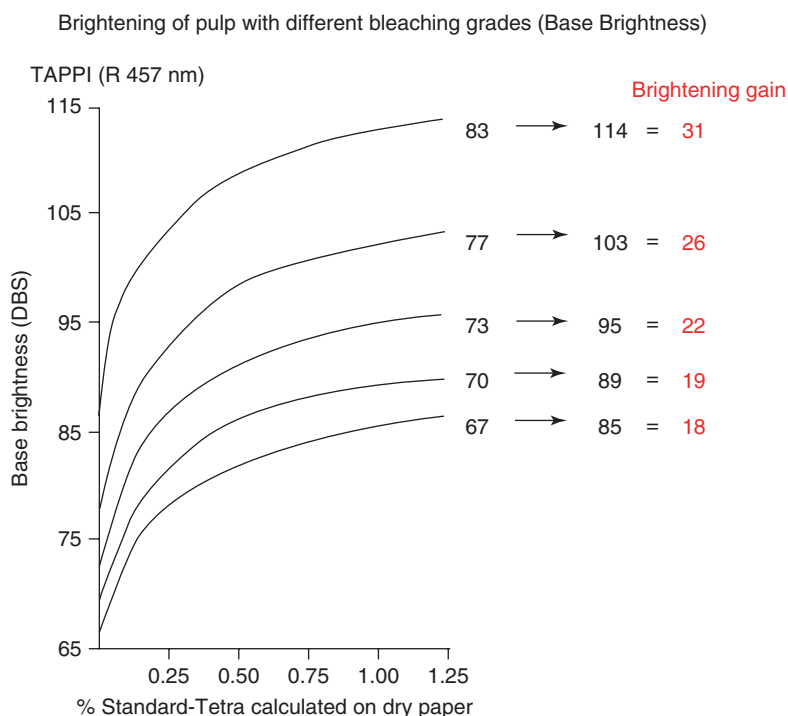


Figure 4.35 Brightening of pulp having different bleaching grades.

visible light range, but absorbs UV radiation below 400 nm. The absorption of the UV radiation reduces the effectiveness of FWAs. So, FWAs do increase the whiteness and brightness of papers filled with titanium dioxide; however, their effectiveness is not as high as with other fillers. Combinations of titanium dioxide with other fillers such as calcium carbonate, sodium aluminum silicate, or calcium silicate can achieve higher degrees of whiteness and brightness than titanium dioxide alone. The low UV absorption levels of these products, combined with FWAs, give this effect of improved whiteness.

4.4.5.4 Acid and Alum

When paper is made in an acid pH range, the papermaker can use FWAs in the stock or the size press. The loss of efficiency indicates the influence of acid or alum by precipitating, generally speaking, the soluble FWA-sodium salt into the insoluble FWA-free acid or the FWA-aluminum salt. In severe cases, the paper, as a result, has a greenish tint. The higher the FWA addition rate the greater the effect of a low pH value. When the FWA has exhausted onto the cellulose fiber, acid and alum interfere to a far lesser extent. In order to reduce the influence of acid and alum, the following measures are suggested:

- Select acid-resistant FWAs.
- Avoid an excess of alum.
- Add FWA prior to alum or acid.
- Buffer the acid backwater by adding the pulp prior to the FWA.
- In extreme cases, raise the pH value with caustic soda or sodium aluminate before adding pulp and FWA, and finally, acidify with alum.

Acid and alum affect the FWA not only when added to the stock but also when applied via the size press.

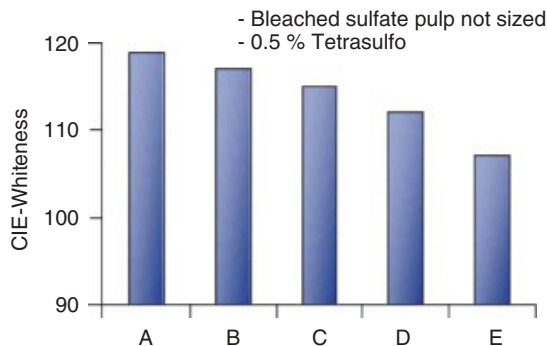
4.4.5.5 Sizing

Rosin size and alum can also affect the degree of whiteness achieved. Rosin size increases the amount of UV radiation absorption (below 400 nm) and imparts a yellowish tint to the paper. Thus, the FWA added to the stock has to overcome this yellow tint first before it can be effective. Also, as previously shown, the alum can have a negative influence on the FWA. Strongly cationic synthetic sizing agents can reduce the efficiency of the anionic FWAs because of their conflicting charges. Often, this problem can be solved by either adding the sizing agent to the stock and the FWA via size press or vice versa.

4.4.5.6 Cationic Additives

Cationic additives such as wet-strength agents, retention agents, and some of the synthetic sizing agents mentioned above can precipitate anionic FWAs and thus impair their whitening ability. The impact of the cationic auxiliaries is influenced by the following parameters:

- the addition points and the order of addition of both products
- the degree of cationic charge of the auxiliary as shown in Figure 4.36



- A: without additive
 B: 0.01% of a slightly cationic polyacrylamide
 C: 01% of a slightly cationic polyamidoamine
 D: 01% of a medium cationic mod. PEI
 E: 01% of a strong cationic polyamidoamine

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Figure 4.36 Cationic additives – influence on whiteness.

- the amount of the cationic auxiliaries.

The reduction in whiteness and brightness is very severe when both the cationic auxiliary and the anionic FWA are together in an aqueous solution. This occurs when the FWAs and the cationic auxiliary addition points are in close proximity. Once again, this problem can be solved to some extent by applying the FWA via size press or by separating the addition points.

4.4.5.7 Greening/Graying Limit

Figure 4.37, illustrating the increase in whiteness versus FWA addition rate, shows that whiteness increases initially in proportion to the addition rate of the FWA. From a certain FWA addition rate onward, the curve levels out. Increasing the FWA addition rate correspondingly increases the degree of whiteness until the maximum whiteness, or the so-called greening/graying limit, is reached. Exceeding an FWA's greening limit does not improve whiteness or brightness. In fact, the whiteness can even decrease, thereby producing a distinct greening of the paper.

Greening is a result of the absorption of visible violet light when an excess FWA is added to the paper. Variations in the greening/graying limit of FWAs depend on the following parameters:

- FWA type
- application point (stock, size press, pigment coating)
- the extent of FWA fixation to a suitable carrier
- the papermaking conditions, that is, the pH value and the aluminum ion concentration.

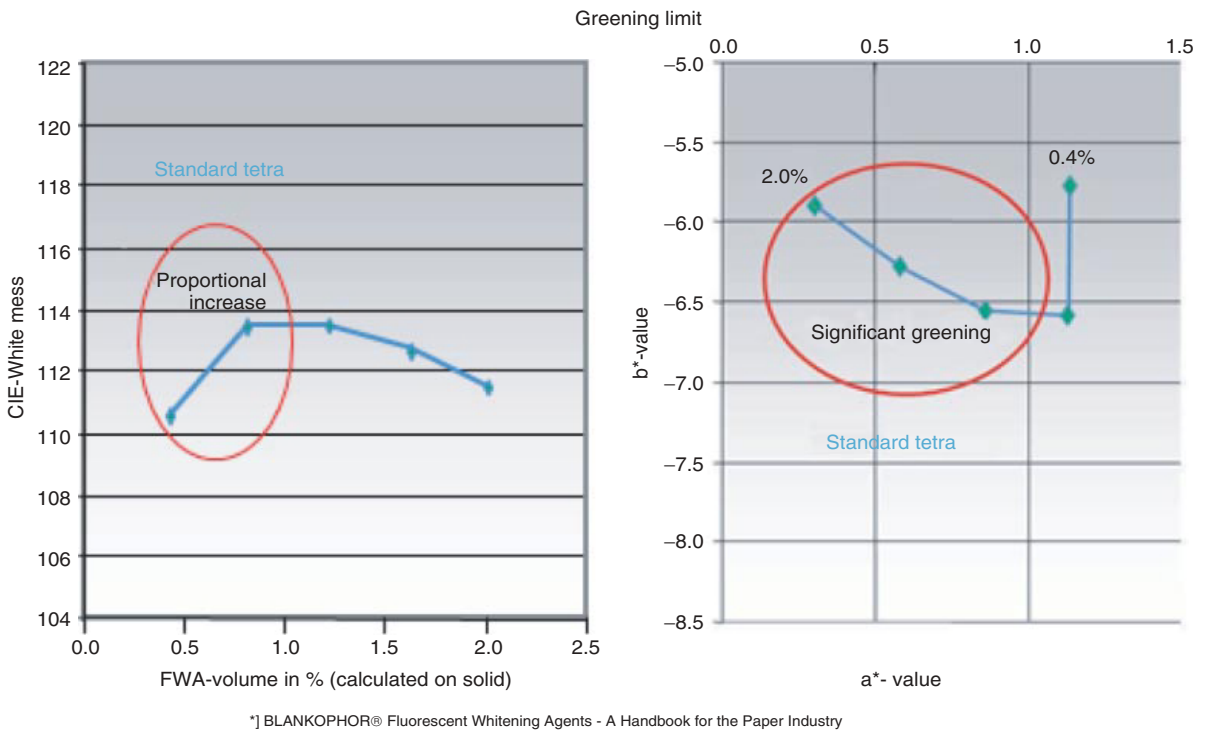


Figure 4.37 Addition rate and greening/graying limit of FWAs.

4.4.5.8 Light Fastness

The double bond in the center of the typical FWA molecule is vulnerable to destruction by light. Paper FWAs, which have exhausted on the cellulose fibers, usually have a light fastness of 3 on the Blue Wool Scale (ranging from 1 to 8). If the FWA is not properly fixed to an appropriate carrier, which often happens in pigment coating mixtures, the influence of light destroys the FWA quickly. In other words, an FWA can exhibit a wide range of light fastness depending on the type of carrier and the corresponding fixation.

4.4.6

Application of FWAs

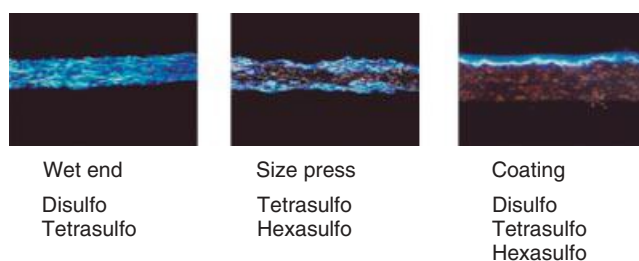
FWAs are applied in various ways (Figure 4.38):

- addition to the stock in the wet end
- addition at the size press: from aqueous starch and/or CMC/PVA solutions for surface sizing
- addition to pigment coating mixture.

When cost-effectiveness is important, application of FWAs to the paper surface is preferred. This is particularly true for high basis weight papers. When uniformity of whiteness, brightness, and good bleed fastness are important, stock addition of FWAs is beneficial. Generally, a split application, with the addition of about one-third of the FWA to the stock and about two-thirds to the surface, leads to best effects. In each individual situation, the optimum ratio of split addition needs to be determined. Such a screening could be most effectively and economically done on a small pilot paper machine.

4.4.6.1 Addition of FWAs to the Stock

Liquid FWAs can be added to the stock as received. Further dilution of these liquid FWAs is only necessary when the accuracy of addition or the uniform distribution in the stock needs to be improved. Deionized water for dilution of all FWAs, liquid, and powder is recommended. Hard water should not be used as it may



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Figure 4.38 Applications of FWAs.

precipitate FWAs. Liquid FWAs are tailor-made for continuous addition to stock by means of metering pumps. They can be pumped directly out of the delivery container.

Preferred addition points for the continuous addition of FWAs are the suction side of the stock pump or fan pump. Usually, it is suggested to pump the liquid FWAs into the high-consistency stock for achieving maximum yield in fixation on the fiber and in fluorescence, respectively.

4.4.6.2 Addition of FWAs via Size Press

In most cases, the size press application of FWAs is more economical than stock addition since the FWA is more effective on the surface of the paper instead of through the sheet. On the size press, FWAs are usually combined with a starch solution and other products designed for surface sizing. In special cases, it is possible to apply certain FWAs via size press from an aqueous solution. The FWA application via size press in combination with a suitable surface sizing agent is cost effective.

4.4.6.3 Addition of FWAs to Pigment Coating Mixtures

FWAs used in the coating are most effective when fixed to a suitable carrier. White pigments themselves are not suitable carriers. Therefore, the obtainable whiteness and brightness, the greening limit of the individual FWA, and its light fastness depend almost entirely on the system of binders and co-binders. Generally, liquid FWAs are used in coating mixtures because they can be added as received in their liquid form. It is common for the FWAs to be added to the coating mixture only after all the other components have been added and the coating mixture is ready to use.

However, the FWA must be thoroughly mixed into the coating mixture.

4.4.7

New Developments

New FWAs, which can significantly improve the performance of standard tetra-types and are close to or even better than hexa-types in surface applications such as film or size press and coating, have appeared on the market. Compared with anionic modified tetras or anionic modified hexas, which contain higher anionic load as expected by the number of sulfo groups, these new advanced “true” tetra-types are still based on the same anionic load as standard tetras. This property is important when using repulped surface-treated broke. The less anionic charge in the wet end (anionic trash) resulting from the repulped broke, the less cationic additives are needed for retention, sizing, and all other properties based on cationic additives. Thus, the paper machine runs better with broke containing these newly developed FWAs, and less fresh FWA was needed because of the better substantivity of these advanced tetra-types. In total, cleaner wet end and improved machine productivity at lower costs were achieved.

4.5 Sizing Agents

Jochen Hoffmann

4.5.1 Fundamental Aspects of Sizing of Paper

In general terms, *sizing* can be defined as the control of the interaction of liquids with the paper substrate. The primary purpose of sizing is to make paper resistant against liquid absorption and penetration, but other properties such as surface strength, smoothness, coefficient of friction, or surface free energy can also be influenced by sizing. Depending on the end use and specific requirements of the final paper product, there are different test methods in use (Table 4.8).

Two main factors determine the interaction of liquids with paper, which are

- 1) the physicochemical nature of the fiber surface, characterized by its surface free energy or rather (in contact with other media than air) its interfacial energy and
- 2) the microstructure of the paper web with pores and capillaries.

On unsized paper, which is readily wettable, the liquid forms a small contact angle with the paper surface ($\theta \ll 90^\circ$), whereas on a sized, liquid repellent paper surface the contact angle is large ($\theta > 90^\circ$) (Figure 4.39).

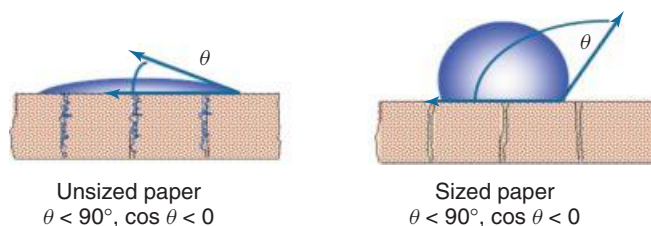


Figure 4.39 Interaction of liquids with paper.

The relation between contact angle θ and the interfacial energy γ is described by the Young equation

$$\cos \theta = \frac{\gamma_{\text{sol-gas}} - \gamma_{\text{sol-liq}}}{\gamma_{\text{liq-gas}}} \quad (4.2)$$

Accordingly, a large contact angle ($\theta > 90^\circ$, $\cos \theta < 0$) and, therefore, sizing is accomplished when the interfacial energy of paper toward air ($\gamma_{\text{sol-gas}}$) is lower than toward the liquid ($\gamma_{\text{sol-liq}}$). Vice versa, under conditions of poor sizing and easy wettability ($\theta < 90^\circ$, $\cos \theta > 0$), the interface to liquid is energetically more favorable than to air ($\gamma_{\text{sol-liq}} < \gamma_{\text{sol-gas}}$).

Sizing agents impart partial hydrophobicity to paper. This means a decrease in the surface free energy $\gamma_{\text{sol-gas}}$ and at the same time an increase in the interfacial

Table 4.8 Sizing test methods.

Absorption tests	
Cobb test	Amount of liquid absorbed per unit area (g/m^2) at a specified time (e.g., 60 s, 1800 s)
Immersion/dip tests	Liquid pick-up (% on paper) through cutting edges of laminated board at specified time (from few minutes to 24 h)
Raw edge penetration test (REP)	Special version of immersion test for liquid packaging board; test liquids: hydrogen peroxide, lactic acid; result given as kilogram per square meter cutting area
Capillary rise test	Migration length of liquid in a vertical positioned paper
Penetration tests	
Hercules sizing test (HST)	Photometric recording of ink penetration time until specified degree of strike through (e.g., 80%)
Flotation tests	Penetration time by visual assessment of liquid strike through on a paper tray floating on the (colored) test liquid; special versions: Stockigt test (Japan); hot water flotation test (gypsum board)
Dynamic liquid penetration	Recording of short-term liquid penetration by ultrasonic absorption measurement (millisecond range)
Surface tests	
Contact angle	Angle between the tangent of a droplet at its base and the paper base line; also as dynamic recording in millisecond time intervals
Drop test	Time for a liquid droplet to be fully spread and absorbed; for slack-sized papers, for example, newsprint
Ink feathering	Visual assessment of spreading of an ink stroke, applied with a pen; special version with defined inks according to French AFNOR
Inkjet printability	Assessment (image analysis) of ink jet printouts from specified printers
Toner adhesion	Adhesive strip peel test

energy $\gamma_{\text{sol-liq}}$ toward aqueous liquids, turning $\cos \theta$ into negative and hence the contact angle to $>90^\circ$.

The contribution of the capillary structure to the paper–liquid interaction is described by the simplified Washburn equation

$$h \approx 1/r \times \cos \theta \quad (4.3)$$

Under conditions of wettability ($\theta < 90^\circ$, $\cos \theta > 0$), the height h , to which the liquid penetrates into the paper structure, is the higher the smaller the radius r of the capillaries.

4.5.2

General Features of Sizing Agents

Basically, there are two application modes for sizing agents. On internal sizing, they are added to the papermaking stock prior to the sheet forming step. On surface sizing, the sizing agent is applied onto the paper web by means of a size or film press. In a combined sizing process, internal sizing is followed by surface sizing.

The typical and most representative sizing systems for each application are listed in Table 4.9.

Although different in their specific chemical constitution and composition, internal sizing agents exhibit some common features. Thus, the active sizing molecules comprise a large hydrocarbon moiety (“hydrophobic shield”) and a bridging group to the cellulose fiber (“anchor”). In the case of rosin sizes, the hydrophobic shield is formed by a polycyclic terpene-like hydrocarbon frame, and the anchor is a carboxylic group, which, in the presence of an aluminum source, is bound via its aluminum salt to the cellulose.

The hydrophobic part in AKD and alkenyl succinic anhydride (ASA) is a linear long-chain alkyl- or alkylene group with 14–20 carbon atoms, respectively, which are linked to a cellulose-reactive group. Even though the mechanism has not been fully understood, these substances are referred to as *cellulose-reactive sizing agents*, which are chemically bound to the cellulose.

As nonpolar, hydrophobic substances, the active size components are insoluble in water. For use in the papermaking process they need to be transferred into a water-applicable form, which is accomplished by emulsification in water in the presence of emulsifiers and optionally stabilizer additives. Commercial products obtained in this way contain the sizing agent in fine distribution with a particle size in the order of magnitude of 1 μm , which is stable over several months without loss in efficiency. (ASA is an exemption; because of its fast hydrolysis, it cannot be stored in aqueous formulation but must be emulsified directly before use). Figure 4.40 shows a schematic model of a dispersed size particle.

The stabilizer additive, which is typically a cationic synthetic or starch-based polymer, not only prevents the dispersed size particles from agglomeration and coalescence but also facilitates fixation of the size particle onto the fiber. The cationic size particles have a great affinity to anionic fines, including filler and pigments. Hence, next to complete adsorption onto the suspended furnish particles, high retention of fines and fillers is a prerequisite for good sizing performance. This is the first of the three main steps of internal sizing and takes place in the wet end

Table 4.9 Sizing systems – overview.

Internal sizing systems	Surface sizing systems
Rosin	Styrene-maleic anhydride copolymers (SMA)
Alkyl ketene dimer (AKD)	Styrene-acrylic ester copolymers (SAE)
Alkenyl succinic anhydride (ASA)	–

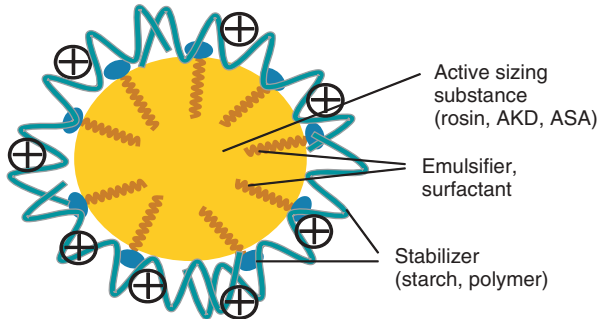


Figure 4.40 Dispersed size particle.

(Figure 4.41). After the press section, in the pre-dryer, when most of the water is released, the hydrophilic shell of the size emulsion particle breaks up and the active sizing substance is laid off. Under further thermal action, in the dryer section, the sizing substance spreads, the molecules orient themselves sticking the hydrophobic part outside and are fixed via the anchor part on the fiber surface. The driving force throughout the whole process is the minimization of interfacial energy.

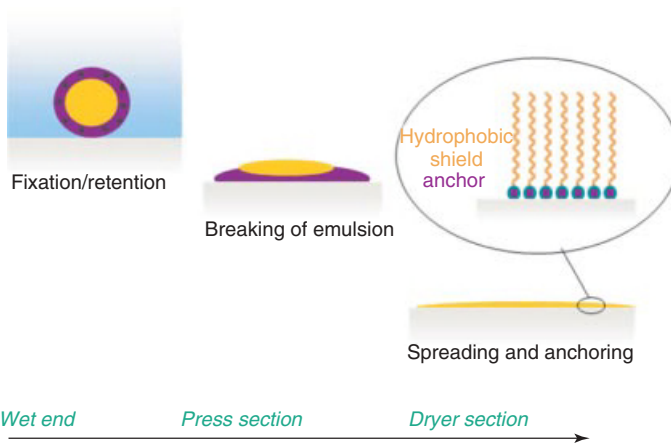


Figure 4.41 Three main steps of internal sizing.

4.5.3

Rosin Sizes

4.5.3.1 Raw Materials and Chemical Modifications

Rosin represents the oldest class of internal sizing agents. The raw material rosin or colophony is produced from renewable natural sources. One way of preparation is harvesting from living coniferous trees, a method that is employed mainly in Asia and South America but not any longer in Southern Europe and North America. After refining the crude oleoresin and separation from volatile terpenes, gum rosin is obtained as an amber to light transparent brittle substance. Another source of

rosin is crude tall oil, a by-product from the Kraft pulping process, out of which it is isolated by distillation (tall oil rosin).

Rosin is a complex mixture that contains 80–90% resin acids in different isomers. Their common feature is the polycyclic di-terpene structure with a carboxylic group. For use as a sizing agent, rosin is chemically modified in a Diels–Alder reaction with fumaric acid or maleic anhydride. The resulting so-called fortified rosin gives more stable aqueous size preparations (liquid soap, rosin dispersion) and is more effectively retained on the cellulose fiber (Figure 4.42).

Instead of fumarated or maleinated rosin, treatment with formaldehyde (hydroxy-methylation) is also possible. For special rosin size products, rosin is blended with rosin esters.

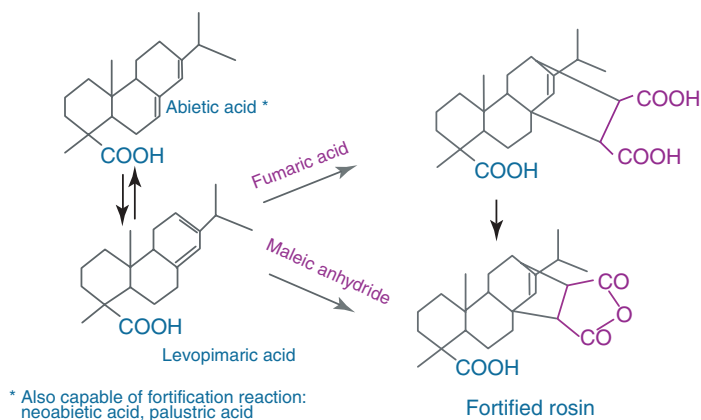


Figure 4.42 Rosin and fortified rosin.

4.5.3.2 Delivery and Application Forms

In its first application for internal sizing of paper, as it was discovered by Moritz Illig in 1807, rosin was saponified with alkali into rosin soap. Till today, rosin soap is used and therefore supplied with different rosin content as liquid soap (up to 50%), paste soap size (70%), and dry soap size (90%).

Dispersed rosin sizes, introduced in the 1930s, contain chemically modified rosin in its free acid form. Anionic dispersions with up to 40% active content are typically stabilized with casein, but casein-free products are also in use.

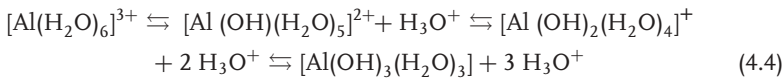
Since 1980, cationic rosin size dispersions have become more and more common. These products, with up to 40% rosin content, are formulated with a synthetic or starch-based cationic polymer. The so-called one-shot products contain the aluminum component, which is essential in rosin sizing.

4.5.3.3 Rosin Sizing and Aluminum

Any type of rosin size needs an aluminum compound for sizing development, for example, aluminum sulfate (“papermakers’ alum”) or PAC. It provides the anchoring of rosin as aluminum salt (aluminum resinate) onto the fiber, even

though the process, by which this status is accomplished, differs with the type of rosin product.

In general, rosin sizing needs an acidic environment. This holds true, in particular, for rosin soaps, which are most effective at a pH of 4–5. Under controlled application conditions, dispersed rosin sizes can be used also in a pseudo-neutral range up to pH 6, and cationic rosin dispersions allow for neutral sizing even at pH 7. This pH dependence of rosin size performance is attributed to the reactivity of the aluminum salt. The precipitation of aluminum resinate from rosin soap needs active aluminum ions, which exist primarily at pH 4.5 and below. With increasing pH, aluminum cations undergo hydrolysis to aluminum hydroxide via several intermediate stages, thereby losing cationic activity.



At a pH of 5–6, the intermediate polyaluminum species may react with anionic dispersed rosin particles, turn them into cationic, and fix them onto the cellulose fiber. The aluminum compound may also attach directly to the fiber and provide cationic fixing points for anionic rosin emulsion particles. In addition, cationic rosin dispersions are characterized by a high degree of self-retention, independent of the aluminum source.

Sizing is then developed under heat treatment in the drying section when the rosin spreads and forms the aluminum resinate bridges to the cellulose fiber.

The aluminum chemistry gives rise to side reactions, which may negatively affect rosin size performance. In the prevailing acidic milieu, calcium ions are formed by dissolution of calcium carbonate, which may lead to the formation of calcium sulfate depositions (gypsum). Furthermore, calcium may deactivate rosin by the formation of insoluble calcium resinate.

4.5.3.4 Features of Rosin Sizing

Sizing with rosin is readily developed on the paper machine and remains unchanged during storage of paper, even at tropical storage conditions. The sizing level can be adjusted gradually from slack to hard, which represents one of the major advantages over AKD and ASA. On Yankee dryer machines, rosin makes the paper glossy and glazed, which is not accomplished with synthetic sizes.

Rosin sizing is sensitive toward alkaline liquids and is thus not compatible with an alkaline coating. In liquid packaging board is one term rosin imparts resistance to hydrogen peroxide raw edge penetration.

Especially in applications at higher pH, rosin exhibits surface active properties and tends to foam.

4.5.3.5 Application of Rosin Sizes

The application of rosin sizes requires good control of pH and careful selection of dosing points. Depending on the specific requirements and process conditions, the addition amount of rosin may vary from 1 kg t^{-1} for slack-sized paper and board in acidic milieu up to 15 kg t^{-1} for hard-sized grades in (pseudo)neutral range. The

aluminum compound is used in a ratio of 1 : 1 to 2 : 1, given as alum or PAC with 18% Al_2O_3 .

4.5.4

Alkyl Ketene Dimer (AKD)

AKD was initially patented for textile treatment, and has become a paper sizing agent since the 1960s. It induced the conversion from acid to neutral papermaking, using calcium carbonate as filler.

4.5.4.1 AKD Wax

The base material for the active ingredient of AKD sizes are fatty acids from vegetable or animal sources. They are converted into the corresponding fatty acid chlorides, and finally dehydrohalogenated with an amine, forming the ketene, which is obtained in its dimeric form (Figure 4.43). The AKD hence comprises two hydrophobic alkyl chains, which may attribute to its high sizing effectiveness.

Most AKD products with a melting point around 50°C are made from blends of palmitic (C16) and stearic (C18) acids in varied ratios. Particular application conditions may require higher melting AKD, which is based on pure C18-fatty acid (mp 62°C) or, on the other hand, liquid AKD from unsaturated fatty acid (oleic acid).

4.5.4.2 AKD Dispersions

AKD sizing products are supplied as aqueous dispersions with an active content from 6 to 20%. They are formulated with a cationic polymer as stabilizer, which also facilitates the self-retention of the size particles. Cationic starch is the most conventional stabilizer, which gives the dispersion a moderate cationic charge.

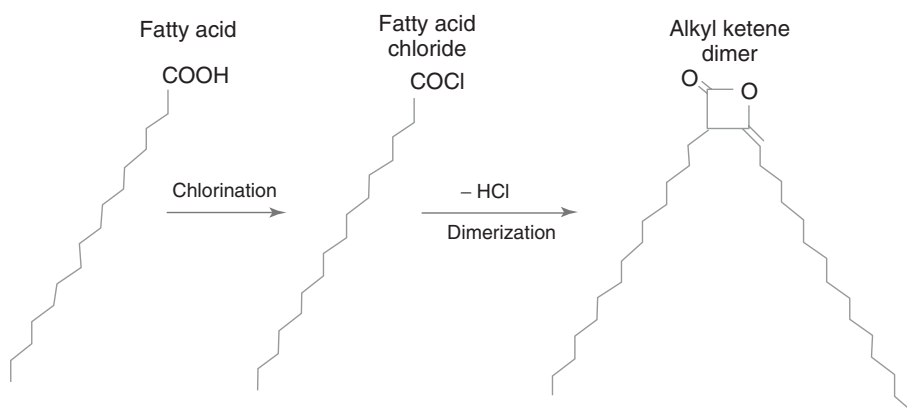


Figure 4.43 AKD – manufacture.

Products with higher cationic charge, intended for use in furnishes with high anionic trash load, contain synthetic polymers such as polyamines, polyamidoamines, or polyvinylamines (PVAs).

The so-called promoted AKD dispersions contain size cure promoters, typically cationic polycondensation products of dicyanediarnide with formaldehyde, which accelerate AKD reaction and sizing development on the machine.

4.5.4.3 AKD Reactions/Features of AKD Sizing

By virtue of its β -lactone ring the AKD molecule is able to chemically react with hydroxyl compounds, forming a β -keto ester. It is common understanding that the respective reaction with cellulose hydroxyl groups is the basis of AKD sizing, by which the sizing molecule is chemically bound to the fiber. However, there is still a scientific debate going on about the exact mechanism.

AKD can react with water as well, and the major part of AKD in a sized paper ends up as its hydrolysis product, the dialkyl ketone (Figure 4.44). It has virtually no contribution to sizing, but rather may give unwanted effects to paper, such as slipperiness, poor toner adhesion, and may cause problems like dusting and deposits in converting machines.

The sizing reaction proceeds in neutral to alkaline media. That is the reason why AKD sizing is best suited for chalk-loaded furnish. It is the alkalinity rather than just the wet-end pH that is effective for the reaction with the fiber after sheet forming.

Clay-type fillers are detrimental for AKD sizing, as well as large amounts of aluminum salts. In practice, sizing is not fully developed on the reel but needs some curing time. This can last from a few hours to several days and is dependent on the paper stock composition and process conditions. The high dry content of the wet web after press and high drying temperature help to get full sizing on the machine. Sizing development can be further enhanced by the addition of a cure promoter.

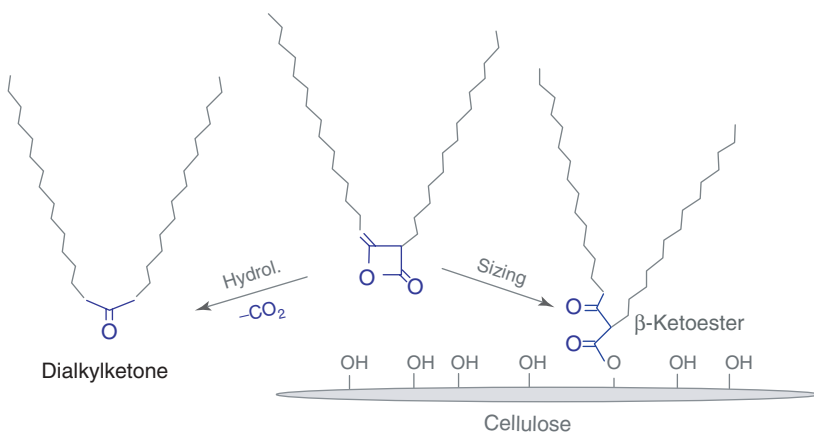


Figure 4.44 AKD reaction with cellulose and water.

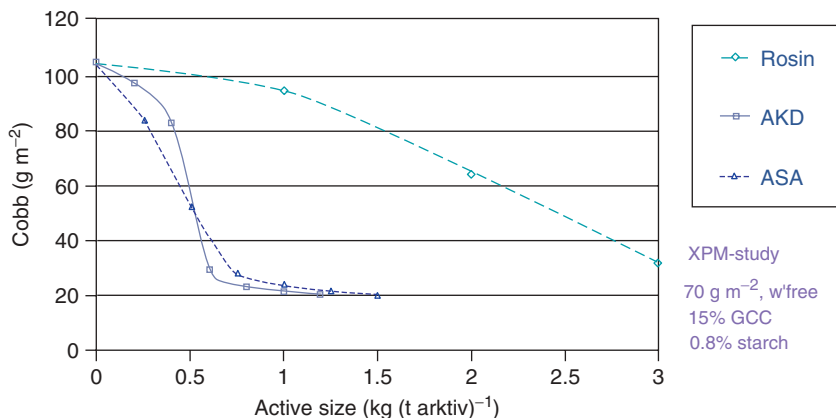


Figure 4.45 Sizing response curves – AKD, ASA, Rosin.

The size dose–response curve of AKD exhibits the typical “hockey stick” profile, that is, a small difference in addition amount decides between nonsizing and full sizing. Hence, graduate sizing is hard to achieve with AKD (Figure 4.45).

AKD sizing is resistant toward acidic and alkaline fluids and exhibits moderate stability also against organic solvents such as alcohol or acetone.

4.5.4.4 Application of AKD Sizes

AKD is the preferred sizing system when hard sizing is required. One typical application is for calcium-carbonate-loaded fine paper, where less than 1 kg t^{-1} as active AKD is sufficient to achieve full sizing.

Large volumes of AKD go into sizing of liquid packaging boards to provide lactic acid resistance and, in combination with rosin, hydrogen peroxide resistance of the raw edge.

In wood-containing and recycled fiber furnishes with a higher anionic trash load, highly cationic AKD dispersions are best suited. The addition rate is normally higher than in clean wood-free systems, and for hard-sized solid board up to 5 kg t^{-1} may be necessary.

AKD sizing performance is strongly enhanced in the presence of cationic starch (Figure 4.46). This effect is not the result of better size retention alone but starch also provides a sort of primer on the fiber surface for the interaction/reaction with AKD.

The required alkalinity (typically $>100 \text{ mg/l}$ as CaCO_3) for AKD sizing reaction is usually provided by calcium carbonate, added as a filler or with coated broke. In filler-free systems, sodium carbonate or sodium bicarbonate can be added to compensate for the lack of alkalinity.

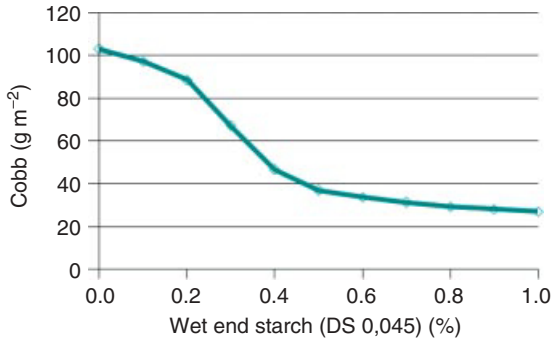


Figure 4.46 Effect of starch on AKD sizing performance.

4.5.5

Alkenyl Succinic Anhydride (ASA)

4.5.5.1 Preparation and Chemical Properties of ASA

Unlike AKD or rosin sizes, which are provided as stable aqueous formulations ready for use, ASA is supplied in neat substance and must be converted into a water-applicable form by emulsification on site at the paper mill just before use.

Raw materials for ASA are linear olefins from a petrochemical source. They are obtained from ethylene by oligomerization and subsequent isomerization. The reaction with maleic anhydride yields ASA as yellow to amber oil (Figure 4.47).

The cyclic anhydride represents the chemical anchor of the sizing molecule, which is supposed to react with the cellulose under formation of a semiester (Figure 4.48). Owing to its high reactivity, ASA is sensitive to water and undergoes fast hydrolysis, the reason why ASA cannot be marketed as an aqueous preparation. The hydrolysis product, alkenyl succinic acid, is ineffective for sizing, and may rather cause deposits in the papermaking equipment.

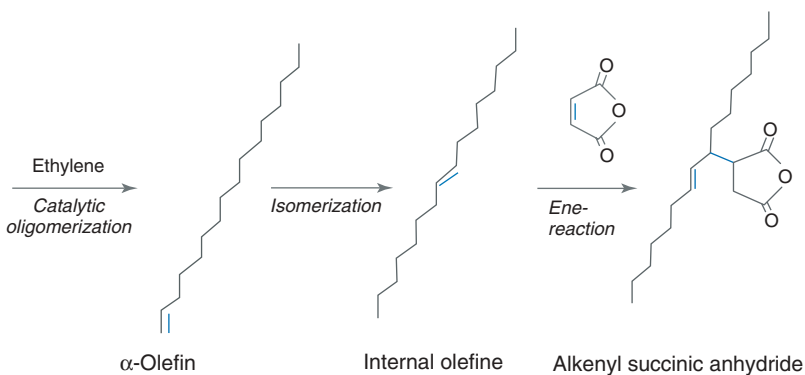


Figure 4.47 ASA manufacturing process.

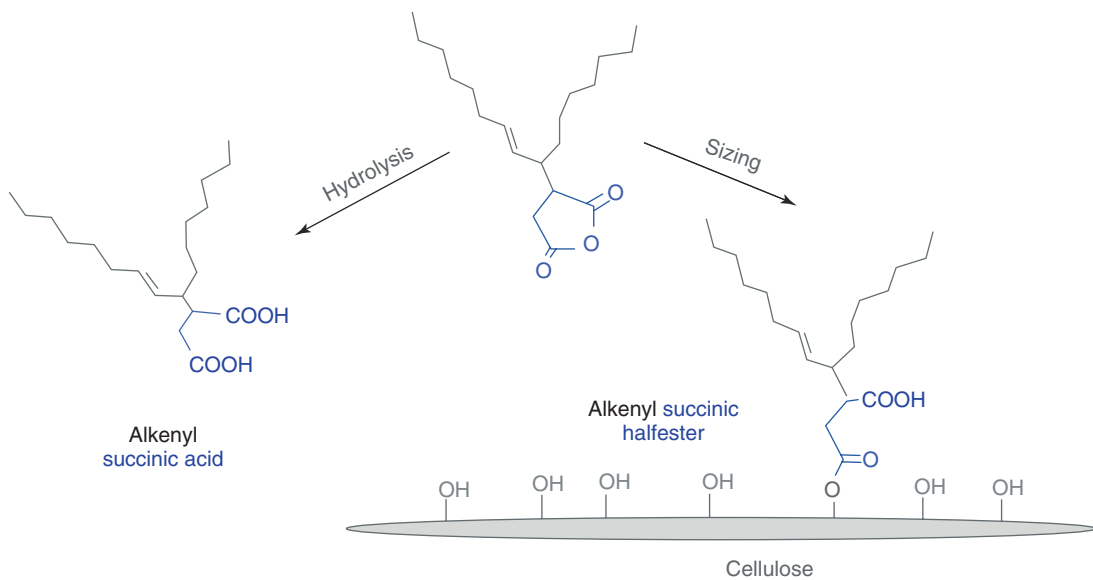


Figure 4.48 Reactions of ASA with cellulose and water.

The rate of hydrolysis and the resultant loss of sizing efficiency increases with pH, temperature, and residence time.

4.5.5.2 Preparation of ASA Size Emulsions

Emulsification of the ASA oil is carried out by means of an automated high-shear turbine pump, which provides continuously the desired amount of size emulsion to the paper machine. A surfactant, which is optionally contained in the ASA oil, may enhance the effectiveness of the emulsification process. In most applications, the size emulsion is produced with cooked cationic starch as a protective colloid and stabilizer. It facilitates the emulsification process and generation of small emulsion particles as well as their self-retention on the fiber. It further adds some stability/protection against hydrolysis to the ASA droplet under wet-end conditions. In mills, where cooked starch is not available, cold-water-soluble starches or liquid cationic polymers can be used instead. Among the latter aqueous solutions of polyacrylamides (PAMs) and special cationic-starch-based bio-polymers are most common. Figure 4.49 shows the process flow diagram of a typical ASA emulsifier unit.

The emulsification equipment represents quite a large cost factor, which could be justified primarily for large production units with a high ASA consumption. In recent years, ASA products with special emulsifiers have been launched, which are easily dispersible. They are processed in a simple low-cost mixing head and thus make ASA applications attractive also for small paper machines.

4.5.5.3 Features of ASA Sizing

ASA sizing is effective in a pH range from mildly acidic to alkaline (pH 5–9). As compared to AKD, ASA exhibits a much higher curing rate and sizing is fully developed on the machine before size press or coater. This holds true, in particular, for fine paper, whereas on wood-containing and recycling paper and board it can take from a few hours to one day until sizing is complete.

The sizing dose–response curve is similar to that of AKD, but the overall efficiency of ASA is somewhat behind that of AKD (Figure 4.45).

ASA sizing is compatible with calcium carbonate filler, whereas clay has a negative effect.

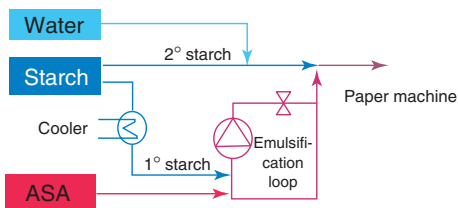


Figure 4.49 Flow diagram of ASA emulsification process.

4.5.5.4 Application of ASA Sizes

Both for technical and commercial reasons, ASA is going to more and more replace AKD in uncoated fine paper. In order to minimize the risk of deposit formation (see subsequent text), the ASA addition amount is kept below 1 kg t^{-1} and the final sizing target is achieved with additional surface size.

On packaging paper and board, kraft, and testliner, ASA is an alternative for rosin sizing, and has superseded it completely in gypsum board.

Because of its high tendency towards hydrolysis, the focus in any ASA application should be given to minimization of the residence time of the ASA emulsion in the wet end. This implies the need for high fines and filler first-pass retention, and the addition point should be in a late position of the paper machine approach system.

Cationic starch, in amounts that are typically used in fine paper production (0.3–1%), has a strong enhancing effect on ASA sizing.

In the presence of calcium ions, hydrolyzed ASA is precipitated as its calcium salt (calcium succinate), which is the main component of ASA-related deposits. Therefore, a measure against deposit formation is the suppression of calcium carbonate dissolution by pH control and, optionally, the addition of water-soluble sodium carbonate or bicarbonate. Further, by addition of an aluminum compound such as PAC, hydrolyzed ASA is better retained and eliminated with the paper.

4.5.6

Comparison of Internal Sizing Systems – Rosin, AKD, and ASA

In Table 4.10, different paper grades are listed with the sizing systems that are typically used. In most cases there is not just one alternative, so the choice each individual paper mill has to make will depend also on the design of the paper machine, raw materials and wet-end conditions, and, last but not the least, economic considerations.

4.5.7

Polymeric Sizing Agents

Polymeric sizing agents are primarily designed for surface applications. Only in special cases are they used in the wet end, and optionally in combination with another internal sizing agent.

The product class comprises a broad variety of copolymer compounds with styrene as the main building block, which imparts the hydrophobic character. Depending on the co-monomers and polymerization technology, polymer sizes are split into two main groups, which are styrene-maleic anhydrides (SMAs) and styrene-acrylic esters (SAEs).

4.5.7.1 Styrene-Maleic Anhydride Copolymers (SMAs)

SMAs are supplied as 20–30% aqueous solutions of corresponding sodium or ammonium salts, whereby part of the maleic acid groups may be also esterified with C1–C4 alcohols (Figure 4.50).

Table 4.10 Selection guide internal sizing.

Class	Grade	Rosin	AKD	ASA	Remark
Wood-free uncoated	Copy, Offset, P&W	—	++	+++	Optionally combined with surface sizing
	One-side gloss, MG	+++	—	—	—
Wood-free coated	Offset	—	++	+++	—
	Label	—	+++	++	—
	Photo	—	+++	—	—
Mechanical uncoated	Specialty (thermo-print, NCR, release)	+	++	++	—
	Newsprint	—	—	++	—
Mechanical coated	Wall paper	—	+++	+	—
	Folding box board	++	—	++	Rosin for coated top ply
	Liquid packaging board	++	+++	+	Rosin or ASA for H2O2 edge wick
Kraft	Kraft liner	++	—	++	—
	Sack	+++	—	++	—
Recycled	Office, P&W	+	++	+	Optionally combined with surface sizing
	Newsprint	—	++	—	—
	White top liner	++	—	++	Rosin for coated white top
	Testliner	—	—	++	Also: surface sizing without internal sizing
	Core board	+++	—	++	—
	Grey solid board	++	++	++	Optionally combined with surface sizing
	Gypsum board	—	—	+++	

They are anionic in character and thus compatible with most common size press additives (native and anionic starch, optical brighteners, dyes). In the slightly alkaline medium of the size press, liquor SMAs show surface active properties with a tendency to foaming.

On paper, their film-forming characteristics give good ink feathering and toner adhesion properties at a moderate degree of hydrophobization. The effectiveness

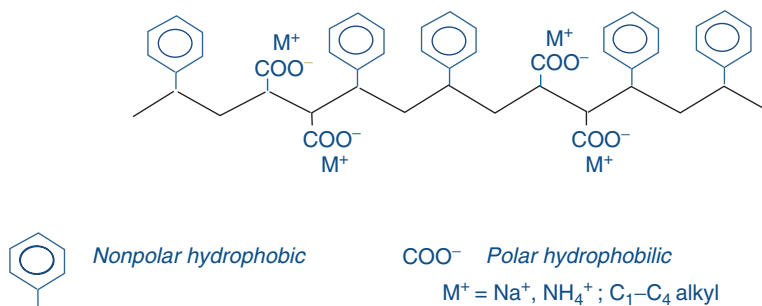


Figure 4.50 Styrene–maleic anhydride copolymer (SMA).

of SMA polymers is enhanced by aluminum compounds or cationic additives in the base paper.

The typical use of SMAs is for uncoated office paper in combination with AKD or ASA internal sizing. At an addition rate of 0.2–0.5 kg t⁻¹ as dry polymer, together with starch, the negative effects of the AKD-like slipperiness and poor toner adhesion can be overcome.

4.5.7.2 Styrene-Acrylic Ester Copolymers (SAEs)

SAE copolymers (Figure 4.51) form aqueous dispersions of fine particles in the range of 50–100 nm. Not only anionic and cationic but also bi-ionic products are available, the charge character being determined by the selection of the co-monomers and the emulsifier/stabilizer system.

SAEs show good thermal and chemical stability in the size press liquor and are applicable in a wide pH range. Sizing is developed under heat treatment in the post-drying section where the molten polymer particles spread along the fiber starch network. By variation of the monomer composition, the melting characteristic of the polymer can be adapted to given drying conditions.

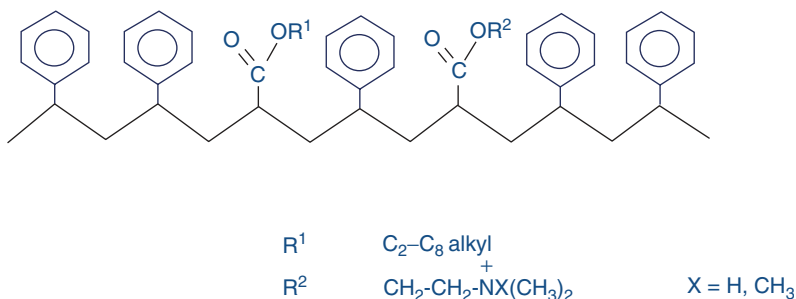


Figure 4.51 Styrene–acrylic ester copolymer (SAE).

SAEs feature high sizing efficiency without negatively affecting the surface properties. These properties make them well suited for modern office papers to meet the demands in terms of ink jet printability and toner adhesion.

Cationic SAE dispersions especially are little affected by colloidal trash and electrolytes in size press solutions. Hence, they are widely used for surface sizing of recycling paper and board, where internal sizing may present more difficulties (e.g., testliner).

4.6

Wet-Strength Resins (WSR) and Dry Strength Resins (DSR)

Gunnar Kramer and Dominik Stumm

4.6.1

Introduction

In order to form a sheet of paper no glue is required. Unlike glass fibers or most synthetic fibers, cellulosic fibers have the unique ability to adhere to each other when they are dried while in contact. Reading: Hubbe, M.A. (2006) *BioResources*, 1 (2), 281–318. See also at the end of the chapter: further readings of section 4.6

The strength of paper sheets is an inherent structural property that is due to the development of fiber-to-fiber bonds during forming, consolidation, and drying of the fiber web. Depending on the application of paper, different specific mechanical properties are important. In terms of function, paper can be grouped into four groups: packaging, writing and printing, absorbing and wiping (hygienic papers), and specialty papers.

Packaging paper and paper board require sufficient strength to protect the contents of the paper boxes. Typical strength properties for packaging paper are tearing resistance, folding endurance and burst strength, internal bond, and compression resistance.

Writing and printing papers need – depending on the printing and converting operations – other strength characteristics. Offset printing, for example, one of the most important printing processes, demands high tensile strength and surface strength owing to the high ink tackiness.

Absorbing papers should provide high porosity within the sheet structure to maximize water penetration. At the same time, the paper needs a certain strength to withstand the manufacturing and converting processes.

The huge variety of demands on the properties of specialty papers can hardly be described within the framework of this chapter. Taking banknote paper as an example, we could focus on two major issues: folding endurance and extraordinary wet strength (resistance to alkaline washing liquor). Both mean a total change in the natural behavior of cellulose fibers; advanced and tailor-made paper additives need to be applied.

Paper strength is affected by many raw material and process variables. The type of fibers and how they were produced significantly influence the paper strength.

Longer softwood kraft fibers produce stronger papers than shorter hardwood fibers. Mechanical pulp and recycled fibers form weaker papers than virgin chemical pulp. Good water quality improves the strength potential of fibers. Fillers reduce strength. On the process side, both increased refining and wet pressing increase paper strength. Alkaline pH conditions in the wet end produce stronger papers than paper formed under acid conditions, especially after aging. Reading: Marton, J. (1991) in *Paper Chemistry* (ed. J.C. Roberts), London, pp. 63–75. See also at the end of the chapter: further readings of section 4.6.

The basic factors that influence paper strength are

- individual fiber strength
- interfiber bond strength
- the number of interfiber bonds (bonded area)
- the distribution of fibers (sheet formation).

While the first factor is not dependent on strength additives, the remaining three can be strongly influenced by such products. Many water-soluble hydrogen bonding polymers will act as dry strength additives (DSAs). In fact, wood fibers contain their own natural DSA in the form of hemicelluloses. It is well known that the removal of hemicelluloses from wood fibers makes it more difficult to develop their bonding characteristics.

4.6.2

Theory of Paper Strength

4.6.2.1 Models to Explain Strength Increase

It is generally accepted that the major factors contributing to dry strength development in paper manufacture include van der Waals forces, hydrogen bonding, and electrostatic interactions. Hydrogen bonding is supposed to play the critical role in paper strength when assuming that at least parts of the surface of fibers approach each other within 0.27 nm. The surface of cellulose fibers is rough in a range between 0.01 and 10 μm . Studies of refined fibers showed a wide range of fibrils and microfibrils. Owing to this fibrillation, the effect of fiber roughness is reduced and enables the fibers to get into close contact. In Figure 4.52, two models depict the effect of surface roughness of cellulose fibers in wet state. On the left side, the conventional view of the fiber surface is displayed. On the right side, the model with fibrils and microfibrils is shown, which entangle each other to increase the surface contact. Reading: Linhart, F. (2005) *Wochenbl. Papierfabr.*, **133** (11/12), 331–338. See also at the end of the chapter: further readings of section 4.6.

On the basis of the second model, DSAs can further improve the efficiency of bond formation between fibers as water is evaporated from the paper web. To make sure that fiber surfaces get into contact, they have to be drawn together. Two principles are responsible for this fiber surface approach, the capillary forces and the interdiffusion of macromolecules.

The capillary forces can easily be recognized by assuming a water drop between two ribbon-like fibers. The surface of the fibers is perfectly wettable (contact angle

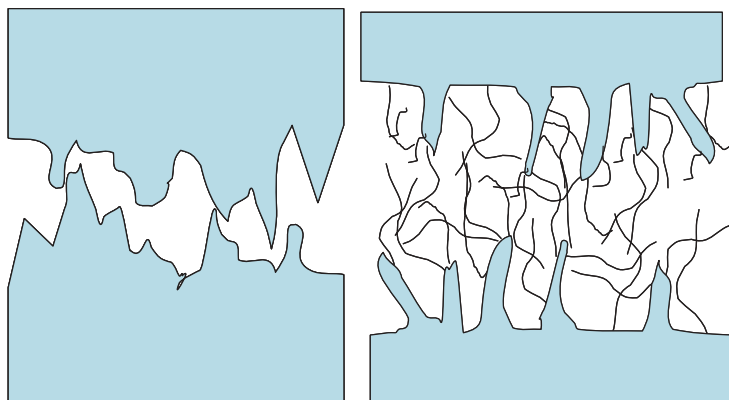


Figure 4.52 Schematic models of fiber surface: conventional view (a) and fibrillated surface (b).

of zero). Estimations showed a negative pressure up to 2 t cm^{-2} during drying. These forces are far lower than the pressure in wet pressing, but act during the whole drying process in order to get parts of the fibers close together (into molecular distances).

A strong evidence in support of this molecular contact mechanism is the massive decrease in surface area when paper is dried.

The second explanation is based on the thermodynamics of mixing polymer solutions. At the surface of fibers, water acts as a solvent for segments of macromolecules of hemicellulose and microfibrils (cellulose). In the wet state, the macromolecules tend to mix before drying. This mixing tendency increases the effect of approach of the fiber surfaces (Figure 4.53).

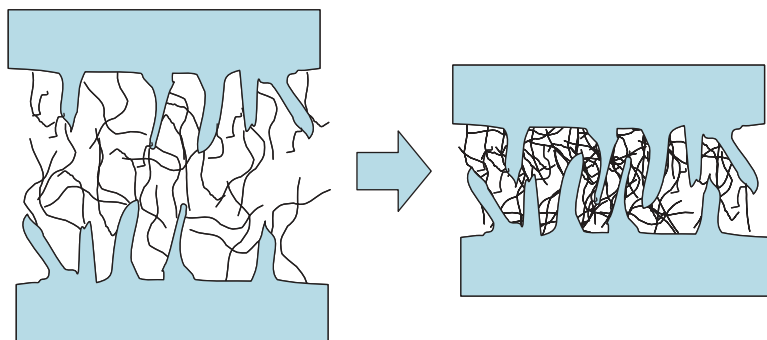


Figure 4.53 Schematic concepts of diffusional mixing of macromolecular segments of microfibrils from to wetted fiber surfaces.

4.6.2.2 How Dry Strength Additives Can Improve Paper Strength

Two concepts can be applied when water-soluble, hydrogen bonding polymers are used as DSAs to improve interfiber bonding. The first concept is to improve the

interfiber contact. The polymers act as additional bridges or extensions between the fibers. This bridging can be formed only by polymers or in conjunction with fines. The second concept is the bonding strength between the fibers owing to stronger hydrogen bonding or electrostatic interactions.

4.6.2.3 How Wet-Strength Additives Can Retain Paper Strength

Papermaking is a reversal process. Water is the tool and lubricant to form new paper from virgin fibers or old recycled pulp. For some paper grades such as adsorbing and wiping and laminate or label paper, this reversibility is detrimental to their usage. Such papers have to retain a certain paper strength when they are saturated with water. To retain a proportion of the dry paper strength, the following approaches can be selected:

- add or strengthen existing bonds
- form bonds that are insensitive to water
- protect existing bonds
- produce a network of polymers that entangles with the fibers.

The main issue is to prevent the fibers from swelling and to maintain the stiffness of the fibrils that hold the individual fibers in the paper web together.

On the basis of the considerations of Westfelt [16], four mechanisms can be assumed for wet-strength resins (WSRs) (Figure 4.54).

Model A postulates a WSR that is not reactive and forms no chemical bonding. The wet-strengthening effect is only due to the physical entanglement of fibers and resins itself.

Model B and C assume reactive WSRs that form either chemical bonding only with itself (homo-cross-linking) or only with fibers (co-cross-linking).

Model D is a mixture of model B and C and describes best the mode of action of the commercial available WSRs.

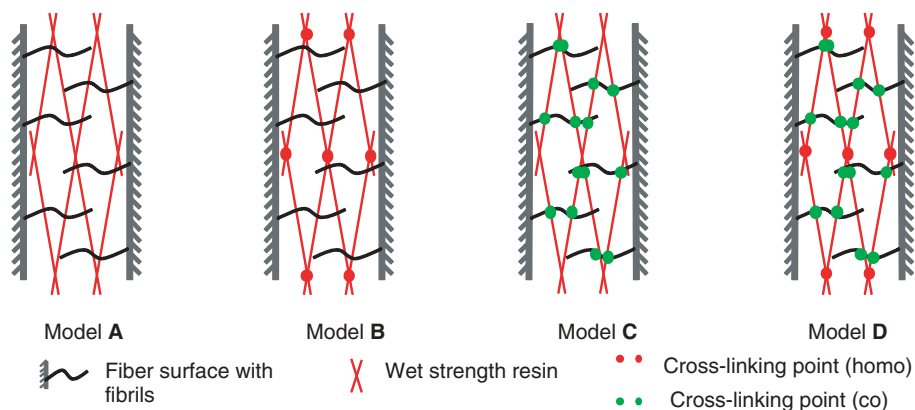


Figure 4.54 Schematic action mechanisms of wet-strength resins.

4.6.3

Dry Strength Additives (DSAs)

DSAs can be grouped into modified natural and synthetic dry strength resins (DSRs). A natural DSA brought by wood fibers themselves is hemicelluloses. Pure α -cellulose fibers (e.g., linters) or the removal of hemicelluloses from wood fibers makes it more difficult to develop bonding characteristics of the fibers. Reading: Auhorn, W. (2006) *Handbook of Paper and Board*, (ed. H. Holik) Wiley-VCH Verlag. See also at the end of the chapter: further readings of section 4.6.

Typical modified natural DSAs are

- modified starches
- vegetable gums, for example, guar gum
- modified celluloses.

Synthetic DSAs are

- Polyacrylamides (PAMs)
- Polyvinylamines (PVAm)
- polyamines
- polyvinylalcohol and wet strength agents (PVA, WSRs).

Modified natural DSAs hold the main share of the DSA market. Starch and its derivatives are among the most commonly used to improve paper strength. Vegetable gums play only a minor role within this group.

4.6.3.1 **Cellulose Derivatives**

4.6.3.1.1 Starch Starch derivatives represent the most common and by far the largest amount of DSAs (see Section 4.2).

4.6.3.1.2 Vegetable Gums Water-soluble vegetable gums, such as guar gum, are not as important as starch derivatives. The chemical structures are rodlike polysaccharides composed of mannose, similar to cellulose, enabling them to participate in extensive hydrogen bonding with fiber surfaces. The natural materials are nonionic or weakly anionic charged and are only adsorbed on the fiber surface by van der Waals forces and hydrogen bonding. To improve polymer retention of the gum on the fiber, cationic groups have to be attached to the polymer chain. Owing to the combination of high retention and effective dry strength, enhancement of only 0.1–0.35% of the material has to be added in most instances. Owing to its structure, it reduces the flocculation of long fiber pulp and improves formation and interfiber bonding.

4.6.3.1.3 Carboxylated Celluloses CMC or cellulose gum is the most common cellulose derivative in use within the paper industry. The DS of these types of CMC is between 0.5 and 1.5%. Normally, CMC is used in combination with cationic components such as alum salts, polyamines, or WSRs. A different approach is to

treat fibers without cationic additives. It appears that enough CMC adsorbs of the fiber surface to achieve substantial dry strength gains [17].

4.6.3.2 Synthetic Dry Strength Additives

The fully synthetic DSAs are competing with their natural counterparts and gaining a certain importance in application of mass and specialty papers. Their worldwide consumption is an average of 300 g dry polymer per ton of paper. The market share of synthetic DSA is about 10–20% of the total DSA market worldwide. Japan is an exception as it uses the largest portion of the total consumption of DSA.

4.6.3.2.1 Polyacrylamides In the group of synthetic DSRs, the PAM-based products are still dominant. The polymers were synthesized from acrylamide and charged monomers such as acrylic acid, dimethylaminoethyl acrylate, or dimethylaminoethyl methacrylate. When used as DSAs PAMs may carry anionic, amphoteric, or cationic charge. Typically, 10–30% of the monomers are charged and their molecular weight is within 100 000 and 500 000 g/mol [18]. Other literature claims increased effectiveness with higher molecular weight.

The polymer chain length is in a range that, on the one hand, the polymers will not bridge between particles and cause flocculation, and, on the other hand, will not or only slowly penetrate into the fiber pores (which would result in strength decrease). Figure 4.55 describes the chemistry of PAM manufacturing.

Negatively charged PAMs are not directly attracted to paper fibers. Certain adsorption tendencies can be measured by zeta potential. Cationic additives, such as alum or cationic polymers, can promote their retention and the dry strength gain in the paper. As an alternative to cationic fixatives, cationic groups (e.g.,

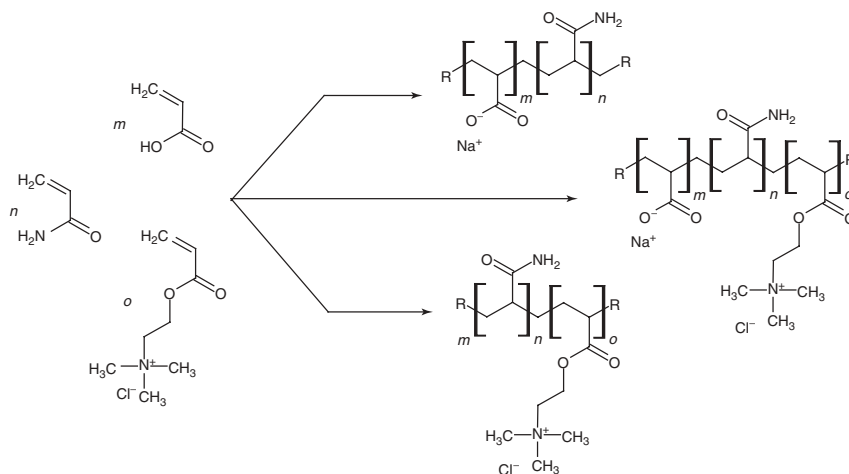


Figure 4.55 Preparation of polyacrylamides (anionic, amphoteric, and cationic).

dimethylaminoethyl acrylate or dimethylaminoethyl methacrylate) can be directly copolymerized into the PAM backbone.

4.6.3.2.2 Polyvinylformamide/Polyvinylamine Resins (PVF/PVAm) The recently developed polymers in papermaking are polyvinylformamide (PVF) and PVA. This type of polymer can be produced either by polymerizing vinylformamide and then hydrolyzing it or by Hoffmann degradation of PAMs (Figure 4.56).

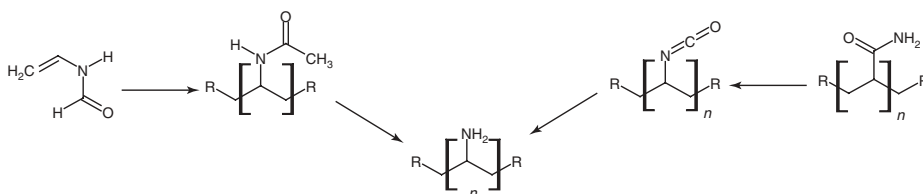


Figure 4.56 Preparation of polyvinylamines, left: polymerization via polyvinylformamide and right via Hofmann degradation of polyacrylamides.

The synthesis via polyvinylformamide has the advantage that the polymers may be varied within a wide range of molar mass and charge density owing to a hydrolysis degree of 0–100%

Similar to PAMs, low or medium charged PVAs of medium molecular mass are suitable as high performing DSRs.

4.6.3.2.3 Other Dry Strength Additives (PVA or Wet-Strength Resins) Other DSAs are different hydrophilic polymers with strengthening potential, but are mainly used because of their other functionality in papermaking. The most important are the WSRs, which improve the dry strength properties of paper besides their main function of providing wet strength to paper.

4.6.3.3 Application

The typical application of DSAs is to dose continuously into thick stock between pulper and machine chest. A batchwise addition is possible but is inferior to continuous dosage. Addition rates of 0.1–0.5% of solid dry strength agents are adequate for most applications and may reach up to 1.5% solid polymer depending on the paper quality. On the other hand, excessive use may cationize the stock suspension and reduce the effectiveness of DSA and of other cationic additives.

Further improvements in cost-performance can be achieved by product combinations, for example:

- Natural and synthetic product combination, such as anionic starch or CMC together with a low/middle charged cationic PVA or PAM
- Pure synthetic combination, such as medium molecular mass, middle charged anionic PAM, or anionic PVF with cationic polyvinylamide or alum salt (poly aluminum chloride).

4.6.4

Wet-Strength Resins (WSA)4.6.4.1 **Overview**

Wet-strength agents are synthetic resins intended to reinforce the mechanical properties of wet paper. They are applied in various paper grades such as tissue, packaging papers (liquid packaging board), specialty papers (bank note paper, filter paper, abrasive paper, label paper, decorative laminating paper, wall paper, etc.).

To retain a certain part of the paper strength under wet conditions, the following approaches are possible:

- add or strengthen existing bonds and form bonds that are insensitive to water;
- protect existing bonds and produce a network of polymers that entangles with the fibers;
- increase the hydrophobicity of the individual fibers or the fiber network;

The first two goals can be attained by WSRs, whereas the last one is typical for sizing agents. However, real wet strength is the mechanical strength of paper remaining after complete soaking in water. The apparent wet strength of sized paper is due to the incomplete or reduced penetration of water into the paper.

Some useful definitions are

Absolute wet strength	Tensile strength after defined time of wetting (N)
Wet breaking length	Length of a paper tape, at which the tape tears off due to its own weight
Relative wet strength	Wet strength/dry strength \times 100 (%)
Temporary wet strength	Paper loses its wet strength in a defined period of time under wet conditions
Permanent wet strength	No significant strength loss of wet paper within a defined period of time

WSA can be divided by chemistry and permanence of wet strength into

- permanent WSRs
 - urea resins (nonionic/anionic, acidic curing)
 - melamine resins (nonionic/anionic cationic, acidic curing, lightfast)
 - polyamidoamine-epichlorhydrine (PAAE) resins (cationic, neutral curing)
- temporary WSRs
 - PAM-glyoxal resins (weakly cationic, neutral to weak acidic curing)
 - glyoxal, glyoxal resins, dialdehyde-starch (nonionic, neutral to weak acidic curing)

PAAE resins have taken more than 80% of the global market (300–350 Mio Euro) owing to the breakthrough of neutral-pH papermaking in almost all the different

paper grades. Figure 4.57 shows the efficiency of different chemistry as a function of the pH value in papermaking.

The mode of action of WSA can be described as

- enwrapping of the fiber–fiber touchpoints → formation of a kind of collar
- chemical cross-linking of the collar (polymer cross-linking) during drying and storage (curing)
- formation of resin–fiber bonds

As shown in Figure 4.58, the wet strength develops during paper drying and includes

- evaporation of water
- concentration of the WSA close to the fiber cross-links
- formation of chemical bonds during final drying or storage of the finished paper.

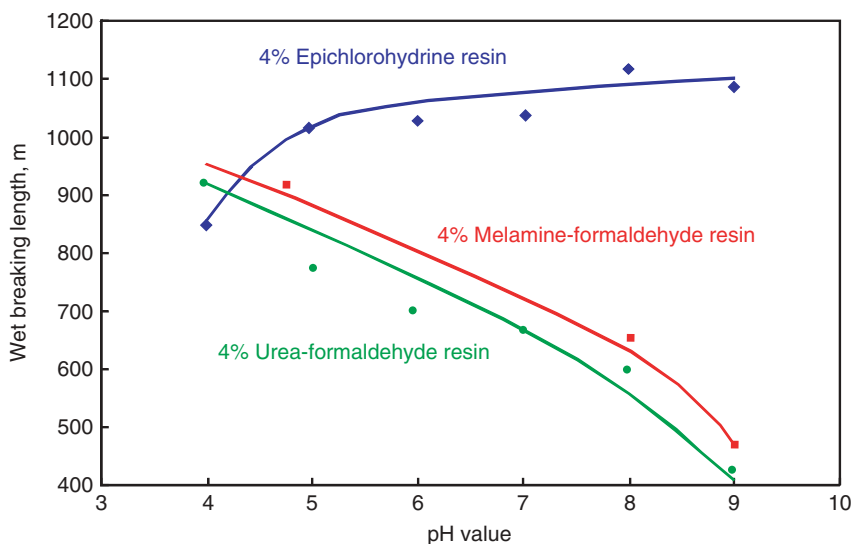


Figure 4.57 Wet-strength performance of paper with different wet-strength agents as a function of the system pH value.

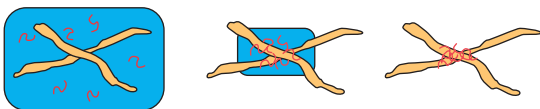


Figure 4.58 Wet-strength development during paper drying and storage of the finished paper.

4.6.4.2 Melamine–Formaldehyde Resins

Melamine and formaldehyde form monomeric methylol melamines from monomethylol melamine up to hexamethylol melamine. Further condensation reactions lead to oligomeric or polymeric, colloidal structures, promoted by high temperature and low pH, creating methylene or ether linkages with elimination of a water molecule in each in the polymerization steps, as described in Figure 4.59.

Added to a papermaking system, the melamine formaldehyde product can cross-link with itself (homo-cross-linking) forming a methylene link or an ether link, as well as with cellulose carboxyl groups (co-cross-linking) to form covalent bonds, which contribute to wet strength (Figure 4.60).

The advantages of melamine formaldehyde (MF) resins are that they may reach, when added in similar rates to urea– formaldehyde (UF)-resins, wet tensile strength levels up to 50% and to even higher wet bursting strength. MF-resins also provide a very high alkaline resistance; therefore, such products are mainly used for label papers, sack papers, bank note papers as well as for map papers.

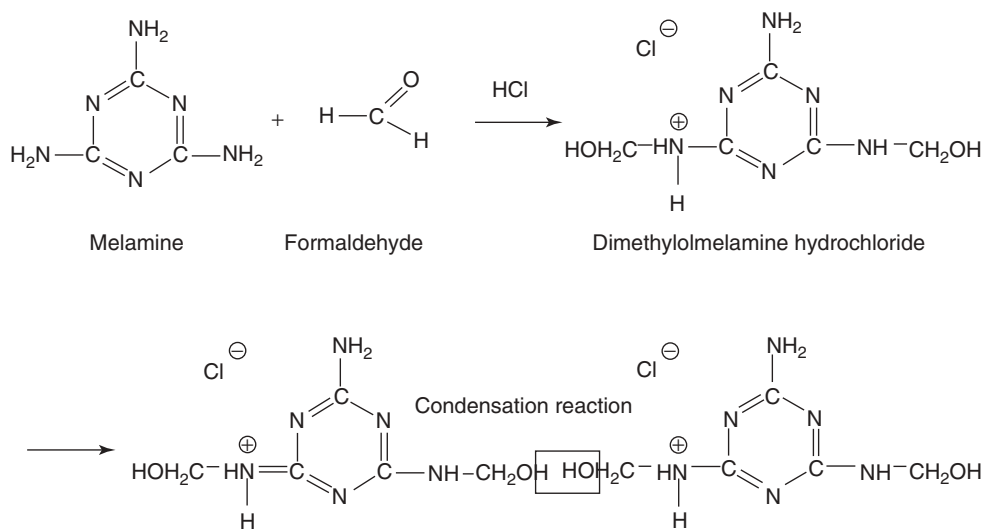


Figure 4.59 Synthesis of melamine formaldehyde resins.

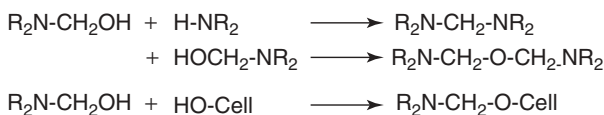


Figure 4.60 Cross-linking reaction of melamine formaldehyde resins.

4.6.4.3 Urea–Formaldehyde Resins

The formation of aqueous solutions of UF condensation products involves the stepwise reaction of urea with formaldehyde, and the first step is undertaken at pH 7–8 to form dimethylol urea. When pH is lowered to 4–5, self-condensation of methylolurea forms a condensation product in an aqueous solution to a controlled degree, which can be stored and transported (Figure 4.61).

Commercial UF-resins for paper wet end are cationic, made by urea, formaldehyde, and water-soluble polyfunctional amines such as ethylenediamine, diethylenetriamine (DETA), and so on. The cationic resins achieve good retention without the use of alum. Most commercial UF-resins have a pH of 6–7, whereas colloidal MF-resins have a pH of about 2. The UF-resins are the least expensive ones. An important area of application is the manufacture of sack paper for shipping and cement packaging. With addition rates of 0.5–3%, calculated on dry paper stock, up to 40% relative wet strength can be achieved.

UF- and MF-resins are delivered in aqueous solutions with solid contents of 12% (MF) and 40% (UF) as well as in powder form (MF). They are mainly applied in the wet end, but they can be also used in surface applications in the paper machine. Suitable feeding positions for the continuous wet-end addition are between the stock consistency controller and the mixing pump, shortly before final stock dilution, where an optimum of mixing is guaranteed. pH has a dramatic effect on the curing rate of MF- and UF-treated paper. An optimum pH of 4.5 is recommended for the system. Fifty percent of wet-strength properties are attained off-machine. Most of the wet strength is achieved after a curing period of two weeks.

MF- and UF-resins contain free formaldehyde in equilibrium with the resin. Hydrolysis also can contribute to free formaldehyde depending on the manufacturing and storage conditions. There is a tendency toward reducing free formaldehyde content to less than 1% as well as products with lower formaldehyde emission during paper production.

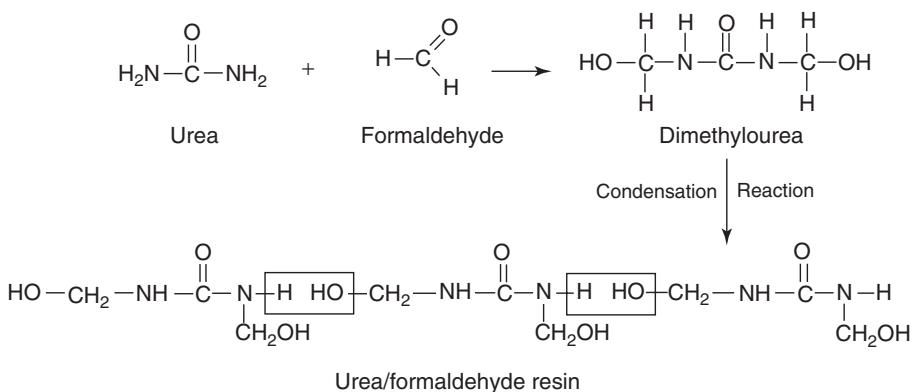


Figure 4.61 Synthesis of urea formaldehyde resins.

4.6.5

Epoxidized Polyamide Resins

The need for WSRs that could be used in neutral or slightly alkaline papermaking systems led to the development of polyamidoamine epichlorohydrin (PAAE) resins many years ago. Nowadays, the PAAE resins are extensively used in practically all types of wet-strength papers. Major examples are towels, napkins, facial tissue, laminate paper as well as packaging materials for liquid packaging, corrugated boxes, paper bags, and specialties such as photographic paper and disposables. PAAE resins are recommended for hot filter paper such as coffee filters and tea bags.

The chemistry of the first production step is a polyamide synthesis. In the case of polyamide resin, a dicarboxylic acid such as adipic acid is reacted with an amine, DETA, to form a water-soluble polyamidoamine. In a further step, the secondary amine groups of the polyamidoamine are alkylated with epichlorohydrin. This results, predominantly, in the formation of tertiary aminochlorohydrine groups that cyclize to form a 3-hydroxy-azetidinium salt (Figure 4.62).

These polyamidoamine epichlorohydrin intermediates are then cross-linked to form aqueous oligomeric resin solutions (Figure 4.63). The polymerization reaction is terminated by dilution and acidification. The amount of azetidinium groups is mainly responsible for the reactivity and the cationic charge of the slightly viscous PAAE resin. These commercially available resins are supplied in the form of aqueous solutions with a solid content of 12–20% and sometimes up to 25%.

In the drying section of the paper machine, the azetidinium groups have several reaction possibilities. In case of homo-cross-linking, the azetidinium groups react with amine functionalities forming a network. Furthermore, a reaction with the carboxyl group from cellulose might take place (co-cross-linking). There is some evidence suggesting that homo-cross-linking in PAAE resins is more likely rather than being cellulose reactive. The azetidinium salt also slowly and undesirably reacts with water to form a nonreactive diol. Figure 4.64 shows these reaction mechanisms.

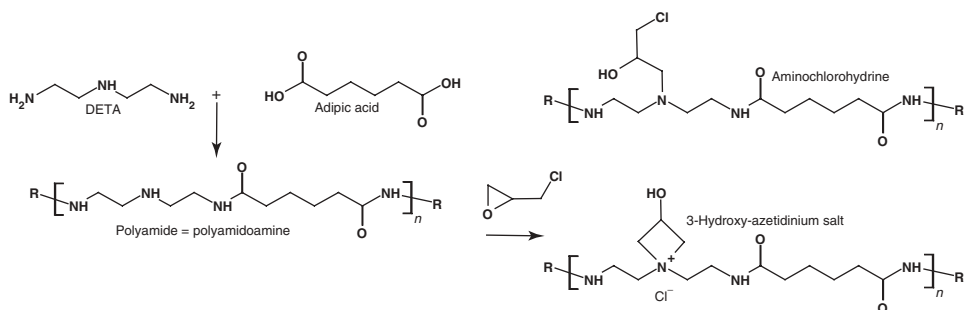


Figure 4.62 Preparation of polyamidoamine epichlorohydrin intermediate.

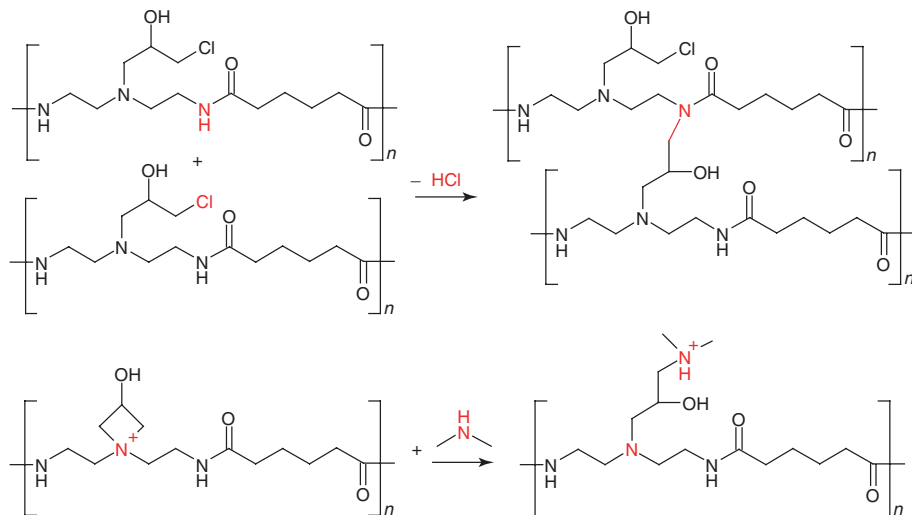


Figure 4.63 Cross-linking of polyamidoamine epichlorohydrin intermediates.

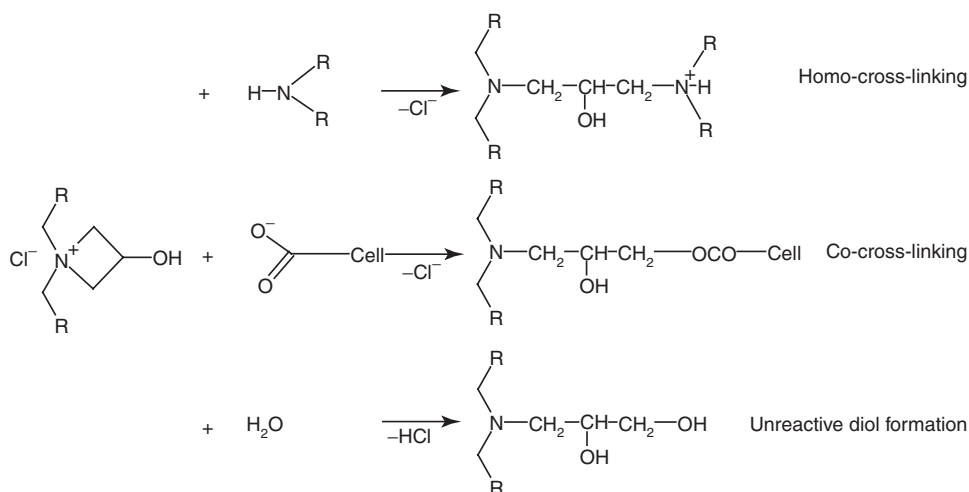


Figure 4.64 Reaction mechanism of hydroxy-azetidinium chloride with amine groups of other resin molecules, with carboxyl groups from cellulose and with water.

PAAE resins are effective in the pH range 5–8, although the best wet-strengthening effect is obtained in the neutral or slightly alkaline range; they are therefore often called *neutral wet-strength resins*. The amount of polyamidoamine epichlorohydrin resin required in hygienic paper production is between 0.1 and 3% dry substance, calculated on dry paper. As PAAE resins are cationically charged, they adsorb rapidly on the negatively charged fibers when added to a papermaking furnish. At low dosages there is a steady increase in wet strength,

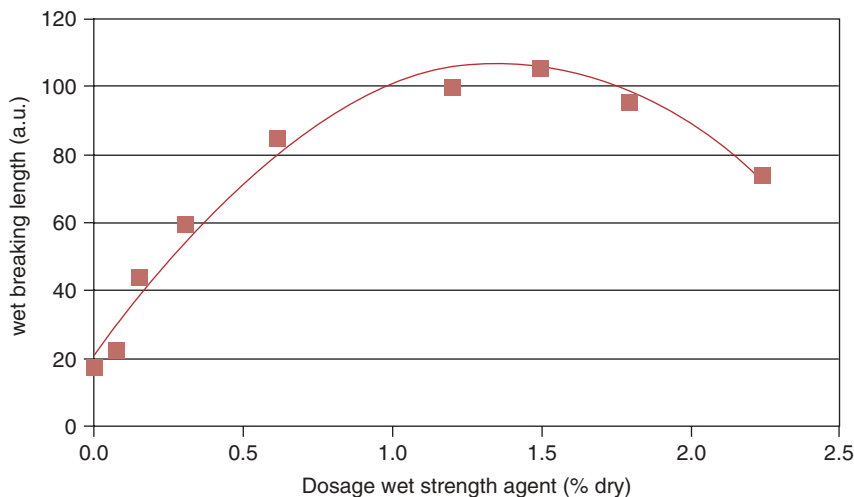


Figure 4.65 Development of wet breaking length versus dosage of wet-strength agent.

but at a certain point the resin retention starts to decrease as the adsorption sites on the fibers diminish and the furnish becomes less negatively charged or even cationic (Figure 4.65). The carboxyl content in the pulp as well as the increase in surface area owing to refining also affects the performance of the resin.

There is a synergistic effect between PAAE resin and water-soluble anionic CMC in many practical applications; however, higher wet and dry strengths can be developed when the resin is used alone. Up to 0.4%, CMC improves resin retention and allows more resin to be added before the wet-strength slope levels off.

The cationic PAAE resins are sensitive to anionic interfering substances, both naturally occurring or as anionic chemical additives. Recommended pre-dilution of the resin before addition should thus be done with high-quality fresh water. If pulp contains high amounts of anionic trash, a pre-treatment with cationic trash catchers might be advisable. High conductivity reduces electrostatic interaction, the driving force for resin adsorption. So, a lower salt content in the paper machine circuit improves the wet-strength retention.

In the majority of cases, PAAE resins are added to the stock, preferably just before the last stock pump in front of the headbox. This ensures that the fiber/resin bond is not impaired by high shear forces. However, depending on the paper machine system and the paper additives used, other dosing points and even splitting at high amounts are possible (Figure 4.66).

The wet strength of the thermosetting PAAE resins is not fully developed by the time the paper reaches the end of the paper machine. The strength increases during the storage period of three to four weeks, depending on the temperature and the length of the time at elevated temperature, as shown in Figure 4.67. Depending on the amount added, the relative wet strength can be increased to over 35% without significantly reducing the absorbency of the paper. WSRs, in general, also increase the dry strength of the paper (i.e., tear and burst). Moreover, they

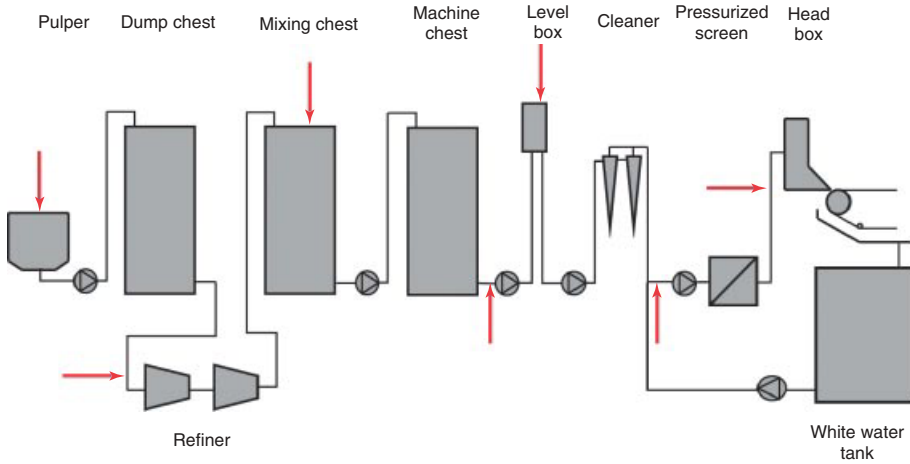


Figure 4.66 Potential dosing points of PAAE wet-strength agents.

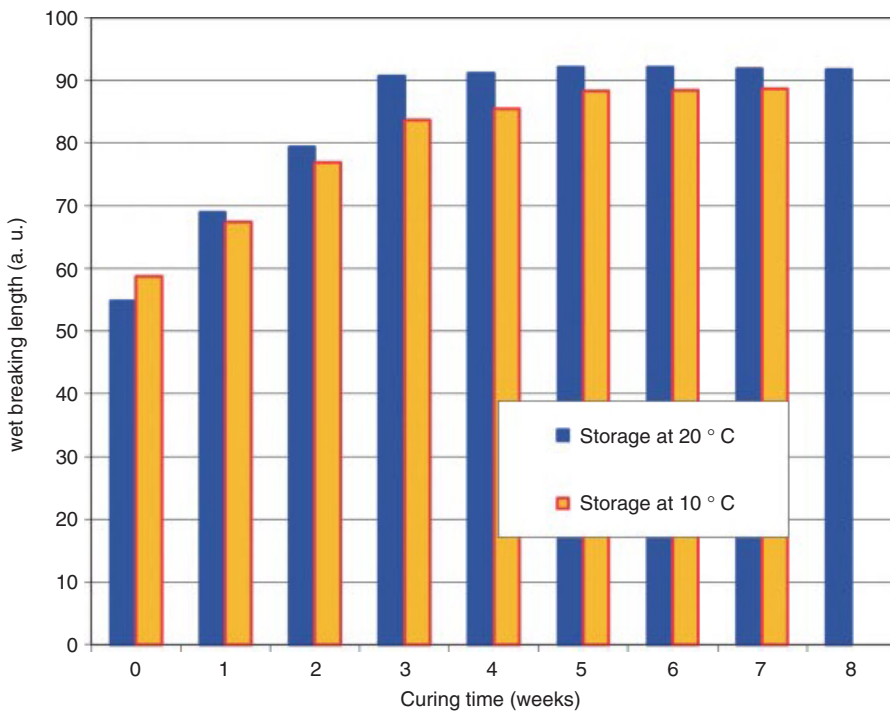


Figure 4.67 Development of wet breaking length versus curing time (a.u.: adjusted units, 100 = 10 min curing at 120 °C).

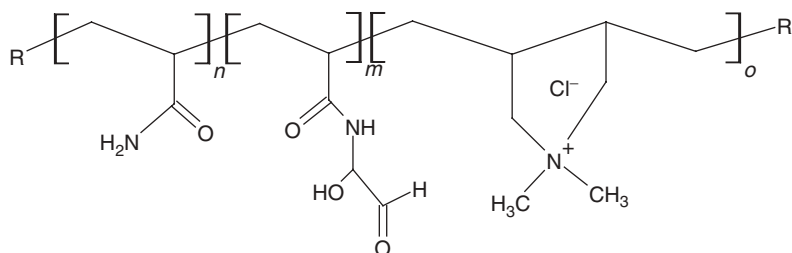


Figure 4.69 General structure of cationic modified glyoxalated PAM.

improve the dry and wet abrasion resistance of the paper. In addition, the retention of fillers and fines is clearly increased, for example, in laminate paper production. A special effect of PAAE resins, even with small quantities, is to form a coating on the Yankee cylinder of a tissue machine to control the adhesion of the paper web on the cylinder and allow proper creping of the tissue.

A disadvantage of PAAE resins is a slight yellowing tendency compared to MF-resins, and the AOX and by-product aspect. Much effort was put into developing “low-AOX” and recently also “AOX-free” polyamide-epichlorohydrine resins with no detectable amount of by-products. The two most important by-products regarding European food contact approval are the chloropropanols MCPD (3-monochloro-1,2-propanediol) and DCP (1,3-dichloro-2-propanol). Nowadays, the by-product-reduced PAAE resin types are able to fulfill all demands regarding paper used for food contact application, for example, kitchen rolls, tea bags, and baking paper. The history of this progress is shown in Figure 4.68.

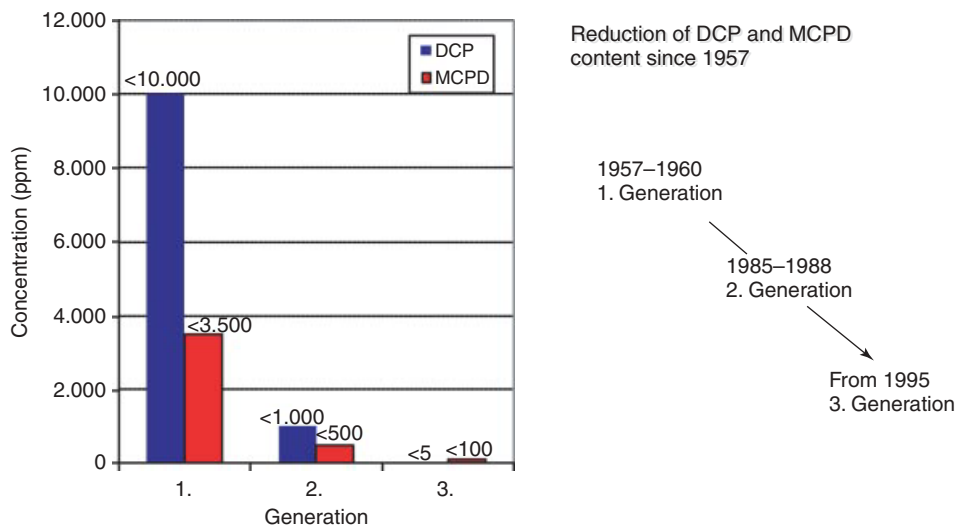


Figure 4.68 History of reduction of MCPD and DCP in PAE resins [19].

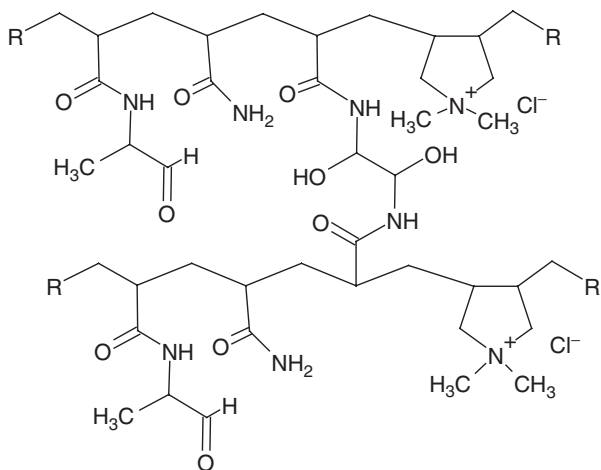


Figure 4.70 Homo-cross-linking of cationic modified glyoxalated PAM during production as well as adsorbed on the fiber surface.

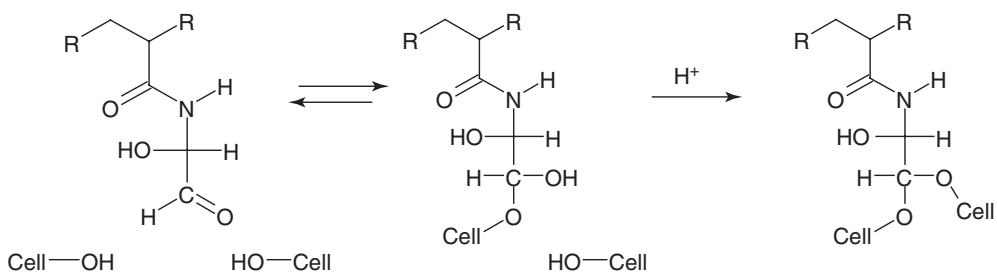


Figure 4.71 Co-cross-linking of glyoxalated PAM with cellulose forming hemiacetal and acetal bonds.

4.6.5.1 Glyoxalated Polyacrylamide Resins

These products are prepared by cross-linking a low-molecular weight PAM with glyoxal. The PAM is normally a copolymer of acrylamide and a quaternary ammonium cationic monomer which is prepared in aqueous solution (Figure 4.69). This results in a cationic polymer which is attached to pulp fibers. The cationic backbone is cross-linked with excessive glyoxal to react with most of the PAM backbone amide groups. The cross-linking proceeds until the desired level is obtained, indicated by a viscosity increase. The product is stabilized by acidification or dilution with water.

The PAM backbone may also be anionic, in which case a cationic retention agent is required to attach the finish resin to fiber.

During storage, the resin continues to cross-link and can ultimately gel (Figure 4.70). In order to achieve the desired stability, paper mills dilute the resin on receipt. At 25 °C, a 10% solution will gel in about 8 days, whereas a 6% solution will take about approximately 65 days to gel at room temperature. There

is strong evidence that glyoxalated PAM imparts wet strength primarily through covalent bond formation between the resin and the fibers. The co-cross-linking results in the formation of hemiacetal bonds between the free aldehyde groups on the resin and the cellulose hydroxyl (Figure 4.71). However, intermolecular cross-linking can be expected as well. The reaction of glyoxalated PAM with cellulose is rapid at neutral pH 6–8 and even more rapid at acidic pH 4–6, resulting in 80–100% of the potential wet strength. Aging or curing of the paper gives little or no additional wet strength. The reaction is reversible in the presence of water and a resin-treated paper gradually loses wet strength on soaking for some minutes. Different from the WSA described, glyoxylated PAM thus provides not a permanent but a temporary wet strength. This can be sufficient for some paper grades, for example, paper towels, and also during the paper manufacturing process when the sheet passes through a size press or coater. Contrary to gradual loss, glyoxalated PAM wet strength is immediately, completely and irreversibly destroyed by strong alkali, possibly due to the destruction of aldehyde functionality [20]. Glyoxalated PAM resins also contribute significantly to the dry strength of treated paper. The best point of addition is the thick stock to avoid adsorption on fines and loss of efficiency. A rapid mixing for uniform distribution of the resin on the fiber surface and pH conditions below 8 are beneficial. A dosage after refining enables adsorption on newly exposed fiber and fibril surfaces [21].

4.6.6

Other Wet-Strength Resins

- *Polyethylenimines* (PEIs; Figure 4.72) is the oldest group of substances in this category, but they are only of limited use nowadays.
- PEI are effective WSRs under neutral/alkaline pH conditions in papermaking without influencing the absorbency of the paper. PEI develops wet strength without curing time and the level of wet strength that can be attained is less than with the thermosetting resins. PEIs seem to create stronger interatomic interactions rather than homo- or co-cross-linked networks. The cationic amine groups responsible for wet strength have dissociation constants of around 12 and the retention and performance of PEI is best at pH 7–9. PEI has not been

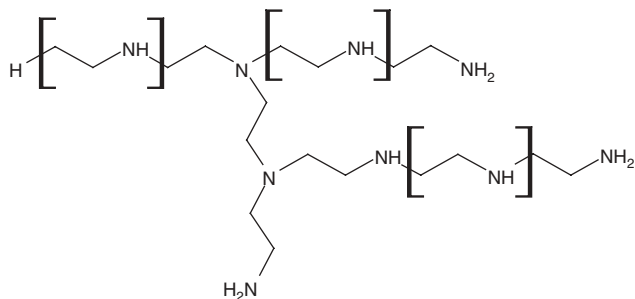


Figure 4.72 General chemical structure of polyethylenimines.

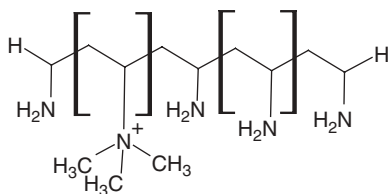


Figure 4.73 General chemical structure of polyvinylamines.

used more extensively as a WSR because of higher costs than with thermosetting resins and because of yellowing and loss of brightness in white printing and writing papers. Industrial filter papers and shoe board are two products made with PEI resins.

- *PVAm*s are a new group of WSRs (Figure 4.73). Similar to PEI, PVAm does not carry reactive groups for cross-linking but creates strong ionic interactions and is hence considered less harmful than the cross-linking resins. Their cost–performance ratio is less favorable than for the conventional WSR in most cases.
- *Polycyanate* is another type of WSR, up to now with very little practical use.
- *Dialdehyde starch (DAS)* also has the potential for cross-linking cellulosic hydroxy groups in paper to give temporary wet strength (Figure 4.74).

DAS is essentially a highly modified starch (80–90% conversion) in which the vicinal hydroxyl groups (at the C-2 and C-3 carbons) are selectively attacked by periodic acid, severing the C-2 to C-3 bond to form DAS. The aldehyde groups are not present to any extent as free aldehydes, but rather as hemiacetals or as hemialdals. As the linkages in these compounds are weak, DAS reacts as if the aldehydes were free, permitting its use as a reactive polyaldehyde capable of reaction through hydroxy amino or imino groups. DAS can further be modified to give a cationic or anionic product. Cationic DAS has been found particularly effective in this regard because of its affinity for cellulosic pulp. DAS is supplied in the form of fine powder, similar to the original starch.

Wet strength from DAS is due to co-cross-linking of DAS aldehyde groups and cellulose hydroxyls to form hemiacetals or acetal bonds (Figure 4.75). High pH favors the formation of hemiacetal bonds that are temporary and easily broken in water. Low pH encourages the formation of acetal bonds that are more permanent. In addition to the wet strength, DAS also gives high dry strength [22].

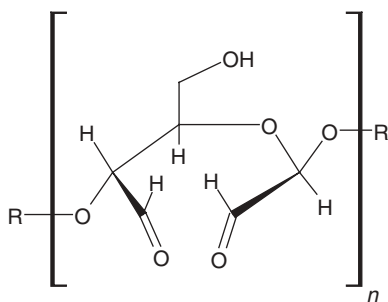


Figure 4.74 Dialdehyde starch molecule.

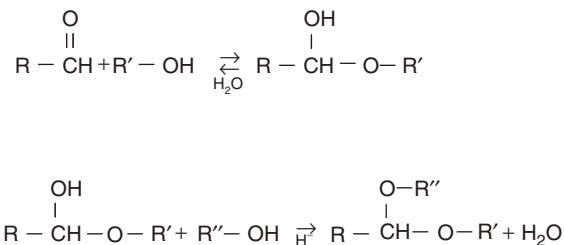


Figure 4.75 Cross-linking reaction of DAS.

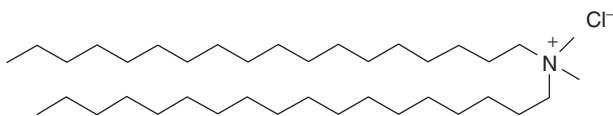


Figure 4.76 Distearyl-dimethyl-ammoniumchloride.

4.7

Properties of Specialty Papers and Related Chemical Additives

Roland Pelzer

Specialty papers is an umbrella term for paper grades with special properties, which, in general, cannot be achieved without the addition of functional chemicals. Some of these papers do also need specific process chemicals to enable the particular production process.

4.7.1

Tissue

Tissue, by global output the biggest share of specialty papers, is an excellent example for the use of both chemical additive groups. Beside dyes (in particular for the production of napkins) and wet-strength agents (for napkins, handkerchiefs, and kitchen towels; BfR and FDA approval, Nordic Swan, and other specific requirements) functional chemicals are used in order to increase softness by reducing the amount of hydrogen bridge bonds. There are two basic principles:

- 1) Increase in the equilibrium moisture content by humectants (sorbit, glycerol, polyethylenglycol are suitable, but need to be applied via the surface – no wet-end chemicals available).
- 2) Use of quaternary ammonium compounds, as shown in Figure 4.76.

The hydrophobic chains disturb the formation of hydrogen bridge bonds. High dosages have an impact on water absorptivity. Alternatively, air-through drying technology is used to reach the same goal. A general disadvantage of this chemical is the loss of dry strength.

If the desired strength properties cannot be reached, synthetic dry strength agents can be used (Section 4.6). Among the chemistries introduced there, CMC is the most common product used in tissue production.

Process chemicals also play a particular role in tissue production, where the paper web is creped off the drying cylinder (Yankee dryer). During creping, the sheet is compressed (creped) and gets its typical softness and stretch ability. To perform this process, the sheet needs to adhere to the Yankee surface.

In case of insufficient adhesion, sheet fluttering will appear and lead to weak creping. If not fixed at once, the sheet may release from the Yankee surface by centrifugal force and tear off. If the adhesion is too high, tear-off will appear at the creping blade. The strength of adhesion needed depends on machine speed, basis weight, and furnish.

Creping additives are usually sprayed on the Yankee, but can be added into the stock as well in some cases. The strength of the creped paper may be influenced by other chemical additives as well.

As WSAs provide a creping effect as well, a release agent needs to be sprayed on the Yankee in case of high WSA dosages. Creping and release agents are mixtures of chemicals. The ingredients and ratio are kept as a secret by the suppliers.

- Creping additives:
 - phosphates as a base coating of the Yankee cylinder
 - WSA or other cationic polyelectrolytes
 - PVOH (for spraying only)
- Release products:
 - mineral oils
 - tenside mixtures.

Other chemical additives that contain some of these components, for example, PAM-emulsions as retention aids (oil!), have an impact on the creping result as well.

4.7.2

Parchment and Barrier Papers

Real parchment is an information carrier derived by abrasion and limewashing of animal skin (calf, first of all).

Vegetable parchment is obtained when a paper sheet made from highly beaten pulp (80° SR) is driven through a bath of concentrated sulfuric acid and neutralized after a short impregnation time. Thanks to chemical changes (hydrolysis reactions), the surface is transformed to be very dense and closed. Vegetable parchment offers excellent grease-proof properties.

Another grade produced in a similar way is vulcanized fiber. Impregnation with a solution of zinc chloride causes a compression of the cellulosic fibers similar to the vulcanization of natural rubber. Vulcanized fibers are used as reinforcement pulp in technical specialty papers (engine head gasket board).

Artificial parchment is obtained from paper produced with highly beaten pulp and surface sizing with starch (and CMC or PVOH) as shown in Figure 4.77.

CMC and PVOH (high MW grades) offer superior film-forming properties compared to starch. A closed film on the surface is essential to reach maximum performance of additional chemical additives such as silicon oils for self-adhesive label release paper or fluorochemicals to gain grease-proof paper. The latter have the general chemical structure as shown in Figure 4.78.

Perfluoroalkylated amines and acrylics have been described with improved performance, and several approaches have been launched on the market to substitute fluorinated compounds in grease-proof papermaking, most of them based on acrylic emulsions, but up to now there is no breakthrough with an economic replacement.

Other barrier properties requested for packaging paper are

- vapor resistance
- oxygen resistance = aroma barrier

Again, the paper surface needs to be covered with a dense film to reach these barrier properties. This can easily be reached by laminating the paper with an appropriate plastic foil (polyethylene). On the other hand, this does not allow

- on-machine manufacturing in one line
- easy recyclability of the final product.

Suitable products to reach barrier properties close to laminates are

- polyvinylacetate/polyethylene copolymers
- polyvinylidene chloride
- modified styrene/butadiene (S/B) emulsions.

Recent developments of modified S/B latex allow reducing the migration of oily substances into the packed goods (foodstuffs) as claimed by the supplier. In all

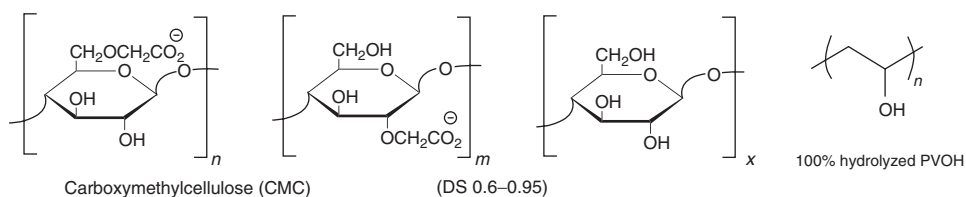


Figure 4.77 Suitable film-forming products for barrier coatings.

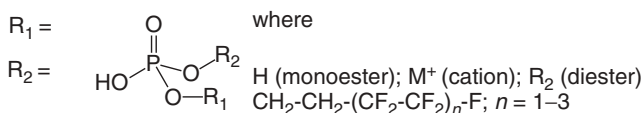


Figure 4.78 Perfluoroalkylated phosphoric acid esters.

these applications, two coatings of 5 g m^{-2} each perform better compared to one coating with 10 g m^{-2} .

4.7.3

NCR-Paper (Noncarbon Required)

NCR or self-copying paper is woodfree base paper coated with a donor (CB, coated back) layer or an acceptor layer (CF, coated front) or both coatings. The principle is shown in Figure 4.79. The reaction partners are a leuko dye and a developer, which create a visible dye when they come in contact. The leuko dye is separated from the dye developer by microencapsulation. The capsules are formed by dissolving the leuko dye in an oily phase (DIPN = diisopropyl-naphthalene). The oily phase is emulsified and duroplastic polymer (polyurethane or melamine resin) formed in the interface layer between the oily drops and the aqueous phase. The microcapsules are separated, formulated to a coating color (see Chapter 5) and applied on the paper back to form the CB layer. The CF layer contains developers such as activated bentonite, phenolic resins, or zinc salicylate in the coating formulation.

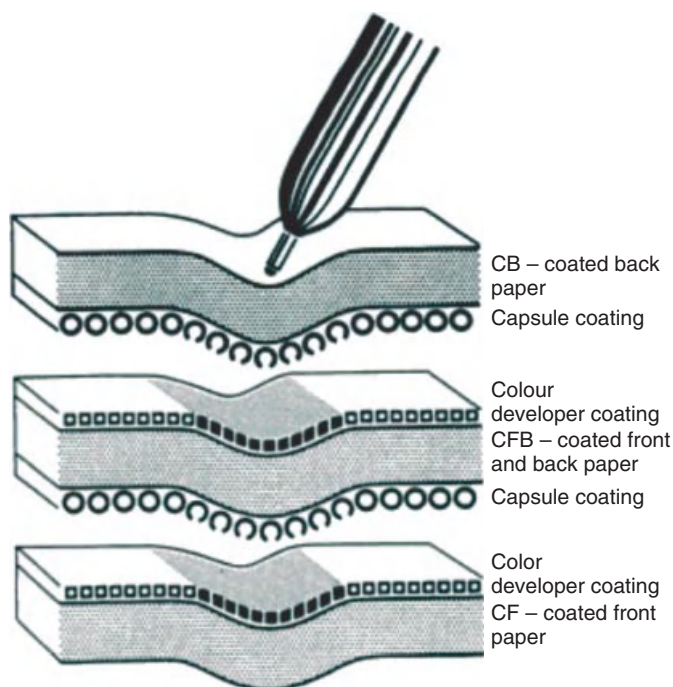


Figure 4.79 Principle of NCR paper.

4.7.4

Thermographic Paper

Leuko dye and developer are in one coating, separated by waxes, which melt during thermoprinting. Bisphenol A and Bisphenol S are used as dye developer, and they came into consideration recently due to their toxicological classification.

An example for a leuko dye is the well-known Indigo (Figure 4.80). Textile dyeing with Indigo is done in a vat dyeing process, where the dye is first transformed to its leuko form (which retains on the fibers) and then developed again (refer to sulfur dyes as well).

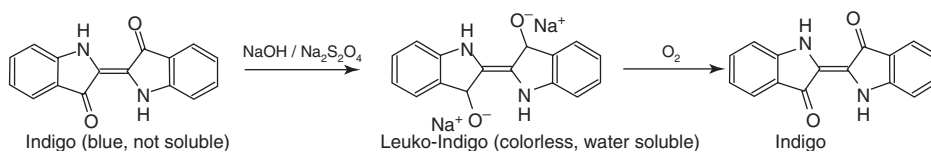


Figure 4.80 Principle of a vat dyeing process.

Table 4.11 Flame retardants suitable in paper manufacturing.

	Halides	Ammonium phosphates/ sulfates	Al(OH) ₃	Borax Na ₂ [B ₄ O ₅ (OH) ₄]·8H ₂ O
Mode of action	Chemically Halide radicals bind oxygen Hydrohalide (HBr-gas) replaces the air	Chemically/ physically NH ₃ burns to water and NO _x phosphoric acid settles on surfaces	Physically Releases water	Physically Releases water
Efficiency	++	++	0	+
Environment	-	0	+	0
Costs	0	0	+	0

4.7.5

Flame-Retardant Paper

Fire resistance is expected in some special paper grades, not only in paper lanterns, but in several paper grades intended in the building industry. Ammoniumpolyphosphates dominate this market. In paper production with this additive, the pH has to be kept strictly neutral or slightly acidic to prevent the liberation of ammonia gas. Table 4.11 shows the main chemical additives providing flame resistance and compares some pros and cons.

There is currently no flame-retardant additive on the market for internal application. In the size press, a high wet pick is necessary to reach high addition rates up to 50%. Hence, the base paper should not show any internal sizing. Figure 4.81 shows a flame retardant applied on the paper as a function of the size press concentration in a particular case. In this case the flame resistance that was expected could be reached at an application above 6 g m^{-2} (dry/dry).

4.7.6

More Specialty Papers at a Glance

Paper grades and related chemical additives are listed in Table 4.12.

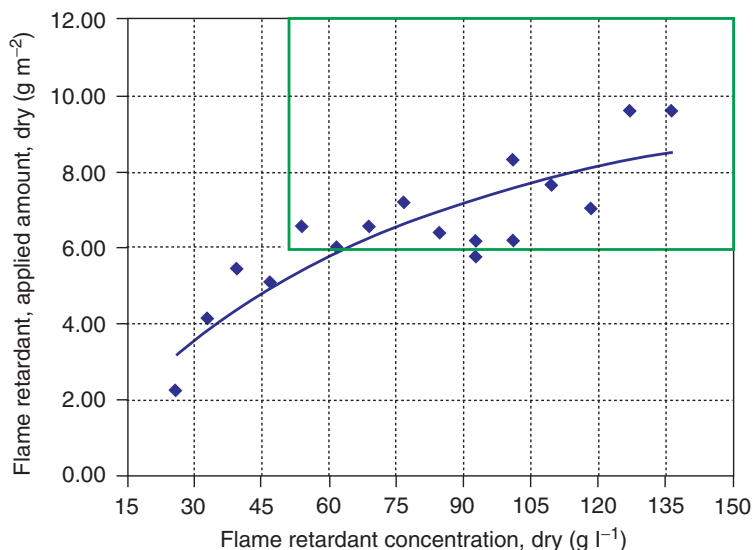


Figure 4.81 Typical flame-retardant dosages in size press applications (working box). (Source: BK Giulini.)

Table 4.12 Specialty papers and respective chemical additives.

Paper grade	Properties of the paper	Major chemical additives
Multi-purpose office – paper	Adjusted hydrophobicity and absorptivity for the demands of Writing (ink absorption)	AKD/ASA for internal sizing Starch, PVOH, and polymer sizing agents as surface application
	Laser printing (dusting) and InkJet-printing (wicking, bleeding)	OBA limits cationic additives AKD addition limited to ketone migration in the OCE process
Photographic paper	Wet strength	Wet-strength agents and adjusted internal (rosin) sizing for conventional baryte paper. PE-Papiers have a polyethylene-film on top of the photo-sensitive layer. The base paper needs ultra-hard internal sizing (with AKD) to avoid swelling of the paper from the cutting edge
Photographic ink jet paper	Coated paper aiming for a high-resolution wiping-proof image with water-soluble inks	Precipitated or fumed silica with polyvinylalcohol and polyvinylpyrrolidone as binder. Cationic additives improve wiping fastness
Tea bags, coffee filter	Wet strength (BfR and FDA approval)	Wet-strength agents
Technical filter papers (air/oil filter, vacuum cleaner bags)	Porosity, strength properties	Wet and dry strength agents Polymer dispersions
Beverage filtration beds	Wet strength, filtration properties (BfR and FDA approval)	Wet-strength agents Cationizing agents Specialty fillers (silicas, bentonites)
Condenser papers	Zero conductivity	Wet-strength agents, deionized process water
Laminate papers (and finish foils)	Highest absorptivity and light fastness Wet strength for post-impregnation	Wet-strength agents (colored) pigments with high light fastness

Table 4.12 (Continued)

Wall paper, wall poster paper, label paper	Wet strength	Wet-strength agents (coating additives see Chapter 5)
Security paper (bank notes, ID-cards, check, and document paper)	Wet strength, safety features, folding number	Wet-strength agents Polyvinylalcohol
(Wet-) abrasive paper	Very high wet and dry strength	Wet and dry strength agents Polymer dispersions

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5

Coating Colors – Components, Make Down, and Properties

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5.1

Overview

5.1.1

General Aspects

The paper-coating process was first developed in the United States late in the nineteenth century, but did not find broader application until the middle of the twentieth century. Since that time, the European paper industry has become a leader in coating technology. Today, the most modern coaters are invested in Asia.

Coated papers suit the highest requirements with regard to printability. In paper and board coating, an aqueous suspension, called *coating color*, is applied to one side of the sheet (mainly in the case of board) or to both sides (mainly for printing papers). After application of the required amount, the coating is dried and finished. In finishing, the coated paper and board achieve their smoothness and gloss potential. Coating is done either in the paper machine (on-machine coating) or in a separate step after the base paper production (off-machine coating).

It is desirable that, besides filling the cavities, the coating also covers the highest lying fibers on the base paper surface (Figure 5.1). There are methods that tend to favor filling of the cavities, while higher spots remain covered by only thin or practically no coating (equalizing or leveling coat, e.g., with blade equipment). Some other methods give a coating of more or less uniform thickness, thus also covering the highest spots on the base paper surface, yet the cavities remain only partially filled (contour coat, e.g., roll applicators).

Coating colors consist of several components, white pigments (e.g., clay, calcium carbonate, talc, and titanium dioxide) and binders (e.g., starch and latexes) being the most important with regard to volume and cost. Further specific additives influence and control the applicable solids content, rheology, water retention, and immobilization of the coating color during the coating process (e.g., dispersant, co binders,

[†] Deceased.

* Contributed to the First Edition.

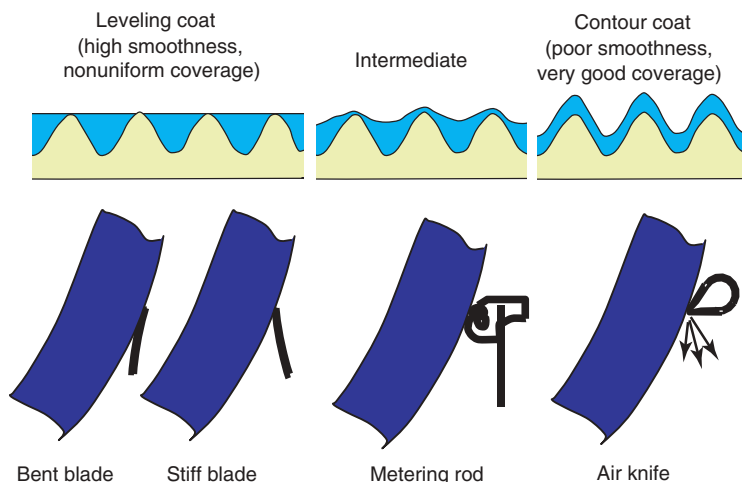


Figure 5.1 Coat structures of different coating systems.

and thickeners), and others influence the physical and optical surface structure and properties of the coating layer (e.g., associative thickeners, lubricants, hardening agents, fluorescent whitening agents (FWAs), defoamers, and degassing agents).

Water is an essential component of a coating color, making it possible to mix the components of a coating color, for example, so that all the pigment particles are separated from each other, which is impossible in the dry state. Water also makes it possible to transport the color elsewhere and apply it onto the base paper so that the coating color remains uniformly dispersed. As water evaporates from the coating layer, the coating layer consolidates when the binder forms bridges between pigment particles and base paper. Coating colors should contain only as much water as the flow properties need to save energy and costs for drying. The solid contents of the coating colors can be as high as about 70 wt%.

The composition of coating colors resembles that of paints, containing similar components. Of course, there are differences in detail: the additives may be totally different, there are different kinds of binders, and paper coatings are white, while most paints are colored; hence, the pigments are different, and so on. One major difference between paints and coating colors is the amount of binder: paints contain much more binder than do coating colors. This is partly due to their different objectives: the purpose of painting is to improve the looks of the surface to be painted and also to create a protective layer. This latter function mostly requires a pore-free paint layer that can be achieved by using sufficient binder to completely fill the spaces between the pigment particles.

As for the coating colors, other than to improve the looks of the paper, the purpose of their application is to achieve the desired properties on the paper surface, the most important being the printing properties. The coating layer should be strong enough to resist the stresses of the printing process; the surface strength of the coating dictates the allowable minimum amount of binder. For example,

offset printing inks are tacky, which requires a comparatively high z-strength, or pick-strength of the coating. On the other hand, increasing the amount of binder has a negative effect on several coating properties, and excess binder may cause quality concerns, for example, low opacity and gloss, or glueability problems. Therefore, adding more binder to the coating than the surface strength requires should be avoided; there is also a cost consideration. However, the coating process and base paper absorbency can make high binder levels necessary.

5.1.2

Market Situation and Future Trends

Coated papers show an excellent printability, high esthetic attractiveness, and a valuable feel. Printed paper is a cost-efficient medium with a high capacity for information, universally easily available, and fully recyclable. Paper- and board-based packaging material is also cost efficient, esthetically attractive, and environmentally friendly.

Most pigments are significantly cheaper than chemical pulps, and so increasing both the proportion of coated paper in general and the coating layer(s) compared to fibers (Figure 5.2) is an important economic factor.

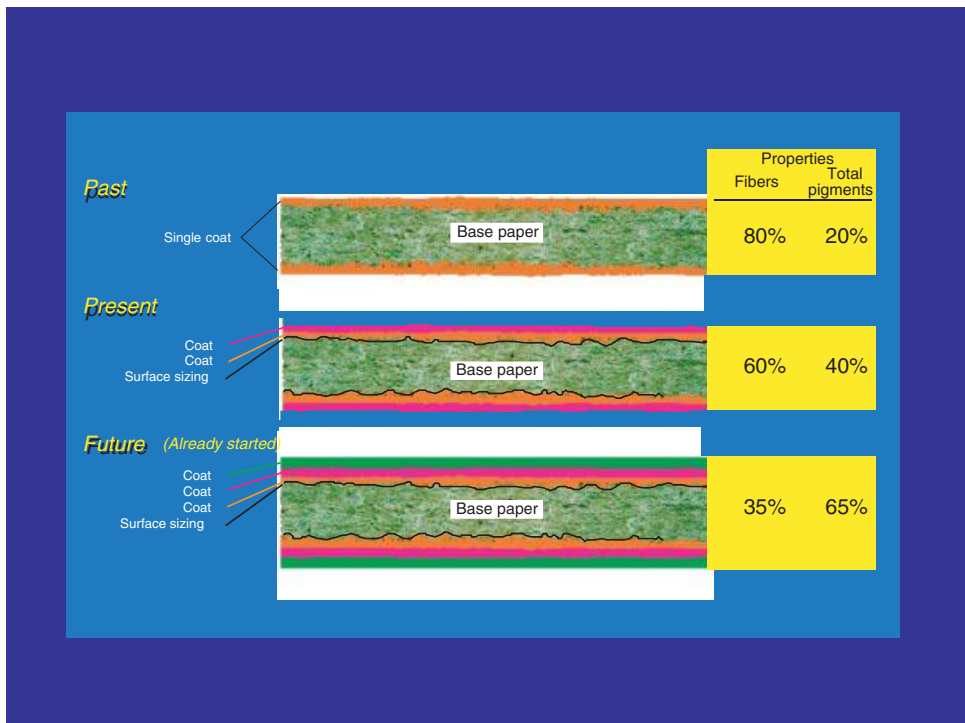


Figure 5.2 Predicted increasing of fillers and coatings versus fibers/base paper.

The proportion of coating layer compared to the total weight for paper is significantly higher (30–65%) than for board (5–20%). The future trends for coated papers will involve more specific paper products, further development of coating technology, ongoing progress in printing technology, environmental issues, development of coating color raw materials, and globalization of paper companies.

The development and fast worldwide expansion of electronic media has led to a certain shift in paper qualities and challenged the development of new paper and board qualities. Growth rates in paper consumption have changed significantly after the financial crisis in 2008/2009.

Packaging grades have recovered from the general decline in demand, while printing papers still suffer from a continuing reduced demand in important regions. Negative growth rates are expected for printing and writing papers in mature markets such as North America, Japan, and Western Europe, while other regions, especially China, are expected to continue to show significantly growing demand.

5.2

Coating Color Components

5.2.1

Coating Pigments

Coating improves the surface quality of paper and board, resulting in higher brightness, smoothness, and gloss as well as better opacity and generally significantly improved printability. Pigments are the main coating components for improving the surface properties of coated paper and board grades. Usually they account for 80–95% of the total dry coating weight or, as a volume fraction, 70–80% of the solid material of the coating. This is based on a pigment density of about 2.5 g cm^{-3} and a density of the rest of the solid material in the coating of about 1.0 g cm^{-3} . In 2010, a total of approximately 32 million tons of minerals was used worldwide in the paper and board industry. Natural ground calcium carbonate (GCC) holds a 52% share of the total demand. Kaolin (clay) and precipitated calcium carbonate, PCC, account for about 21% each, and talc minerals make about 5% of the total worldwide paper minerals. About 18 million tons of minerals have been used for paper coating, where GCC and clay have a much stronger and PCC a much weaker position than for the whole papermaking process, as shown in Figure 5.3.

Pigments largely determine the cost of coating. A number of white pigments is available for surface finishing in the paper and board industry. A large majority of these is of natural origin, being physically and chemically homogenous minerals formed by inorganic processes. Organic products such as plastic pigments may also be used in coating colors in special cases. A more detailed description of minerals used for papermaking, their origin, preparation, and properties is given in Chapter 3. Coating pigments can be classified according to Table 5.1.

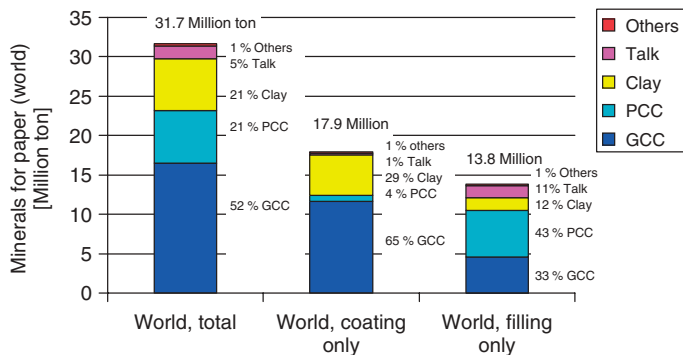


Figure 5.3 Consumption of minerals in 2010 in the paper industry worldwide, and separated into coating and filling minerals. (Data: Omya).

Table 5.1 Pigment classification.

Main pigments	Ground calcium carbonates (GCC) Kaolin clays Precipitated calcium carbonates (PCC) (recently switching from a special pigment to a main pigment)
Special pigments	Talc Gypsum (calcium sulfate) Plastic pigments (e.g., polystyrene) Satin white (calcium sulfoaluminate) Barium sulfate
Additional pigments	Calcined clays (kaolins) Titanium dioxides Alumina trihydrates Others

Central properties of pigments are particle size and size distribution, particle shape and shape distribution, refractive index, light scattering and light absorption, and density. The properties of coating color and the final coating can be influenced and explained to a great degree by these factors. Table 5.2 simplifies how different quality parameters of coated paper can be improved by changing specific pigment properties.

5.2.1.1 Pigment Characteristics: Aspect Ratio, Particle Size, and Particle Size Distribution

There may be only one single pigment type in a coating color, or, more commonly, a combination of several types, for example, clay, calcium carbonate, talc, and titanium dioxide. The share of pigment in the dry coating is about 85–95 wt%.

An overview and comparison between the most important physical and optical properties of minerals for papermaking is given in Chapter 4. Particle shape, particle size, and particle size distribution (PSD) are most important for the coating

Table 5.2 Effects of changes in pigment properties.

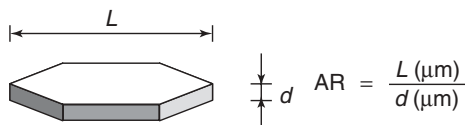
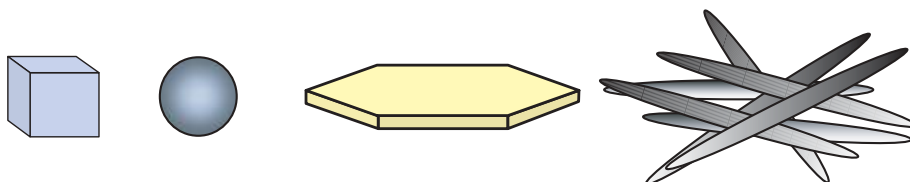
Increased platiness and/or decreased particle size	Better gloss development
Increased refractive index and/or decreased particle size	Higher opacity
Decrease in light absorption	Higher brightness
Decrease in packing (less compact pigment layer), for example, by mixing different particle shapes	Higher porosity and better ink absorption
	Higher bulk and better coverage

process, because the highly concentrated dispersions (solids content up to 70% and even higher) still need to be processed at high speed at a convenient viscosity.

5.2.1.1.1 Aspect Ratio The “platiness” of pigments has a considerable influence on the maximum solids content of the coating color and is responsible for many coated paper properties such as gloss, openness of the surface, and so on. In general, this property is described using the aspect ratio (Figure 5.4). This value is defined by the largest dimension of a pigment, for example, the radius of a surrounding circle, and the thickness of the platelet.

5.2.1.1.2 Particle Size Pigments often are agglomerates (can be separated in dispersing processes) or aggregates of many particles. It is not trivial to describe the size of a particle, especially if it is not shaped regularly like a ball or a cube. Therefore, there is no general answer to the question, which of the particles in Figure 5.5 is smaller or larger than the others.

Historically, particle size is determined using sedimentation analysis resulting in a PSD of spherical particles of the same density and sedimentation speed.

**Figure 5.4** Aspect ratio of platy particles.**Figure 5.5** Particle shape – particle size.

Other measurement devices such as laser light diffraction may provide the PSD of spherical particles with the same diffraction pattern. This usually does not correlate with sedimentation analysis. Pigment habitus, which influences, for example, liquid uptake and penetration, cannot be described using PSD. Sometimes, the specific surface is provided as additional information to complement pigment description. It is essential to mention the measuring method, when particle size or PSD of a pigment is given.

5.2.1.1.3 Particle Size Distribution PSD In many cases, pigment size distribution is plotted as a cumulative mass distribution according to the common measuring method of PSDs of pigments, that is, sedimentation analysis. Figure 5.6 indicates the portion of the total mass of pigments that is provided by particles larger or smaller than a specific particle size. Note that the graph does not reveal the number of particles that are smaller or larger than a certain particle size.

A change in particle size has consequences both on the properties of the coating color and on the coated paper properties. An increase in particle size results in a shift of the curve to the right as illustrated in Figure 5.7. This shift is not necessarily a parallel shift as shown; the steepness of the curve may also be changed.

Controlling the width of the PSD, for example, during the grinding process is an additional method to influence various properties. Removing small and large particles is one way to provide a “steeper” curvature, a PSD that is “narrower,” as shown in Figure 5.8.

The narrower PSD provides a lack of very small and very large pigments. There are no or only few small particles that could increase the solids content because they do not need extra volume but fill the spaces between the larger pigments. For a steep or narrow PSD, particles will jam (\Rightarrow dilatancy) at a lower solids content than for particles with a broader PSD (Figure 5.9).

The consequences of a changed PSD in terms of increasing or broadening the PSD of particles as indicated before are listed in Table 5.3.

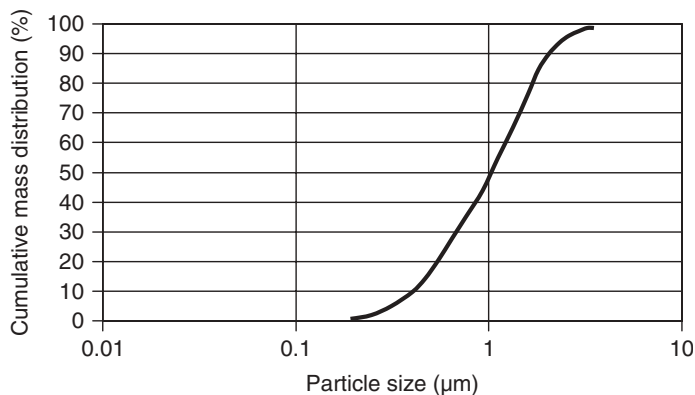


Figure 5.6 Particle size distribution: cumulative mass distribution.

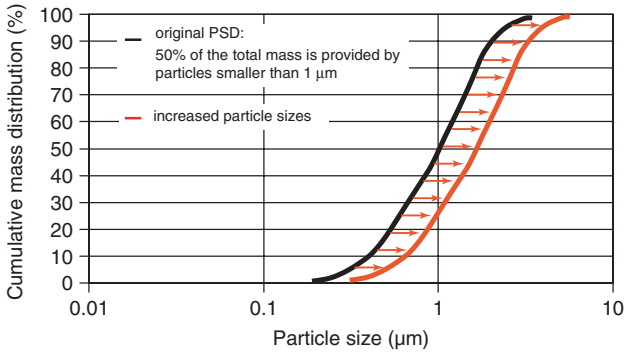


Figure 5.7 Particle size distribution: increasing particle size (here: parallel shift of PSD).

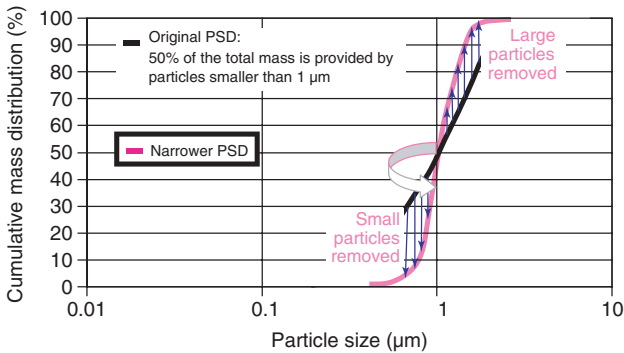
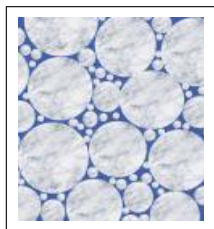


Figure 5.8 Particle size distribution: narrower particle size distribution by removing of fine and large particles (here: median particle size remains constant).

5.2.1.2 Main Coating Pigments

5.2.1.2.1 Kaolin Clays Kaolin clays in paper coating have probably been used since the second half of the nineteenth century when paper coating was developed. Since that time, they played a dominant worldwide role as a coating pigment almost until today. Kaolin is one of the most widely occurring minerals. Kaolinite, the principal constituent of kaolin, is a layered aluminosilicate having the chemical formula $\text{Al}_4\text{Si}_4\text{O}_{10}(\text{OH})_8$. Kaolin is an intrinsically valuable coating pigment because of its platy particle shape, good color (high brightness), and the relative ease with which it can be processed to a fine particle size. In general, primary clay has a higher aspect ratio, that is, it is more platy and naturally appears together with higher amounts of quartz and feldspar than secondary kaolin, which is purified and cleaned by the erosion process. Some data to kaolin as a coating pigment are shown in Figure 5.10.

5.2.1.2.2 Ground Calcium Carbonate (GCC) GCC as a coating pigment was successfully introduced in 1973. It marked an epochal step toward lower production costs and improved paper and print quality by the successful development of “high



Broad particle size distribution:
Volume between large particles is
filled with fines
⇒ high solids possible



Narrow particle size distribution:
Volume between large particles is
filled with fluid
⇒ low solids possible

Figure 5.9 Schematic illustration how a broader PSD can fill the available volume and thus allow for a higher solids content at similar viscosity.


	Kaolin (Clay)
Shape	 platelet
Chem. composition	$\text{Al}_4(\text{OH})_8(\text{Si}_4\text{O}_{10})$
Refractive index	1,56
Brightness (R_{457}) (%)	80 – 92
Surface energy (J/cm^2)	500 – 600
Mass density (g/cm^3)	2,6
Particle size (μm)	0,3 – 5
Abrasion (AT 1000) (mg)	2,0 – 10

Figure 5.10 Typical properties of coating kaolin.

solid” coating in the 1980s. Herewith, GCC allows reduced binder requirements and drying energy savings. The development of finer-grade carbonates with particle sizes down to 99% $<2\mu\text{m}$ and special PSD curves covers a broad spectrum of whiteness, paper and print gloss, as well as opacity. The rhombohedral structure allows for high solid contents of pigment slurries (up to 76%) and coating colors with excellent runnability even at the highest coating speeds of $>1800\text{ m min}^{-1}$. This also explains the overproportional growth of GCC as a coating pigment during the last decades, whereas kaolin stagnates and talc shows constant growth, especially for gravure coating colors. Some properties of coating GCC are shown in Figure 5.11.

Table 5.3 Consequences of a changed particle size distribution.

Consequences for the coating color	Increasing particle size	Reason	Broader particle size distribution	Reason
Flow behavior	More demanding(depends on PS, PSD)	Less small particles in the crotches	Less demanding	Space in crotches can be used
Solids content	Lower (depends on PS and PSD)	Less small particles in the crotches	Higher	Space in crotches can be used
Specific surface area	Lower	From geometry	Higher (depends on PSD, solids)	More small particles
Binder demand	Lower	Less contact areas	Higher (depends on PSD, solids)	More small particles
Consequences for the coated surface	Increasing particle size	Reason	Broader particle size distribution	Reason
Gloss	Lower	Big particles at the surface	Lower (depends on PSD)	Big particles at the surface
Smoothness	Lower	Big particles on the surface	Lower (depends on PSD)	Big particles on the surface
Total pore volume	Higher(depends on PSD)	Less small particles in the crotches	Lower (depends on PSD)	Space in crotches can be used
Pore size distribution	More larger pores (depends on PSD)	Less small particles in crotches	Less larger pores (depends on PSD)	Space in crotches can be used

Source: PTS.

5.2.1.2.3 Precipitated Calcium Carbonate (PCC) PCC allows for the production of coating pigments with specific morphologies by controlled synthesis. Particle size, PSD, and particle shape can be controlled. The surface properties of the calcium carbonate particles can also be changed if needed. Commercial PCC pigments typically have CaCO_3 contents higher than 97%. The remainder is MgCO_3 (magnesium carbonate) and other residues. Industrially, it has been found practical to produce PCC near the paper mill by using satellite plants. This saves inbound transportation costs because the necessary CO_2 gas (40% of the final product weight) can be taken from a local source and also because calcium oxide can be delivered to the PCC satellite plant in a dry form. Outbound savings are possible as well because the produced coating or filler pigments can be delivered in a slurry form to a paper mill, possibly through a pipe. Figure 5.12 shows some typical properties of coating PCC.


	Ground Calcium carbonate (GCC)
Shape	 Rhomboider
Chem. Composition	CaCO ₃
Refractive index	1,56
Brightness (R_{457}) (%)	87 – 95
Surface energy (J/cm ²)	75 – 80
Mass density (g/cm ³)	2,7
Particle size (μm)	0,3 – 5
Abrasion (AT 1000) (mg)	5,0 – 10

Figure 5.11 Typical properties of coating GCC.

5.2.1.3 Special Pigments

5.2.1.3.1 Talc *Talc* as a coating pigment was introduced industrially in Finland and France in 1982. Since then, talcs are used in light-weight-coated (LWC) gravure and coated fine papers in offset formulations.

The characteristics generally differentiating talcs from delaminated Georgia kaolin clays (the United States) or Cornish kaolin clays (the United Kingdom) are hydrophobicity, low cohesion between the crystal layers inside the talc particles, resulting in extremely low friction coefficient, softness, and low abrasivity in spite of a large particle diameter. The brightness of European coating talcs varies from ISO brightness 82 to 88, depending on the origin.

Especially the developments of Jumbo rolls in rotogravure printing (wider than 4 m in the printing press) have pushed the importance of talc as a gravure coating pigment. The friction between the plies on the roll is reduced if a considerable amount of talc is part of the coating formulation. This successfully prevents core bursts and creeping when these Jumbo rolls are handled in the printing machine.

5.2.1.3.2 Gypsum Gypsum consists of calcium sulfate crystallized with different degrees of hydration, all of which can be referred to as *gypsum*. However, in most cases, gypsum refers to *calcium sulfate* in the dihydrate form and the other forms are distinguished from each other by additional names (e.g., hemihydrate, calcined gypsum, and stucco gypsum). The solubility of gypsum pigment is high, so that the water circulation of a paper machine are enriched not only with Ca ions from internal broke but also when gypsum-containing paper is recycled. A saturated

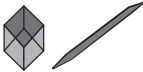
	Precipitated calcium carbonate (PCC)
Shape	 Rhomboeder / needle
Chem. composition	CaCO ₃
Refractive index	1,59
Brightness (R_{457}) (%)	92 – 97
Surface energy (J/cm ²)	75 – 80
Mass density (g/cm ³)	2,7
Particle size (μm)	0,1 – 1
Abrasion (AT 1000) (mg)	3,0 – 7

Figure 5.12 Typical properties of coating PCC.

gypsum solution contains approximately 2.1 g l^{-1} of CaSO₄, which equals 2.5 g l^{-1} as dihydrate and 580 mg l^{-1} as a calcium concentration.

Gypsum is a neutral salt that, unlike carbonate, does not buffer the pH of circulation water. When it comes to solubility, it makes no difference whether gypsum pigment is used in an acidic or a neutral papermaking process. The major advantages of gypsum pigment include brightness, bulk, and offset printability. Additional optical brighteners used with gypsum are very effective.

5.2.1.3.3 Plastic Pigments Plastic pigments are used in paper coatings to provide a surface with the desired appearance and printability. If properly chosen and formulated, these pigments provide a coating with surface smoothness, brightness, and opacity, as well as a balance of ink holdout and ink receptivity upon which to print. Organic pigments, commonly referred to as *plastic pigments*, are used as partial replacements for inorganic pigments to improve the optical and print properties of coated paper and paperboard. There are two general classes of plastic pigments used in the preparation of coatings for paper and paperboard: solid beads and hollow spheres. Both are available in a variety of particle sizes and compositions and, in the case of hollow spheres, in a range of void volumes. All plastic pigments are supplied as polymeric particles dispersed in water. In the case of hollow sphere pigments, those particles are water-filled spheres. During drying, the water diffuses through the shell, leaving an air-filled core – hence the term *hollow sphere*. The thermoplastic spheres are flattened when they contact the calendar roll and thus improve smoothness and gloss.

Plastic pigments are used in paper coatings wherever improvements in finishing efficiency, sheet gloss, or print gloss are important. They are used especially in the United States in coated folding boxboard, wood-free coated printing papers, and also in LWC and ultralight-weight-coated (ULWC) papers.

5.2.1.3.4 Satin White Satin white (calcium sulfoaluminate) is still of some importance in paper coating, especially if it comes to cast coating. This pigment has very fine needlelike particles, is extra white, and has a low density. It increases ink absorption and gloss. The disadvantages of satin white are its sensitivity to increase in temperature and decrease in pH, and its high adhesive demand.

5.2.1.3.5 Titanium Dioxide Titanium dioxide pigments show extremely high refractive indices. This and their whiteness, that is, their high reflectance in the visible region of light, as well as their optimal particle size, make them the most effective white pigments. Titanium dioxide exists in three crystal forms: anatase, rutile, and brookite. The first two are stable and therefore of commercial importance. Titanium dioxide pigments are used in paper coatings to increase the opacity of coated paper. To ensure good optical efficiency of titanium dioxide in coatings, TiO_2 pigments must be properly dispersed in the coating color. Undispersed aggregates or agglomerates diminish the optical efficiency of TiO_2 pigments. Rutile slurry pigments are usually the most effective titanium dioxide grades in paper coatings because they have the highest TiO_2 content and refractive index, as well as optimal particle size and PSD. TiO_2 pigments are often used together with extenders to ensure an optimal spacing between single particles and thus provide the highest efficiency. The effect of optical brightening agents (OBAs) is limited or negligible if TiO_2 is used as white pigment.

5.2.1.3.6 Other Pigments Of course, there are many other pigment types that can be used for paper coatings. Aluminum trihydroxide is an example for an extender of TiO_2 ; calcination of clays improves the opacity of these kaolins, but reduces the maximum solids content. Many research projects covered different modifications of commonly used pigments in lacquering, such as ZnO. Imposing a structure on the pigment to control sorptivity and penetration of the coating layer is also an example for other pigments in the paper industry. Higher costs of raw materials, however, have to be compensated by higher paper prizes, which is the most important reason why tailor-made products sometimes cannot conquer the markets.

5.2.2

Dispersants

In the dry form, pigment particles form clusters, in which individual particles are more or less tightly attached to each other. More tightly attached ones are called *aggregates*. Aggregates and primary particles together can also form clusters that are less tightly bound – then called *agglomerates* or *flocks*. The purpose of dispersing

is to make a dispersion where neither agglomerates nor aggregates exist and only primary particles are present. Primary particles are evenly distributed in water, and the system stays stable for a certain time.

Disruption of aggregates, disaggregation, is typically an irreversible process, after which particles cannot be bound as tightly as they used to be. Instead of forming aggregates, disaggregated particles tend to form agglomerates. Disruption of agglomerates is called *deflocculation*. Deflocculation is a reversible process. Agglomerates reform when the force for deflocculation is removed.

The process of dispersion can be divided into three stages: wetting, disruption of particle clusters, and stabilization.

Wetting means that all the external surfaces of pigment particles must come into contact with water. Air must also be displaced from the internal surfaces between pigment particles in agglomerates and aggregates. Wetting is usually not a problem with paper pigments except for talc that is not spontaneously wet by water. When talc is dispersed, a separate surfactant is required to provide proper wetting.

Disruption of particle clusters, disaggregation, is accomplished by mechanical energy. Disruption can be performed using crushing mills, kneading mixers, or mixers with a high local specific power input. Crushing mills are needed when the shear forces induced by mixers are not sufficient for disaggregation. Although dispersing can be performed in mixers, there is a certain difference between mixing and dispersing. Mixing does not change the size and surface area of particles, while dispersing changes both.

Stable pigment dispersions with the highest solid content can be achieved only by using chemical dispersants. When pigment clusters are broken down by mechanical forces, the surface area of pigment in the dispersion increases; there is more surface for particles to interact with each other, and the viscosity in the dispersion increases rapidly. The use of dispersants stabilizes deflocculated particles in the dispersion and hinders their interaction. The dispersant must be in the water before deflocculation starts to occupy the newly formed surfaces to avoid interaction and reagglomeration of particles. For this reason, dispersant is added to water at the beginning of dispersing, even before the pigment is added.

A sufficient distance between particles is necessary to avoid reagglomeration. Electrostatic and steric mechanisms, or a combination of them, “electrosteric” mechanisms are responsible for particle stabilization in a dispersion (Figure 5.13). In electrostatic stabilization, all particle surfaces are loaded with the same charge, positive or negative. Dispersant is adsorbed onto the particle surface, and thus the surface gets a highly localized charge with the sign of the dispersant. A negative charge on the surface, when anionic dispersant is used, creates a cloud of positive counterions around the particle (the so-called electric or ionic double layer). The closer to the surface, the more localized are the counterions. At a greater distance from the particle, in a continuous water phase, negative and positive ions are in balance. The counterion cloud acts as a stabilizer, creating repulsive forces between particles.

Electrostatic stabilization is the most commonly used stabilization method in paper pigment dispersions. To act as a good stabilizer, the dispersant must be

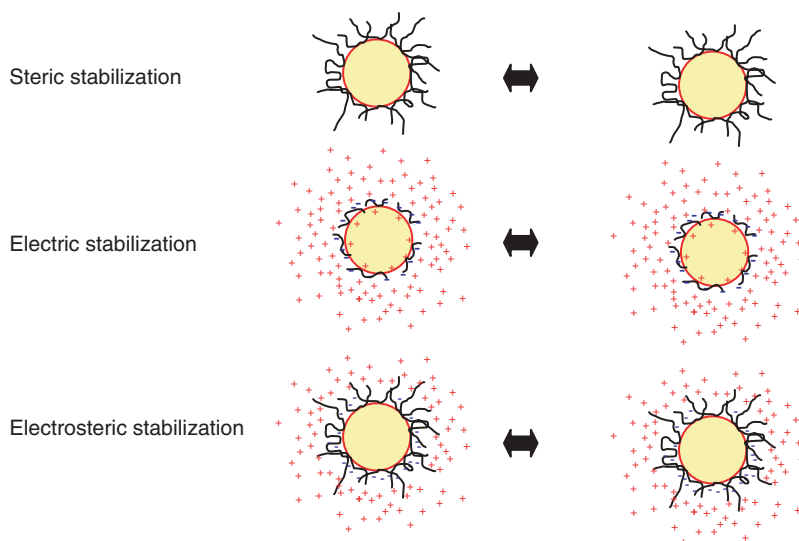


Figure 5.13 Stabilization of dispersions.

highly charged. Examples of these kinds of dispersants are salts of poly(acrylic acid) and polyphosphates. In steric stabilization, particle surfaces are covered with uncharged polymer, the chain of which extends into the water. When two particles with polymers on them approach each other, they cannot approach too closely because the polymer chains would overlap, and this is not entropically favored. Thus, polymers create a steric hindrance against particle interaction. Dispersants, which work as steric stabilizers, are also called *protective colloids*. Examples of these are starches and poly(vinyl alcohols). A good example of a dispersant, which works as an electrosteric stabilizer, is carboxy methyl cellulose (CMC).

The viscosity minimum is the optimum dosage of dispersant. After the optimum, the viscosity is slowly increased. Viscosity decreases when dispersant is added, due to the increased stability of the dispersion. The stability is a maximum at the viscosity minimum. The viscosity starts to increase after the optimum because additional dispersant can no longer be adsorbed onto the pigment surface and thus stays in the water increasing its electrolyte concentration and decreasing the stability. Overdosing of dispersant, therefore, must be avoided. Pigment type, dispersant type, pH, and additional components all affect the dispersant dosage required. The smaller the particle size, the larger the total surface area of pigment, and the more dispersant is needed for stabilization. Generally it can be said that the required dispersant dosage is in the range 0.1–0.5% of dry pigment.

Today, the most commonly used pigment dispersants are *polyacrylate salts*. Usually they are low molecular weight (MW) polymerization products of acrylic acid, which have been neutralized with sodium or ammonium hydroxide. They are very resistant toward different types of attack such as high pH, high temperature, or high shear forces. *Polyphosphates* were previously used as dispersants. They are

effective, but lack hydrolytic stability during storage of the dispersion; they easily hydrolyze to orthophosphates, which have no deflocculation power. This causes an increase in the viscosity of the dispersion. The longer the polyphosphate chain, the more effective it is as a dispersant. Tetrasodium pyrophosphate, $\text{Na}_4\text{P}_2\text{O}_7$, is the simplest polyphosphate that can be used as a dispersant. Sodium tripolyphosphate, $\text{Na}_5\text{P}_3\text{O}_{10}$, is widely used as a dispersant and as a builder in detergents. Other anionic polymeric dispersants are lignin sulfonic acid salts and formaldehyde condensation products with aromatic sulfonic acids. Because of the nature of sulfonic acid, these types of dispersants bear the maximum anionicity over the whole pH range typically used in pigment dispersions. Lignin sulfonates are made from native lignin. Their effectiveness as a dispersant depends on their purity and degree of sulfonation. Lignin sulfonates can be used as a dispersant with hydrophobic surfaces. Their disadvantages are poor thermal stability, tendency to foam, and they bring a high load of detrimental substances to the papermaking process. Formaldehyde condensation products with aromatic sulfonic acids have an aromatic backbone and are also effective dispersants with hydrophobic surfaces.

Nonionic polymers, which can be used as stabilizers, are, for example, starches, poly(vinyl alcohol)s (PVAs), and polyacrylamides. Nonionic polymers work as protective colloids; their mechanism of stabilization is steric stabilization. CMC bears a small anionic charge along the chain. However, it is often considered to act as a protective colloid. Actually, CMC can be considered to use both its protective colloid properties and its charge in stabilizing, thus acting as an electrosteric stabilizer.

The charge of pigment dispersants is usually anionic, but in some applications, cationic dispersants are preferred. They are seldom needed in coating color pigments, but they are beneficial in pigment dispersions meant for filler applications or for specialty coating applications. Cationic dispersants are typically cationically charged polymeric compounds, for example, modified polyethylenimines, poly(vinyl amines). Usually they do not act as effectively as anionic dispersants.

5.2.3

Binders

Binders are the second most abundant component in the coating color after the pigments. Different binder types are used (Figure 5.14). With a share of 54% of the 2.2 million tons of dry binders used in 2010, styrene–butadiene (SB) -based latexes are most important, followed by starch with a share of 33%. Styrene acrylate (SA) latexes were used to 9%, and 4% were binders based on other monomers.

The most important aims for the application of binders in coating colors are the binding of pigment particles to base paper, the binding of pigment particles to each other, partial filling of voids between pigment particles (porous coating structure), and affecting the viscosity and water retention of the coating color.

An ideal binder can be characterized by good binding power, good water retention properties, ease of mixing or dissolving in water, general ease of handling, good compatibility with other coating components, low or desired effect on the viscosity

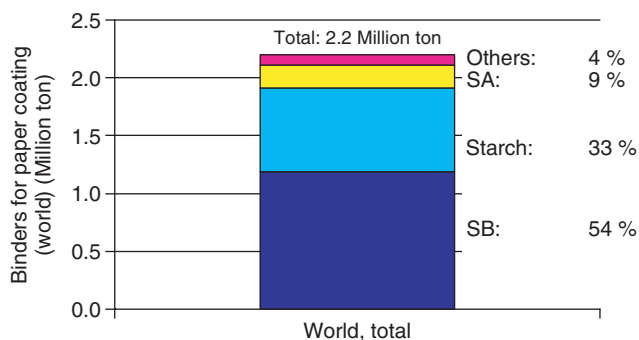


Figure 5.14 Market shares of binders for paper and board in 2010. (Source: Styron).

Table 5.4 Binder classification.

Soluble in water	Starches Proteins Cellulose derivatives: ethers, for example, carboxy methyl cellulose Poly(vinyl alcohol) (PVA, PVOH)
Insoluble in water	Carboxylated styrene butadiene latexes (XSB Latex) Styrene acrylate latexes (SA Latex) Poly(vinyl acetate) latexes (PVAc Latex)

of the coating color, good mechanical and chemical durability, good optical and mechanical properties, nonodorous and harmless to health, low tendency to foaming, resistant to bacteria, constant quality properties, low price, and good availability. Again, as with pigments, there is no single binder, which can meet all these requirements. Latexes meet many of them; however, they often need a cobinder or thickener to adjust the rheology and water retention to the desired level.

There are three kinds of binders in coating, the (main) binder, cobinder, and sole-binder. A sole-binder is a single binder that alone can perform all the desired binder functions in a coating. Usually the binder systems consist of a combination of two binders, in which the (main) binder is responsible for the binding function. The cobinder is used to affect the rheology and water retention properties of the coating color. Its dosage is smaller than that of the main binder. The binders can be classified by their origin and solubility in water (Table 5.4).

Water-soluble binders give better water retention for the coating layer than latexes that are not soluble in water. They also affect the rheological properties of the coating colors, making them more viscous and also shear thinning (pseudoplastic) and thixotropic. Some synthetic cobinders have a similar effect. Carboxylation of SB-Latex means incorporation of small amounts of unsaturated carboxylic acids such as acrylic acid, methacrylic acid, and maleic acid, to considerably improve

the compatibility of these highly hydrophobic polymers with the other coating components.

5.2.3.1 Derivatives of Natural Polymer Binders

In the initial phases of paper coating, that is, the late nineteenth century until the middle of the twentieth century, these binder types were used exclusively. All are hydrophilic. The most widely employed binders of this type are starch and its derivatives with a consumption of approximately 700 000 tpa worldwide at present. Additional natural binder types are cellulose ethers such as carboxy methyl cellulose, in the United States, hydroxyethyl cellulose (HEC), soybean protein, and, to a very small extent, casein, and alginates. Natural binders act as protective colloids that prevent the flocculation of the pigments; they increase the viscosity and water retention of coating colors and give the coat a higher stiffness. Natural binders have a relatively low water resistance (wet pick). They are mainly used in combination with synthetic polymer binders and/or hardening agents.

Starch derivatives of various types are used in mixtures with other binders. For example, oxidized starches are usually employed together with polymer dispersions. Hydrolyzed starches exhibit high stability in solution, good binding power, and good flow behavior. Hydrolyzed, esterified starches exhibit good stability in solution, high binding power, and increased reactivity toward wet-strength additives (hardening agents) such as urea- or melamine-formaldehyde resins. Hydrolyzed, etherified starches exhibit the same properties as the esterified derivatives. However, in contrast to the esterified derivatives, they can be used at pH values above 8 without the risk of saponification. Starch derivatives that contain phosphate and amino groups are compatible with cationogenic substances such as satin white. The phosphate groups react with multivalent metal ions, such as aluminum ions, which lead to a certain degree of water resistance. The amino groups react with aldehydes, which enhance the activity of hardening agents.

Cellulose Derivatives: Pure CMC coats of 0.5–3 g m⁻² increase the grease resistance and printability of paper. Depending on the use, various mixtures of low- and high-viscosity CMC are employed. Pigment-containing CMC coats, which can be applied on the size press, contain up to 10% semitechnical, low-viscosity CMC, or salt-free, purified CMC. CMC is usually applied together with other natural or synthetic binders. Above all, CMC increases the effectiveness of optical brighteners and the water retention of the coating mixture. Water retention is so high that it is fairly necessary to add additional binders that promote water retention in the coat. In general, the amounts of CMC employed are 0.3–1.5% based on the pigment, and very low viscosity types are preferred. This gives an adequate coating color viscosity, even if the solids content of the coating color is high. Types of CMC that are soluble in cold water are rapidly becoming established because they do not require dissolving at elevated temperature. The presence of satin white pigment can cause strongly interfering coagulations in the coating color.

Casein has been used as a central binder type in the past, but nowadays is of only marginal importance in cast coatings. Casein needs to be dissolved by the addition of alkali (e.g., ammonia, sodium hydroxide, borax, or sodium carbonate)

either separately in a cooker (up to 70 °C) or with the pigment in a kneader. The casein concentration is limited to about 20% due to its high viscosity. The limit of processability is shifted to about 33% by the addition of urea or dicyanodiamide, which reduces the viscosity and increases the storage stability of casein solutions. The mixing of casein solutions with pigments, especially China Clay, can cause a “shock” phenomenon (a rapid increase of viscosity).

Soybean protein is a very important binder type, especially in North America. It has properties very similar to those of casein. Isolated soybean proteins are hydrolyzed, isoelectric proteins. They are used in the form of alpha and delta proteins with four different viscosities (extra low, low, medium, and high). The viscosity refers to the *dissolved soybean protein*, the solvent of choice being aqueous ammonia (26 Bé). Proteins dissolved in this way exhibit very low sensitivity to water after drying. As casein, soybean protein is mostly used as a mixture with polymer dispersions. This combination permits the preparation of coating colors with high solids content and a relatively low viscosity. Solid contents of about 60%, suitable for blade coaters, can be achieved.

5.2.3.2 Synthetic Latex Binders

The ongoing development of coating equipment and applicators in connection with the increasing production speed (actual process up to 2.000 m min⁻¹; pilot coaters up to 3.300 m min⁻¹) has forced the development of new binder types, which meet the changed requirements better. In Europe, the first *styrene-butyl acrylate dispersion (SBA)* was polymerized by Badische Anilin-und Soda-Fabrik, today BASF, in 1929. In the following years, a partial substitution of the natural polymer binders began and from the 1950s onward an extensive and continuous growth in market demand has been observed. The corresponding pioneer work in the United States took place in Dow Chemicals, where, from 1944 onward, the production and market introduction of *carboxylated styrene-butadiene latexes (XSB)* started. *Poly(vinyl acetate) latexes (PVAc)* as a coating binder was first researched and introduced to the market in 1955, also in the United States, where a higher proportion than in other world regions is still used.

These synthetic latex binders made it possible for the first time to attain a high solid content at low viscosity, a prerequisite for modern high-speed coating machines. In addition, polymer dispersions give the coat a higher water resistance, better flexibility, higher gloss, and better printability. The products employed today are aqueous dispersions of polymers, usually stabilized with anionic emulsifiers. The solid content of the dispersions is generally about 50%. Very often, the polymers are copolymers of several monomers, for example, styrene, butadiene, acrylic esters, vinyl acetate, and acrylonitrile. Apart from these main monomers, small amounts of auxiliary monomers, such as acrylamide, acrylic acid, maleic acid, and methacrylamine, are also added to modify the dispersion properties.

SB dispersions lead to varying film hardness, depending on the proportion of styrene used. Approximately equal proportions of styrene and butadiene result in binders that provide a relatively soft film and a very good pigment binding capacity. Disadvantages are the odor of the dispersion and the tendency of the

films to yellow when exposed to light. Acrylate dispersions are specialties and of high importance for impressive prints. Butyl acrylate is mainly copolymerized with styrene or vinyl acetate. The ratio of the soft component (butyl acrylate) to the hard one (styrene or vinyl acetate) determines the application characteristics of the dispersion. In general, acrylate dispersions have an excellent brightness and ageing resistance and are less odorous. Apart from these two most important groups of polymer dispersions, vinyl acetate homo- or copolymers have gained acceptance in paper-coating plants, especially in the United States. These products generally have a lower binding power, but provide very hard and porous coats, and have an excellent ageing resistance. Polymer dispersions based on methacrylates and copolymers of vinyl acetate and ethylene are less important in paper coating.

In recent years, the requirements for coating binders have become more and more diverse. Changes in raw materials for paper production and/or production process conditions as well as new requirements for paper characteristics and printing technologies have forced the development of *tailor-made binders* with very specific property profiles. Such products are not generally different from XSB- or SBA-latexes, with regard to the principles of physics and chemistry. However, with the know-how of correlation and influence factors of monomers, functional monomers, process auxiliaries, functional additives, process parameters, and interactions with different pigments, together with a flexible polymerization unit, it is possible to optimize, very flexibly and quickly, a binder in respect of binding power, stiffness, print evenness, print gloss, blister resistance, low yellowing, and coater runnability.

Apart from the two-component systems, binder + cobinder, synthetic *sole binders* that do not require a cobinder have been available since the early 1960s. Synthetic binders are low-viscosity aqueous dispersions, which usually do not influence properties such as viscosity and water retention that are important for the flow behavior of the coating. For this reason, these “multipurpose dispersions” are used alone in only a few cases. They are usually mixed with cobinders, which are responsible for adjusting the flow properties of the coating color. On addition of alkali, these products develop the required viscosity and water retention, but retain their dispersion form. Table 5.5 lists the various binder systems, their influence on the production of coating colors, the rheological properties of the coating color, and the coating properties.

5.2.4

Additives Influencing the Properties and Processing of the Coating Color

It is desirable that coating colors have moderate pseudoplastic, shear thinning flow behavior. Too drastic shear thinning can cause excessive water penetration into the base paper and, accordingly, loss of binder. To adjust the rheological properties and water retention of a coating color, synthetic cobinders, and thickeners are used. They have a profound effect on the runnability of a coating color and, hence, of the coating machine, on account of their thickening action, their characteristic rheology at different shear rates, and their water retention. The mechanisms for dissolving,

Table 5.5 Comparison of various binder systems.

Binder system	Production	Rheological behavior	Coating properties
Polymer dispersion alone (rarely used)	Simple mixing process	Usually unfavorable	Variable via type of dispersion; waterproof, glossy coat attainable; no activation of optical brighteners
Polymer dispersion + water-soluble cobinder, for example, casein, starch, and CMC (very frequent)	Mixing and dissolving processes, sometimes separately with heating	Largely controllable via cobinder	Variable via single components; limited water resistance and gloss; full activation of optical brighteners
Polymer dispersion + synthetic cobinder (frequent)	Integrated mixing/dissolving processes, no heating	Controllable via cobinder	Limited variability; waterproof and glossy coat attainable; full activation of optical brighteners
Polymer dispersion + viscosity regulating additives (in special cases)	Integrated mixing/dissolving processes, no heating	Limited controllability	Variable only via type of dispersion; good water resistance and gloss, no activation of optical brighteners
Special dispersion (for publication papers)	Integrated dissolving/mixing processes, no heating	Slight controllability	Limited variability; improved water resistance with additives; good gloss attainable; and optical brighteners can be activated only via auxiliary components

thickening, water retention, and rheology of synthetic cobinders are very similar to those of synthetic thickeners. Cobinders and thickeners can be roughly divided into, “natural” and “synthetic” products. Natural products are proteins (casein and soy protein) and polysaccharides (starch, alginates, and cellulose ethers), and synthetic products are, for example, acrylic copolymers, PVA, poly(vinyl acetate), and associative thickeners (Figure 5.15).

5.2.4.1 Cobinders

These are primarily used to adjust the viscosity and water retention of coating colors to the required levels and to modify their rheology according to the demands

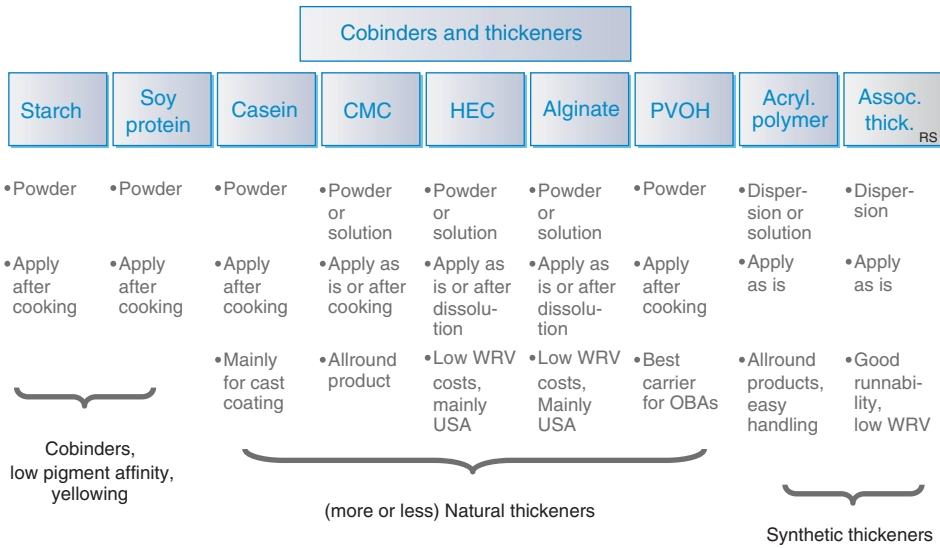


Figure 5.15 Cobinders and thickeners. (Source: Lehtinen).

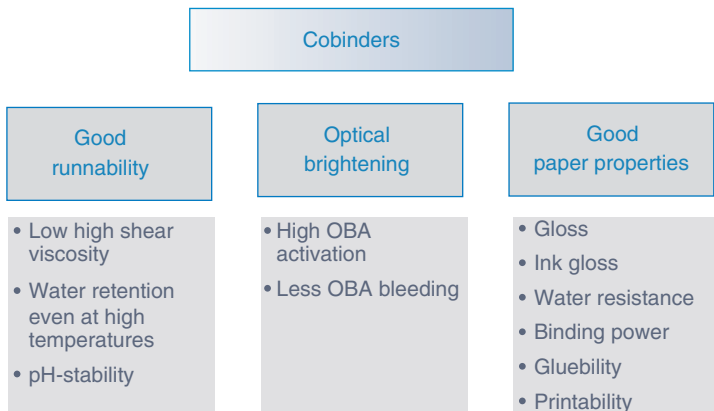


Figure 5.16 Main requirements placed on cobinders. OBA, optical brightening agent. (Source: BASF).

of particular coating techniques. However they should also offer some additional advantages over the thickeners to justify the higher recipe costs, for example, binding power and activation of optical brighteners (Figure 5.16).

Natural products, such as casein, starch, and soy protein used as main binders in the past, also impart the necessary viscosity and water retention to coating colors. However, they were unable to satisfy the increasing demands that were placed on runnability and coating quality, and they have gradually been superseded by synthetic binders. Hence, natural products, principally starch and soy protein, are nowadays only used as cobinders. Casein is only used in cast coating because it

has some special features that make it difficult to replace with synthetic products. Alginates and HEC are mainly used in the United States and Japan and have not been adopted to any significant extent in Europe.

CMC is a versatile product with an all-round range of properties and is popular in many regions. CMC improves the water retention efficiently. By choosing the optimum grade, the water retention can be adjusted to the individual needs, which are dependent on the coating conditions and the coating color formulations. In formulations with kaolin clay, the differences in water retention between different CMC grades are much smaller than in colors based on calcium carbonate. One reason for this is that CMC quickly builds up a network structure with clay particles, which imparts extra water retention. With calcium carbonate pigment, the water retention is more dependent on the viscosity of the water phase. A higher MW and higher viscosity type of CMC is needed to give good water retention for coarse calcium carbonate-based precoatings. Low MW and low-viscosity-type CMC grades give good performance for fine clay-based coatings. Lower MW and lower viscosity-type CMC grades are closer to Newtonian-type behavior, while higher MW and higher viscosity-type CMC grades are more pseudoplastic. CMC is mechanically stable in high shear conditions and compatible with all common types of coating raw materials.

Synthetic products comprise poly(vinyl alcohol) (PVOH), poly(vinyl pyrrolidone) (PVP) in combination with PVOH, acrylic copolymers, and associative thickeners. Because of the high degree of carboxylation of acrylate ester dispersions, they turn into colloidal dispersions on addition of alkali. Thus, the laborious and energy consuming dissolving and cooking processes involved in the use of natural binders are avoided. The binding power of PVOH exceeds that of all other binders used in paper coating; nevertheless, it is usually only used in relatively small fractions in coating colors. This is mainly due to the fact that the application of large amounts of poly(vinyl alcohol) leads to rheological problems on the coating machine during processing. PVOH is a solid compound, which is composed of a hydrocarbon chain bearing hydroxy groups on every second carbon. Depending on the extent of the poly(vinyl acetate) hydrolysis, more or less acetyl groups remain attached to the chain. The stereochemical structure of poly(vinyl alcohol), the direction in which the OH groups/acetyl groups point, is already fixed during vinyl acetate polymerization. As most free-radical-induced reactions, the PVOH polymer shows an atactic structure. This means that the functional groups are randomly oriented. Their MW and degree of hydrolysis primarily characterize poly(vinyl alcohols). In practice, further features such as tacticity, branching, average length, and distribution of residual acetyl group sequences play only a minor role. Since PVOH is fully soluble in water, its viscosity under defined conditions is taken as a proportional measure of its MW. Coating grades range from 3 (very low MW) to 6 mPa s (low MW). PVOHs with viscosities higher than approximately 6 mPa s should not be used on coating machines. The degree of hydrolysis is based on the measurement of the ester value and indicates how much mole percentage of the basic poly(vinyl acetate) is “saponified” to PVOH. For coating purposes, a degree of hydrolysis is selected from a range of 88% (partially hydrolyzed) to

99% (fully hydrolyzed). At the same degree of hydrolysis, higher concentrations or lower temperatures lead to an increase in viscosity. Given the same MW, fully hydrolyzed grades display a higher viscosity than do partially hydrolyzed grades due to increased hydrogen bonding. Going from about 97 to 100 mol% hydrolysis, the crystallinity of the polymer increases considerably, which has an impact on the solid state in particular. One apparent change is the reduction in cold water solubility of the PVOH.

The choice of other monomers for synthetic cobinders is not restricted to acrylic acid, methacrylic acid, and esters such as methyl acrylate, ethyl acrylate, butyl acrylate, methyl methacrylate, and ethyl methacrylate. Other functional monomers such as acrylonitrile, acrylamide, and vinyl acetate can also be used, and so there is a great scope for varying the chemical composition of synthetic cobinders. The proportion of carboxylic acids to the other monomers is usually lower, with the result that synthetic cobinders are less anionic and they adsorb more readily on the surfaces of clay pigments. Important differences of synthetic cobinders compared to the thickeners (see below) are their shorter chain length and their low proportion of acids. This explains the low thickening effect of synthetic cobinders and hence they can be added to coating colors in larger quantities. They are usually added at rates of 0.5–3 parts per 100 parts of pigment, expressed as solids. These relatively high levels of addition and the presence of functional monomers can have a substantial effect on the properties of the coating.

5.2.4.2 Thickeners

The main function of thickeners is to adjust the viscosity of the coating color to the desired level and to impart the necessary degree of water retention (Figure 5.17). Thickeners must be able to interact strongly with water molecules if they are to increase the water retention of coating colors. They also need to interact with other ingredients of coating formulations, especially pigments, to display a thickening effect. The nature and strength of these interactions depend on the chemical composition of the polymer. Thickeners also need to display pronounced pseudoplastic flow. High runnability depends on a combination of these features. Most synthetic thickeners are supplied in the form of aqueous, acidic dispersions (which are often erroneously referred to as *emulsions* in the literature) or alkaline solutions of synthetic polymers. Some are supplied in the form of true water-in-oil emulsions, but they are much less common.

The main products used as thickeners are CMC, PVOH, acrylic copolymers, and associative thickeners. The acrylic copolymers are nonionic monomers and acrylic acid or methacrylic acid. The nonionic monomers are mainly esters of acrylic acid (principally methyl acrylate and ethyl acrylate) and methacrylic acid (principally methyl methacrylate), and acrylamide. The monomers that are selected need to be fairly hydrophilic and polar in order that the polymer is able to dissolve in aqueous coating colors and interact with other polar coating ingredients such as pigments. Strongly hydrophobic monomers such as styrene, butadiene, and ethylene are hardly ever used because they interfere with the interaction between the polymer and water molecules. Poly(acrylic acid) can also be used as a thickener in its

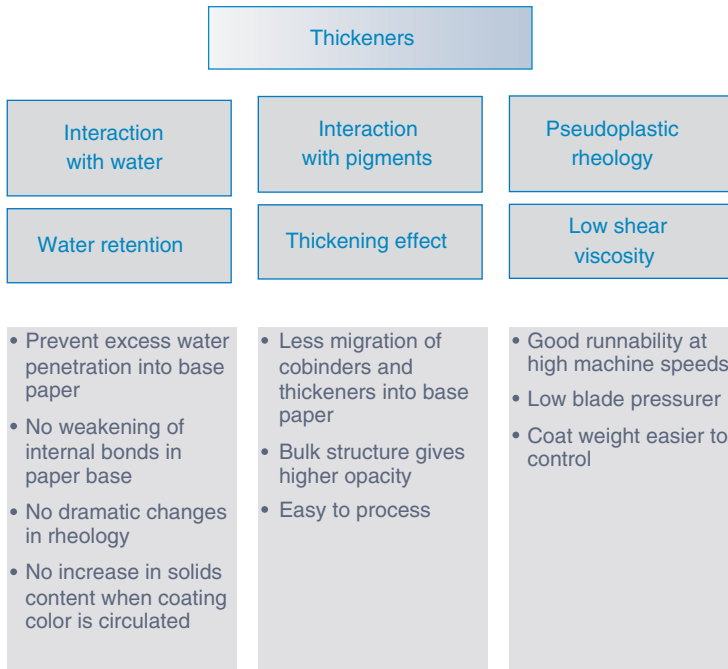


Figure 5.17 The role of thickeners in coating colors.

dissociated form, that is, as the sodium or ammonium salt, if its molar mass is high enough. Polymers have to be able to dissolve before they can exert a thickening effect. Most natural products have to be heated and converted to make them capable of being dissolved, whereas acrylic copolymers are soluble on account of the alkali ions contained in the coating color. When the addition of alkali increases the pH of the dispersion, the carboxyl groups dissociate and donate a proton, which causes them to become anionic. The formation of anionic charges along the polymer chain causes it to stretch owing to mutual repulsion, and water molecules are attracted to the polymer chain and become attached to it. The dispersed thickener particles then dissolve, which allows them to unfold their effects. It only takes a few minutes to dissolve them completely. Nevertheless, it is important to ensure that sufficient alkali is available in the coating color because the thickener dispersion consumes alkali and the stability and viscosity of the coating color can suffer if the pH is allowed to drop. Another important point to be considered is the sensitivity of the dissolved polymer to electrolytes. Polyvalent cations such as Ca^{2+} , Mg^{2+} , Al^{3+} , and Fe^{3+} can have a detrimental effect on the performance of these products by occupying the sites of anionic charge on the polymer.

The interaction between the polymer and water has a pronounced effect on the viscosity of the aqueous phase as well as on the water retention of the coating color. As all hydrocolloids, synthetic thickeners bind a large number of water molecules along their polymer chains, with the result that their diameter and volume increase






Principle	Example	Illustration
High molar mass	Poly(vinyl pyrrolidon)	
Intramolecular charge separation	Acrylamide–sodium acrylate copolymers	
Cross-linking	Cross-linked polyacrylates	
Higher structural order	Polysaccharides	
Intermolecular association	Associative thickeners	

Figure 5.18 Thickening mechanisms in the aqueous phase. (Source: BASF).

and they occupy a greater space in the aqueous phase (Figure 5.18). Apart from this hydrodynamic mechanism, there are a number of other mechanisms by which the thickeners are able to restrict the mobility of the aqueous phase. The high molar mass and the high degree of structural order cause a large increase in the volume of the dissolved polymers under hydrodynamic forces. The anionic charges along the length of the polymer also have the effect of stiffening the polymer chain by causing it to unfurl and stretch out because the charges repel each other. The mobility of the aqueous phase is lower because of the stiffness and extension of individual polymer chains and the cross-linking between different polymer chains. The maximum degree of internal cross-linking is obtained as the result of the associative interaction between the hydrophobic side chains. The common feature of all these effects is that the mobility of the aqueous phase is reduced owing to intramolecular and intermolecular cross-linking and the viscosity is increased due to the increase in the volume of the polymer. The pronounced thickening effect of thickeners is the result of their interaction with pigment particles. Acrylic and cellulosic thickeners have a high affinity for pigments because the polar functional groups of the thickener molecule are attracted by the polar surfaces of the pigment. The polymer chains are adsorbed on the surface of the pigment particles and bind them together by means of a bridging mechanism, leading to a higher degree of cross-linking within the entire system. The thickening effect, that is, the increase in viscosity at low shear, is principally the result of the thickener forming “bridges” by means of adsorption.

5.2.4.3 Associative Thickeners

These have a long history of use in paints. They consist of an essentially hydrophilic, water-soluble polymer with strongly hydrophobic terminal groups or side chains.

The hydrophobic terminal groups are aliphatic or aromatic hydrocarbons, and they are completely insoluble in water. They are joined to the main polymer backbone by means of a hydrophilic spacer, which ensures that they remain flexible. Their structure is similar to that of surfactants, and they also tend to join together in water to form micelles. This associative interaction between the hydrophobic side chains increases the degree of internal coordination of the whole system, with the result that the coating color has a very high viscosity at low shear (Figure 5.19). The association between the hydrophobic groups is the result of van der Waals' forces, which are very weak and easily overcome. If the coating color is subjected to shear, they quickly lose their attraction for each other and no longer form a network. The micelles breakdown and the thickener molecules are oriented in the direction of flow, which causes a reduction in the viscosity of the coating color. However, because the hydrophobic constituents are no longer associated with each other, a consequence of the low viscosity of the coating color under high shear is that its water retention is much lower.

The associative thickeners can be divided into three different categories according to the chemical composition of the hydrophilic polymer backbone (Figure 5.20).

- 1) **HEURs (Hydrophobic Ethoxylated Urethanes):** These thickeners consist of relatively short-chain, ethoxylated polyurethanes that have been terminated with hydrophobic substituents. The associative interaction between the hydrophobic chain ends causes them to join together to form long chains, and the viscosity increases accordingly. Another feature of these products is that they also interact with the dispersed polymer binder particles. There are variants in which the main polymer backbone consists of alternating hydrophilic and hydrophobic blocks. HEUR-type associative thickeners have long been used in the paints industry, but they have been less successful in coating colors, because of their lack of affinity for pigments.

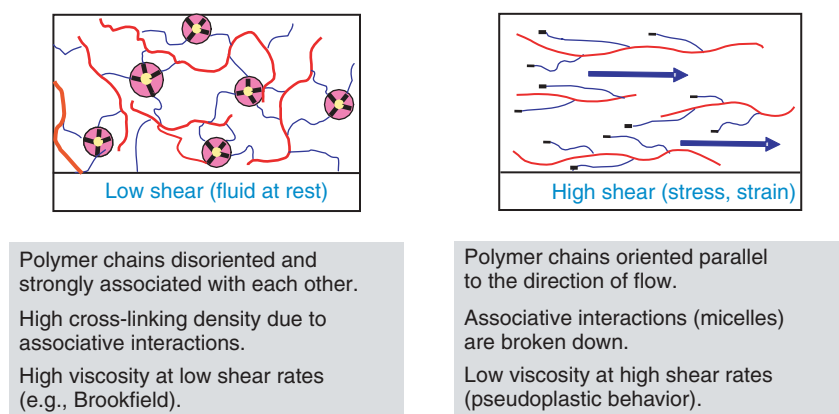


Figure 5.19 Rheological behavior of coating colors influenced by an associative thickener. (Source: BASF).

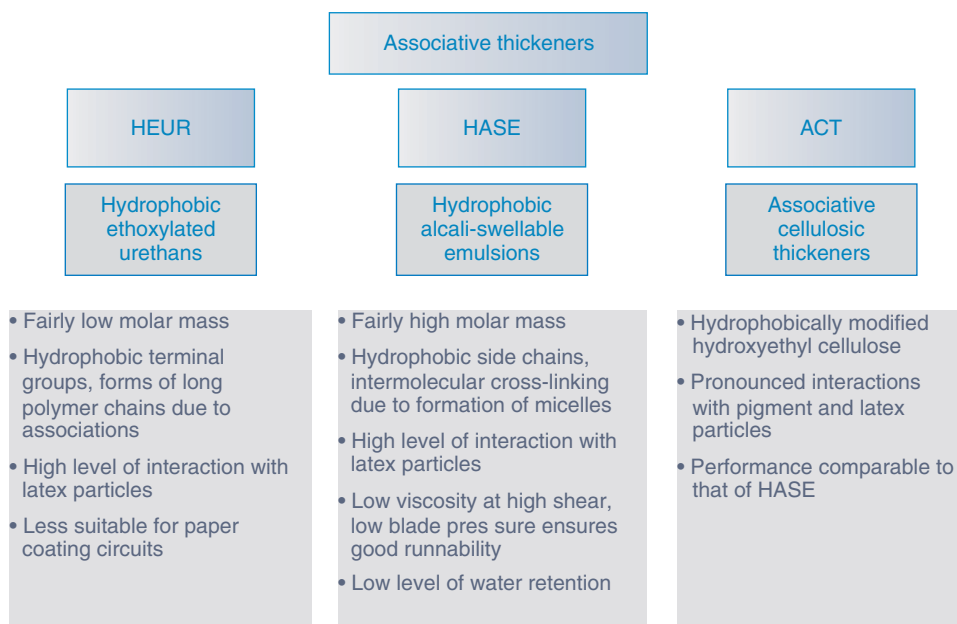


Figure 5.20 Types and properties of associative thickeners used for coating. (Source: BASF).

- 2) **HASEs (Hydrophobic Alkali-Swellable Emulsions):** The hydrophilic polymer backbone consists of an alkali-soluble polyacrylate, and they do not differ from the other acrylic-based thickeners described above in this respect. The most commonly used monomers are ethyl acrylate, acrylic acid, and methacrylic acid. The hydrophobic side chains are attached to the polymer backbone by means of a polyethylene oxide spacer. The associative thickening effect can be controlled by varying the ratio of associative monomers to conventional monomers in the polymer backbone, the hydrophobicity of the polymer (i.e., the chain length of the aliphatic hydrocarbons), and the number of ethylene oxide units in the spacer. The intermolecular association of hydrophobic side chains and with other side chains and with the dispersed binder particles is responsible for the very high viscosity that can be achieved. The relatively high molar mass of the acrylic polymer backbone and its high affinity for pigments mean that these products can be used in paper coating, but the water retention level is lower than with conventional thickeners.
- 3) **ACTs (Associative Cellulosic Thickeners):** Products in this category consist of cellulose ethers with hydrophobic substituents. The most important product in this group is hydrophobic modified hydroxyethyl cellulose (HMHEC), which also has a high affinity for SB binders and clay pigments. The applications open to these products are comparable to those for HASE products. The low water retention can be compensated for by the speed with which the filter cake forms on the surface of the base paper.

Table 5.6 Comparison of conventional with associative thickeners.

	Nonassociative thickener	Associative thickener
Thickening effect	High	Very high Very effective in low dosage Especially suitable for low solids formulations
Water retention	Medium to high	Low Not suitable for processes with critical water holding behavior (e.g., online board coating) Additional water retention aid is necessary (cost effective)
Rheology	Pseudoplastic	Highly pseudoplastic Low high shear viscosity Good runnability Reduces blade pressure
Immobilization	Slow	Fast Bulk coating structure Good coverage

Source: BASF.

Associative thickeners bring about a very high increase in viscosity, and so they only need to be added in very small amounts. This is an economic advantage over conventional thickeners, but only if the water retention of the coating color is unimportant. Other products need to be added to boost the water retention of the coating color if, for instance, highly absorbent paper is coated with a precoat or if coarse CaCO_3 is used as the pigment.

It has to be noted that the results obtained for water retention with static methods do not correlate with the water retention in practice under dynamic conditions. The great advantage of associative thickeners is that they are much more pseudoplastic than conventional products, and coating colors have a lower viscosity at high shear (Table 5.6). This gives better runnability and less blade pressure need to be applied to control the coat weight. Associative thickeners cause a large, immediate increase in viscosity when the shear applied to the coating is released, and this can lead to a more bulky coating being formed with a superior optical appearance.

5.2.4.4 Lubricants

Lubricants are used in the coatings of paper and board for a number of reasons. They improve the runnability of the coating color by reducing the friction between the machine and the coating color and also by reducing the friction between the base paper and the coating unit. This can be seen, for example, as fewer scratches in the coating and longer lifetime of coater blades. They enhance the plastic deformation of the dry coating in the supercalender by preventing the

cracking of the soluble binder film that leads to dusting. This also improves gloss. During calendering, lubricants migrate from the coating onto the hot calender rolls forming a monolayer on the rolls and thus preventing the sticking of the coating to the rolls that causes buildups. Different kaolins have different dusting tendencies, and dusting can often be solved by using a lubricant. The most commonly used lubricant is *calcium stearate*. It is produced by reacting stearic acid with calcium hydroxide, followed by emulsification and processing to a 50% aqueous dispersion. The critical properties of the calcium stearate dispersion are mechanical impurities and free Ca^{2+} , a good dispersion contains a minimum amount of both. Particle size and shape are important for antidusting properties. The optimum size is 5–10 μm and the shape should be platy. The platy shape enables the stearate to gather on the pigment, plasticize the surface of the dry coating, and reduce the dusting at calenders and printing machines. *Wax emulsions* are mostly emulsions of paraffin waxes, microcrystalline waxes, or polyethylene waxes. These are the oldest group of lubricants in paper and board coating. These emulsions give good runnability but have less effect as antidusting agents than does stearate. Particle size is small and the dry solids content of the emulsion is usually 20–30%. *Soy lecithin/oleic acid* blends are a new group of substances used as lubricants. *Polyethylene* and *poly(propylene glycols)* are used in blends with calcium stearate or alone as a lubricant. These lubricants are claimed to have influence on the rheology and flow properties of the coating color (Figure 5.21).

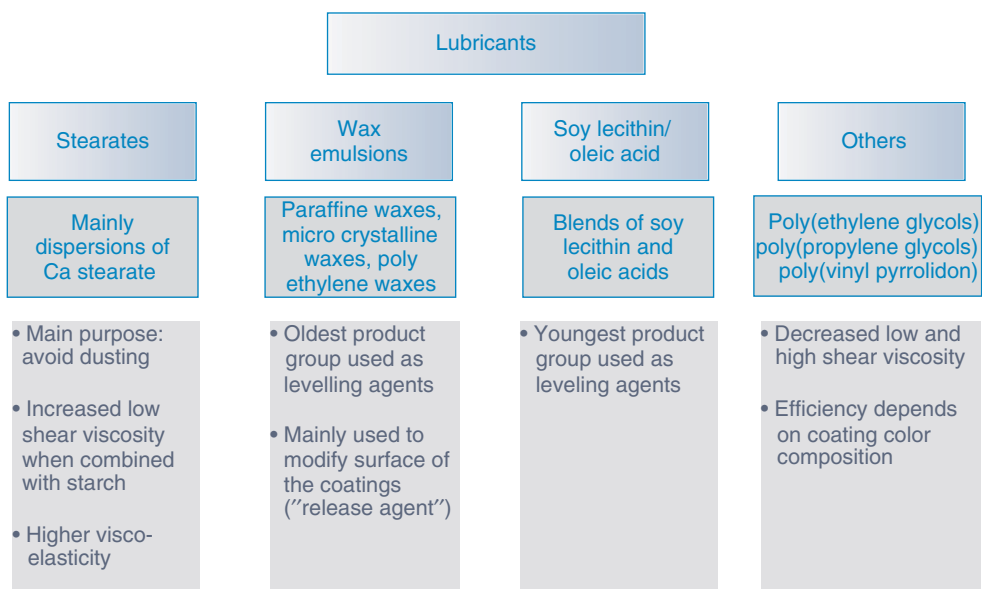


Figure 5.21 Lubricants, leveling agents.

5.2.4.5 Defoamers/Deaerators

In the coating process, entrapped air or gas can give rise to production problems and quality loss. The major part of the air seems to get mixed into the coating color during the coating application and circulation. Such air is mostly dispersed as small bubbles that, because of the high viscosity of some coating colors, may remain in the color until drying. Higher coating speeds (2000–3000 m min⁻¹) and total solid content of coating formulations possibly contribute to more stable microfoam. The formation of *foam* is a topic in many industrial processes including the coating of paper and board. Foam is formed through an interaction of mechanical forces and physical chemical properties of the chemicals. From a physical chemical point of view, foam can be defined as a dispersion of air or a certain gas in a liquid or fluid medium. The formation of foam always involves a substantial increase in surface area between the dispersed air or gas and the liquid. Foams in general are inherently unstable and are suspect to decay with time. However, under certain circumstances, foams can be quite stable and may persist over long periods of time. Pure liquids and liquid mixtures, which do not contain a surface-active ingredient, are not able to produce stable foams. Surface-active ingredients or surfactants reduce the surface tension of the liquid and, in consequence, the surface energy renders the system more stable than without surfactants. Besides surface activity, other parameters such as foam structure, lamellae thickness, foam drainage, surface rheology, and elasticity contribute to the stabilization or destabilization of foams. These parameters are dependent on time, pH, the presence of surfactants, polymers, proteins, and/or salts, as well as the chemical composition and the physical properties of the liquid. Foam generation can occur at different levels of mechanical energy input to the liquid system. Different foam volumes can be generated using the same liquid composition but with different mechanics involved.

Foam reduction, defoaming, or deaeration can be achieved by various means. Apart from pressure reduction or mechanical influences (e.g., skimmer or separation grids), special chemical additives are applied to control the foam. In general, it can be stated that there is a need for formulations of specific defoamers for each specific foaming liquid system.

In those cases where surfactants are already a part of the chemical composition of the liquid medium, high-foaming surfactants may be replaced by low-foaming surfactants, for example, methyl- or butyl-capped alkyl- or fatty alcohol ethoxylates or propoxylate or polymeric materials such as poly(oxyethylene) or poly(oxypropylene) or both as block copolymers. In contrast to these water-soluble defoamers, usually insoluble hydrophobic additives are widely used as very efficient defoamers. Among these should be mentioned hydrocarbon/fatty acid/ester or wax blends, (poly) siloxanes, fluorocarbons, dispersions of solid particles (hydrophobic silica, organic microwaxes, etc.) in hydrocarbons or (poly) siloxanes. The chemical composition of the defoamer and the PSD of the dispersed additive in the liquid medium determine the efficiency of these defoamers. In these defoamers, the fluid component serves as a dispersal aid for the solid, crystal-like particles. When added to the foam, the hydrophobic liquid component spreads out on one side of the foam lamella surface,

producing a nonzero contact angle to the surrounding water phase. After further drainage of the foam lamella, the hydrophobic drop finally bridges the lamella and causes lamella breakdown due to the high contact angles and ongoing drainage. In this respect, the dispersed solid particles enhance these processes and improve the efficiency of the defoamer system to a great extent. Foam control agents are usually applied during coating preparation. In systems where the pigments, binder(s), and the other additives are made up simultaneously, the antifoam agent is added before the pigment and adhesive. Normal dosages lie in the range of 0.05–0.2% on dry coating solids. Defoamers are sometimes added prediluted and should be properly mixed into the system to ensure an even distribution throughout the volume. Spots in the finished coating layer, commonly referred to as *fisheyes* and *birdeyes*, can have a variety of causes. Such deficiencies can be related to the type of antifoam or to too high a dosage of antifoam, where the foam control agent counteracts the complete spreading or wetting of the paper surface at these positions.

5.2.5

Additives Influencing the Quality and Printability of the Paper Surface

5.2.5.1 Cobinders and Thickeners

The structure formed by the pigments plays an important part in determining the physical properties of the coating, and because cobinders and thickeners have a high affinity for pigments, they play an important part in influencing the structure of the coating by controlling dewatering. The physical properties of the coating that are affected most by the use of synthetic cobinders and thickeners are the smoothness and porosity and the brightness of coatings that contain FWAs. Careful attention needs to be paid to all these factors, when the paper or board is to satisfy all the market demands made on its gloss and print gloss, ink uptake and holdout, glueability, brightness and opacity, water resistance, and absence of mottling. Synthetic cobinders also help to bind pigments to each other. They largely contribute to the pick strength of the coating. The amount of binder employed in the coating can be reduced, if large proportions of synthetic cobinder are employed. Generally speaking, two parts of cobinder can be used to replace one part of binder. They also increase the water resistance of coatings. Once they have formed a film, they become firmly integrated within the structure of the coating and are no longer soluble in water.

5.2.5.2 Insolubilizers

There are many chemically different types of insolubilizers or cross-linkers, but they all have the same function – to add water resistance to the coated paper surface. Water resistance is particularly important not only in offset printing but also for wallpaper, label paper, poster paper, and in the storage of board packages. In double-coated boards, cross-linkers are used in the precoating to impart water resistance against the topcoat. The water resistance can be measured as wet rub and wet pick or seen as less pick, print mottle, or binder migration. The water sensitivity of paper and board coating originates from the fact that water-soluble

binders tend to lose their binding power in contact with water and dissolve. This water sensitivity of binders can be described as the amount of O-atoms in the molecule (in hydroxy and carboxyl groups). The water sensitivity can be decreased by cross-linking the soluble binders with insolubilizers or by building an insoluble net around the binders.

Traditional insolubilizers in paper and board coating are based on formaldehyde and its amino compounds (melamine, urea) or on glyoxal. Imidazoline derivatives are also used as cross-linkers. Next-generation insolubilizers are based on zirconium; the product most widely used is ammonium zirconium carbonate (AZC).

Glyoxal is the simplest aliphatic dialdehyde. It is an effective cross-linker of starch and gives the coating an immediate curing. The cross-linking mechanism is a reaction with the hydroxy groups. Glyoxal first reacts with one starch molecule and then with another one, leading to cross-linking of two starch molecules. Glyoxal is a less effective cross-linking agent for synthetic water-soluble binders. Some of its derivatives, such as condensate products with urea or ethylene urea, can be used here. Glyoxal is ineffective at $\text{pH} > 8.5$. Difficulties have resulted with viscosity build-ups due to cross-linking in the wet form.

Melamine-formaldehyde (MF) and urea-formaldehyde (UF) resins have been used in paper coating since 1940. In the 1970s, methylated MF and UF resins for the most part replaced these resins. *MF* and *UF resins* have reactive imino- ($>\text{NH}$) and methylol ($>\text{N}-\text{CH}_2-\text{OH}$) groups. Methylated MF and UF resins have also some functional methoxymethyl groups ($>\text{N}-\text{CH}_2-\text{O}-\text{CH}_3$). These groups undergo reactions with paper-coating binders: the hydroxy group of starch and poly(vinyl alcohol), and the carboxyl groups of latexes. Both UF and MF resins can also self-condensate. The reaction of MF/UF and their derivatives is an acid-catalyzed condensation reaction that requires a certain temperature and pH. The curing reaction takes up to two weeks to complete.

Environmental pressures against formaldehyde-based resins, higher pH in coating formulation, and the need for faster curing are the reasons why AZC is more used in the paper industry. AZC reacts with carboxyl and hydroxy groups in the coating, hydroxy groups in starch and PVA, carboxyl groups in latexes, and oxidized starch. The reaction takes place when ammonia is evaporated and water is removed on drying. AZC forms covalent bonds with carboxyl groups and weaker hydrogen bonds with hydroxy groups. High pH does not affect the reaction. Other zirconium-based cross-linkers are *potassium zirconium carbonate* and *zirconium acetate*. The reaction mechanism is similar for all these products. Some groups of cross-linkers are listed in Figure 5.22.

The amount and type of binder in the coatings determines the required amount of cross-linkers. It is recommended to use 5–10% cross-linker based on total dry binder. In general, starch-based coatings require a higher amount than coatings based on synthetic binders. It is important to optimize the dosage of cross-linker. An excessive amount can result in cracking problems or even in increased, instead of decreased, solubility of water-soluble coating components. A cross-linker should be added to the coating color as the last ingredient.

Cross-linkers				
Glyoxals	Urea-formaldehyde resins	Melamine-formaldehyde resins	Eoxyde resins	Ammonium-zirconium carbonate
<ul style="list-style-type: none"> • Immediate effectiveness • Very low content of formaldehyde 	<ul style="list-style-type: none"> • Carrier for OBA 	<ul style="list-style-type: none"> • Carrier for OBA • Content of formaldehyde lower than with UF resins 	<ul style="list-style-type: none"> • Free of formaldehyde • Very effective crosslinker • Long time stability 	<ul style="list-style-type: none"> • Free of formaldehyde • Immediate effectiveness
<ul style="list-style-type: none"> • Prone to yellowing 	<ul style="list-style-type: none"> • High content of formaldehyde • Slow cross-linking reaction • Low storage stability 	<ul style="list-style-type: none"> • Slow cross-linking reaction 	<ul style="list-style-type: none"> • Toxic substance • Careful handling! 	<ul style="list-style-type: none"> • No carrier for OBA • Odor (ammonium)

Figure 5.22 Cross-linkers.

5.2.5.3 Tinting (Shading)

In many cases, the yellowish color of the coating clay does not satisfy market requirements. Apart from the addition of pigments such as titanium dioxide, which increase brightness, blue–violet dyes (*shading dyes*) are often used at a concentration of about 2 g per 100 kg of pigment to attain a bluish white coating surface that appears brighter to the eye. Different dye types are listed in Figure 5.23. Not only basic dyes, but also considerably more lightfast direct dyes and pigments may be used. If the required brightness is very high, optical brighteners are also added.

5.2.5.4 Optical Brightening Agents (OBA)

The brightness of paper and board has increased significantly during recent years. The brightness of pulp, fillers, and coating pigments is not high enough to reach these brightness targets. Therefore, optical brighteners, also called *optical whitening agents*, *optical bleaching agents*, or *FWA*, are applied in coating colors.

Fluorescence is a phenomenon where the molecules of a fluorescent substance become electronically excited by absorbing light energy and then emit this energy at a higher wavelength. Fluorescence is usually restricted to compounds with large conjugated systems containing π -electrons. Most of the OBAs on the market are derivatives of bis(triazinylamino)stilbene. Only the *trans*-isomer exhibits strong fluorescence, and the *cis*-isomer is nonfluorescent. The OBAs used in the paper industry are sodium salts and are thus water soluble. There are three types of optical brighteners used in the paper industry, all based on the stilbene molecule. The main difference is the number of solubilizing sulfonic groups. Disulfonated OBAs have two sulfonic groups; the two other substituents could be hydrophilic groups. This OBA has a very good affinity to cellulose, but limited solubility and is

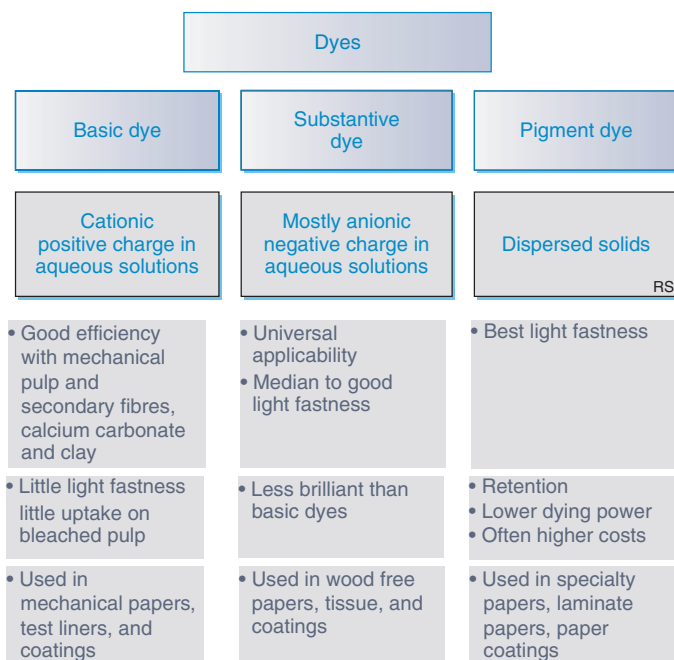


Figure 5.23 Dyes.

mostly used in the wet-end. The most commonly used OBAs are the tetrasulfonated types. Tetrasulfonated OBAs are versatile products because of their characteristics of medium affinity and good solubility. They can be used in most applications in the paper industry: wet-end, size-press, and coating. The hexasulfonated OBAs are specialties used mostly in coatings where high brightness is required.

OBAs absorb ultraviolet radiant energy at 300–360 nm and re-emit the energy in the visible range, mainly in the blue wavelength region. This increases the amount of light emitted, resulting in higher brightness or whiteness. Because the reflected light is bluish, the yellow shade of paper is compensated, contributing to making the paper look still whiter. *Whiteness* is defined as the measured reflectance of light across the visible spectrum including color components. *Brightness* again is defined as the reflectance of light at the wavelength 457 nm without color in the measurement. To measure the brightness or whiteness of paper and board containing OBAs requires an instrument having a known amount of UV in the illumination. The test method used increasingly is the CIELAB color space (L, a,b-system) (CIE) whiteness (SCAN method P66) instead of the traditional ISO brightness, which does not define the illuminant. An increase in OBAs at lower concentrations results in an increase in whiteness. As the concentration goes up to 1.5 parts of dry pigment, there is no more gain in whiteness when adding more tetrasulfonated OBA. This is called the *saturation point* or the *graying point*. The hexasulfonated OBA actually has no graying point because of its high solubility.

5.2.5.5 OBA Carrier

Optical brighteners work only when they are fixed to a carrier. A good carrier is linear and contains OH– or other hydrophilic groups. Linearity increases the contact between the carrier and OBA so that physical bonds (such as hydrogen bonds and van der Waals forces) can be formed between the OBA and the hydrophilic groups of the carrier. Carriers in a coating color are, among others, starch, CMC, or PVA. By adding one of these products in coating color, higher brightness can be achieved.

UV exposure causes yellowing of brightened paper, but a good carrier increases the light stability. Furthermore, the carrier has an influence on the migration of OBA; the more efficient the carrier, the better the resistance of OBA to the migration. In general, latexes do not act as carriers.

5.2.5.6 Influencing Opacity

The main contribution to opacity has to come from the pigments. Synthetic products are usually less opaque than natural products and this can be a problem, especially when coating ULWC grades of paper. Products with a very pronounced thickening effect are only added in small quantities, and so they hardly have any effect on opacity.

5.2.5.7 Influencing Smoothness and Gloss

The gloss of paper largely depends on its smoothness. High gloss depends on the evenness of the topology of the paper surface. As all hydrocolloids, cobinders and thickeners have an effect on the smoothness and the gloss of the paper. They are able to migrate in the wet coating, and migration can lead to them becoming unevenly distributed on the surface. They can also absorb water and swell, which also impairs the smoothness of the paper. Synthetic cobinders are usually less detrimental to gloss than natural products. One of the reasons for this is that natural products are able to absorb moisture and swell after they are dried, whereas acrylic polymers are much less sensitive to moisture once they have dried to form a film. Another reason is that acrylic polymers are highly thermoplastic and respond very well to calendering. The films formed by natural products are thermosetting, and so they are not deformed as easily under heat and pressure in the calender nip.

5.2.5.8 Influencing Porosity, Print Gloss, and Glueability

The gloss of the printed paper is determined by the smoothness of the paper surface and the ink holdout. In turn, the ink holdout is mainly determined by the porosity and the chemical and physical structure of the coated surface. Coatings need to be porous on a microscopic scale so that the soluble component of printing inks is able to penetrate the paper and dry more quickly. The intensity and brilliance of the printed image and the ink consumption depend on the pigments staying on the surface. The hydrophobicity of the coated surface and the surface tension both influence the ink uptake.

Coatings that contain synthetic thickeners and cobinders are more hydrophobic and take up more ink, but their porosity can have a detrimental effect on the print gloss. Synthetic cobinders give rise to an open-pored structure, which can increase the rate of ink absorption and give a lower print gloss. The task here is to find the best compromise between the pore size distribution and the hydrophobicity of the coated surface to obtain the highest possible print gloss without prolonging the drying time of the ink too much. An open-pored structure is often highly desirable in multiple coats applied to board because this guarantees high ink absorption.

Another important aspect governed by the porosity of the coating is the glueability of coated board. Here the affinity of the adhesive also plays an important role. High porosity can be obtained by using binders based on vinyl acetate, and it is for this reason that large quantities of vinyl acetate binders are used in the United States to coat folding boxboard, in spite of disadvantages such as low binding power, poor printability, and build up of stickys (“white pitch”) in the wet-end of the paper or board machine. The approach taken in Europe is to use styrene–acrylic and SB binders, which give a more compact, less porous coating, and to add special cobinders that form a porous film and aid glueability. The porosity of the films formed by acrylic-based products and their compatibility with acrylic and acetate-based adhesives give very good glueability when they are applied to folding boxboard.

5.2.5.9 Influencing Printability

The evenness of the printed image is a very important criterion for quality. The acceptance of coated paper by printers depends on its runnability in the printing process and its printability in terms of an even image that is free of defects (see also Chapter 24).

The printability of paper is principally determined by the surface of the coating, and its structure and topology, pore size and pore size distribution, chemical nature, and homogeneity all play an important part in influencing the interaction between paper and ink. The binder has the greatest influence on printability, but cobinders and thickeners also play a part and they have to be adapted to the printing process.

In offset litho, mottling is mainly caused by the uneven distribution of coating ingredients at the surface of the coating. There are different types of mottling depending on the causes and the way in which the mottling manifests itself. In gravure printing, missing dots can be avoided if the paper has a very smooth surface and a defined microscopic roughness.

In both printing processes, it can be assumed that cobinders and thickeners with very high water retention will have a detrimental effect on print quality. Very high water retention prolongs the drying time of the wet coating and the various different ingredients in the coating migrate at different rates, which cause the binder, cobinder, and thickener to become unevenly distributed. This patchiness gives rise to mottling in offset litho printing processes. Low web speeds and low

drying capacity tend to exacerbate this problem. Excessively high water retention can also give rise to a rough, uneven coating, which can cause missing dots in gravure printing.

There are no hard and fast rules with cobinders and thickeners when it comes to avoiding mottling. All natural and synthetic products can cause mottling under adverse conditions. Coatings that contain starch are known to have a high tendency to mottle, even if starch is only contained in the precoat. Soy protein behaves in a similar manner. Synthetic products are not usually prone to mottling, although CMC can give rise to missing dots in gravure printing processes.

5.3

Properties of Coating Colors

Coating colors have a very simple composition, although the interactions between ingredients are far from simple. A coating color consists primarily of pigments dispersed in water, plus binders, cobinders, and additives (see also Chapter 17). Calculations are, as a rule, based on the dry product, even if the actual ingredients deployed are mainly liquid commercial products with differing dry contents (proportion of active substances). The basis of calculation is 100 parts of pigment, to which all additions are referred. As an example 24 kg of commercial product binder must be added to 100 kg of dry pigment to obtain 12 parts of dry binder in the formulation if the synthetic binder has 50% dry content.

5.3.1

Coating Color Formulations

The main driving forces to develop new or improved coating color formulations are as follows:

- customer needs for improved coated paper quality such as higher brightness, print gloss, and bulk, better coating coverage;
- requirement of high uniformity of paper quality that calls for accurate process control during coating color formation, color application, and drying;
- trends in printing technology such as higher printing speeds or digital color printing;
- new developments in coating technology such as new coating methods or higher coating speeds requiring good coating color runnability and uniform coating color quality at the same time;
- need for less energy consumption in drying, which means higher solids content of coating colors; and
- environmental requirements including recirculation and reuse of coating colors.

Today, the need for cost reduction to maintain competitiveness has to be added to this list.

Coating color application requires its special formulation:

- 1) The solids content greatly influences the runnability of the coating color in the coating machine. The solids content basically influences the viscosity of the color and its flow behavior at varying shear stresses in the coating machine.
- 2) The various components of the coating color determine the highest possible solids content attainable for the target viscosity. The highest possible solids content is aimed for saving energy for drying of the coating color.
- 3) Most coatings are processed in the pH range 7.5–11.5. The alkaline range is preferred because most of the color components are anionic in character and, from a colloidal chemical viewpoint, form considerably more stable systems at higher pH values than at low pH values. In addition, the drying time in offset printing is greatly reduced with increasing pH, because of the oxidative drying system mostly used.
- 4) For nearly all coating processes, the water retention capacity of the coating color is most important, that is, the ability of the coating color to retain water in spite of the sucking action of the coating base paper. If the water retention capacity is too low, the coating color may be too strongly dewatered between application and leveling. This leads to an increased solid content of the coating color before it comes into contact with the leveling blade, which causes streaking and an uneven coat surface.

Coating color formulations and their solid content and properties differ according to the kind of application and coating process. Typical ranges of coating weight applied to the paper as well as solids content of the coating color for the various principles of pigmentation and coating are shown in Figure 17.18.

Another crucial factor in coating color formula design is the intended use, that is, the envisaged paper type and printing process. Formulations differ between matt and glossy grades, as well as for single or double coats with pre- and topcoats, and triple coats with precoat, intermediate, and topcoat. All coating color formulations aim for maximum solids content for quality and economic reasons. The coating color formulations listed in Table 17.16 are examples that are commonly used in Europe at present. However, they must usually be adapted to suit the particular conditions in the individual paper and board mills. All formulations are in dry parts of the individual substances. In many cases, coated web offset paper has to have high stiffness of paper and freedom from blistering and creasing, the latter especially for heat-set web offset. Manufacture of higher-weight papers such as Median Weight Coated (MWC) and Heavy Weight Coated (HWC) involves formulations similar to those used for wood-free grades.

Today, the costs are the most important factor in coating formulation. Depending on the quantities and grades of chemicals of different coating colors, their direct product cost can vary within a wide range:

- precoatings €400–500 per ton of coating (dry base)
- top coatings €450–600 per ton
- LWC coating color €400–500 per ton
- specialties €500–3000 per ton.

Generally, a coating recipe for offset or rotogravure printing papers consists of the following components (dry materials):

100	Parts of pigments (clay, calcium carbonate, talc, and TiO ₂)
0–0.3	Parts of dispersant
5–12	Parts of binders
0–1	Parts of thickener
0–1	Parts of lubricants (calcium stearate)
0–1	Parts of optical brightening agent (OBA)
0.01–0.05	Parts of shading dyes
0.01–0.1	Parts of defoamer/deaerator

More details about coating color formulations depending on the specific paper and board grades are discussed in Chapter 17.

5.3.2

Important Coating Color Properties

The shear-viscosity and viscoelastic properties of paper coatings and their time-dependent behavior are important attributes that need to be measured for better understanding and optimization of the process.

5.3.2.1 Viscosity

The viscosity of a fluid

- describes how pasty the fluid is;
- describes the resistance of a fluid against flow or deformation; and
- is determined by inner friction and cohesive forces.

It can be distinguished between pseudoplastic or shear thinning fluids or dilatant fluids. Usually, coating colors are expected to show a shear thinning behavior to make sure that newly formed structures in zones of high shear or elongation, as in filters, in the nozzles or under the blade do not lead to any kind of plugging that would influence runnability or paper quality.

In the case of extremely high solids contents, the pigments may jam as a consequence of external forces and thus lead to a dilatant coating color (Figure 5.24). Such “dilatancy humps” often can be measured at shear rates of some 100.0001 s⁻¹, when the solids content is elevated only by a fraction of 1%.

A dilatant behavior due to dewatering before or during metering of the coating color must be avoided, which practically is done by using thickeners to control the final viscosity instead of running at extreme solids contents, which are too close to the immobilization point.

Viscosity is measured with rheometers or viscometers. The methods used include rotational deformation, squeezing deformation, extrusion (capillary) flows, and free surface stretching. For rotational instruments, there are two modes of operation: controlled strain and controlled stress. Rotational measurements can be further

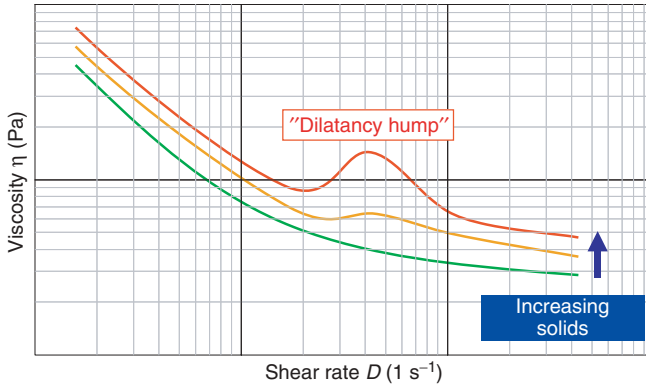


Figure 5.24 Shear thinning behavior of a typical coating color, which tends to be dilatant if the solids content is too high.

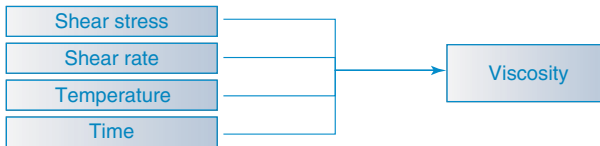


Figure 5.25 Measurement conditions determine the value of the measured viscosity.

subdivided into different measuring methods (flow, oscillatory, stress relaxation, and creep) and different measurement devices (spindle, cone-and-plate, parallel plate, and concentric cylinder). As for a capillary rheometer, there are two modes of operation: controlled flow (strain) and controlled pressure (stress).

The measurement conditions and devices have to be mentioned when the viscosity of a coating color is provided, because the viscosity depends to a large extent on shear stress, shear rate, temperature, and time (Figure 5.25).

5.3.2.2 Viscoelasticity

Viscoelasticity is not a physical property. Viscoelastic fluids exhibit both viscous (liquidlike) and elastic (solidlike) properties and show time-dependent deformation at constant stress and time-dependent stress at constant deformation.

Ideal elastic behavior is called *Hookean*, where the stress is directly proportional to the strain. A Hookean solid deforms as long as stress is applied. Once stress is removed, it fully recovers its original shape. This behavior can be modeled by a spring that stores energy under deformation and then releases it. Ideal viscous behavior is called *Newtonian*, where the stress is directly proportional to the rate of strain.

A Newtonian fluid flows as long as a stress is applied and retains its final shape once the stress is removed. This behavior is modeled by a dashpot that consists of a piston moving in a viscous liquid.

Paper coatings can be generally considered as viscoelastic fluids. The viscoelasticity of a material is most often measured by applying oscillatory shear instead of steady shear. There are two common types of oscillatory tests. A strain sweep test is carried out at a fixed frequency while the amplitude of the oscillation is varied. As the amplitude is increased, more energy (or shear) is applied to the sample. This energy may begin to break down the internal structure of the material. This is analogous to stretching a spring too far. The strain at which the coating structure begins to break down is called the *critical strain*, which gives some information on the nature of the internal structure of the material. For example, flocculated dispersions have critical strains of about 1%, polymer solutions have critical strains of about 10%, and polymer melts have critical strains of about 100%. Most paper coatings have critical strains of about 0.5–5%, indicating that their elastic behavior is a result of a weak network structure between pigment particles and/or thickener. The second common type of oscillatory test is a frequency sweep where the amplitude of oscillation is fixed while the frequency of oscillation is varied. The amplitude for the frequency sweep is chosen to be within the linear viscoelastic region, as determined by the amplitude sweep measurement.

An alternative way to measure the viscoelastic properties of a material is to apply a step change in stress or strain and then measure the response of the material over time. This is the basis for stress relaxation and creep testing of materials. In a stress-relaxation test, a constant strain (or shear) is applied for a period of time and then removed. On removal of the strain, the stress begins to relax. Typically, one measures the relaxation time needed for the stress to relax to half of its equilibrium value at long times. Closely related to stress relaxation is a stress-growth test. Here a sudden increase in strain is applied to the sample, and the growth in stress is monitored over time. Both stress-relaxation and stress-growth measurements are used to characterize paper coatings. A correlation between the stress-relaxation time and the healing of coating defects can be observed in practice: coatings with a shorter relaxation time (more fluid-like) show narrower residual widths of an induced blade streak. Stress-relaxation properties of a coating also correlate with improved leveling of orange peel patterns for high-speed metered film coatings.

5.3.2.3 Water Retention

During coating consolidation, the liquid coating color on the base paper transforms into an immobilized (stiff) coating layer. The runnability of a coating color in coating is determined by the properties of the liquid color, that is, wet coating structure, whereas the final quality of the coated paper depends on the dry coating structure. The transfer from wet to dry coating structure is a result of the aqueous phase penetrating from the coating color into the base paper and, later, due to evaporation on drying. A prerequisite for liquid transport in porous material is the presence of a driving force. Some common examples for water transport in paper are capillary pressure, external pressure, vapor pressure, concentration gradient, and temperature gradient. Several driving forces may be present at the same time, which makes the transport mechanism complex.

The various water retention measurement techniques can be divided into static (direct and indirect) as well as dynamic methods. The first provides a quantification of the amount of aqueous phase leaving the coating color and penetrating into the base paper. The measurement principle is based on filtration of coating color under the influence of external pressure. The indirect methods measure other parameters reflecting the penetration of aqueous phase into the base paper, such as electric conductivity, ultrasonic transmittance surface gloss, and coating viscosity. The dynamic techniques are usually based on measurement of solids increase in the coating pan or various scrape-off experiments during laboratory and pilot coater trials.

Some examples on the importance of water retention and the adjustment of coating color to the base paper are given in Chapter 17.

5.3.2.4 Solids Content

The right solids content of pigments is important as pigments are the biggest portion in the coating color recipe. The solids content of the coating color being too high or too low directly affects the coat weight, the runnability of the coating unit, and the necessary drying energy. Binder demand and a number of quality parameters also are influenced by the solids content.

The solids content is measured by drying a sample in an oven and calculating the amount of dry components as a percentage. Because the traditional oven method takes several hours to measure solid content, quicker methods have been developed for “just-in-time quality control.” In these quick methods, infrared and microwave drying are used.

5.3.2.5 pH

In practice, it is easy and quick to ascertain pH from aqueous suspensions and chemicals. However, pH is sensitive to temperature variations; therefore, pH measurements should be performed under constant conditions and the calibration rules of each individual pH gauge have to be followed carefully. The normal coating color pH is between 8 and 8.5, but higher levels are needed when using some synthetic thickeners or pH-dependent latexes. The ISO 787-9 method should be followed for pH value measurements.

5.3.2.6 Screening Residue

This is defined as the percentage of coarse particles in the measured material after screening through a given Mesh-number screen (e.g., for pigment slurries and finished coating colors a Mesh number of 300 is used, and for latex Mesh numbers 150 and 80 are used). If blade stripes or other similar coating problems occur, it is worth measuring the screening residue and determining whether any larger particles are mixed in the coating color.

5.3.2.7 Bacteria Level

A high bacteria level of coating color chemicals may influence the machine runnability. Furthermore, for coated paper that comes into contact with food, the

bacteria level has to be low. The bacteria level of a material can be counted by the so-called Easicult Combi test. This method of control is easier than doing a plate cultivation.

5.4

Coating Color Preparation

5.4.1

General Aspects of Coating Kitchen Set Up

The objective of a coating color preparation plant is to prepare the desired amount of coating color in the required quality using a combination of mixing, pumping, storing, conveying, metering, and screening processes. Such a plant consists of storage tanks, pipelines, pumps, valves, mixer, screens, and dosing equipment. Figure 5.26 shows the key processes starting from unloading chemicals to the coating color application.

In the coating kitchen, all raw materials needed for coating are combined in the requisite form and sequence. In the past, work in the coating kitchen was largely manual. Today, the same tasks are usually handled by a process-controlled system, without much human intervention except for monitoring. The mill operators can track every detail of preparation and coating operations. All the process data are stored for instant recall. This is to support uniform high quality by selection of the appropriate raw materials, their separate or joint preparation with strict adherence to timed dosing sequences, and clean working practices.

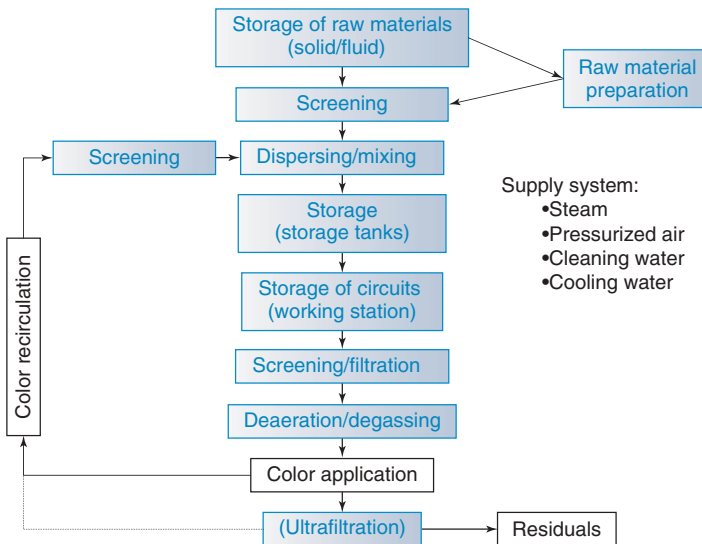


Figure 5.26 Steps in coating color preparation.

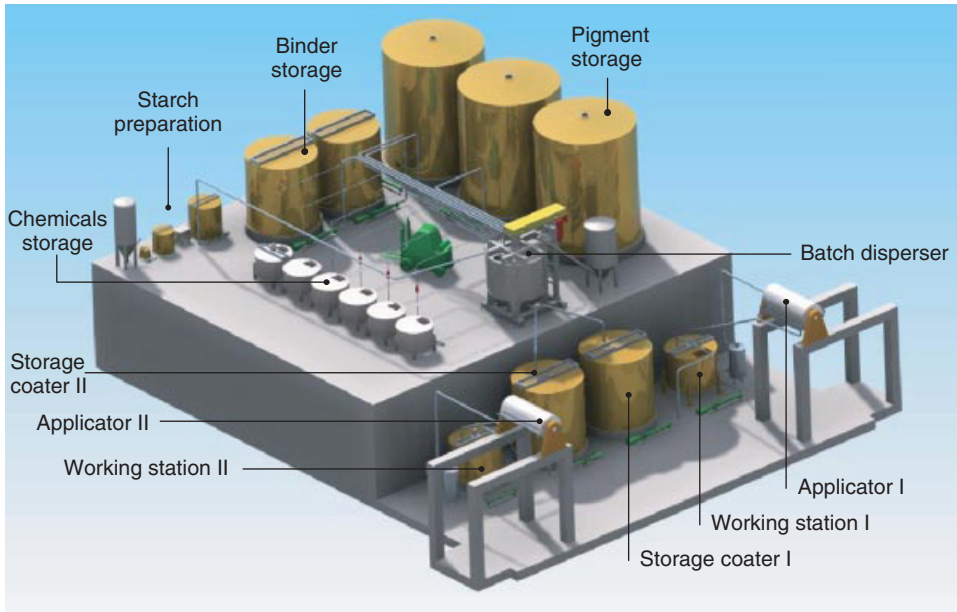


Figure 5.27 Model of a batch coating color preparation line. (Source: PGA).

Coating kitchens operate either batchwise or continuously. In view of problems such as dusting of powdery products and for operational reasons, many paper mills have switched from dry to liquid storage of their starting materials. This also brings the advantage that individual components can be precisely dosed. In every case, a special handling and make-up process for the individual products is necessary. In Figure 5.27, a model of a batch color preparation line is illustrated.

5.4.2

Dispersing of Pigments

These days, most of the pigments are delivered as slurries or dispersions with 60–78% solids. These pigments are very well dispersed by the suppliers. Pigments supplied in the dry form have to be carefully dispersed in the paper mill before being temporarily stored and converted in liquid form. Poor dispersing leads to problems such as blade scratches, excess rejects at screens, rheological fluctuations, and runnability disturbances at the coaters.

The first step in dispersing is wetting the particles, eliminating the air layers on the pigment surfaces. Water is absorbed into the agglomerate pores by capillary action. Chemical deflocculation will proceed slowly by diffusion. The resulting dispersion will not be homogenous and will contain agglomerates, which require physical stress to break them down. For good pigment dispersion at high dry solids content, a disperser is used to create the physical shear and mixing forces. Two examples of batch dispersers are shown in Figures 5.28 and 5.29. To achieve

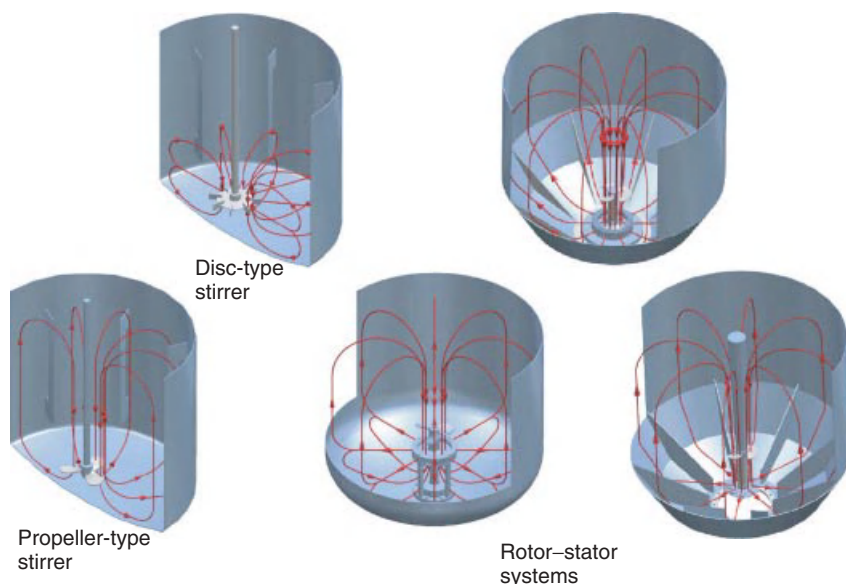


Figure 5.28 Different principles of dispersing units. (Source: PGA).

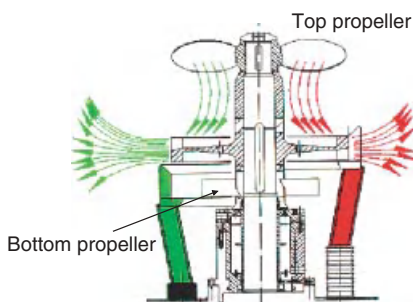


Figure 5.29 Principle of Rotor-stator dispersing with variable shear technology. (Source: GAW.)

the required high solids content of the coating colors, some chemicals, namely, dispersing agent and caustic soda, must be added to the suspension to improve and stabilize the dispersion.

A complete pigment make-down batch process is shown in Figure 5.30. Railway cars or truckloads are emptied into a hopper. The pigment is conveyed and dosed into a disperser by measuring the weight of pigment with load cells. The same is done with the feed water and dispersing agent plus pH-control chemical. After dispersion, the content of the disperser is emptied into an intermediate tank. Screening is a continuous process to ensure maximum capacity and screening efficiency. From the screens, the slurries go to a screening tank. The slurry will

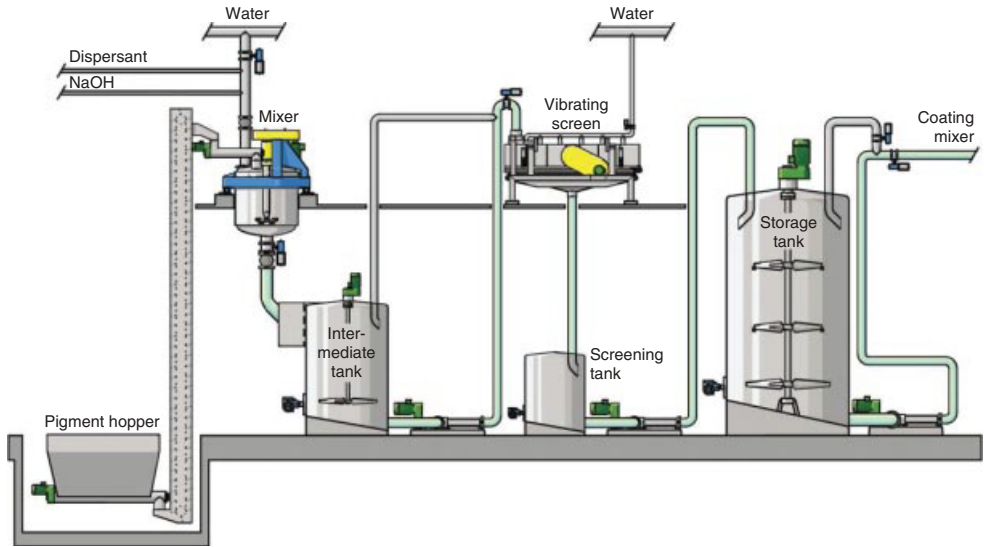


Figure 5.30 Pigment make-down process. (Source: Metso).

then be pumped to a large storage tank where it waits for pumping and dosing into the coating color mixer.

5.4.3

Processing of Binders

5.4.3.1 Latexes

Latexes are delivered by the manufacturers as a water-containing dispersion of polymerized synthetic chemicals at dry solids levels of approximately 50%. Latexes contain certain surface-active chemicals, and the main task in coating color preparation is not to disturb or break their balance. This means that the whole handling must be clean and without any harmful chemicals. For delivery and storage of the different latexes, a truck or railway car is emptied, using either its own pumps or a pump from the mill. The storage capacities of latexes are optimized according to their consumption. Normally, these storage tanks are made of stainless steel and not equipped with any agitators. From these storage tanks, latexes are pumped and screened into the coating color mixer.

5.4.3.2 Starch

Starch has been one of the most popular binders for decades, because it is a cheap product, especially when using low-cost unmodified starches. These grades are normally sold at lower costs than pulp. Starch is also a very flexible material and a paper or board coating mill can convert it to their specific coating requirements. The starch producing companies can also modify starch by introducing esters or ethers of starch. A special feature of starch acetates for the paper industry is that these

Table 5.7 Basic characteristics of starch.

	Potato	Barley	Wheat	Corn	Waxy maize	Tapioca
Source	Tuber	Grain	Grain	Grain	Grain	Tuber
Particle size (m)	10–100	10–35	3–35	5–25	4–30	3–30
Gelatinization temperature (°C)	60–65	80–85	80–85	75–80	65–70	65–70
Moisture at 65% RH (%)	19	13	13	13	13	13
Protein (%)	0.05–0.1	0.3–0.5	0.3–0.5	0.3–0.5	0.2–0.4	0.05–0.1
Fat (%)	0.05	0.4	0.8	0.7	0.2	0.1
Ash (%)	0.3–0.4	0.1–0.2	0.2–0.4	0.1–0.2	0.1–0.2	0.2–0.3
Phosphorus (%)	0.08	0.02	0.06	0.02	0.01	0.01

ester groups are efficient in preventing amylose retrogradation (see below). They have extremely good viscosity stability. An ether starch, for example, is appropriate for its good film-forming property or holdout of organic solvents.

Native or unmodified starch dispersed in cold water settles out rapidly due to the lack of solubility. A dispersion of starch in water has no adhesive power. To become an adhesive, the starch has to be heated in water above the gelatinization temperature of the starch, which differs depending on its plant origin (Table 5.7). When a starch suspension is heated beyond the gelatinization temperature, the individual starch granules begin to swell and, after a time, a colloidal sol or starch paste is obtained with adhesive and binding properties. The hot gelatinized starch paste is a non-Newtonian fluid. A starch paste derived from unmodified starch has relatively high viscosity at very low solids concentration. In practice, it is nearly impossible to prepare a manageable starch paste exceeding 7% unmodified starch. With time and temperature decrease, an increase in viscosity or thickening can be observed. This thickening is due to a well-known phenomenon for all unmodified starches called *setback*. It occurs because during thermal decomposition, for example, gelatinization, the original crystalline arrangement of the starch molecules is lost. When cooling the starch paste, the molecules cling together again, thus forming insoluble aggregates. As a result of this crystallization process, the paste solution gradually turns turbid, while the viscosity increases. Finally, the viscous paste turns into an opaque mass or gel. In very dilute solutions, there is not enough material to gel the entire solution, and so insoluble starch particles sink to the bottom. It is mainly the linear amylose molecules that exert this usually undesirable tendency, called *amylose retrogradation* or *simply retrogradation*, which is an irreversible process. To prevent retrogradation effectively, modification of the starch is necessary. Methods to reduce and stabilize the viscosity of starch by gelatinization and depolymerization are discontinuous or continuous cooking processes. All starch cooking applications involve an initial dispersion of starch in water to give a slurry. According to the intended application of the starch, the slurry concentration will vary between 5% and 40% dry substance.

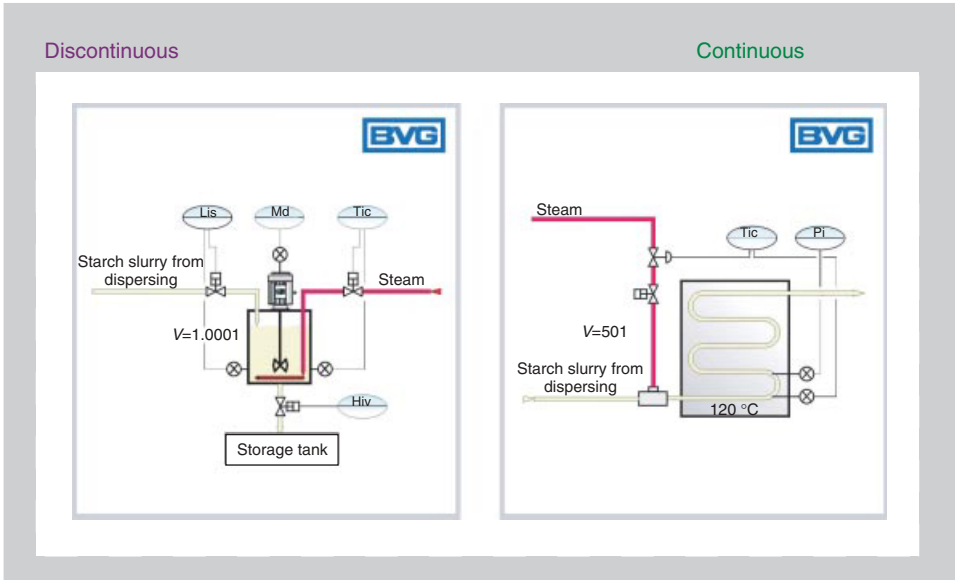


Figure 5.31 Starch cooking process (a) discontinuous and (b) continuous. (Source: BVG).

The batchwise cooking of modified starch takes place unpressurized at temperatures about 95°C for approximately 30 min under good stirring conditions (Figure 5.31a). Continuous starch cooking is done in the so-called jet cooker at a steam temperature of approximately $120\text{--}130^{\circ}\text{C}$. The steam immediately interacts with the starch in a Venturi tube and the gelatinization is completed within a few seconds (Figure 5.31b). Another common possibility is the enzyme conversion of native starch, again done either discontinuously or continuously. With the aid of highly active protein molecules from bacteria, the so-called α -amylase, the starch molecules are broken up at $70\text{--}85^{\circ}\text{C}$ and the enzyme must be inactivated after approximately 10–20 min, to stop further breakup. The inactivation can take place through the addition of acids and holding at 95°C for 10–15 min or by swift heating up to 130°C . A continuous starch cooking and converting system is shown in Figure 5.32.

5.4.3.3 Other Binders

PVA and *proteins* are delivered to the paper or board mills as dry powder in sacks or big bags. The handling system for these products has the same features, cooking with steam, as starches. The key equipment here for the batch process is a heavy-duty mixer with steam inlet tubes for even distribution of steam bubbles. The product slurries are heated to $90\text{--}100^{\circ}\text{C}$ with direct steam heating and then held at this temperature for 20–30 min, until there is a clear solution of the product in the batch cooker. For example, the PVA solution has a viscosity maximum at temperatures of $65\text{--}75^{\circ}\text{C}$. The major difference between PVA and starch cooking is that in a PVA cooking system the molecular structure or polymer chain length is

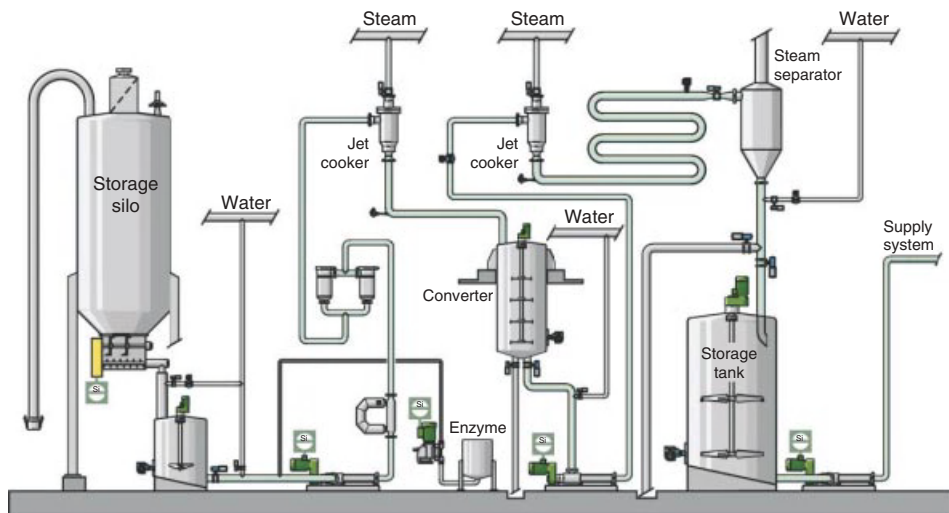


Figure 5.32 Continuous starch cooking and converting process. (Source: Metso).

not altered. The hot PVA solution is also held warm in its storage vessels to avoid viscosity changes due to decrease in temperature.

The key control parameter of a protein solution is the solids content; therefore, the metering of water and protein powder must be accurate. Some pH-controlling chemicals must be added to have the right caustic process conditions. Typical protein processing parameters are 10–25% solids content, alkali amount (one-third of sodium hydroxide and two-thirds of ammonium water) around 7% of the protein, heating to 60 °C and holding at this temperature for between 15 and 30 min. The protein will be cooked until the binder is a lump-free solution.

5.4.3.4 Additives

Additives are, for example, CMC, flow modifiers, pH-controlling chemicals, preservatives (biocides), defoamers, deaerators, dyes, and optical brighteners. All products except CMC are delivered as solutions, emulsions, or dispersions. Their concentration can be suitable for direct metering into the coating color preparation, or they may be diluted to a lower concentration to improve the metering accuracy or to avoid shocks caused by too strong chemicals. Therefore, proper investments in handling and metering systems of these additives have to be made.

5.4.4

Tanks

The mixing, storage, and circulation tanks for coating colors are made of stainless steel, since the pH range of raw materials and coating colors tends to corrode standard steels. Most vessels are equipped with an agitator, and some also have a shell/jacket that may be heated or cooled. Agitators are mostly indispensable

because, in low-viscosity colors especially, solid color components are prone to sedimentation unless the suspension is stirred continuously.

5.4.5

Screens and Filters

Impurities of any kind in coating colors may lead to serious problems in coating machines, and so these contaminants have to be removed by means of either open vibrating screens (Figure 5.33) or closed filters (Figure 5.34). Open screens are frequently preferred, because the retained dirt is visible and defective screens can be quickly replaced. However, there is a risk of air becoming entrained with the coating color. In addition, color splashes and blocked screens can heavily contaminate the immediate environment. Closed filters are clean by comparison. In parallel arrangement, they incorporate pressure controls and automatic backwashing functions. In everyday practice, color losses inevitably occur during backwashing. In addition, retained dirt particles can only be identified after filter cartridges are removed. Whichever system is chosen, the mesh of screens or filters has to be small enough to retain all particles $>50\ \mu\text{m}$.

In modern coating kitchens, the various starting materials are usually pre-screened over mesh widths about $50\text{--}60\ \mu\text{m}$ before the finished coating color is passed through $100\text{--}150\ \mu\text{m}$ screens or filters in the circulation system. Smaller mesh sizes are inadvisable, because they would largely restrict the passage of the highly viscous color. Coarser screens are frequently installed in the coater recirculation system to retain scraps of paper that may have been introduced into the coating circuit after web breaks.

5.4.6

Degassing of Coating Colors

Coating colors contain air and gas bubbles of various sizes that originate from the raw materials and turbulence during color preparation. Gas content can vary greatly: 10–15% by volume is typical, although it may exceed 35% in extreme cases. Gas levels in coatings have become a major quality issue since the introduction of

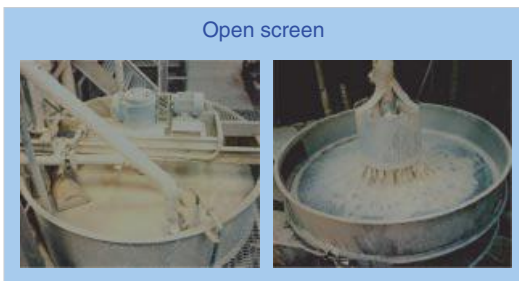


Figure 5.33 Open screen for filtration of slurry/coating color. (Source: Omya).

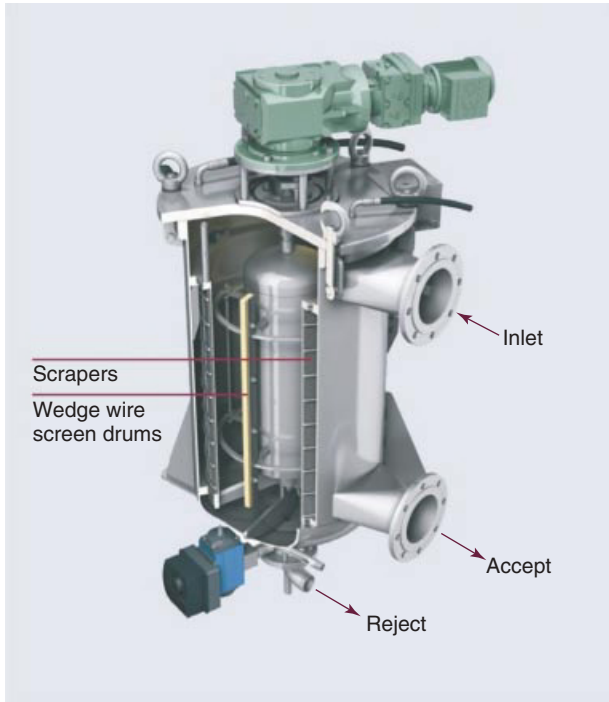


Figure 5.34 Closed filter system. (Source: Metso).

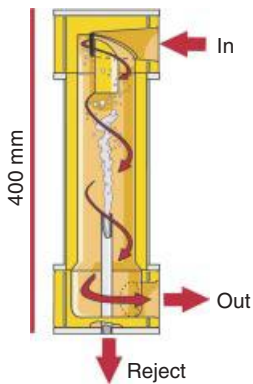


Figure 5.35 Degassing cyclone. (Source: Metso).

new jet applicators because every air or gas bubble leaves a crater in the coating surface. This compelled papermakers to install online degassing equipment in coaters with jet applicators. Most of the degassing systems are based on the density differences in a centrifugal field of a cyclone (Figure 5.35). Modern systems are capable of reducing gas levels to 4%. The efficiency of such physical degassing apparatuses will be further improved by the additional use of chemical deaerators.

5.4.6.1 Vacuum Degassing for Curtain Coating

The curtain coating process requires a coating color that is free of gas bubbles. Any bubble will be visible on the paper surface because there is no force destroying these bubbles after the application process. Today, vacuum deaerators are in use, but experiences are also gathered with membrane degassing devices.

5.4.7

Batch Preparation of Coating Colors

All components of the coating color formula are pumped from their storage tanks into a mixer and hereby screened once again. A recirculation pipe installed between the component storage tank and the mixer is used for those chemicals that have a settling tendency, such as pigment slurries, or to keep certain products homogeneous in their temperatures and concentrations, such as starch, CMC, or proteins. The mixer is placed on load cells to accurately measure the batch sizes and weights of the major components. Other precise ways to dose the additives are mass flowmeters and metering pumps. In batch processes, these metering devices can be optimally calibrated and dimensioned because the flow rates are normally kept constant and the dosing time is varied depending on the amount of each additive used in a coating color formula. Batch processes are also very flexible for a wide dosing range of each component. The difference between the maximum and minimum rates does not negatively influence their accuracy or the flexibility. One set of metering instruments and valves can easily be used to serve two mixers optimizing investment costs and space in the coating color kitchen. The flexibility of a batch process is obvious in cases where the rheological or other properties of coating colors have to be changed by altering the order of addition of the same chemicals. The mixing time and mixing energy can also be easily changed (Figure 5.36).

5.4.8

Continuous Coating Color Preparation

The major advantage of a continuous process is the smaller size and thus lower cost of pumps, valves, flow meters, and pipings. The so-called calibration systems for each line ensure the metering accuracy and are fully automated. These continuous systems are most effective in high-capacity coating with large volumes of coating colors with the same color quality, such as in a one-grade paper mill. Here, the number of different coating colors is low and, if there is a grade change, different coatings are usually allowed to be mixed with each other. This continuous system differs from a batch process in many aspects: The components of coating colors are continuously pumped, screened, and metered into a continuous mixer. Besides the size difference of the piping equipment, the mixers are completely different because mixing must be completed during the short time when the components are passing through the mixer. It is equipped with high-shear, high-energy mixing

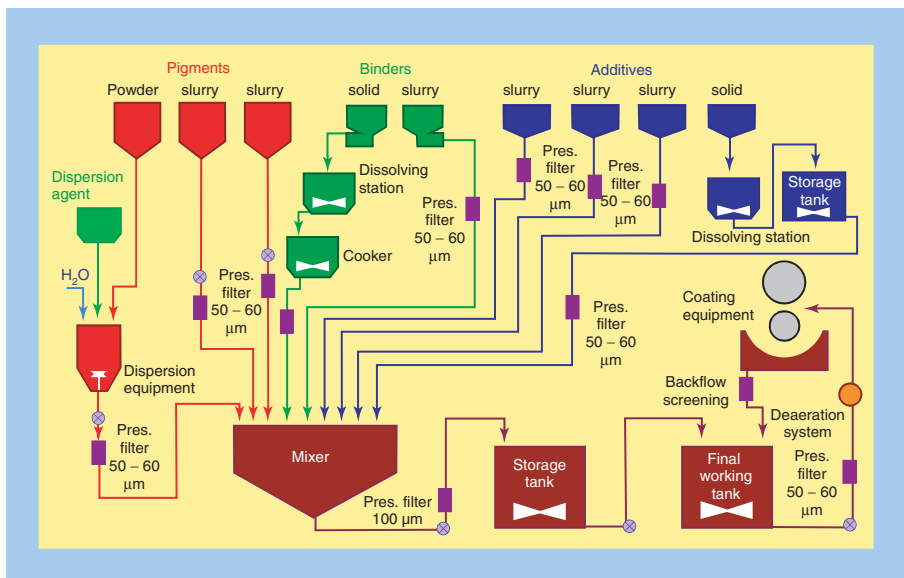


Figure 5.36 Batch preparation of coating colors. (Source: Metso).

zones, usually two, or two separate mixers in series are operated. Dosing of all additives is crucial for constant coating color quality; they are metered with mass flow meters, magnetic flow meters, or metering pumps. The mixer feeds its ready-made coating color directly to the coater supply tanks, which results in a low storage volume of processed coating color (Figure 5.37). The advantages are fast control measurements of the coating color properties and the possibility of quick changes in the color composition. On the other hand, the range of volumetric capacity of each chemical line is strongly limited for a given installation. Lower fixed costs for construction and equipment and lower variable costs (energy) are important factors that favor continuous operation; reaction times of ingredients and experience often favor batch operations.

5.4.9

Coating Color Supply Systems for Coaters

The basic function of the coater supply system is to supply coating color to the coating heads to be evenly spread on the paper or board web. In most cases, only about 10% of the pumped coating color will be applied onto the running fiber web. About 90% of the coating color flows back to the supply tank. This high internal coating color recirculation is required to ensure homogenous and constant color properties for trouble-free coater operation. The feed of the fresh color into the supply tank is controlled by its level. From the supply tank, the coating color will be pumped first to the screens, which eliminate all impurities larger than 50 µm, depending on the geometry of the screening elements. The second key process is

degassing of the coating color. Depending on the design of the coating heads, the coating color flow is led to the ponds or chambers through one or two inlet pipes (Figure 5.38) controlled by a throttling valve for accurate flow. The overflow goes back freely to the supply tank. The contents of solids and gas as well as temperature and pH and their variations are monitored continuously.



Figure 5.37 Continuous preparation of coating colors. (Source: BVG).

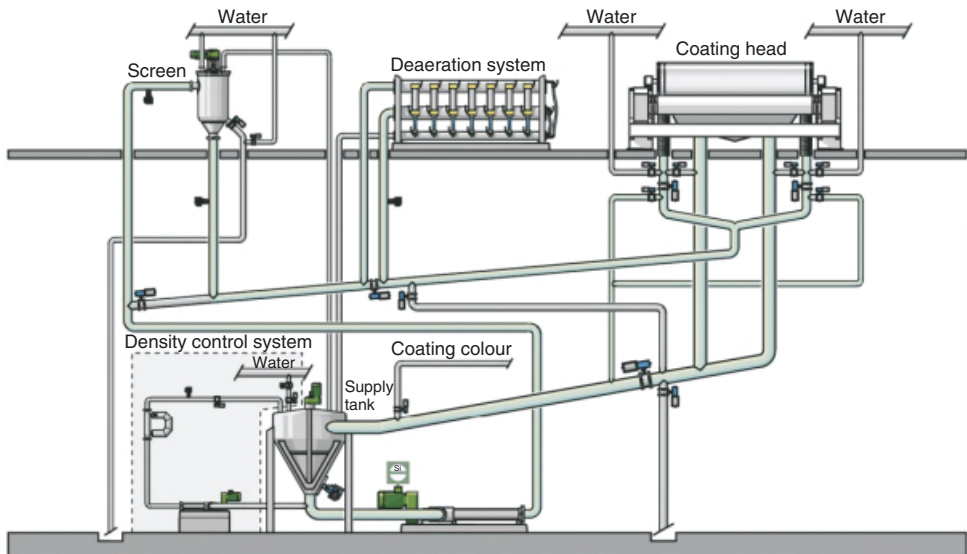


Figure 5.38 Coating color supply system. (Source: Metso).

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6 Process Chemicals

6.1 Overview

Roland Pelzer

Process chemicals are used to ensure a proper run on the paper machine to produce the desired paper quality at maximum output. With the global trend to neutral pH paper manufacturing (driven by the increasing use of cheap calcium carbonate fillers), the consumption of aluminum compounds, in particular, that of aluminum sulfate has dropped. However, in a number of production sites, including sites that have taken up pH neutral manufacturing, these products are still used. All other chemical additives discussed in this chapter have growth rates higher than that of paper production, driven by the pressure to ensure maximum machine productivity.

6.2 Aluminum Compounds

Hubert Dörrer

Aluminum compounds have been known since ancient times. Egyptians reportedly used the coagulant alum as early as in 1500 BC to reduce visible cloudiness (turbidity) in water [1]. Pliny the Elder describes alum as an antiperspirant and deodorant [2]. Aluminum is the third most abundant element of the earth's crust and surrounds us everywhere.

Owing to the high cationic charge of the aluminum ion in water and the white color of the hydrolysis end product, aluminum hydroxide, the benefits of the application of aluminum salts in paper manufacture are various, such as

- purification of circuit water by flocculation
- reduction of anionic trash in the circuit water by adsorption to the aluminum hydroxide
- rosin sizing
- retention aid
- cleaning of sewage water.

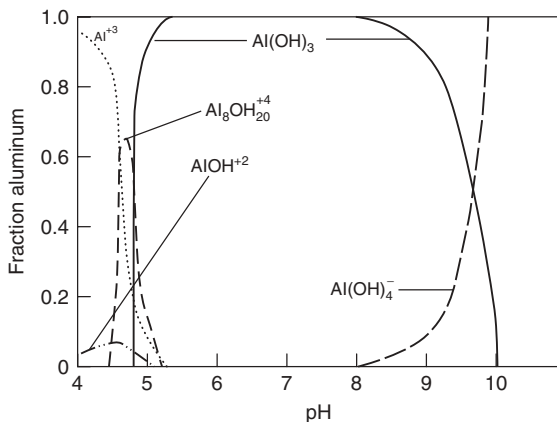
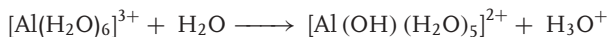


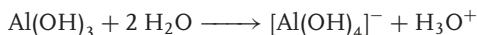
Figure 6.1 Alum species as a function of pH.

The high cationic charge of the aluminum ion is able to destabilize suspensions; aluminum hydroxide adsorbs small particles and partly dissolved molecules containing dipoles and incorporates them into flocs. The aluminum hydroxide flocs, together with the adsorbed material, may be retained in the paper or removed in water treatment devices by microflotation.

In water of low pH, the aluminum ion exists as an octahedral hexa-aquo complex. With increasing pH, the behavior of aluminum in water can roughly be described as follows:



Further formation of aluminum hydroxide takes place via dimer and oligomer aluminum hydroxide hydrate species [3]. Increasing the pH into the alkaline region above pH 9, the aluminate ion with negative charge is formed:



Figures 6.1 and 6.2 both give an overview of the different species formed as a function of pH.

Aluminum salts can be described in terms of the molar ratio of hydroxide to aluminum, if they do not contain other cations. Another description uses the term *basicity*, which is defined by

$$B = (n_{(\text{OH})} / (3n_{\text{III}} + 2n_{\text{II}} + n_{\text{I}})) \cdot 100$$

B , basicity in percentage

$n_{(\text{OH})}$, moles of OH

n_{III} , sum of moles of trivalent cations

n_{II} , sum of moles of bivalent cations

n_{I} , sum of moles of monovalent cations

In simple words, the basicity describes the amount of “preneutralization” of these kinds of salts. Stoichiometric salts have a basicity of 0%, aluminum hydroxide has a basicity of 100%.

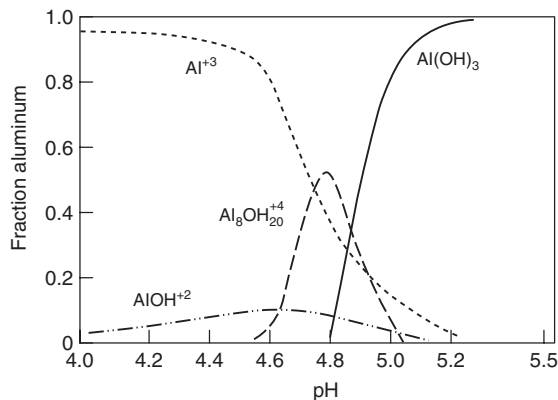


Figure 6.2 Alum species in the pH range of acidic paper manufacturing.

Aluminum chloride and aluminum chloride hydroxide are examples of typical products containing only aluminum as cation (Table 6.1):

Table 6.1 Basicity of Polyaluminum Chloride (PAC).

Basicity (%)	Salt	Acidity of the product
0	AlCl_3	High
40	$\text{Al}(\text{OH})_{1.2}\text{Cl}_{1.8}$	Medium
70	$\text{Al}(\text{OH})_{2.1}\text{Cl}_{0.9}$	Low
83	$\text{Al}(\text{OH})_{2.5}\text{Cl}_{0.5}$	Very low

As a rule of thumb it can be stated that the higher the basicity, the quicker is the formation of flocs and therefore more care has to be taken for proper distribution of the aluminum salt into the water to be treated. Aluminum salts of low basicity have a bigger acidic influence on the pH of water than those with higher basicity.

Aluminum compounds used in flocculation and paper manufacturing are listed in Table 6.2.

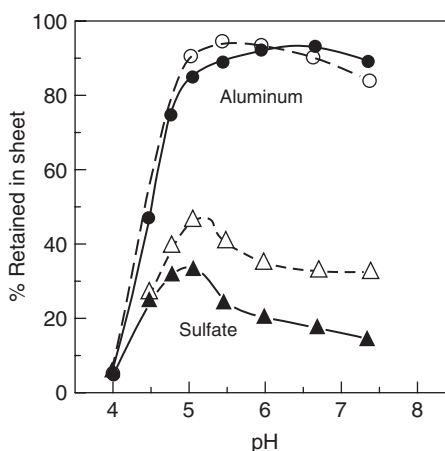
Sodium aluminate in solution and powder forms is the only commercially relevant alkaline aluminum compound used in papermaking and water treatment. Sometimes, the use of sodium aluminate is used together with aluminum sulfate achieves good results in cleaning circuit water.

Aluminum sulfate and aluminum chloride hydroxide are the mainly used aluminum salts in paper manufacture and water treatment. Other anions in the salts are used to reach different goals. For example, aluminum formates are used to give paper a mild hydrophobic effect and aluminum nitrates are used to prevent malodors caused by anaerobic degradation.

The use of alum products in papermaking impacts the level of sulfate or other counterions mentioned in Table 6.2. In Figure 6.3, the retention of aluminum is plotted against pH-value showing the simultaneous influence on sulfate retention.

Table 6.2 Commercially Available Aluminum Compounds.

Substance name	Chemical formula	
Aluminum sulfate	$\text{Al}_2(\text{SO}_4)_3$	Available as solution and powder
Aluminum hydroxide sulfate	$\text{Al}_2(\text{OH})_x(\text{SO}_4)_{(3-x)/2}$	Available as solution
Aluminum chloride	AlCl_3	Available as solution and powder
Aluminum hydroxide chloride	$\text{Al}(\text{OH})_x\text{Cl}_{(3-x)}$	Available as solution
Aluminum hydroxide chloride sulfate	$\text{Al}(\text{OH})_x\text{Cl}_{(3-1/2y-x)}(\text{SO}_4)_y$	Available as solution
Sodium aluminate powder	$\text{NaAlO}_2 \cdot 0.25 \text{Na}_2\text{O}$	Available as powder
Sodium aluminate solution	$\text{NaAl}(\text{OH})_4 \cdot x\text{NaOH}$	Available as solution
Aluminum nitrate	$\text{Al}(\text{NO}_3)_3$	Available as solution
Aluminum hydroxide nitrate	$\text{Al}(\text{OH})_x(\text{NO}_3)_{(3-x)}$	Available as solution
Aluminum hydroxide nitrate sulfate	$\text{Al}(\text{OH})_x(\text{NO}_3)_{(3-2y-x)}(\text{SO}_4)_y$	Available as solution
Aluminum triformate	$\text{Al}(\text{HCO}_2)_3$	Available as solution or powder
Aluminum hydroxide formate	$\text{Al}(\text{OH})(\text{HCO}_2)_2$	Available as solution

**Figure 6.3** Aluminum and sulfate retention in the paper as function of the pH-value [4].

This impact has to be taken into consideration, as chloride may be a source of corrosion and excessive sulfate could be utilized by anaerobic microbes to form H_2S . Alum compounds with nitrate as counterion have been introduced in the market to avoid both these problems.

The benefit of alum compounds in papermaking can be summarized as

- fixation of interfering substances
- retention of fines and fillers
- fixation of rosin size
- support of alkenyl succinic acid anhydride (ASA) sizing

- fixation of internal starch
- optimization of retention and drainage.

6.3 Retention Aids and Drainage Accelerators

Jan-Luiken Hemmes

6.3.1 Functionality

The main functional reason for using retention and drainage chemicals in papermaking is to assist and enhance the mechanical filtration of fibers on the paper machine's wire and press sections. If one compares the dimensions of the paper machine wire openings to the fibers, fillers, and fines in the paper stock (Figure 6.4), it is easily understood that effective sheet formation and water removal needs flocculation of the fines material onto the fibers. This can be achieved by different chemicals that work according to different flocculation mechanisms.

The main advantages of retention and drainage chemicals for paper manufacturing are as follows:

- increased first-pass total and ash retention and reduced losses of solids;
- improved dewatering;
- increased efficiency of all other paper chemicals (sizing, fixation, deaeration, colorants, and fluorescence whiteners);
- reduced fines and filler load in the short circulation and as a consequence reduced deposit formation and reduced frequency of downtime for boil-outs;

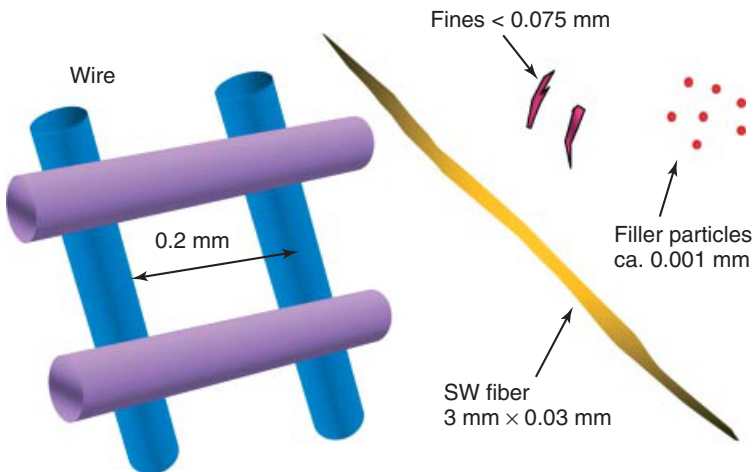


Figure 6.4 Dimensions of wire openings and main paper stock components SW, softwood fiber.

- more stable wet end system and smooth response of online retention control, resulting in more stable paper quality;
- more efficient wastewater treatment and clarification.

In the early days of papermaking with slow machine speed and low shear forces, alum was the preferred retention and dewatering chemical. It is effective in coagulating the pulp suspension by charge neutralization and fixation of anionic material to the fibers. However, with increasing shear forces and highly effective mechanical drainage and pressing, new and more complex mechanisms had to be additionally introduced to make the flocculated pulp survive the process conditions.

6.3.2

Chemistry

An overview of the most important retention chemicals and their chemistry is summarized in Table 6.3. Retention chemicals are usually nonionic, cationic, or anionic water-soluble polymers of high molecular weight. The dominating polymers are polyacrylamide (PAM) and polyethyleneimine; these can be produced with very high molecular weight and charge densities, which is important for high efficiency of the retention polymer.

PAMs are obtained by the copolymerization of acrylamide with various derivatives of acrylic acid, such as acrylic salts or sulfonate-modified acrylamides to yield anionic polymers, ammonium salt-modified acrylic esters, and acrylamides for cationic products. Global production of water-soluble synthetic polymers for paper and board is around 260 kt a⁻¹. The value of the world consumption of retention and dewatering chemicals is difficult to estimate because many of those products are also used as strength agents or fixatives; however, close to 70% is covered by PAMs (Figure 6.5).

There is a smaller group of other polyelectrolytes including various modified polyamines, polyethyleneoxide (PEO), polyamidamines, polydimethylammonium-chloride (p-DADMAC, and, more recently, polyvinylformamide copolymers such as polyvinylamines (PVAMs). These products are used as retention components or dewatering additives alone or in formulations with other chemicals.

Additionally, micro- or nanoparticles with high specific surface have been developed for more than two decades. These are usually colloidal solutions of polymeric silica or modified bentonite clays. Owing to their role in the complex flocculation process to form very small aggregated flocs – leading to papers with high retention, fast dewatering, and improved formation – they have been used first in graphical grades. Microparticle technology is now also being applied more and more in the manufacture of packaging grades.

The newest systems on the market are organic micropolymers, developed to balance the controversy of retention and formation by specifically responding to filler/ash retention and uniform ash distribution in the sheet.

Table 6.3 Chemistry of Common Retention Polymers.

Product	Chemistry	Structure	Charge	Molecular weight (Mio D)
CPAM cationic polyacrylamide	Copolymers of acrylamide, DiMAPA	$\left[\begin{array}{c} \text{---CH}_2\text{---CH---} \\ \\ \text{C=O} \\ \\ \text{NH}_2 \end{array} \right]_n \left[\begin{array}{c} \text{---CH}_2\text{---CH---} \\ \\ \text{C=O} \\ \\ \text{NH}_2 \end{array} \right]_m \text{---N}^+\text{---(CH}_2\text{)}_3\text{---N}^+\text{---(CH}_3\text{)}_3 \text{Cl}^-$	0–5.5 meq g ⁻¹	0.6–14
APAM anionic polyacrylamide	Copolymers of acrylamide, acrylic acid	$\left[\begin{array}{c} \text{---CH}_2\text{---CH---} \\ \\ \text{C=O} \\ \\ \text{NH}_2 \end{array} \right]_n \left[\begin{array}{c} \text{---CH}_2\text{---CH---} \\ \\ \text{C=O} \\ \\ \text{O}^- \end{array} \right]_m \text{Na}^+$	0–7 meq g ⁻¹	0.6–14
PEI polyethyleneimine	Polymer of ethyleneimine	$\text{---N---CH}_2\text{---CH}_2\text{---N}^+\text{---CH}_2\text{---CH}_2\text{---N}^+\text{---CH}_2\text{---CH}_2\text{---N}^+\text{---} \\ \quad \quad \quad \quad \\ \text{(CH}_2\text{)}_2 \quad \text{H} \quad \text{H} \quad \text{H} \quad \text{H}$	6.5–17 meq g ⁻¹	0.5–2
PAAm polyamidoamine	Copolymer of acrylic esters and amines	$\text{---[CH}_2\text{---CH}_2\text{---C---N---CH}_2\text{---CH}_2\text{---N]}_n$	1.8–2 meq g ⁻¹	0.5–1.2
PVAm polyvinylamine	Hydrolysis of poly vinylformamide	$\text{---[CH}_2\text{---CH---CH}_2\text{---CH}_2\text{---} \text{]}_{n/2} \\ \quad \\ \text{CHO} \quad \text{NH}_2$	Up to 23 meq g ⁻¹	0.1–30
PEO polyethylenoxide	Polymer of ethylenoxide	$\text{---[CH}_2\text{---CH}_2\text{---O]}_n$	Nonionic	1–10
p-DADMAC polydiallyldimethylammonium chloride	Polymer of diallyldimethylammonium chloride	$\text{---[CH}_2\text{---CH---CH}_2\text{---CH}_2\text{---} \text{]}_{2n} \\ \quad \quad \quad \\ \text{CH}_2\text{CH}_2 \quad \text{CH}_2\text{CH}_2 \quad \text{N}^+\text{Cl}^- \quad \text{CH}_3$	5.9–6.3 meq g ⁻¹	0.1–1.8

See section Abbreviations.

Global market value for retention and drainage chemicals

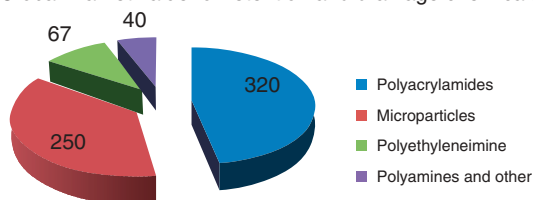


Figure 6.5 Global market value (in Mio€/year) for retention and drainage chemicals (starch and inorganic coagulants are not included).

6.3.3

Application

As high molecular mass creates high viscosity even at low polymer concentration, water in oil emulsions and solid polymers in the form of granules or small beads have become important owing to easier handling and reduced transportation costs.

The function of retention and drainage chemicals and their suitability for the specific paper stock composition depends on their ability to interact with paper stock components forming flocs of different size, density, and stability against shearing. Apart from straightforward charge neutralization, which leads to agglomeration of small as well as colloidal particles, two other important mechanisms that lead to flocculation and coagulation are generally used – bridging and patch charge.

Flocculation by bridging for linear polymers with lower charge density, especially when they have high molecular weights. It results in effective retention at very low polymer dosages but has the disadvantage of poor formation of the paper and is further impaired by high mechanical shear. Patch charge flocculation is achieved with polyelectrolytes of high positive charge densities and medium molecular weights (Figure 6.6). This creates areas of positive charge on negatively charged surfaces, which leads to flocculation by the attractive forces of oppositely charged areas on particles when they approach each other. Through mechanical shear in the process, initially large flocs are dispersed and smaller secondary flocs are formed. The result is better formation but lower overall retention and dewatering – depending on the shear history, pulp components, and polymer chemistry involved.

Typical retention polymer dosages are in the range of 100–500 g of polymer per ton of paper. In graphical papers where high filler levels are employed, additionally 1–4 kg t⁻¹ of microparticles are typically dosed.

Anionic microparticles have been developed during the past 30 years to improve retention, dewatering, and, most importantly, formation. They support the reflocculation of the shear-treated primary flocs usually induced by cationic retention polymers into small tight flocs, which attach to the furnish components and promote open and uniform sheet structure.

Agglomeration		Patch charge flocculation		Bridge flocculation	
	Destabilization by coagulant		Local charge reversion by polymer absorption		Polymer absorption in loop and tail configuration
	Examples : PAC, Alum		Examples : PEI, p-DADMAC		Examples : PAA with high MW and lower charge
	Particles are destabilized by charge neutralization		Particles are destabilized by interaction of anionic and cationic sites		Particles are destabilized by polymer chains connection several particles
	At higher concentration of coagulant redispersion is possible.		Stronger and more stable flocs, reflocculation after shear		Big flocs, poor reflocculation after shear

Figure 6.6 Retention mechanisms.

The newest developments in retention technology are the so-called micro-polymers. These new anionic or cationic combinations of retention polymer formulations have been introduced as a tool to further enhance retention and dewatering. Micropolymers, as an additional component of a retention system, induce a selective response to filler and fines retention and have a smaller negative impact on sheet uniformity. This is achieved by a complex mechanism of initial flocculation, shear dispersion, and reflocculation that needs to take place with an optimized design of dosing sequence and concentration of all components involved. The value for the papermaker is that higher filler retention, better filler distribution, and thus better sheet properties can be achieved.

6.3.4

Trends

Higher filler loading, in general, and the trend to replace lightweight coated (LWC) printing papers with highly filled supercalendered (SC) mechanical grades in publishing is driven by cost as well as the need for improved optical and print properties of papers. As filler content in the sheet increases, the need for higher amounts and more functionally developed retention chemicals grows.

While process water systems get more and more closed, and more recycled fibers are used in packaging as well as graphical grades, new technologies will have to evolve in order to cope with the high levels of conductivity, colloidal impurities, and anionic trash material. Continuous measurements of changes in the furnish and control of process chemistry will allow to optimize dosing costs and balance retention and dewatering chemicals with broke treatment, process water treatment, and functional chemicals employed.

Abbreviations

APAM	Anionic polyacrylamide
CPAM	Cationic polyacrylamide
DiMAPA	Dimethylaminopropylacrylamide
Meq/g	Milliequivalents per gram
Mio D	Million daltons
PAAm	Polyamidoamine
p-DADMAC	Polydimethylammoniumchloride
PEI	Polyethyleneimine
PEO	Polyethylenoxide
PVAm	Polyvinylamine

6.4

Fixatives and Charge Control

Antonius Moormann-Schmitz

6.4.1

Overview

The increased usage of recycled fibers, mechanical pulps, and higher filler contents combined with more closed water circuits and increased machine speeds have challenged the papermaker to come up with improved treatment strategies.

The chemical nature, as well as the physical properties of the interfering substances has to be clearly understood in order to develop strategies for their effective removal from a paper machine system. Closing the water circuits is one of the biggest challenges facing the papermaker because of the enrichment of detrimental substances that accompanies this move.

Higher concentrations of solids and colloidal dispersed materials in a paper machine system very often create problems with deposits, which can adversely affect paper quality and machine runnability. The effectiveness of wet end additives can also be reduced. Problems caused by alkyketendimer (AKD) or alkenyl succinic acid anhydride (ASA) which can hydrolyze, react with detrimental substances, and form deposits under these conditions, are well known.

The predominant sources of detrimental substances introduced into a paper machine system are listed in Figure 6.7.

6.4.2

Treatment Strategies for Interfering Substances

Knowledge of the type and origin of interfering substances, as well as their chemical and physiochemical nature, is of utmost importance when developing efficient treatment strategies. Two physiochemical parameters, charge and particle size, have been identified to be particularly important when deciding on a treatment strategy.

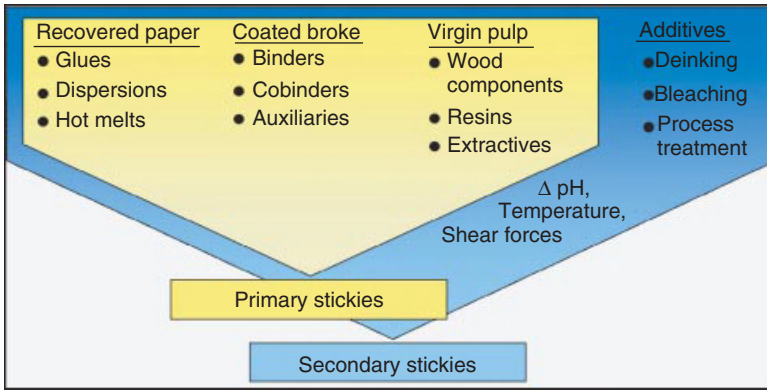


Figure 6.7 Sources of detrimental substances. (Source: BASF.)

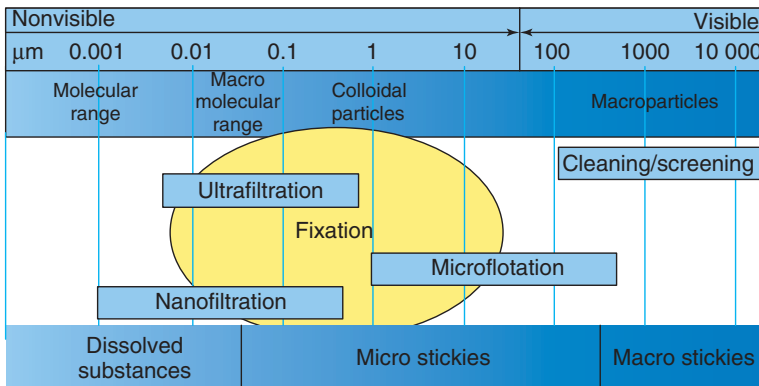


Figure 6.8 Treatment of detrimental substances. (Source: BASF.)

As can be seen from Figure 6.8, interfering substances span a wide range of different particle sizes. A rough distinction can be made between macro stickies with a particle size larger than 100 μm and micro stickies ranging from 100 nm to 100 μm .

There are three different ways for the removal of detrimental substances from a paper machine system:

- Mechanical separation (sorting and filtration)
- Chemical treatment (fixation with cationic polymers)
- Mechanical/chemical treatment (dissolved air flotation).

Mechanical separation techniques, such as pressure screens and cleaners, have been improved over the years and are commonly used for the removal of macro stickies. Mill trials have shown that up to 80% of macro stickies can be successfully removed with modern cleaner systems. A conventional flotation system allows the

Table 6.4 Classification of Fixing Agents.

Chemistry	Charge density (meq g ⁻¹)	Molecular weight (10 ⁶ g mol ⁻¹)
Poly-DADMAC	~6	0.2–0.3
Dicyandiamide	3–4	<0.05
Polyacrylamide	1–4	1–3
Polyamine	6	0.05–0.2
Modified polyethylenimine	11 ^a	0.8
Polyvinylamine	0–15 ^a	0.1–5

^aCharge density per gram of cationic polymer without counter ion measured at pH 7.0.
Source: BASF.

efficient removal of hydrophobic particles between 5 and 500 μm. One of the most efficient ways to remove highly dispersed colloidal micro stickies from a paper machine system is the microflotation process, which requires a well-balanced chemical program of coagulants and flocculants.

6.4.3

Chemistry of Fixing Agents

The most commonly used fixing agents in the papermaking process can be divided into six categories (Table 6.4).

Next to their chemical nature and molecular structure, these polymers mainly differ in their charge density and molecular weight. In general, polymers with a combination of high charge density and high molecular weight perform best in terms of eliminating dissolved anionic material from a contaminated paper machine system. They normally promote the performance of other wet end chemicals such as starch, sizing agents, wet strength resins, or the retention aid system. However, highly cationic polymers can also interfere with other functional chemicals. A negative impact on the performance of optical brighteners can often be observed when highly charged polymers are used. The most efficient way to overcome these negative side effects is the utilization of a fixing agent, whose molecular weight and charge density can be adjusted over a wide range.

In addition to these fully synthetic cationic fixing agents, dispersions based on polynaphthalene or lignosulfonates can also be used to prevent agglomeration of anionic detrimental substances. Aluminum sulfate (alum) is frequently used to support the fixation process in acid papermaking, while polyaluminumchloride (PAC) can be applied for the same purpose under alkaline conditions. Adsorbents such as microcrystalline talc and bentonite have high specific surface areas and therefore react with small hydrophobic particles helping to remove them from a contaminated system. Furthermore, semisynthetic, starch-based fixatives as well as enzymes are successfully applied for deposit control in certain cases.

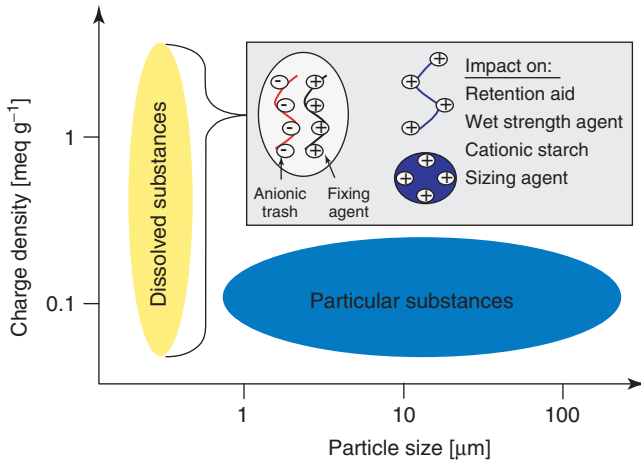


Figure 6.9 Reaction of a fixative with dissolved substances. (Source: BASF.)

6.4.4

Fixation of Dissolved Substances

Compared to particular substances such as white pitch or stickies, dissolved and colloidal dissolved detrimental substances are smaller in particle size while their anionic charge level is significantly higher (Figure 6.9). The performance of fixing agents for the treatment of dissolved anionic trash is directly proportional to their charge density and molecular weight.

The main problem with dissolved anionic substances in a paper machine system is their interaction with cationic process chemicals. Dissolved and colloidal dissolved substances can strongly reduce the performance of, for example, sizing agents, wet strength resins, cationic starch, or the retention aid system. Furthermore, they very often promote the formation of secondary stickies causing runnability problems and sheet defects. These negative effects can be substantially enhanced by temperature and pH shocks in the white water circuit. Figure 6.9 shows the interaction of a fixing agent with dissolved anionic trash. The fixing agent is appropriately chosen so that it forms a complex with the dissolved substances and removes it from the system by attaching it to the fibers. Deposit formation will be prevented and full performance of the process chemicals can be achieved.

6.4.5

Treatment of Particular Substances

White pitch deposits are formed from synthetic binders, cobinders, and other coating color auxiliaries. The main contributors are styrene–butadiene, polyvinyl acetate, and acrylics.

Compared to dissolved detrimental substances, white pitch particles carry a significantly lower anionic charge. The main negative effect of white pitch is its

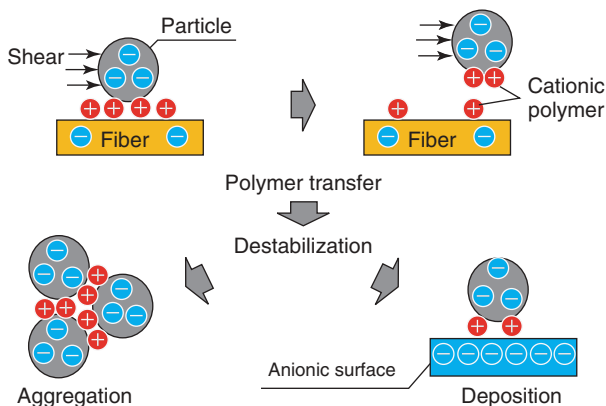


Figure 6.10 Aggregation and deposition. (Source: BASF.)

potential to form large aggregates causing deposits and runnability problems. Therefore, it is important to fix the particles before they have a chance to form bigger agglomerates. Compared to wood pitch particles; however, the particle size of white pitch is spread over a much wider range (0.2–50 μm). The shear forces acting on large particles will be higher, and initially fixed particles will be sheared off from the fiber surface and pushed back into the system. Taking into account the collision probabilities of particles and fibers under practical conditions, one can imagine that the tear-off and fixation process takes place a number of times before the particle finally gets fixed. For particles undergoing several successive fixation and tear-off cycles, a net transfer of cationic polymer from the fiber surface onto the particle surface has been observed (Figure 6.10). When the amount of transferred cationic polymer is high enough, a destabilization of the particles will take place.

Eventually collisions between destabilized particles will occur and they will form bigger aggregates. As a result, poor fixing performance is observed when particle size increases. In practice, large aggregates will be mechanically entrapped in the fiber mat, potentially causing sheet defects and machine deposits.

In order to avoid the formation of aggregates and the deposition of destabilized particles, one has to avoid the polymer transfer between fibers and hydrophobic particles. Therefore, the bonding strength between fibers and particles, as well as the colloidal stability of particles has to be controlled.

Besides molar mass and the charge density of cationic polymers, a third molecular parameter can be used to control the bonding strength between fibers and particles. The modification of cationic polymers with nonpolar hydrophobic groups will also influence the interaction of the polymer with the hydrophobic particles. This interaction will either strengthen the attraction between the cationic polymer and the hydrophobic particle, or it will weaken the interaction. While the first process is easy to understand, the second one needs to be explained in more detail.

When the distance between the modified polymer and the particle decreases, hydrophobic interaction starts to become effective at a certain point. An orientation

of the hydrophobic functional groups toward the surface of the hydrophobic particle will take place. If the molecular volume of the functional group is large enough to act as spacer between the particle surface and the main chain of the polymer, it can control the distance between them. By controlling the distance, the total interaction strength between polymer and particle can be weaker than would be the case for direct contact between the main chain and the particle surface.

The weakest bond sets the bonding strength between the fibers and the particle. If the interaction between fibers and polymer is weaker than the interaction between polymer and particle, the bond between fibers and polymer will break. As a result, cationic polymer will be transferred from the fibers to the particle, decreasing the particle's colloidal stability. If the interaction between particle and polymer is slightly weaker than the interaction between fibers and polymer, the bond between polymer and particle will break without polymer transfer. In both cases, the total bonding strength between fibers and particle is almost the same. The second case, however, is more favorable in terms of colloidal stability.

6.4.6

Test Methods for Fixing Agents

The most popular tests available for quantifying the general contamination of a paper machine system are chemical oxygen demand (COD), cationic demand, and conductivity. However, for specific insights regarding pitch contaminants there are other useful tests. Turbidity of stock filtrate can serve to quantify the presence of colloidal dissolved material. It is inexpensive but nonspecific. Soxhlet extraction with dichloromethane (DCM) is commonly used for quantitative pitch analysis of paper samples. The hemocytometer is frequently used to measure dispersed pitch in the paper machine system. However, it is unfortunately manipulated by human subjectivity. Particle size and volume can be measured with an optical laser pitch counter.

6.4.6.1 Tests with an Optical Laser Pitch Counter

A coated broke furnish was treated with the various polymers to evaluate their fixation performance. The treated furnish was filtered through a dynamic drainage jar. All hydrophobic particles not fixed to the fibers were collected in the filtrate. The sample was treated with a fluorescent dye. This special dye is absorbed by hydrophobic substances only. It has no affinity to fibers, fines, or fillers that can also be found in the filtrate. The dye-treated particles were then passed through an optical laser counter (Figure 6.11).

Hydrodynamic focusing separates the particles and they are irradiated by a laser beam at 442 nm. The resulting light emitted from the fluorescent dye on the particles is monitored at 550 nm. The number of particles per unit volume is counted. The particle size is determined through the intensity of the fluorescent light emitted by an individual particle. Information on the total volume of hydrophobic particles in the filtrate can be calculated from the number of particles per unit volume and their respective diameters. A decrease in volume, parallel to a decrease in particle

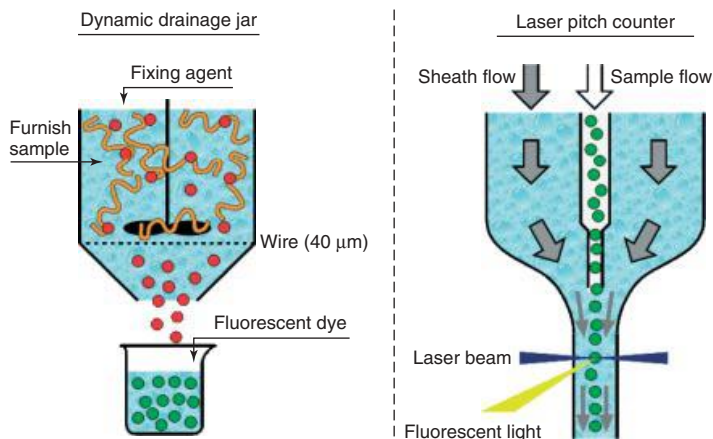


Figure 6.11 Optical single-particle counting. (Source: BASF.)

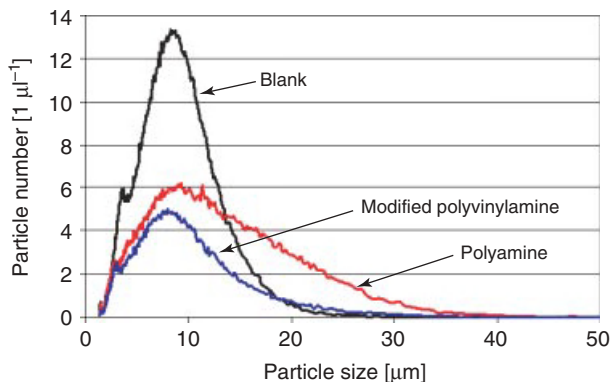


Figure 6.12 Volume distribution of unfixed particles in the filtrate. (Source: BASF.)

counts, provides information about the state of agglomeration. Reduction of particle volume approximately equal in magnitude to the reduction of the particle number (on a percentage basis) indicates the fixation process of particles onto fibers and fines. This technique allows conclusions to be drawn on the effectiveness of the various fixing agents tested.

6.4.6.2 Results

The particle size distribution of white pitch before and after treatment with hydrophobically modified polyvinylamine (PVAm) and a standard polyamine is shown in Figure 6.12. The area under the curves reflects the total volume of nonfixed pitch particles in the filtrate.

With the same addition rate of 0.05% (active substance), both polymers show a significant reduction of pitch particles compared to the blank. However, it can also be observed that the reduction achieved with the polyamine is accompanied by a

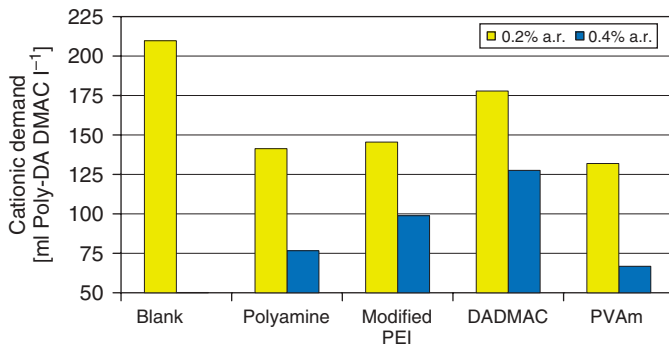


Figure 6.13 Cationic polymers for charge control. (Source: BASF.)

pronounced tendency of pitch agglomeration. In contrast, basically no shift in the distribution curve can be identified after treatment with the modified PVAm.

The number and the total pitch volume were simultaneously reduced. As a result, very good fixation without aggregate formation was achieved. These results show the superior performance of hydrophobically modified polymers for the fixation of white pitch particles.

6.4.7

Charge Control with Cationic Polymers

Charge measurement and online charge control has become a well-established technology in modern papermaking over the years. The most commonly used method is the measurement of cationic demand by polyelectrolyte titration. The main advantage of online charge control is a stabilization of the entire papermaking process. Improved machine runnability and paper quality as well as cost reduction of process chemicals has been the driving force for the implementation of this technology. Online charge control is very often integrated into a multiple closed loop control strategy including consistency, and ash and entrained air control.

Cationic polymers for charge control are selected on the basis of their capability to reduce the cationic demand of the treated furnish (Figure 6.13). Polymers applied for this purpose are similar to the already described fixing agents used for fixation of dissolved and colloidal dissolved substances. Depending on paper grade, furnish, and process conditions, the charge in a paper machine system can vary in a wide range. The optimum charge level is machine specific and therefore needs to be evaluated for each individual case. The charge is normally controlled within a certain range. In order to maintain the charge within the restricted access area, the polymer flow will vary substantially. This is why polymers used for charge control should be low in molecular weight. Products with higher molecular weight have a much stronger impact on the degree of flocculation and therefore can adversely effect sheet formation.

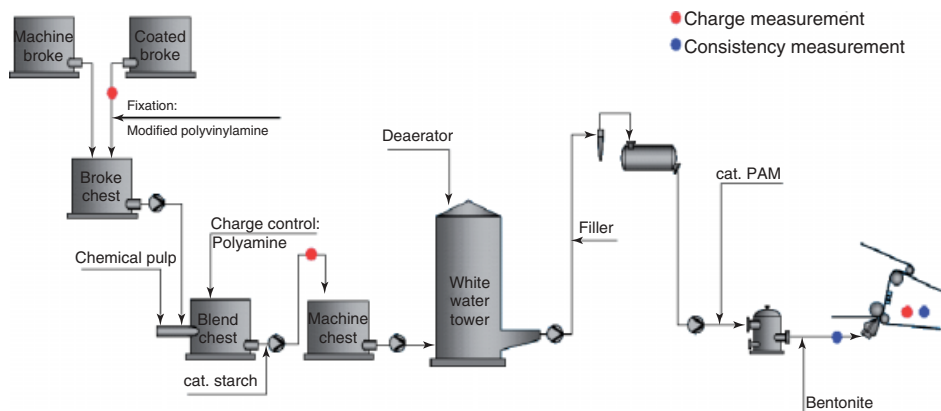


Figure 6.14 Charge and consistency control in a coated broke system. (Source: BASF.)

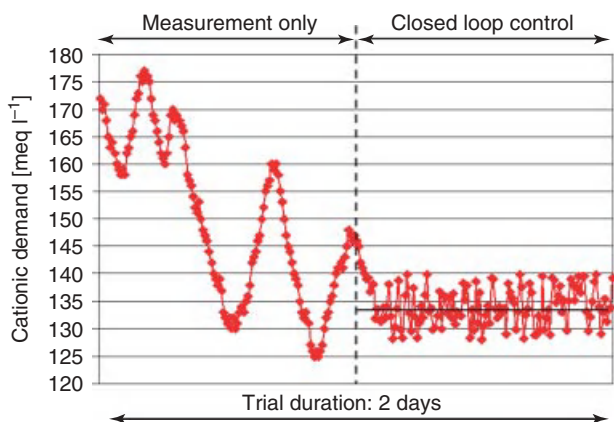


Figure 6.15 Online charge control. (Source: BASF.)

The flow sheet (Figure 6.14) shows a combined charge and consistency control system in a coated fine paper mill. The retention aid dosage is adjusted by white water consistency control while charge is measured at three different points in the system. During machine trials, the charge measurement in the white water system was identified as the best area for online charge control. The most efficient polymer for charge adjustment was a polyamine added into the mixing chest. The results achieved are shown in Figure 6.15.

With the implementation of closed loop control, the cationic demand in the white water system was adjusted in a narrow range between 130 and 140 meq l^{-1} . With the reduction of both the cationic demand and, more importantly, the charge variation, an improved stability of the entire process was achieved. The main accomplishments are a more balanced fixation process, better runnability and sheet formation, as well as a reduction of the retention agent consumption. From these results, it can be concluded that controlling the balance of bonding strength

between fibers, polymers, and pitch particles by the variation of molar mass and the charge density of cationic polymers does not seem to be efficient enough. Modification with hydrophobic functional groups, however, opens up a new field of variation for the treatment of particular substances. The chemical nature of the functional groups and the degree of modification can be adjusted to meet the specific requirements set by the chemical nature of the contaminants and the process conditions. Online charge control can be an important tool to support the fixation process and help to stabilize the entire wet end system.

6.5

Deposit Control and Biocides

Ute Höötman

6.5.1

Introduction

Biologically caused phenomena in papermaking are mostly considered as a side issue. Their causes are invisible, their effects are more than unpleasant, and the process chemicals used against them do not support papermaking; they are only a necessary evil. Therefore, microbiology is a commonly neglected aspect although it is a decisive factor in paper production.

This chapter should add to a better understanding of what is happening in the microscopic area: what is invisibly living in paper machines and their environment, how do things interlock to lead to severe production problems, what can be done to prevent these effects, and what may be the solution in the end when microbiological and related problems have already arisen.

6.5.2

Some Basics of Microbiology in PaperMaking

Biology is not an exact science and evidence for this statement is the taxonomic classification of life. We distinguish between plants, animals, and microorganisms but there are organisms that cannot be associated to the one or other group. For example, single-cell bacteria, which gain energy by photosynthesis, are neither clearly microorganisms nor plants.

What can be found in paper production are prevailing microorganisms, namely, bacteria and fungi.

The composition of the population and their characteristics varies and depends on physical and chemical conditions. However, the actualities in paper machine circuits are optimal for microbial life. Water, heat, and nutrients are available and closed circles as well as moderate pH values support the growth of microbiology in any form. A feared phenomenon is the production of exopolysaccharides (EPS) by microorganisms which – by proliferation in masses – leads to highly hydrous slimes.

6.5.3

Impairments Caused by Microorganisms

Malfunctions in papermaking caused by microorganisms are manifold. The most mentioned are slime deposits, which are quite apparent and may lead to severe quality losses. Paper stains, it gets pitted or patchy, paper sheets break off; in the worst case, production has to be stopped. The microorganisms responsible for these problems may have different sources. Bacteria and fungi are present everywhere, and generally all starting materials used in papermaking can be target to microbial infestation. These may be freshwater, additives, starch and coating colors, waste paper, even fresh fiber itself, and so on. Under optimal growth conditions, which are present in most paper machine circuits, these contaminations form slimes (Figures 6.16–6.18) that can be controlled only by preventive measures and deposit-controlling actions.

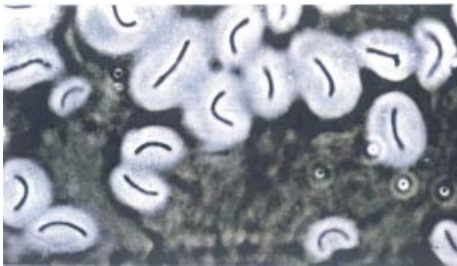


Figure 6.16 Bacteria with slime envelopes.



Figure 6.17 Spore-forming fungi.



Figure 6.18 Slime pins.



Figure 6.19 Microbial-induced corrosion.

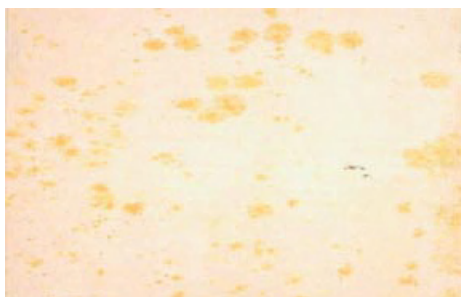


Figure 6.20 Recalled paper with spots.

There are other consequences of microbial activity that may disturb the production process. Bad odor is caused by the formation of organic acids by microbial fermentation processes or by the formation of H_2S produced by sulfate-reducing bacteria. As a consequence, there will be complaints of bad-smelling paper. Just as often, there are complaints from the neighborhood, especially when paper mills are located in residential areas.

Besides the bad H_2S smell, sulfate-reducing bacteria can be the reason for microbial-induced corrosion (Figure 6.19). MIC frequently is the reason for expensive and lengthy maintenance work.

Many raw materials used in papermaking fall prey to biodeterioration. If these materials are used, there will be support for biofilm formation. Otherwise, the deteriorated material should be recalled (Figure 6.20) and the material should be disposed of; this is unpleasant and expensive.

The last two examples show that microbiology is not only an unpleasant factor but can be dangerous for humans. The presence of *Legionella pneumophila*, a bacteria causing lung inflammation, is detected commonly in industrial water systems, more so in paper machine systems.

Further, in recent literature, events of explosions caused by microbial produced gases have also reported.

In summary, it makes sense to take care of biological activity in paper production.

6.5.4

Prevention: What Can Be Done in the Run-Up?

The presence of microorganisms in papermaking processes is an unchangeable fact, but some preventive measures can be taken to reduce the effects of their action.

In optimal cases, those measures are integrated during the planning phase of a new paper mill. As a first step, the quality of surfaces in contact with the suspension should be taken into consideration. Microorganisms tend to adhere to surfaces whenever possible. An irregular and porous surface is very helpful to embed biofilms and other deposits and above that, makes cleaning difficult. So, surfaces should be as smooth as possible, avoiding porosity to the largest extent. Stainless steel is a good example for a material antagonistic toward microbial adhesion.

Another important point is the planning of the water circulation. In cases where water has the opportunity for stagnation, there will be a support of microbial growth and thereby the formation of biofilms and anaerobic zones. So zones without movement and oversized water reservoirs should be avoided.

The choice of the raw materials, including water, should be the result of a cost–benefit consideration. The use of poor-quality recovered paper, highly closed circuits, and, perhaps, “freshwater” from wastewater plants are surely less expensive but follow-up costs caused by complaints, poor runnability, cleaning procedures, and biocides, and so on, should be considered carefully.

6.5.5

Dispersants, Biocides, Cleaners: The Deposit Control Concept

In most of the cases, there are existing paper mills where industrial hygiene aspects were not taken into account when they were built. The more inconvenient the hygienic state of the complete installation, the more actions against the formation of deposits will be necessary.

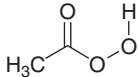
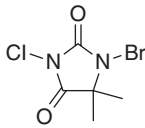
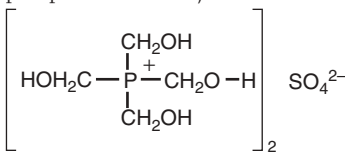
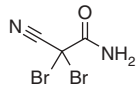
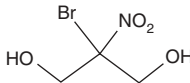
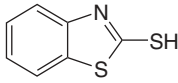
Deposits are rarely made from pure microbiology. Mostly they are hybrid forms made – beside EPS – from additives such as sizing agents, resins or carbonates, starch, and lots of others. It is not easy to distinguish what was first, microbial produced deposit with secondary sediments or vice versa. The knowledge about the components of a deposit allows finding in many cases, a suitable treatment strategy.

The use of dispersants may be helpful in preventing the sedimentation of microorganisms and/or accompanying stuff to a certain extent. Mostly surfactants – they are applied as physically acting agents to coat particles – are able to form deposits. It does not matter whether these particles are of biological origin.

Biocides are the agents of choice in cases when the deposits are clearly of biological nature or when other microbiological activities disturb the production process.

Generally, microorganisms can be controlled by biocides. There are a number of effective active substances that have been applied in the paper industry for decades. Table 6.5 gives an overview of the antimicrobial agents that are available.

Table 6.5 Biocidal Active Substances and their Application.

Classification	Example	Application
Oxidizing biocides	Peracetic acid  Hydrogen peroxide, H ₂ O ₂	Process water, freshwater Process water
Oxidizing biocides, containing halogens	Hydantoin, for example, BCDMH (1-Bromo-3-chloro-5,5-dimethylhydantoin)  Hydantoin procedure	Process water, freshwater Process water, freshwater
<i>In situ</i> produced compounds	Hypochlorite ClO ⁻ , -bromide, chlor dioxide ClO ₂ Ammonium bromide, ammonium sulfate	Freshwater Process water, freshwater
Surface-active compounds	Quaternary ammonium compounds, THPS (tetrakis hydroxymethyl phosphonium sulfate) 	Process water
Bromine nitrogen compounds	DBNPA (2,2-dibromo-3-nitrilopropionamide)  Bronopol 	Process water, preservation
Cyanates	MBT (2-mercaptobenzothiazol) 	Process water, preservation

(continued overleaf)

Table 6.5 (Continued).

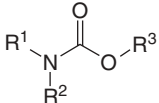
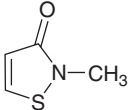
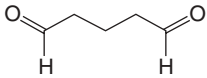
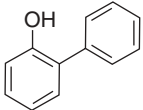
Classification	Example	Application
Carbamates thiocarbamates	 $O=S >$ Thiocarbamates	Process water, preservation
Isothiazoles	CMIT (5-Chloro-2-Methyl-4-Isothiazolin-3-one) MIT (2-Methyl-4-isothiazolin-3-one)	Process water, preservation
Aldehydes	 BIT (1,2-Benzisothiazolin-3-one) Glutaraldehyde, 	Process water, preservation
Cyclic compounds	Formaldehyde separator o-Phenyl phenol 	Preservation

Table 6.5 shows the wide variety of products that can be used as single products or in combination. The choice has to be made very carefully as it needs considerable experience to develop an adapted biocide treatment (Section 6.5.8).

Biocides can preferably be applied as preventives to achieve a prolonged running time and better runnability or they can also be used in cases when biological deterioration has occurred already. In case of the latter, an additional cleaning of the machine may be necessary. According to the constitution of the deposit, different cleaning agents and procedures are applied. Generally, scouring liquor containing cleaning agents is poured into the machine. The cleaning agents may be acidic, alkaline, or neutral agents, often with detergents or organic solvents (e.g., in case of resin deposits). The cleaning procedure can be a simple circulation of the scouring liquor or can be supported by pressurized or depressurized mechanical procedures.

6.5.6

Survey of Deposit Control Applications

The monitoring of deposit control processes is complex. There is no single tool to evaluate success or failure, but a bunch of analyses can be made. So it has to be

Table 6.6 Monitoring Methods to Survey Deposit Control [5].

Method	Example
Biological	Total germ count, anaerobic germ count, sulfate-reducing bacteria, yeast/mold
Physical	Microscopy, pH and redox reading, oxygen demand, online biofilms monitoring
Biochemical	Determination of adenosine-tri-phosphate, analysis of enzyme activity, gene probes

decided what kind of monitoring makes sense in a particular case. Monitoring can be by means of biological, biochemical, or physical methods (Table 6.6).

Normally, several methods are combined to allow an evaluation of the success of a treatment. The method(s) that is/are chosen at least is a question of experience and analytical capabilities, of time need and financial scope.

6.5.7

Regulatory Affairs

The control of biologically caused impairments needs an understanding of interactions between elements from different segments of life sciences. An additional factor that plays an important role is combating life in paper machine systems would mean using chemicals that are critical for humans, as well. That is why lots of users treat biocides with skepticism. This fact has been taken into account by suitable legal regulations and specific recommendations, especially over the last 15 years.

The most important development was Regulation 98/8/EG. Herein, the European Union has established a regulatory framework for the placing biocidal products on the market. This shall ensure a high level of protection for humans and the environment as also the proper functioning of the Common Market. The biocidal active substances are categorized into product types according to their intended use. Product type 12 (slime control) is the most relevant for papermaking. It will take decades to enforce the regulation completely, so in many countries, there are local regulations and transitional agreements that need to be followed carefully.

In addition to the above, there are several other regulations and recommendations that control – among others – the application of biocides for the production of paper for special uses or for the production under environmentally friendly conditions. “Recommendation XXXVI” of the German Federal Office for Risk Assessment lists the process chemicals for the production of paper that would get in contact with food. Another example is the production of environmentally friendly produced paper for the Scandinavian countries, the “Nordic Swan.”

6.5.8

Coordinated Approach: A Deposit Control Project

Microbiological problems cannot be controlled by dosing the first biocide that comes along. A workflow as described in the following has to be carried out.

Initially, the paper mill in question will be surveyed intensively. This involves an inspection of the entire mill, a consideration of the water circulation system, and a comprehensive biological and physical characterization of all raw materials and water samples determining the hygienic state of the plant. In a next step, all suitable biocides, dispersants, and cleaners undergo a test on dose–effect relation to evaluate the most effective products; there can be more than one such test. With respect to functional, environmental, and economic aspects, the daily dosing amount and the dosing points are fixed. The dosing equipment will be accordingly planned in the light of reliability, work safety, and environmental friendliness. Negative effects on biological wastewater plants must be disclosed and local regulations be minded in advance. Before the application starts, the system should be passed through a cleaning program. During a test phase, all settings are checked and optimized. A monitoring program has to be fixed for the business routine.

Despite all planning and care, a paper machine circuit is a living system that may change periodically; it would then require adaption of the deposit control concept.

6.6

Defoamers and Deaerators

Christoph Blickenstorfer

More recycled fibers, higher machine speed, increasing filler content, and reduction of specific water consumption can lead to higher air content or more foam during the paper manufacturing process. Both effects can influence paper quality (e.g., increased porosity, pinholes) or interfere with the production process (e.g., slower dewatering, increased energy demand caused by additional compression work of pumps).

One reason why foam and air control can be complex is the fact that air does not necessarily produce negative effects at points where its concentration is the highest, nor where there is the highest air intake.

This chapter focuses on foam and air control in the wet end process. Air and foam problems can occur during coating color preparation, and/or circulation (Chapter 5), in the effluent treatment (Section 6.11), or foaming in the size press.

6.6.1

Appearance of Air along the Process and Sources of Surface-Active Substances to Stabilize Foam

To reduce the air content and control the foam level along the papermaking process, it is important to know the type of “air” that is present in a stock suspension, the sources of air, and how foam is formed.

Basically, there are two types of “air” present [6]:

- **Dissolved gases (gas molecules):** These are different individual gases such as O₂, N₂, CO₂ that have dissolved in the water.

- **Entrained air (air bubbles):** These are present in a liquid, as freely moving, dispersed air bubbles of a size larger than 100 μm . This free air can lead to surface foam formation in the presence of surface-active substances (Figure 6.21). The entrained air can also be in the form of small air bubbles ($<100 \mu\text{m}$) that are physically retained in the fibers or adsorbed on the fiber surface (bound air, Figure 6.22).

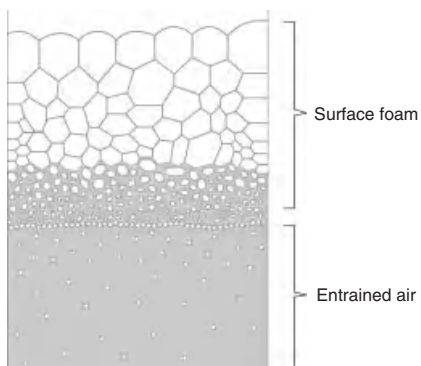


Figure 6.21 Classification of dispersed air bubbles in a liquid in entrained air and surface foam.

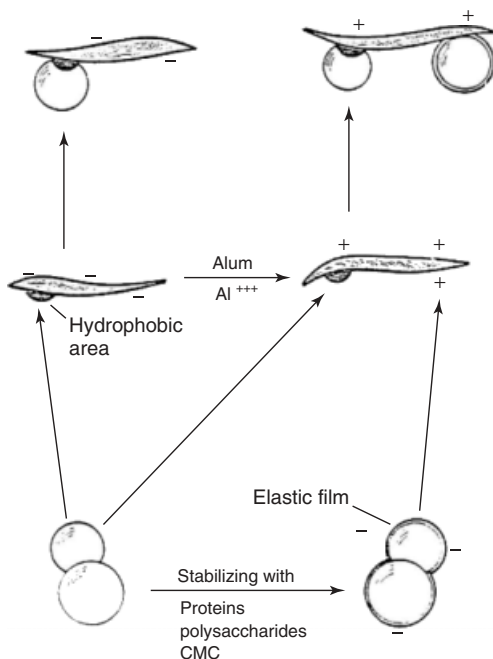


Figure 6.22 Mechanism of air bubble attachment to fibers (bound air) [7] (CMC, carboxy methyl cellulose).

The relative proportion of entrained air and dissolved gases is influenced by the concentration of salts and chemicals, temperature, pH, pressure, and the total air/gas content. If, for example, the temperature of the stock suspension increases, the gas dissolving capacity is decreased, and therefore the molecules are released as bubbles.

Pressure changes along the papermaking process will change the proportion of dissolved gases to entrained air. Thus, the amount of dissolved gas will increase, for instance, by the pressure buildup in a pump. On the other hand, during expansion in the headbox, additional small air bubbles will be formed spontaneously from dissolved gas. This means that even without the introduction of air from outside, higher quantities of entrained air can suddenly appear in the stock suspension.

There are different ways in which air is entrained into the papermaking process.

- Pulping of fibers, especially when fiber surfaces get insufficiently wetted.
- Mechanical effects of mixers, leakages of pumps, or insufficient vacuum systems.
- Unfavorable flow conditions, which lead to cavitations.
- Particularly during dewatering in the forming section, when the removed water sprays, falls, splashes, and runs into the white water trays. Here air is mixed very efficiently into the white water.
- Gas dissolved in freshwater and in process water is released and forms air bubbles.
- Chemical reactions, which lead to the formation of gases: Calcium carbonate from coated papers (introduced as waste paper or coated broke) or when added as filler dissolves in significant quantity when pH is lower than 7, consequently releasing CO₂.
- Biological activities can also bring gas into the system.

This entrained air can be imagined as small bubbles that are surrounded by a liquid phase (continuous phase). In aqueous systems, the free air bubbles tend to rise to the surface of the liquid, where they can form foam when surface-active substances are present; this stabilizes the surfaces between the liquid and air (Figure 6.21).

The presence of surface-active substances is very common during paper production. They can be of natural origin, such as

- resins, fatty acids
- lignin
- starches
- hemicelluloses, proteins, and polysaccharides.

or of mostly synthetic origin, such as

- surfactants, glues, and binders from waste and recycled paper or own broke
- emulsifiers and surfactants from chemical additives
- wet strength and sizing agents
- dispersants.

With an air content of 1 vol%, the proportion of air and fibers in percentage per volume is roughly the same in a stock suspension. In this three-phase system, air and solid matters are dispersed in comparable quantities in a liquid medium. This is important for the mechanisms of how air bubbles are attached to fibers/fines, fillers, or other colloids, and is called *bound air*. These mechanisms of attachment can be explained as shown in Figure 6.22:

- The fiber surface always has hydrophobic patches, for example, from wood resins, where the hydrophobic air bubble can get attached.
- Electrically charged chemical substances increase the polarity of the air bubbles and can also charge them electrically, thus causing electrostatic attraction.

6.6.2

Disturbances Caused by High Foam and Air Content

High air content and a lot of surface foam have a negative influence on both the production process and the quality of the finished product.

- Too high an air content in the headbox suspension has a negative effect on the retention of fibers, fines, and fillers as well as on the paper formation and dewatering in the wire and press sections.
- At high air content, there is an increase in the number of pinholes (with their negative effect e.g., in coating and printing) and the average pore diameter of the paper sheet increase, as well as the surface roughness.
- For all pumping and suction processes, more energy will be consumed. Paper machine runnability and consequently productivity may be lowered.
- The performance of some process chemicals, such as reductive bleaching agents and retention aids, becomes significantly worse in the presence of entrained air.
- Hydrophobic particles adhere to air bubbles and can thus float. This can cause an increase of sticky particles in surface foam and lead to the formation of deposits. These may precipitate on machine parts, leading to higher cleaning frequencies. They can also be incorporated into the paper sheet and may cause sheet breaks.

6.6.3

Defoaming and Deaeration Chemicals

Avoiding constant introduction of air into stock suspension is basically the best way to fight high air content and foam formation. Eliminating cascades and free fall of stock during stock preparation is a very efficient solution to the problem. However, introduction of some air in the stock is inevitable, for example, in the wire section. Therefore, physical and chemical methods have been developed to remove air and control the foam.

Physical air removal can be classified into passive and active methods. The passive method is based on the buoyancy force of air bubbles. In practice, there are two main locations at which entrained air can leave the process in that way, namely,

the white water channel and the silo pit. Air, mixed with white water while falling from the wire, can rise to the surface in the white water channel and silo when the hydrodynamics are correct. Active methods are more effective as they generate circumstances that accelerate the discharge of air bubbles; even dissolved gases can be removed to a certain level. The most common mechanical deaerators are the so-called deculators. Owing to the vacuum generated, entrained air is almost completely removed as also part of the dissolved gas (if configuration and residence time are sufficient). Other possibilities are hydrocyclons, screens, and air-removing pumps (Chapter 12).

Often, physical deaeration is not sufficient, especially when the process is running above designed specification. Therefore, chemical deaerators are used additionally to keep the air content at an acceptable level (below 0.1–1.0% in the headbox, depending on the paper grade) and to control the foam.

On the basis of the application of the chemicals used to remove air, they may be distinguished as defoamers and deaerators. The main aim of defoamers is to destroy existing surface foam and to inhibit further foam generation. Deaerators act in the bubbly liquid zone and improve the creaming velocity (upward movement under the influence of buoyancy) of dispersed air bubbles by increasing the bubble coalescence rate.

The general mechanism for a deaerator or defoamer is to cause coalescence of bubbles by rupturing the thin film separating them. This can happen either during the collision of two bubbles in an aqueous phase or in the lamellae of a surface foam.

A good deaerator disperses quickly and uniformly in the foaming liquid after its addition so that it is present as individual liquid drops or solid particles. These entities then collide with the bubbles in the foaming liquid resulting in the deposition of the chemical on the bubble surface. Following this, if two bubbles collide, the attached degassing drops or particles can be trapped in the formed liquid film and lead to film rupture. Figure 6.23 shows schematically the bridging–dewetting mechanism for entrained air. A particle or liquid drop (a) immerses into a draining foam film (b). As the film further thins (c), the particle or drop forms a bridge (d), which is dewetted when sufficiently hydrophobic (e) and finally causes film rupture.

Active components for deaerator and defoamer formulations are oils (such as nonpolar mineral or silicon oils or polar ones such as fatty alcohols), hydrophobic solids (such as waxes or silica), or nonionic surfactants (such as alkoxyates, if used above their cloud point). The final formulations are either marketed as aqueous dispersions (emulsions or suspensions) or as concentrated products (no water). An overview of the most common deaerator and defoamer formulations are shown in Table 6.7.

Often a clear distinction between deaeration and defoaming cannot be made. For wet end applications, most common product types are the water-based fatty alcohol dispersions and the concentrated alkoxyates. Silicon oils are used for foam control during pulp production or at the effluent plant. For these two applications also mineral oil–based defoamers are still used sometimes.

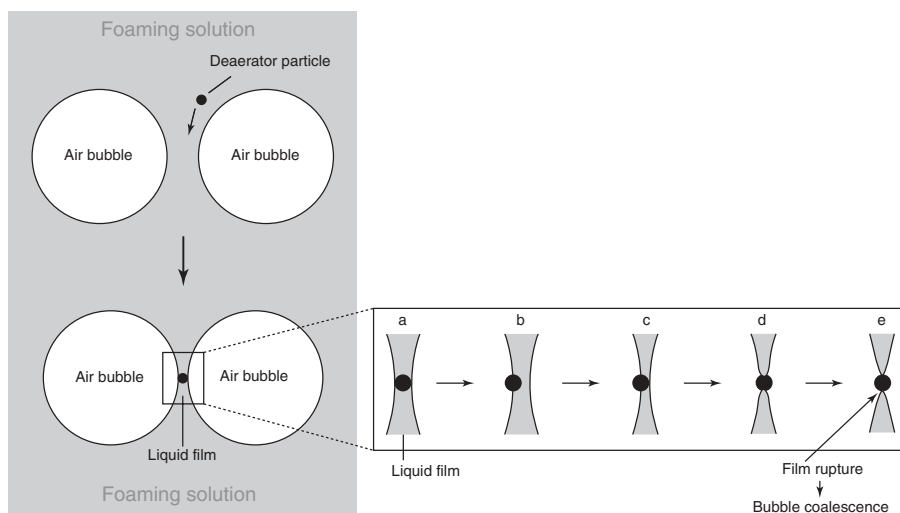



Figure 6.23 Schematic bridging–dewetting mechanism for fast film rupture after [8, 9].

Table 6.7 Typical Chemical Composition of Deaerators and Defoamers.

Deaeration	Type	Compositions
	Aqueous dispersions	Approximately 26% long-chain fatty alcohols (C ₁₆ –C ₂₆) Approximately 4% emulsifiers, thickeners, and preservatives Approximately 70% water
	Concentrated nonionic surfactants (with high cloud point)	Fatty acid alkoxyates Fatty alcohol alkoxyates Fatty acid esters Block copolymers of ethylene oxide and propylene oxide
	Mineral oils	Blend of aliphatic, cycloaliphatic, and aromatic hydrocarbons
Defoaming		

6.6.4

Application of Defoamer and Deaerator and Measurement of Air/Gas

Selecting the appropriate product is rather complex and depends on many factors, such as

- main task it needs to perform: deaeration or defoaming?
- type of foaming system: for example, thick stock, white water, coating color, effluent water;

- process conditions: temperature, pH, conductivity, flow conditions;
- EH&S profile: degradability, FDA, and BfR approval.

For selecting the appropriate water-based dispersions, the temperature of the white water is important as best performance is achieved if the fatty alcohol particles are not melted. Also the dosing point plays an important role, as a homogeneous and fast distribution is essential for a good performance, and for achieving as much dwell time of the chemical as possible in the open system for bubble release.

Defoamers need to be dosed where the foam problem occurs and performance control is best done visually. To control the deaeration performance, an air measurement is suggested, either based on compression/expansion (Boyle's gas law) or on acoustic methods such as ultrasound or sonar (Table 6.8).

Table 6.8 Selected Methods for Air Content Measurement.

Method	Measuring principle
Compression	Measures the change in the gas volume by the change in the applied pressure (pressure application)
Expansion	Measures the change in the gas volume by the change in the applied pressure (vacuum application)
Ultrasound	Sound is scattered at the interfaces of small gas bubbles entrained in a liquid
Sonar	Volumetric gas content is determined on the basis of the speed of sound, which is different in liquids and gases

By first applying the compression method, the entrained air can be measured. If this is followed by an expansion, the total amount of entrained air and dissolved gases can be measured. As a result, the dissolved gas content of the sample can be calculated.

There are cases where the best foam and air control results are achieved when a defoamer and a deaerator are applied at the same time. They are either dosed at the same place or at different places. Thus the total amount of product and even costs can be reduced compared with dosing a high amount of only one product.

In general, defoamers and deaerators have no negative impact on other chemical additives. Nevertheless, an overdose should be avoided as this could reduce the performance of other chemicals (e.g., sizing agents). An overview of possible interactions can be found in Section 6.12.

6.7

Chelating Agents

Gunnar Kramer

The demand for increased brightness on the one hand, and totally chlorine-free pulps on the other, leads to an increased use of chelating agents. Bleaching of fibers with hydrosulfite and peroxide for paper manufacturing cannot be done without

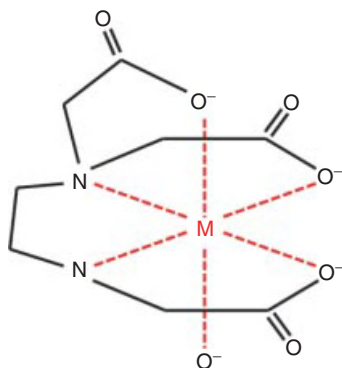


Figure 6.24 Metal–EDTA chelate complex.

chelating agents. The presence of heavy metals, primarily ferric and manganese (II) ions (Fe^{3+} and Mn^{2+} ions), negatively influences many production processes and paper properties. These heavy metals can catalytically decompose hydrogen peroxide, which is used as bleaching agent in chemical and mechanical pulp production.

The chelating agents are able to strongly interact with many cations and effectively mask their detrimental impact. For example, ethylenediaminetetraacetic acid or EDTA is a hexadentate (six-toothed) ligand that can form metal complexes and so sequester metal ions such as Ca^{2+} and Fe^{3+} (Figure 6.24). After being bound by EDTA, metal ions remain in solution but exhibit diminished reactivity. Thus, by addition of chelating agents, a loss of bleaching effectiveness is avoided.

The pulp and paper industry uses approximately 50 000 t per year worldwide in the treatment of fibrous pulps, and the dosages added vary between 0 and 5 kg t^{-1} according to the requirements of the pulp [10].

Generally, chelating agents contain amino, carboxyl, as well as phosphonic groups.

The most important chemical compounds of this type are nitrilotriacetic acid (NTA), EDTA, diethylenetriaminepentaacetic acid (DTPA), hydroxyethylethylenediaminetriacetic acid (HEEDTA), and diethylenetriaminepentamethylenephosphonic acid (DTPMPA) and their salts (Figure 6.25).

Another interesting and well-performing class of complexing agents is based on polyacrylic acid. In such compounds also, copolymers with strong anionic components such as sulfonic acid acrylic monomers as well as their salts can be combined.

Less important complexing agents include the soluble salts of oxalic acid, citric acid, tartaric acid, gluconic acid, amines, and ammonia. In the future, the importance of sustainable and renewable materials will increase, so products from natural source, for example, amino acid types, have to be considered.

The chemicals applied are dominated by DTPA (2/3) and EDTA (1/3). The reason for the dominance of these two chemicals is their good stability over a wide range

<p>The structure shows a central nitrogen atom bonded to three methylene groups. Each methylene group is further bonded to a carboxylic acid group (-CH₂-COOH).</p>	<p>The structure shows two nitrogen atoms connected by an ethylene bridge (-CH₂-CH₂-). Each nitrogen atom is also bonded to two methylene groups, each of which is further bonded to a carboxylic acid group (-CH₂-COOH).</p>
Nitriilo triacetic acid (NTA)	Ethylene diamine tetraacetic acid (EDTA)
<p>The structure shows three nitrogen atoms in a chain, connected by ethylene bridges (-CH₂-CH₂-). The terminal nitrogens are bonded to two methylene groups each, and the central nitrogen is bonded to one methylene group. Each methylene group is further bonded to a carboxylic acid group (-CH₂-COOH).</p>	<p>The structure shows two nitrogen atoms connected by an ethylene bridge (-CH₂-CH₂-). One nitrogen is bonded to two methylene groups, each with a carboxylic acid group (-CH₂-COOH). The other nitrogen is bonded to one methylene group with a carboxylic acid group (-CH₂-COOH) and one ethylene group (-CH₂-CH₂-) which is further bonded to a hydroxyl group (-OH).</p>
Diethylene triamine pentaacetic acid (DTPA)	Hydroxy ethyl ethylene diamine triacetic acid (HEEDTA)
<p>The structure shows three nitrogen atoms in a chain, connected by ethylene bridges (-CH₂-CH₂-). The terminal nitrogens are bonded to two methylene groups each, and the central nitrogen is bonded to one methylene group. Each methylene group is further bonded to a phosphonic acid group (-CH₂-P(=O)(OH)₂).</p>	
Diethylene triamine pentamethylenephosphonic acid (DTPMPA)	

Figure 6.25 Chemical structures of different chelating agents.

of pH and temperatures, and their constant efficiency under varying conditions. DTPA outperformed EDTA in many applications because of the greater stability of its complexes.

An ongoing discussion persists regarding the environmental protection and biodegradability of chelating agents. The disadvantage of EDTA and DTPA is the low biodegradability under standard conditions. Thus these chelating agents pass through effluent treatment plants and are discharged into receiving waters. Heavy metals from the sediments might be remobilized and become bioavailable again. Furthermore, highly concentrated chelating agents can seriously disturb the metabolism of microorganisms (e.g., DTPA) and the degradation rates of an effluent treatment plant will drop [10–12].

However, the products degrade differently, depending on the conditions that exist in the paper mill circuits. EDTA shows adapted bacteria degradation rates of almost 90% under favored conditions of high pH, UV light [13]. DTPA is more difficult to eliminate.

6.8

Additives for Repulping

Gunnar Kramer

These chemical additives are intended to facilitate the repulping of recovered paper, in order to secure proper utilization of recovered paper for the production of paper and board. However, nowadays, aggregates and improved technologies are available for recovered paper treatment without any addition of wetting agents and dispersants – with the exception of high wet strength paper grades such as label paper.

If easier and faster defibering is necessary, nonfoaming, surface-active wetting agents (such as sulfonated oils, alkyl sulfates, alkyl sulfonates, alkyl aryl sulfonates, ethoxylated fatty alcohols) support reduction in the surface tension of water for enhanced impregnation of the furnish, in particular, if internal sizing has been applied in the recovered paper.

Dispersants are beneficial if problems with pitch, waxes, bitumen, and so on, disturb the production. Condensation products of formaldehyde and a naphthalene sulfonic acid sodium salt, or the sodium salt of a polycarboxylic acid and polyphosphates are suitable for this purpose. Further synthetic dispersing polymers are polyvinylalcohol, polyvinylpyrrolidon, polyvinylsulfate, PAM, and polymaleic acid-co-styrene. These products may be added undiluted to the pulper in amounts of up to 0.5%.

Repulping of wet strengthened paper, internal broke, or recovered paper requires additional energy as well as chemical additives.

Depending on the type of wet strength resin used, different methods and chemicals are applied. Broke treatment of paper with glyoxal-based resins can easily be done if good wetting and enough time is available. It is beneficial to apply elevated temperature (up to 60 °C) and high pH of 9–10 during defibering. As Figure 6.26 shows, hemiacetals bonds can easily be hydrolyzed under mild alkaline conditions.

The use of alkaline conditions destroys wet strength of glyoxal-based resins completely, whereas recycling under neutral conditions may restore wet strength (potential savings in production with this kind of furnish).

Paper finished with polyamine–epichlorohydrin and polyamidoamine–epichlorohydrin resin provides permanent wet strength. Fresh broke needs to be repulped immediately before the full wet strength has been developed by paper curing. Elevated temperature from 60 to 80 °C and elevated pH values of 10–12, adjusted with sodium hydroxide (causes yellowing), are highly recommended. Extensively cured or highly wet strengthened paper should be repulped with

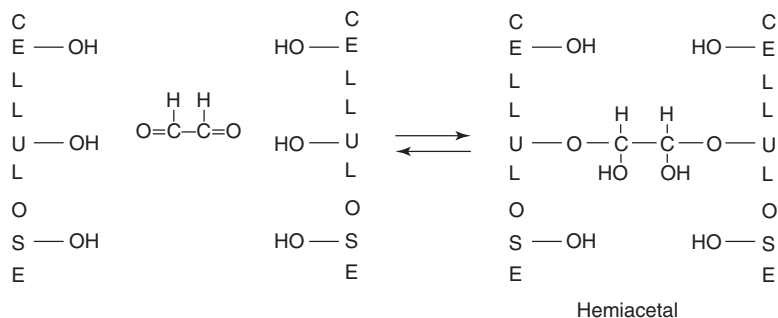


Figure 6.26 Hydrolyzing of hemiacetal bonds under mild alkaline conditions.

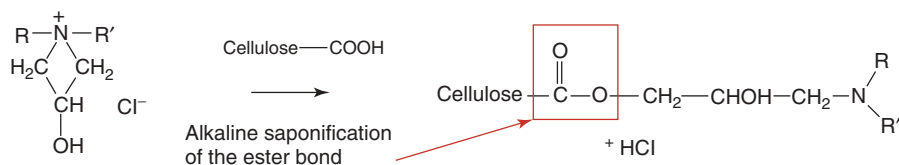


Figure 6.27 Hydrolyzation of the ester bond under strongly alkaline conditions.

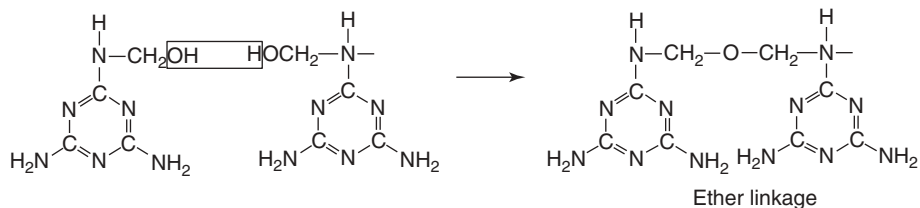


Figure 6.28 Hydrolyzation of melamine resins under strongly acidic conditions.

further addition of oxidizers such as salts of hypochlorite or persulfate. Unlike chlorine-based repulping agents (NaOCl), the persulfate types do not produce absorbable organic halides (AOX) or other chlorinated organics. They also do not degrade the fiber or impact the brightness of oxidatively bleached mechanical pulp. Figure 6.27 explains the hydrolyzation of the ester bond.

Paper wet strengthened with urea formaldehyde resins are easier to disintegrate than that strengthened with melamine formaldehyde resins. Melamine resins form ether linkages during cross-linking with each other and with cellulose as well. Both types of paper have to be repulped in acidic medium. Usually, sulfuric acid and/or alum are applied in the pulper at an elevated temperature of about 60 °C (Figure 6.28).

Cured wet strength paper may be repulped by means of mechanical forces. Appropriate devices work at high consistency, high shear rates, and high temperatures. Such investment pays back in particular, if the whole production is dedicated to the utilization of high wet strength paper, and, in the end also, if such

Table 6.9 Repulping of Different Wet Strength (WS) Paper Material.

Raw material	Chemical additives	Processing
Fresh broke	./.	Together with fresh fibers
Internally sized	Wetting agents	Separate pulper, increased dwell time
<5% relative WS	pH adjustment	Separate pulper, elevated temperature
5–20% relative WS	Repulping additives	Separate pulper, elevated temperature up to 80 °C
>20% relative WS	Repulping additives and oxidizing chemicals	Separate pulper with high shear rate, temperature min 80 °C, increased dwell time

equipment is in place, addition of appropriate chemicals may create savings in energy consumption and dwell time.

The use of appropriate chemicals and mechanical devices insures a more complete disintegration, faster repulping, and hence improved productivity and repulping quality. Table 6.9 summarizes the chemical additives and processing conditions that are recommended for different wet strength paper materials.

6.9

Deinking Additives

Gunnar Kramer

In Europe, almost one-third of all recycled fibers are deinked. Deinking is the process of ink removal, leading to higher degree of whiteness of recovered paper. The deinking process is one of the most important operation steps during recycling of white printed papers. Depending on the paper produced – graphic papers, tissue, or top ply of white board – the two different methods of flotation deinking and wash deinking can be applied. In case of the highly selective flotation deinking, detached ink particles adsorb on air bubbles. The resulting foam is removed from the fiber suspension. During washing of ink components, fines and fillers are separated by fine-meshed screens. Ink particles should be as small as possible in the washing process, whereas optimum particle size is between 10 and 150 µm for the flotation process.

The more selective flotation process results in lower fiber losses (approximately 10%) compared to washing with yields of only 60–70%. In Europe flotation is most commonly used and washing is only used for special deinked pulp (DIP) qualities, whereas in North America, washing is more common.

Generally, the deinking recipes distinguish between woodfree and wood-containing recovered paper and how the removal is carried out, that is, washing or flotation.

The first step and basic prerequisite for printing ink removal is their detachment from the fiber surface, followed by agglomeration of the particles and then separation from the pulp mixture (Figure 6.29).

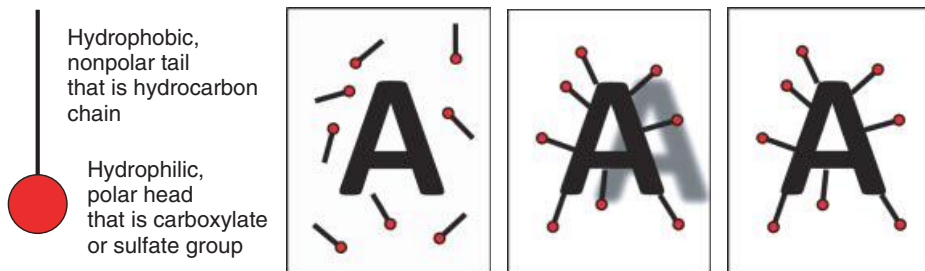


Figure 6.29 Basic structure of surfactant and ink particle release process from paper surface.

The required chemicals are already dosed during defibration into the pulper or the drum. The most frequently woodfree grades such as magazines and newspapers are recycled by flotation deinking. The following chemicals are generally used:

- 1) **Tensides (soaps), mostly oleic acid (octadecene acid):**
They release ink particles from the pulp and form the foam needed for the carryout of the ink particles.
Dosage: between 0.5 and 1%.
- 2) **Caustic soda (NaOH):**
Caustic soda saponifies the oleic acid to the soda-soap and swells the fibers in order to get an improved ink release.
Disadvantage: alkali yellowing.
Dosage approximately 0.8%.
- 3) **Water glass (sodium silicate):**
It improves ink release and stabilizes H_2O_2 .
Disadvantage: anionic load, tendency to form deposits.
Dosage: up to 2%.
- 4) **Chelating agents, usually DTPA:**
These agents are used for peroxide-stabilization.
Dosage: approximately 0.2%.
- 5) **Sodiumdithionite (Hydrosulfite):**
This helps in reductive (lignin sustaining) bleaching.
Dosage: up to 2%.
- 6) **Hydrogen peroxide (H_2O_2):**
 H_2O_2 is added to increase brightness.
Dosage: approximately 1%.

These chemicals support the defibring process and, in collaboration with the mechanical stress in the pulper or drum, effect the release of the ink. The most important chemical is sodium hydroxide (NaOH). NaOH eases the detachment of the ink particles from the fibers as the fibers swell substantially in this environment. Additionally, saponifiable binders in the ink are saponified under alkaline conditions.

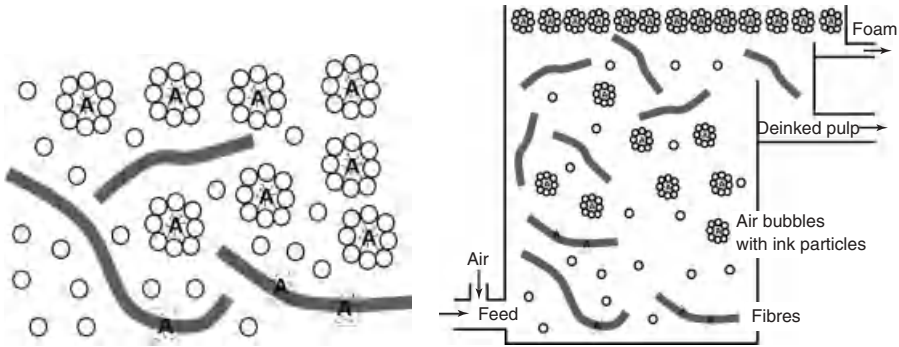


Figure 6.30 Ink removal, foam formation, and principle of a flotation cell setup.

Owing to yellowing of wood-containing pulp by NaOH, the addition of hydrogen peroxide is recommended. The peroxide reduces yellowing, improves detachment of the ink, and has a bleaching effect. As hydrogen peroxide is more effective at higher concentrations, the pulping process is preferably carried out at stock consistencies of 12–20% (high-consistency pulper or drum pulper).

As peroxide can be decomposed by polyvalent metal ions, that is, Mn^{2+} and Fe^{2+} , chelating agents (maximum 0.2%) can mask the detrimental influence of these heavy metals. Decomposition of hydrogen peroxide can also be caused by the activity of microorganisms that produce peroxidase to protect themselves. Here suitable biocides need to be applied; among these, glutardialdehyde has proved to be quite efficient.

In addition, water glass (sodium silicate) is added to stabilize the hydrogen peroxide to assist in ink detachment and to prevent the ink particles from redepositing on the fiber. Sodium silicate can lead to silicate deposits. This can cause holes in the paper and web breaks on the paper machine. Thus the dosage in wood-containing recovered paper is limited to 2%.

For the detached ink particles, dirt collectors or flotation agents are needed to bind the hydrophobic ink to the air bubbles. In case of flotation, deinking active collectors are used on the basis of anionic surfactants. These surfactants further improve the ink detachment and stabilize the foam. In order to build calcium salts, a minimum water hardness of 10 °dH is needed in the system. If the water hardness is lower, calcium ions can be added in the form of calcium chloride, or the process must be switched from fatty acids to synthetic (nonionic) tensides. All flotation additives are discharged together with the foam. Figure 6.30 shows schematically the flotation deinking process.

In the washing process, instead of collectors, 0.2–0.8% nonionic dispersing agents are applied to disperse and wash off the ink particles completely.

For woodfree recovered paper the dosage of water glass and sodium hydroxide is not necessary. Besides anionic collectors for flotation or nonionic dispersing agents for washing, oxidative or reductive bleaching agents, that is, hydrogen peroxide,

sodium dithionite, and formamidine sulfonic acid (FAS) are added. The bleaching process is often performed in two or more stages.

Coated papers can be deinked more easily because the ink particles are fixed only on top of the coating layer.

Problems occur, if the furnish contains high levels of flexographic (water-soluble ink) or ink-jet (small color pigments) printed papers. Increased amounts of process washing and/or lower pH may help in these cases.

6.10

Cleaning Agents and Fabric Conditioning

Kathrin Otto and Christoph Blickenstorfer

6.10.1

Contaminations and Factors for a Successful Cleaning Result

Cleanness in paper production affects the efficiency of the paper machine, the quality of the paper, and the safety. To achieve a clean machine, it is important to know, in a first step, the different types of contaminations and to understand the factors influencing the level of contamination, such as

- use of secondary fibers
- water quality
- enclosure of water systems
- temperature of water systems
- neutral papermaking
- quality of stock preparation
- use of fillers
- use of certain additives, such as sizing, binder, wet strength agents [14].

In general, the deposits on a paper machine are a mixture of different single contaminations, which interact on the basis of weak intermolecular interactions such as Van der Waals forces, electrostatic attraction, affinity because of the similar surface energy phenomena, and steric forces. Once an initial layer is built up, the adhesion of further substances is made far easier.

Contamination is not only brought into the system by raw materials but it can also occur owing to different processes such as precipitations, saponification, and flocculation that take place during the paper production.

The main contaminations found in paper production are shown in Table 6.10, where they are classified into three groups: organic, inorganic, and microbiological.

Commonly, the term *stickies* or also *bitumen* is used to describe deposits of several organic materials that mainly come from recycled paper or build up during the process.

Besides the above-mentioned contaminations and the material that needs to be cleaned (e.g., metal surface, machine clothing based on polyamide or polyester), the four factors; chemistry, temperature, time, and mechanics have maximum influence on successful cleaning (Figure 6.31).

Table 6.10 Classification of Deposit Material.

Class	Contaminations
Inorganic	Aluminum hydroxide, calcium carbonate, calcium sulfate, clay, talc, titanium dioxide, silica, rust
Organic	Adhesives, hot melts, coating binders, fibrous material, lignin, oils, sizes, starch, tar, waxes, wet and dry strength agents
Microbiological	Extracellular polymeric substances, microorganisms

Based on [15].

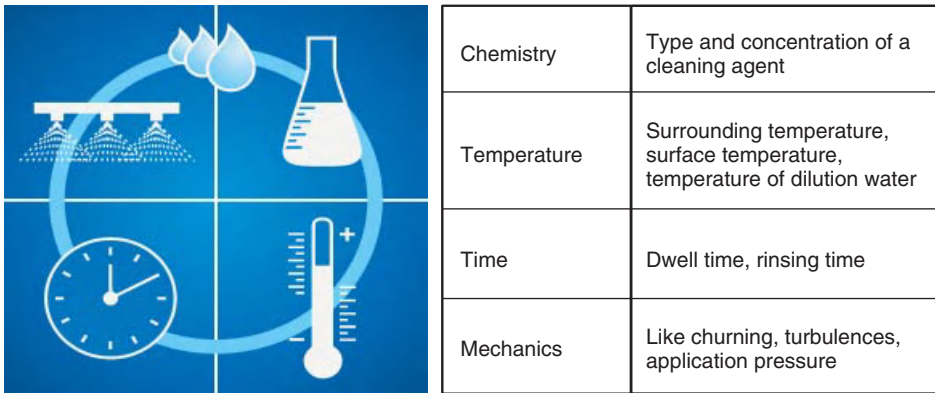


Figure 6.31 Sinner's circle shows the four main factors influencing the cleaning process [16].

These factors influence each other during the cleaning process. By increasing one factor, another factor can be reduced to achieve the same cleaning result. For instance, the duration of system cleaning can be shortened by increasing the temperature from 45 to 60 °C; or, if a highly concentrated cleaner is used, only a short application time is needed. Figure 6.32 points out different cleaning strategies based on the parameters time and chemistry.

For optimal cleaning effect, all four factors need to participate in a certain manner, but for all issues of the Sinner's circle an optimal range exists. An excess of one factor does not consequently give a better cleaning result – it might even reduce the cleaning result and/or damage the material being cleaned [16].

6.10.2

Cleaning Agents

Industrial cleaners used in the paper industry are normally classified as follows:

- by the main active substances, such as acid cleaner, alkaline cleaner, solvent cleaner;

- by their properties, such as neutral cleaner, concentrate cleaner, organic cleaner;
- by purpose, such as shutdown cleaner, system cleaner, metal cleaner.

A cleaning agent must fulfill several requirements, for example, it should be cost efficient, environmental friendly, adapted to the surface to be cleaned, and be able to remove the contaminations. Figure 6.33 shows extractability of different contaminations for the most important cleaning compounds acid, alkaline, and solvent.

Contaminations that are not extractable by acid, alkali, or solvent can just be dispersed by surfactants and washed out with water.

As deposits are a mixture of different contaminations, formulations for industrial cleaners for specific use in papermaking are made by combining the single

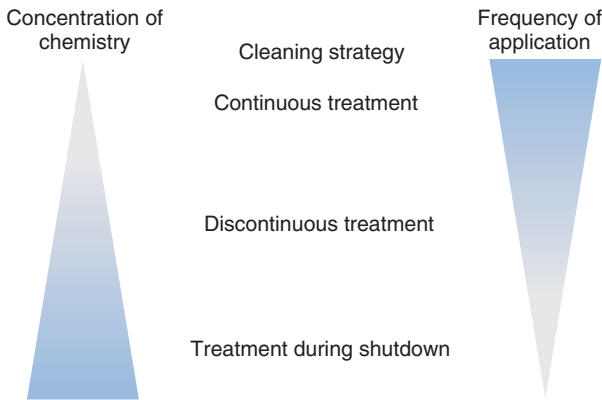


Figure 6.32 Different cleaning strategies based on the parameters cleaning frequency (time) and concentration of cleaning agent (chemistry).

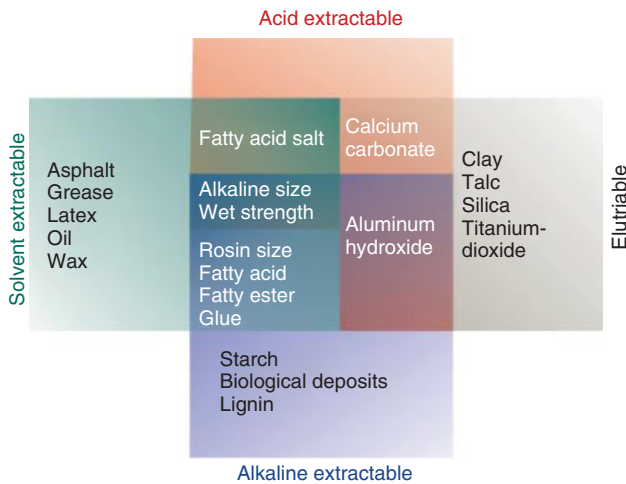


Figure 6.33 Extractability of different contaminations. (Based on [17].)

Table 6.11 Components of Cleaning Agents and their Main Tasks.

Component	Main tasks for cleaning	Common used substance
Acid	Reaction with inorganic particles; hydrolysis of organic substance (pH < 3)	Organic: citric acid, acetic acid Inorganic: sulfuric acid, phosphoric acid, hydrochloric acid, sulfamic acid
Alkali	Changing of charge for repulsion; saponification of organic substances (pH > 12); degeneration of cell walls	Caustic soda
Solvent	Solving of organic components	Aliphatic hydrocarbons, aromatic hydrocarbons, glycol ether, alcohols, D-limonene
Surfactant	Wetting, dispersing, stabilization, emulsifying, foaming, hydrophilization	Nonionic: fatty alcohol ethoxylate, fatty alcohol propoxylate, alkylpoly glucoside Anionic: alcohol sulfates, alcohol ether sulfates, alkylaryl sulfonates
Water	Carrier medium, dilution, washing out	Softened water

Based on [17].

components, tailored to the required application. Different types of surfactants support the cleaning process in an efficient manner by taking over several tasks, namely, wetting, dispersing, emulsifying, and/or foaming. The blend of surfactants needs to be fitted to the purpose of the cleaning agent.

Table 6.11 summarizes the cleaning tasks of the main components of a cleaning agent and lists the most common chemicals used. Additives such as colorants, fragrances, chelating agents can be admixed in addition.

In addition to cleaning agents that have been described, there are a number of special cleaners also available, for example, cleaners with enzymatic formulations [18] or with hydrogen peroxide [19] especially for boil-out cleaning.

6.10.3

Conditioning Agents

Conditioning agents in the wet end have the task of hydrophilizing the surface (Figure 6.34). Conditioning agents differ from cleaning agents in that conditioning agents prevent deposits by lowering the affinity between the hydrophobic contaminations and the treated surface. The two most common ways to hydrophilize the fabric surface in an economical way are by the use of specific cationic polymers or surfactants.

The polymers used for conditioning (sometimes also called passivation) in the wet end are positively charged hydrophilic molecules. By applying the polymer

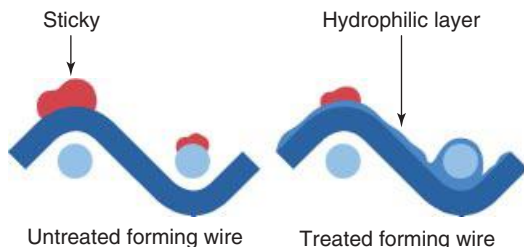


Figure 6.34 Conditioning of a forming wire. (Based on [20].)

continuously during production, a complex layer is formed on the treated material with the hydrophilic cationic polymer on the top [20]. Surfactants attach to the hydrophobic surfaces because of their surface-active properties and can build up an adsorption layer, whereby the hydrophilic parts extend to the top [21].

Intermolecular interactions are just weak connections, which are not persistent in a fluent system. Therefore conditioning agents have to be applied continuously.

Conditioning agents that are applied in the dry end change the release properties of the surface by making it superhydrophobic. Products available for this application are based on silicone and mineral oils [22].

6.10.4

Cleaning of Machinery and Water Circuit

The intention of system cleaning is to remove persistent deposits of scale, organic deposits, and microbiological slime, which cannot be removed or prevented during operational mode. The overall goal is to eliminate or reduce operational problems, paper defects, odor, and electrochemically induced corrosion.

On the basis of the four factors of the Sinner's circle system cleaning is best performed as boil-out, which means that the water is heated up to around 60 °C. Limits are set because of the material resistance and the formation of corrosive gases.

The traditional boil-out is carried out with alkaline cleaning agents. In production with a high filler load and hard water qualities, acidic cleaners are also applied to descale the system, especially piping and pumps. Cleaning agents for system cleaning contain, besides the components shown in Table 6.11, dispersing agents, chelating agents, and corrosion inhibitors [23, 24].

Often a system boil-out cannot include the entire system in an economical way. In this case, foam cleaning can be performed. Cleaning agents for foam cleaning contain high-foaming surfactants, which are frothed up via foam-cleaning devices.

6.10.5

Cleaning and Conditioning of Paper Machine Clothing

The strategy of mechanical and chemical treatment of paper machine fabrics depends on various factors:

- type and degree of contamination
- fabric material and design
- machine section and surrounding conditions
- demands on process and paper quality.

The overall aim of keeping felts and wires clean is to maintain optimal permeability, uniformity, and surface characteristics, as well as to prevent wear and compaction. Common strategies for machine clothing optimization are summarized in Figure 6.35.

Traditional cleaning during shutdown, which is also called batch-down cleaning or shock cleaning, is usually done with high concentrated cleaners, as they do not get in contact with the paper web and have no influence on the running process. This application achieves good results with persistent deposits of pitch and stickies.

Shutdown cleaning is adequate for all sections of the paper machine using cleaners tailored to the material of the single fabrics and the surrounding conditions.

Treatments during production can reduce or eliminate shutdown cleaning. The strategy and chemistry chosen depend to a high degree on the sensitivity of the process and the paper quality. The dosage of chemicals during production on wet end clothing may influence the process, such as tackification due to pH shift and reduced dewatering due to alkaline-induced press felt swelling.

Discontinuous cleaning during production (also, batch-on-the-fly cleaning) means, that small amounts of cleaning agents are applied periodically (e.g., once a day or once a shift). Generally, alkaline and acidic cleaners with medium concentration are applied in the wet end.

Continuous treatment in the wet end is divided into cleaning and conditioning, but often the terms are used interchangeably. Continuous cleaning agents are usually pH neutral or contain just a small amount of acid or alkali. Conditioning, which is also called passivation, differs in that its target is to hydrophilize the clothing in the wet end and to change the release properties in the dry end.

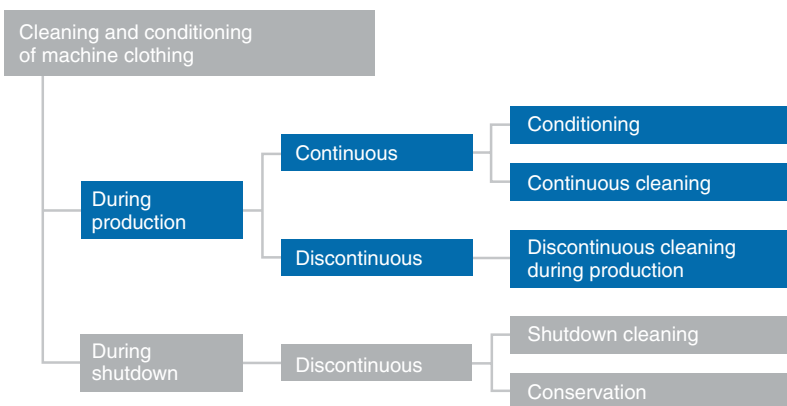


Figure 6.35 Solution strategies for cleaning and conditioning of paper machine clothing.

Very small concentrations of cleaning/conditioning agents are applied continuously to keep the structure of the clothing open and to maintain the performance at the highest level possible. Moreover, certain treatments can improve the capillarity of the fabric (wet end) and lubrication for the run.

The process factors that are influenced by a contaminated and/or worn fabric are various and specific for each part of the paper machine. A cleaning management, which includes monitoring and evaluation of the cleaning and conditioning actions during the fabric lifetime, can be decisive criteria to optimize the process.

For direct evaluation of batchwise cleaning, permeability testers are very common in practice. Process and quality parameters, such as vacuum levels, paper profile, sheet defects, dry content after the last press, and specific steam consumption can also be taken into account [25].

A good monitoring should last over a longer period and several complete lifetimes of the clothing. The intervals of and the reasons for clothing changes should be recorded and statistically evaluated to optimize shutdown planning.

6.11

Internal Water and Effluent Treatment

Arne Hörsken, Andreas Opalka, and Stefan Nierhoff

6.11.1

Water Systems in Paper and Board Mills

In paper and board mills, water is an essential component of production. Water is not only used once, but it is usually recycled during operation. Water recycling makes economic and environmental sense, because the amount of wastewater for the company is minimized and costs can be saved. The water system of a paper or board mill consists of

- prior water treatment, which provides the so-called freshwater or process water for industrial use;
- production water cycle, in which water is used for production purposes;
- downstream wastewater treatment, in which the wastewater from production is cleaned.

The upstream and downstream water subsystems can be provided by public or private water companies or wastewater treatment plants. Figure 6.36 illustrates the trend in recent decades to reduce freshwater consumption by increasing water recycling [26].

Owing to the continuous decrease in water consumption over the past decades, there is an accumulation of ionic compounds and the salt concentration in the water circuits of paper and board mills increases. Further, the increasing use of recycled paper instead of clean virgin pulp leads to more anionic trash, fines, and fillers in the water circuits. As a consequence, additional amounts of chemical additives are required [27]. Increasing coating and painting of paper provides for an

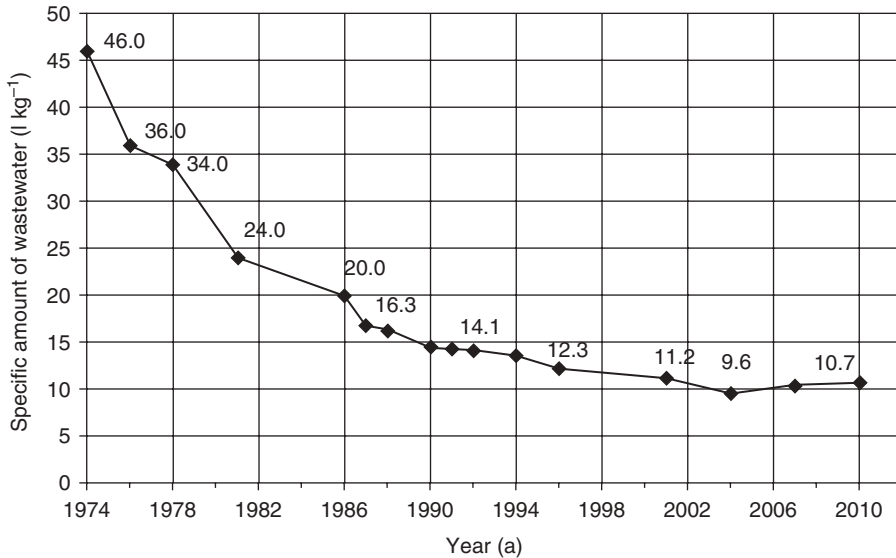


Figure 6.36 Decrease of the mean specific amount of wastewater in the German paper industry from 1974 to 2010, modified after [26].

additional use of chemical additives in papermaking. If these papers are recycled and used as raw material in paper mills, they pose a greater potential for detrimental substances. Figure 6.36 also shows that in recent years, the specific amount of wastewater per kilogram of paper is relatively constant at approximately 10 l kg^{-1} . This development suggests that water recycling without further water treatment cannot be enforced because of the negative impacts on the environment or the produced paper [26].

6.11.2

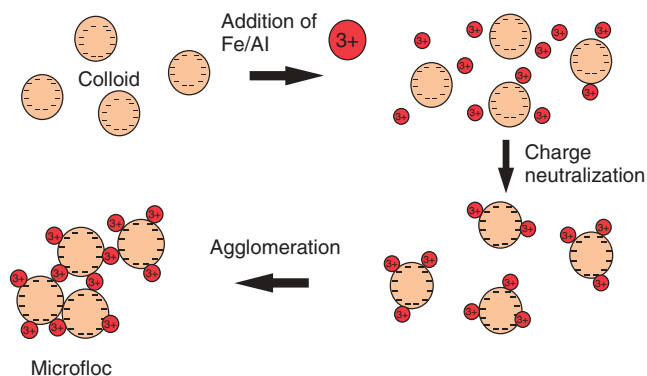
Water: Chemical and Physical Parameters

Characterization of a water system is done in practice by chemical and physical parameters as shown in Table 6.12. Microorganisms suspended in the water phase and agglomerated microorganisms on surfaces, known as *biofilms*, influence the quality of water used by the pulp and paper industry [28].

One of the parameters for the characterization of water quality is the quantity of settleable solids per liter of water. For this method, within a certain period of time, sedimented solids are quantified volumetrically in an Imhoff cone. In addition to easily settleable solids, such as fibers, there are other solids in the water that cannot be detected by the aforementioned method. In an aqueous environment, undissolved solids from a magnitude of less than $10 \mu\text{m}$ in size are known as *colloidal dissolved particles* or simply as *colloids*. Colloids usually carry a negative surface charge because of hydroxyl groups on their surface. Owing to these negative charges, colloids repel each other and remain dispersed in a floated state because of their small

Table 6.12 Important Chemical and Physical Parameters of Water Systems.

Parameter	Unit	Explanation
Settleable solids	mg l^{-1}	Heavier solids such as fibers and particles
Turbidity	TE/F; FTU; FNU	Colloidal substances, particles, solid impurities
COD	$\text{mg l}^{-1} \text{O}_2$	Chemical oxygen demand
BOD	$\text{mg l}^{-1} \text{O}_2$	Biological oxygen demand
pH	pH units	Acid/alkaline conditions
Conductivity	$\mu\text{S cm}^{-1}$	Level of the amount of ions in water
Cationic charge demand	$\mu\text{eq l}^{-1}$	Level of anionic trash

**Figure 6.37** Coagulation: destabilization of colloids by trivalent metal ions and subsequent formation of microflocs.

size and repulsion. Colloids consist of very different substances or microorganisms. Colloids can be inorganic compounds such as iron oxides, silicates, and gypsum or clay particles. Examples of colloids composed of organic compounds are resin particles, humic substances, lignins, fats, or oils [29]. Besides inorganic and organic compounds, microorganisms individually suspended or in the form of agglomerates can also count as colloids because of their small size of $0.5\text{--}10.0\ \mu\text{m}$ [30].

6.11.3

Flocculation

A measure to remove colloidal particles from the water and thus improve the water quality is the so-called process of flocculation. This cleaning method is based on the chemical and physical principles of coagulation, flocculation, and separation and is very similar to the principle of retention on a paper machine (cf. Section 6.3).

The first step of flocculation is called *coagulation* and it results in the formation of microflocs. Colloidal particles with the same or a similar negative surface charge are destabilized by cationic charge carriers with a high charge density so that they aggregate into small agglomerates called *microflocs* (Figure 6.37).

Table 6.13 Summary of Commercial Metal Salt Solutions Used as Coagulants.

Metal salt solution	Aluminum or iron (g l^{-1})	Chloride or nitrate (g l^{-1})	Sulfate (g l^{-1})	“Basicity” (%)
$\text{Al}_2(\text{SO}_4)_3$ -solution	40	0	220	0
AlCl_3 -solution	60	230	0	0
PAC	89	220	0	46
PACS	54	100	30	46
ANS	54	160 (Nitrate)	30	47
FeCl_3 -solution	138	262	0	0
$\text{Fe}_2(\text{SO}_4)_3$ -solution	120	0	320	0

PAC, polyaluminum chloride; PACS, polyaluminum chloride sulfate; and ANS, aluminum nitrate sulfate.

Source: Technical Data Sheets from different manufacturers of commercial metal salt solutions.

Microflocs, in contrast to individual colloids, are visually discernible to the naked eye; their size is on the order of 0.1–2.0 mm. In practice, trivalent aluminum salt solutions with different chemical compositions are mainly used as coagulants. Major factors influencing flocculation are pH, temperature, conductivity, turbulence at the dosage point, and mixing energy during the maturation of the flocs. An overview of metal salt solutions is given in Table 6.13. Data for aluminum, chloride, and sulfate are given in grams per liter. “Basicity” is the percentage of hydroxide ions of the total anions, which stoichiometrically correspond to the metal cations in the metal salt solution.

The mode of action and differences between aluminum salts have already been discussed in Section 6.2. Microflocs formed during coagulation consist of a matrix of destabilized colloids and gel-like aluminum hydroxide. However, it is not only destabilized colloids that are removed by flocculation of the water. During the formation of microflocs, particles or macromolecules are also encircled in the floc matrix of aluminum hydroxide. This process is called *sweep coagulation*. Furthermore it is possible to bind particles or macromolecules by adsorption on the floc surface [31]. Figure 6.38 visualizes such a microfloc schematically.

A problem of the formed microflocs is their high instability to mechanical stress such as turbulence or currents. Microflocs fall apart easily and are often not stable enough to be separated mechanically or physically from the aqueous phase. Therefore, a second step of flocculation with the so-called flocculation aids is applied. A flocculating effect via bridging and adsorption leads to further agglomeration of microflocs into larger agglomerates which are called *macroflocs*. The floc size increases significantly (>2 mm) and the bonds within the macroflocs become much stronger. The process of flocculation is illustrated in Figure 6.39.

Macroflocs with sizes in the range 2–10 mm are visible to the naked eye, and their separation, either mechanically or physically, is much easier from the water

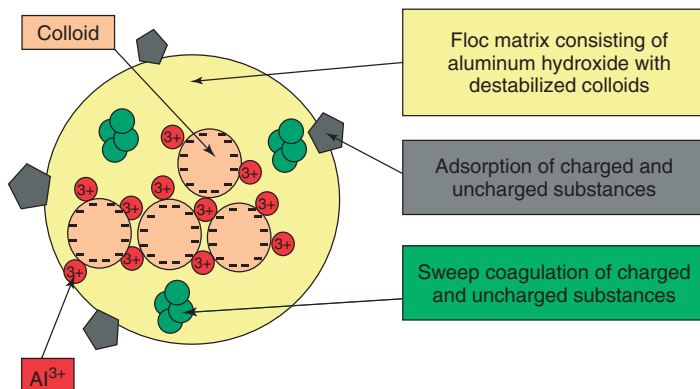


Figure 6.38 Schematic visualization of a microfloc with destabilized colloids, and other possible components (not to scale).

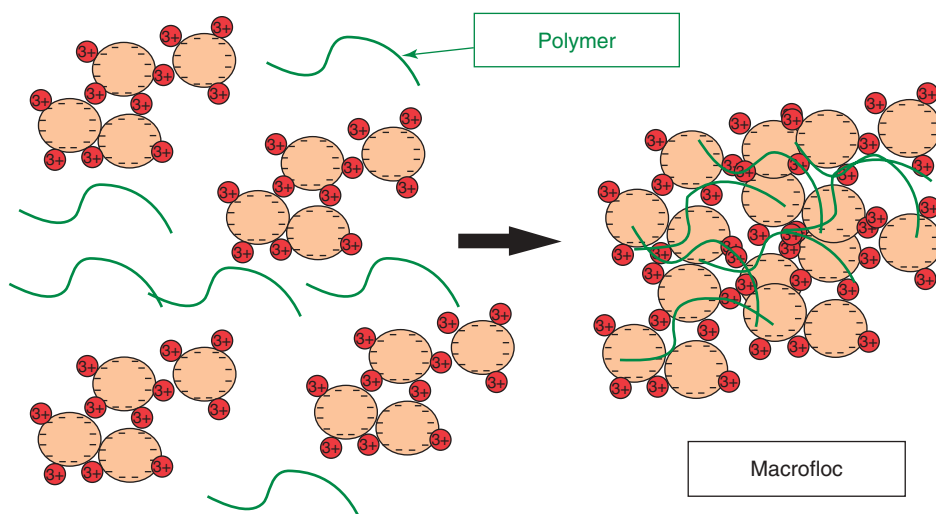


Figure 6.39 Agglomeration of microflocs to macroflocs by use of flocculants.

than that of the smaller microflocs. Owing to their greater stability, macroflocs can be separated through the disc filter, mechanical press, or centrifuge.

Organic polymer compounds on the basis of PAM are among the flocculants predominantly used for the formation of macroflocs (Figure 6.4) with high molecular mass of $200\,000\text{--}20\,000\,000\text{ g mol}^{-1}$. Owing to the existing variables in polyelectrolytes such as polymer type, charge, charge density, molecular weight, and degree of cross-linking, for each application, it is possible to find an optimal interaction between polyelectrolyte and microfloc and thus an optimum flocculant for the macroflocs in terms of floc size and floc stability. Low-molecular-weight polymers with high charge density can be used as coagulants for the formation of microflocs as well.

After flocculation, there are basically three different methods to separate the flocs from the water:

- sedimentation (sinking of the flocs because of higher density);
- flotation (flotation of the flocs because of embedded air bubbles);
- filtration (retaining of the flocs at or on a filter material).

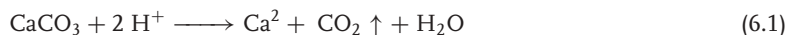
6.11.4

Potential Problems by Use of Acidic Aluminum Salts in Water Systems

After addition of an aluminum salt solution into an industrial water circuit, the dissolved trivalent aluminum cation hydrolyzes (Section 6.2) to undissolved aluminum hydroxide. Owing to its charge, the microfloc binds to anionic paper fibers and is removed via the web from the water circuit. The anion of the aluminum salt solution, either sulfate or chloride, remains in the water and accumulates there. The degree of water circuit closure and the amount of added aluminum salt solution have a strong influence on the increase in the anion concentration in the water. Depending on the kind of aluminum salt solution used, specific problems can arise in industrial water systems [31].

6.11.4.1 Use of Aluminum Sulfate

With the use of aluminum sulfate solutions in paper mills, the concentration of sulfate ions in the water cycle increases. The concentration can reach up to 2000 mg l^{-1} . In completely closed systems, these values may even be higher and the precipitation of calcium sulfate (gypsum) occurs when the solubility is exceeded. This effect is further enhanced by the increasing use of calcium carbonate as filler in the paper industry. A much lower pH results because of the acidic aluminum sulfate solution at the dosage point. This local pH reduction may lead to partial dissolution of calcium carbonate and the concentration of dissolved calcium ions increases:



The increase of calcium ion concentration as described in Eq. (6.1) in conjunction with high sulfate content amplifies the risk of gypsum and calcium carbonate precipitates, and the formation of deposits in pipes and nozzles.

Owing to the local pH decrease at the dosage point of the aluminum sulfate solution, formation of gaseous carbon dioxide can occur. This can interfere with the papermaking process on one hand by foaming and on the other hand through formation of pinholes in the produced paper [32].

High sulfate concentrations, which are caused by aluminum sulfate use, can have further negative consequences for water systems such as formation of hydrogen sulfide by the activity of sulfate-reducing bacteria and microbially influenced corrosion [33].

6.11.4.2 Use of Aluminum (Hydroxide) Chloride

The use of aluminum (hydroxide) chloride solution or PAC leads to an accumulation of chloride anions in the water system. Here, depending on the dosage amount

of the aluminum salt solution, the amount of freshwater, and the degree of circuit closure, chloride concentrations of 100–2000 mg l⁻¹ can be reached. With increasing chloride content, the risk of corrosion increases as well. In most cases, the equipment in the water system of paper and board mills is made of stainless steel. Owing to an expected material damage starting at a chloride concentration > 500 mg l⁻¹, the use of aluminum chloride solutions in highly closed water circuits can be limited.

Another problem that is caused by the high chloride content in water systems is the increasing salt burden, which is measured by the conductivity in water. Through increased interaction among the ions, chemical additives are negatively affected. To compensate for this disturbing effect, a surplus of the chemical additives is necessary. The salinity in the water system of a paper mill has another negative effect, which is the environmental impact. The left over residuals of chemical additives leave the industrial water system into natural waters and thus into the overall water cycle. In order to prevent consequential damages, such as eutrophication, there are often limits for parameters such as phosphate, nitrogen, COD, and BOD. Limits for anions such as sulfate or chloride are often not given, but are important, nevertheless.

6.11.4.3 Use of Aluminum Nitrate

Owing to the above-described problems encountered in the use of aluminum sulfate and aluminum chloride or PAC, there are limits to the quantities of those products that can be used. One possible alternative to the previously used aluminum salt solutions are products based on aluminum nitrate. Aluminum nitrate solutions can be used for cleaning of impurities, fines, and filler or for resin sizing. Because of biological nitrate removal (denitrification) they could provide a lower salinity to the water cycle. The resulting end product of denitrification is nitrogen (N₂). Microorganisms can reduce nitrate to nitrogen directly in the paper mill's water system. Together with microbially utilizable carbon compounds, expressed here as BOD₅, denitrification can proceed:



As BOD₅ or carbon source in this reaction, for example, organic acids, alcohols, or carbohydrates may be used. If the biological metabolism of nitrate by microorganisms is in a similar magnitude compared to nitrate addition via aluminum nitrate solution, an accumulation of nitrate ions can be avoided. This way, by use of an aluminum nitrate salt solution, the salinity can be reduced significantly in paper mill water systems. Consequently, this allows less use of chemical additives and environmental impact on the aquatic environment is also reduced [33].

6.11.5

Freshwater Treatment

Freshwater treatment aims to provide water of sufficient quantity and quality for the production process in paper and board mills. Overall, in 2010, around 300 million

m³ of freshwater has been treated in the German paper industry, of which 77% is surface water and 22% comes from groundwater sources. The use of drinking water is negligible [26].

During freshwater treatment, the raw water is cleaned from particles and fine solids according to the above principles by flocculation and filtration. If groundwater contains large amount of iron and manganese, the water must be ventilated in order to oxidize the dissolved iron and manganese ions and bring them in an insoluble form, so that they can be separated out. Similar to drinking water treatment, a disinfection step with microbicidal agents is often part of further treatment to reduce the number of bacteria in the water phase and limit microbial activity.

6.11.6

Internal Water Treatment

Owing to the number of paper mills and their individual character, the treatment of internally circulated water is carried out very differently. In the case of a completely closed water system, the water treatment takes place to the point that even wastewater is completely sent back into production again. Evaporative losses are supplemented by the use of freshwater. Figure 6.36 illustrates the considerable success that has been achieved in the use of recycled water in the past decades.

The simplest case of internal water treatment is when the loss of fiber material is targeted. The white water can be filtered using, for example, disk filters, can be floated via dissolved air flotation units, or can be sedimented via white water towers. Through the use of chemical additives such as aluminum salts, the treatment efficiency can be increased, and the water can be cleaned not only of fibers but also of fines and fillers.

A special case of internal circulation of a paper mill's water system is the treatment of coating wastewater. This wastewater is either treated separately in its own treatment plant or it is fed to the wastewater of the paper mill. Selective treatment of coating wastewater and recycling of coating color pigment is also being carried out in paper mills.

6.11.7

Wastewater Treatment in Paper and Board Manufacturing

The wastewater treatment in paper and board mills is done with the aim to fulfill regulatory requirements and to release water that has been affected to the least possible extent into the environment. To achieve these two goals, in practice, chemical and physical separation methods as well as biological degradation processes are used:

- Pretreatment of wastewater for removal of solids
 - filtration (filter, classifier, sifter, disc filter)
- Mechanical treatment of wastewater (sedimentation) after flocculation
 - rapid sedimentation of solid particles
 - slow sedimentation of flocs

- Biological treatment of wastewater
 - aerobic (with oxygen supply, ventilation: activated sludge process)
 - anaerobic (without oxygen and without aeration)
- Sludge treatment
 - partial degradation (anaerobic decomposition, formation of biogas: CO₂ and CH₄)
 - thickening (dewatering)
 - disposal.

The average cost of wastewater treatment in German paper and board mills in 2010 was €0.45 m⁻³ for direct dischargers. For indirect dischargers, costs of €1.27 m⁻³ were determined. The trend for the cost of wastewater treatment in Germany has been increasing since 2004 [26].

6.12

Interactions of Chemical Additives

Roland Pelzer

It has repeatedly become a point of discussion among papermakers as to whether too many and too much chemical additives are used in their production cycle. The need now (also driven by economic considerations) is to reduce the number and volumes of chemical additives immediately.

This discussion should have a broader scope: firstly, it should be considered how many chemical substances are being accumulated in the water loops just because the process water is reused. Besides the desired chemical additives, there are plenty that are not needed, not desired, and are even harming the whole process. Production of high-quality paper at high productivity requires

- getting deeply involved into the chemistry of the process water loops;
- putting forth clearly, which chemical additive in which combination with other additives, at which dosage, and which dosage point is going to show best performance
- applying changes only after systematic evaluation and not by following intuition.

As a consequence of these demands, the application of chemical additives should be treated as a service package with a value for the papermaker, involving an in-depth specialist counseling rather than just purchasing products.

Surface charge is a key factor in papermaking and chemical additives may carry anionic or cationic charges, or both (amphoteric), or no charge at all, as well. Products with different charges should not be mixed with each other. Their feeding point to the paper stock should be far apart, so that one component can be mixed properly into the pulp suspension, before the next component is added. Highly charged products should be prediluted before feeding. Figure 6.40 shows the impact on chemical charge in the paper production process while adding charged products along the production line.

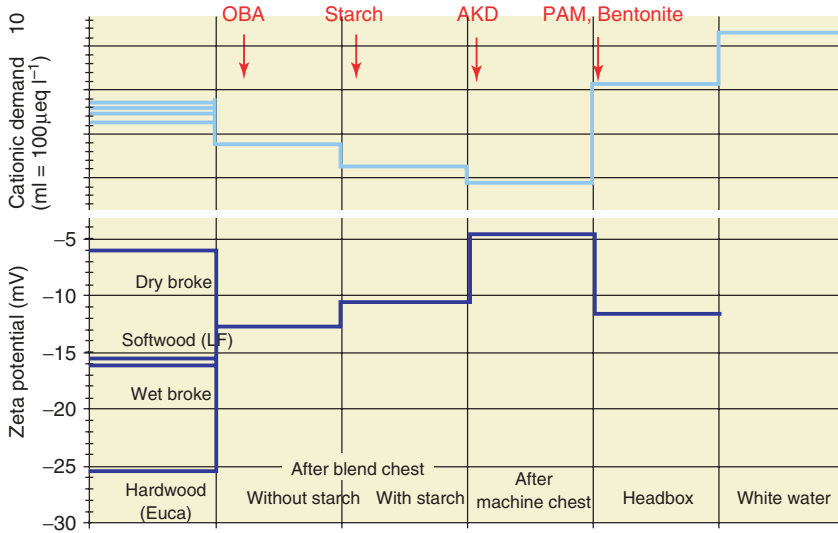


Figure 6.40 Charge development in a fine paper furnish along the stock preparation line. (Source: Voith Paper.)

As most of the fibers are being retained on the wire, no zeta potential measurement was carried out in the white water. The increased value for cationic demand in the white water is due to anionic fines and colloidal matter not being retained in the paper sheet.

Different charges and other surface properties may reduce or even extinguish performance if the products get into contact, and agglomerates may be formed in the worst cases. Table 6.14 explains the impact of particular additives on others, if used together. As explained, this effect can be reduced or avoided, if the components are diluted and added in the ideal order, all of them separate, one after the other. The additives on the horizontal scale have impact on those on the vertical scale. The statements depend on the dosage amount and order.

Figure 6.41 illustrates a general rule on feeding additives (raw materials in *blue*, additives in *red*). According to this rule, chemicals are added from anionic to cationic charges. Papermaking is carried out with slightly anionic charged stock (with the exception of some specialty paper grades). It is advisable, to monitor the charge along the production line in order to avoid huge variations and to keep the stock above the desired minimum anionic charge (minimum cationic demand).

Most frequent critical interactions in daily work are listed here again:

- **Polymer incompatibility:**
When a cationic polymer comes into contact with an anionic polymer, deposits increase, resulting in production problems.
- **pH – variations:**
Reactive products (wet strength, AKD/ASA sizing) do not tolerate pH shocks.

Table 6.14 Possible Interactions between Chemical Additives.

	Dispersing aids	CMC	Biocides	De-foamers	Cationic starch	Fixatives	Dyes / OBA's	Wet strength	Sizing	Retention aids
Dispersing aids		+	0	0	-	-	0	--	-	--
CMC	-		0	0	+	++	0	++	0	+
Biocides	0	0		0	0	+	0	0	0	0
De foamers	0	-	0		0	0	-	0	-	(+)
Cationic starch	-	-	0	0		+	-	+	0	+
Fixatives	-	-	0	0	+		-	+	0	+
Dyes / OBA's	0	0	0	0	+/--	+/--		+/--	0	+/-
Wet strength	-	-	0	0	+	+	0		0	+
Sizing	-	0	0	--	++	++	0	+		+
Retention aids	-	-	0	0	+	++	-	0	0	

- negative impact; 0 no impact; + positive impact; ± may have impact under particular conditions.

- **Emulsion stability:**

The performance of AKD and ASA sizes depends a lot on the formation and stabilization of fine dispersed particles. Anionic trash and surface-active substances may cause agglomeration and insufficient emulsion stability.

- **Performance of cationic additives:**

In case of high anionic load, some weak cationic charged additives (glyoxal resins, dyes) perform badly.

- **Optical brighteners:**

In the presence of cationic polymers, OBAs do not perform.

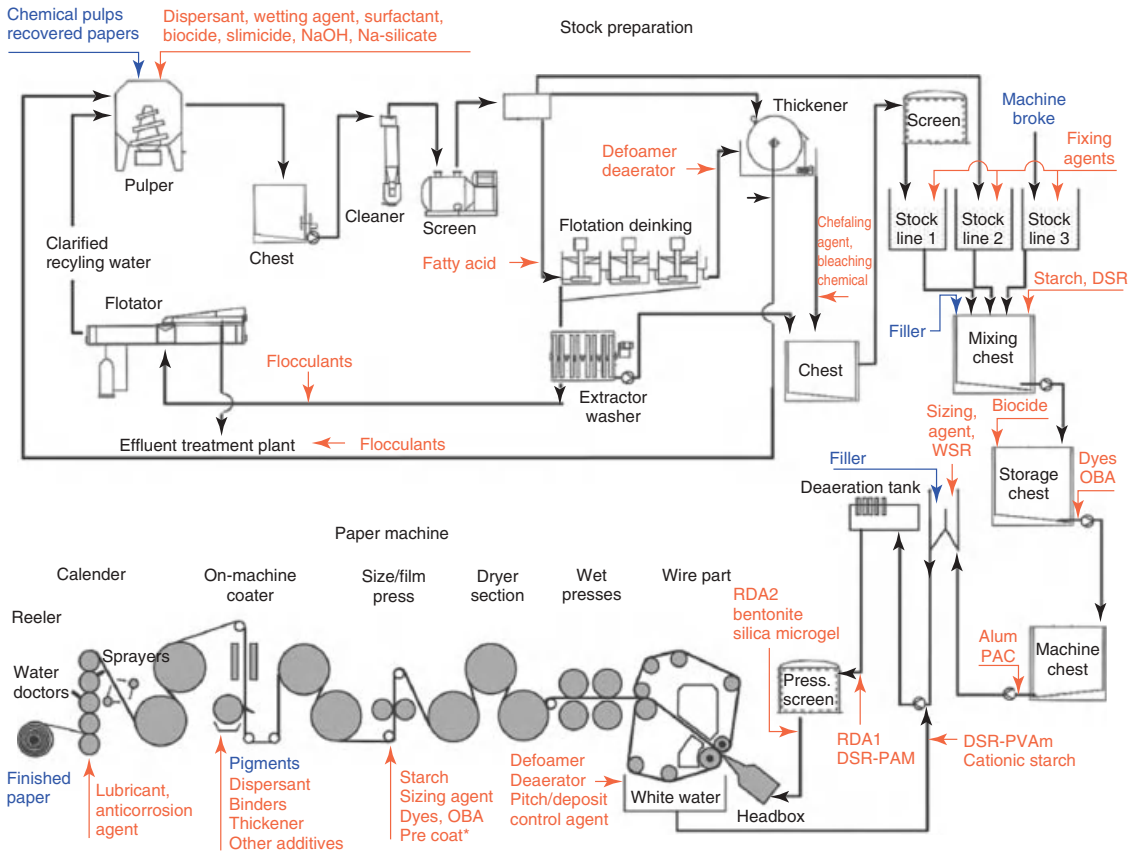


Figure 6.41 Flow sheet of paper production process with integrated metering points and addition sequences of various chemical additives. (DSR, dry strength resin; DSR-PAM, dry strength resin – polyacrylamide; OBA, optical brightening agent; PAC, polyaluminum chloride; RDA, retention drainage aid; WSR, wet strength resin.) [34]. (Source: Figure taken from Handbook of Paper & Board, ED. 1.)

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7 Unit Operations

7.1

Overview

Herbert Holik and Harald Heß

7.1.1

Objectives and General Solutions

7.1.1.1 Systems

The objective of fiber stock preparation systems is to modify the different ingoing raw materials in such a way that the finished stock finally supplied to the paper machine suits the requirements of the paper machine and of the quality demands put on the produced paper or board. The raw stocks used are the various types of virgin pulps as well as recovered paper grades. They are available in the form of bales, loose material, or, in the case of integrated mills, as suspensions. The finished stock is a suspension of defined quality as far as the mixture and characteristics of the fibers, additives, and impurities are concerned. This quality essentially determines paper machine runnability and is the basis for the final paper and board quality.

A stock preparation system consists of several unit processes that are adapted to one another. Their individual efficiency and the reliability of processing machinery depend on suspension properties such as consistency and flake and debris content, on the chemicals entrained or added and on the process design itself. So some of the unit processes may be used several times in a preparation process line, others just once. Most of the machines used for performing the individual unit processes have not just single effect but also some side effects that may or may not be desirable. The systems differ considerably depending on the raw material used and on the quality of the finished stock required. For instance, fiber design by refining is of central importance in the preparation of chemical pulp. For recovered paper processing the cleanliness of both the individual fibers and the suspension are the main objectives and so the removal of interfering materials is most important.

A stock preparation system comprises essentially three levels (Figure 7.1):

- Production level, which comprises the direct line from raw material input to the finished stock. This may include unit processes with some or all of the following

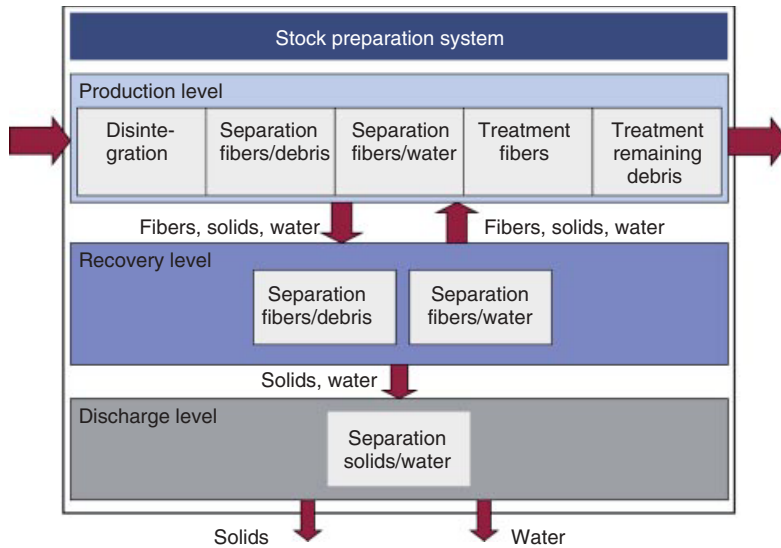


Figure 7.1 Process levels in fiber stock preparation and their functions.

objectives: to break down the raw material into individual fibers, to separate fibers and contaminants, to separate fibers/solids and water, to treat the fibers, and to treat the residual contaminants.

- Recovery level where fibers and other solids, and water are recovered from the rejects of the separation processes applied at the production level. Again fibers and contaminants, as well as solids and water, have to be separated.
- Discharge level, for ecological and economic reasons the final rejects are separated into wastewater and residues with high dry content often used for incineration or reused in other industries.

7.1.1.2 Unit Processes

The unit processes in fiber preparation and their objectives are as follows:

- **Disintegration (slushing and deflaking):** to break down the fiber raw material into a suspension of individual fibers. Slushing should at least result in a pumpable suspension enabling separation of coarse debris, and deflaking if required. In the case of recovered paper, ink particles and other nonpaper particles should be detached from the fibers.
- **Screening:** to separate particles from the suspension, which differ from the fibers in size, shape, and deformability.
- **Fractionation:** to separate fiber fractions from each other according to defined criteria such as shape, length, or deformability of the fibers.
- **Centrifugal cleaning:** to separate particles from the suspension, which differ from the fibers in specific gravity, size, and shape.
- **Selective flotation:** to separate particles from the suspension, which differ from the fibers in surface properties (hydrophobicity).

- **Nonselective flotation:** to separate fine and dissolved solids from water.
- **Washing:** to separate fine solid particles from suspension (solid/solid separation). The separation of organic (fines) and inorganic (fillers) components still needs more research.
- **Dewatering:** to separate water and solids.
- **Bleaching:** to endow yellowed or brown fibers with the required brightness and luminance.
- **Refining:** to modify the morphology and surface characteristics of the fibers.
- **Dispersing:** to downsize dirt specks and stickies that they no longer negatively affect the product quality or production and to detach residual ink particles from fibers and to reduce their size if necessary in order to make them floatable.
- **Mixing and storing:** to generate a uniform blend of suspension components and to prevent suspension components from demixing, or give time for fiber swelling or chemical reactions.

The main unit processes, their principles, and the machinery applied are described in the following sections. The description of fiber stock preparation systems for different kinds of fiber raw material and final application of the finished stock are discussed in Chapter 8.

7.1.2

Separation Processes

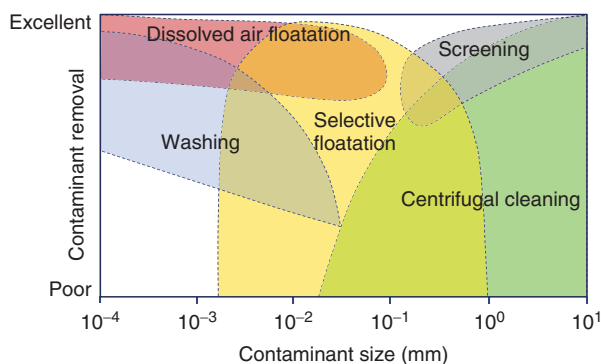
Separation processes are of high importance in recovered paper processing as this material contains

- additives used in the previous paper production process, such as fillers and dyes, coating components, and functional and process chemicals;
- substances added with respect to the application, such as printing inks, varnishes, coatings, foil laminations, adhesives, and waxes;
- materials mixed with the paper during its life cycle, subsequent collection, and handling in the mill, including wires and strings, glass, sand and stones, or paper clips and folders.

Solid particles comprise a wide range of materials with a wide range of properties. Characteristics of the particle used as separation criteria must clearly differ from that of the fiber. These include particle size, shape and deformability, density, and surface properties (hydrophobicity). Table 7.1 lists the characteristics such as “specific gravity and size” for various types of contaminants. Most of these contaminants have to be removed for quality and machine runnability reasons, fillers may be tolerated to some extent depending on the product. Figure 7.2 shows qualitatively the efficiency scatter of the separation processes versus particle size. Nonselective flotation (dissolved air flotation, DAF) separates small particles very efficiently from water. Washing removes small particles are the efficiency of this process mainly depends on the amount of extracted water. Selective flotation effectively removes particles over a wide size range, but removes only hydrophobic particles. Screening is most

Table 7.1 Density and particle size of contaminants in recovered paper processing.

Type of contaminant	Density (gcm^{-3})	Particle size range (μm)
Metal	2.7–9	>1000
Sand	1.8–2.2	>1–1000
Fillers/coating particles	1.8–2.6	<1–1000
Ink particles	1.2–1.6	<1–1000
Stickies	0.9–1.1	<1–1000
Wax	0.9–1.0	<1–10
Styrofoam	0.3–0.5	>100–1000
Plastics	0.9–1.1	>100–1000

**Figure 7.2** Efficiency ranges of unit processes for contaminant removal in recovered paper processing.

successful in removing larger and cubic particles. For small, flat, or deformable particles the separation efficiency is lower. Cleaners have high efficiency in the removal of large particles that differ from water and wetted fibers with respect to their density.

7.1.3

Unit Processes in Stock Preparation Systems

Some of the unit processes are applied more than one time in a stock preparation line. This depends on the degree of disintegration or contaminant content of the stock. In recovered paper preparation, for example, coarse robust machines are used at the beginning. The consistency usually varies for optimum efficiency, too. For example, some kind of screening is applied in advance in the disintegration machines (very coarse screening), after which may follow (real) coarse screening and then fine screening at the end. Hydrocyclones are operated under higher consistency for coarse particle removal or at lower consistencies, among other things to protect the wear-sensitive slotted screens by removing the sand particles.

Many of the unit processes have not just one (desired) effect but may also have secondary effects (desired or undesired). Disintegration, for example, not only

breaks down the fiber bundles into single fibers but may also crush the debris particles to such a size that they can no longer be removed. The change in consistency in separation processes due to a decrease in the accept flow and an increase in the reject flow is an undesired effect, which needs more attention in the process design.

The unit processes generally work at various fiber consistencies (low consistency (LC), intermediate consistency (IC), mean consistency (MC), and high consistency (HC)). In the language of papermakers, the meaning of consistency may vary when applied to different unit processes in stock preparation, and also the transition between the different consistency ranges may be fluid (Table 7.2). Table 7.3 lists the range of consistency as well as the energy demand for the different unit processes in recovered paper preparation systems.

7.1.4

Definitions in Separation Processes

In a stock preparation system a lot of separation unit processes are applied, be it solid–solid or solid–liquid. Separation processes can be assessed by various criteria applicable to unit operations as well as to systems. Cleanliness efficiency, separation ratio, thickening, and enrichment factor are mainly used and are explained in the following paragraphs.

The suspension to be cleaned may be defined as a mixture of water, fibers, and debris particles. In a separation unit the ingoing suspension is split into at

Table 7.2 Different naming of consistency ranges in the various unit operations in stock preparation.

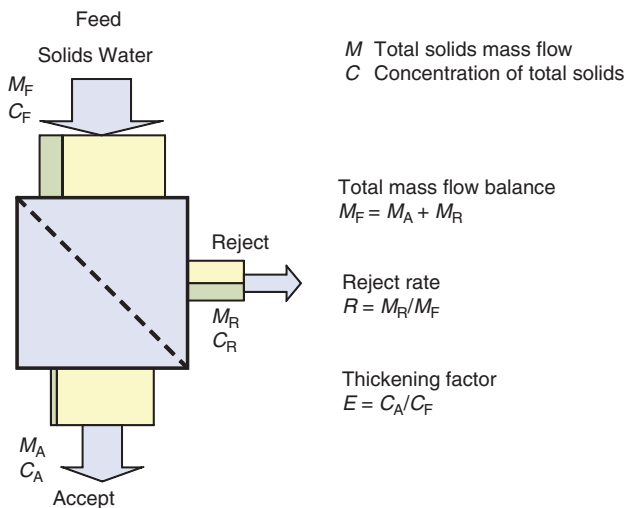
Unit process	Operating consistency (%)	Naming
Slushing (pulper)	3–4.5 (6)	LC
	12–19	HC
Slushing (drum)	15–30	HC
Screening	0.5–1.5	LC
	1.8–2.5	IC
	3.0–4.5	MC
Centrifugal cleaning	0.5–2.0 (3)	LC
	2.0–3.0	IC
	3–5 (6)	HC
Flotation (selective)	0.8–1.5	LC
Mixing and storing	3–5.5	LC
	8–18	MC
	18–35	HC
Refining	3–5.5	LC
	~30	HC
Dispersing	22–35	HC
Bleaching	25–30	HC

Abbreviations: LC = low consistency; IC = intermediate consistency; HC = high consistency.

Table 7.3 Ranges of specific energy demand and operating consistency in the various unit operations of recovered paper processing.

Unit process	Operating consistency (%)	Specific energy demand (kW h t ⁻¹)
Slushing (pulper)	3–19	10–40 (60)
Slushing (drum)	15–30	15–20
Coarse screening (first stage)	3–5	10–20
Deflaking	3–5	20–60
Screening (first stage)	0.5–4.5	5–20
Screening (tail screen)	1–4	20–40
Centrifugal cleaning	0.5–5 (6)	4–10
Flotation (selective)	0.8–1.5	13–30
Flotation (nonselective)	0.01–0.5	10–20
Fractionation (screen)	0.5–4	5–15
Dewatering (twin-wire press)	from 3–10 to 25–50	2–4
Dewatering (screw press)	from 4–12 to 25–40	10–15
Washing	from 0.7–1.5 to 5–12	1.5–20
Thickening	from 0.5–2 to 8–18	1–10
Mixing	3.5–5	0.2–0.5
Storing	3–18 (35)	0.02–0.1
Refining LC	3–5.5	3–25 per ΔSR unit
Refining HC	~30	10–60 per ΔSR unit
Dispersing	22–35	30–80 (120)

least two flows, both usually still containing all three components of the entering suspension but in a different amount. In Figure 7.3 the definitions for total solid mass flow, reject rate by total solid mass flow, and the thickening factor are given,

**Figure 7.3** Mass balance and definitions in a separation system.

and illustrated by mass balance. Figure 7.4 explains the terms debris separation ratio T , debris concentration, debris enrichment factor c_E , and debris removal efficiency η , also called *cleanliness efficiency*. In Figure 7.5 the separation ratio is explained in a diagram as a function of reject rate by weight, often abbreviated as RRM (reject mass rate). At all points above the diagonal, which means also on every point on the screening curve shown, the debris concentration is higher in the reject than in the inlet ($c_E > 1$). Effective screening is achieved with the bow

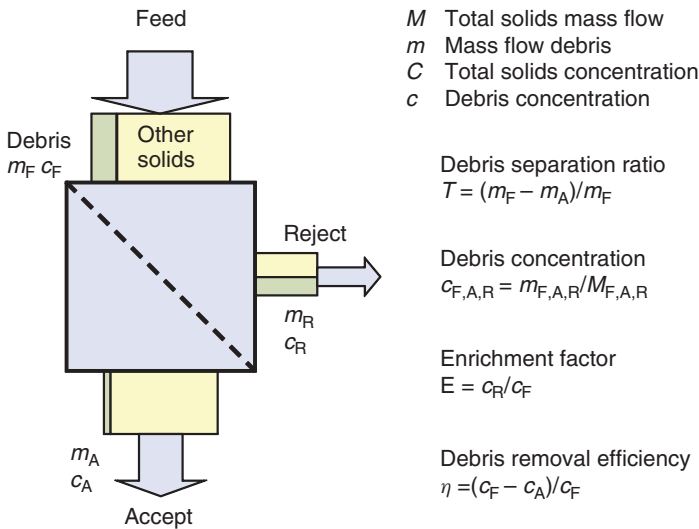


Figure 7.4 Definitions for removal efficiency of solid debris.

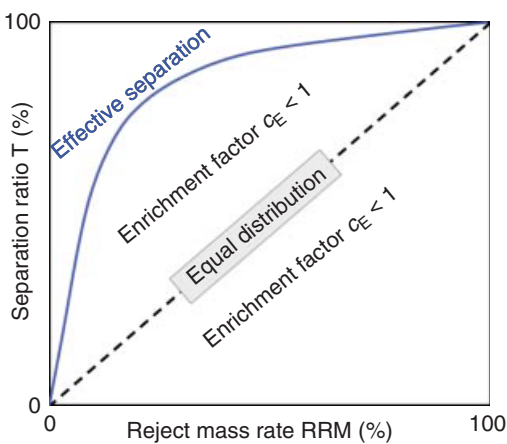


Figure 7.5 Separation diagram.

of the screening curve in as much as possible distance above the diagonal. Below the diagonal the enrichment factor would be smaller than 1. This is not desirable because the debris concentration would be higher in the accept than in the inlet. Figure 7.6 explains the cleanliness efficiency η , which is represented by the ratio of actual separation $x = T - \text{RRM}$ to the maximum separation theoretically possible $y = 100 - \text{RRM}$. These relationships can not only be applied to the separation of debris particles but can also be applied to the separation of fibers of different size. Hence, in addition to debris removal the result of fiber fractionation processes can also be illustrated in the separation diagram (Figure 7.7).

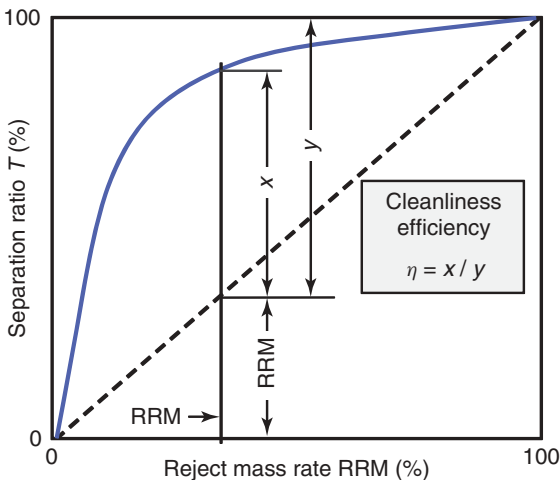


Figure 7.6 Relationship between separation ratio and cleanliness efficiency.

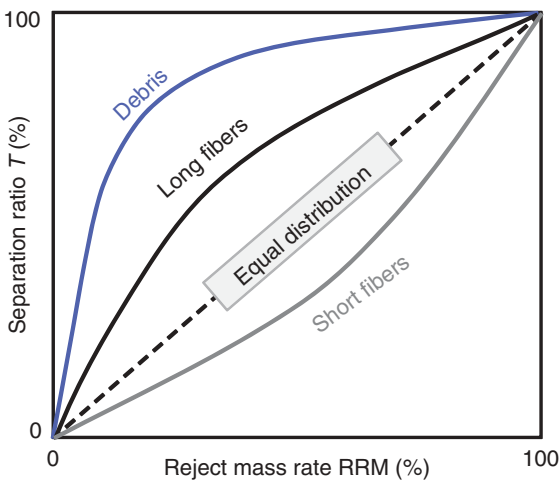


Figure 7.7 Separation diagram for different kinds of solids (fibers and debris).

7.2

Fiber Materials Feeding

Harald Heß and Herbert Holik

7.2.1

Overview

The objective of fiber material feeding is to supply a predetermined and measured amount of fiber stock to the repulping unit. The feed is either continuous or batchwise. The fiber material is delivered to the paper mill in the form of bales (virgin pulp, recovered paper) or as loose material (recovered paper). In integrated mills (pulp mill and paper mill at the same location) the fiber material is supplied to stock preparation by pumping the fiber suspension directly from the pulp mill to the paper mill. An extra feeding system and repulping is necessary only for shutdown periods of the pulp mill.

7.2.2

Virgin Pulp

Virgin pulp is delivered in wired bales (mostly sheet material) which are bound together by wires into stack units of six or eight bales. The first step is to dewire the units by cutting the centrally arranged binding wires, to remove them automatically, and to wind them to coils for easy disposal. The next step is to destack the unit into single bales, thereby preparing the bales for manual and automatic dewiring. Here, wires are cut, removed, and wound up to coils as mentioned above. A metal detector may follow to detect any uncut wires or wire pieces, which would then be cut and removed by hand in the next step. The wire removal efficiency is better than 97% depending on the unit and bale quality. A further handling device may turn the bales through 180° for removal of the bottom wrapping material. Then the bales are fed to the repulping unit. In batchwise working systems the batch is prepared by either counting the number of bales with known weight or by adding a weighing system to the pulper feed conveyor. The capacity of such a virgin fiber material feeding line is up to 180 bales per hour. Figures 7.8 and 7.9 give an overview of single-line handling systems for virgin pulp units and for bales, respectively. In Figure 7.10 a unit dewiring machine and a unit destacker of a virgin pulp handling system are shown.

7.2.3

Recovered Paper

Recovered paper is supplied to the mill in (individual) bales or as loose material. Often a mill has to handle both types. Automatic dewiring of recovered paper bales is more demanding than that of virgin pulp bales since these bales may vary in shape, size, and kind of wiring. In HC pulp lines the wires are generally cut and removed, the probability of bales not being dewatered is less than 2%, depending on the bale quality. In LC pulp lines, when ragggers are installed (mainly in board and

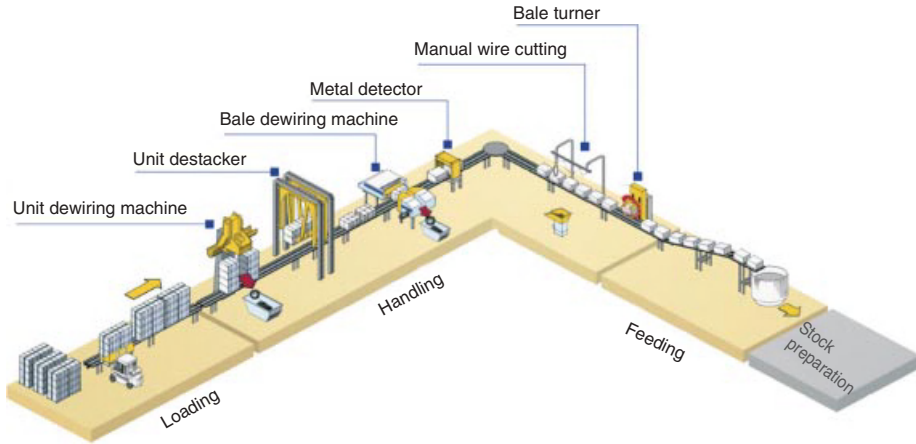


Figure 7.8 Schematic of a single-line handling system for virgin pulp units. (Source: Voith B + G.)

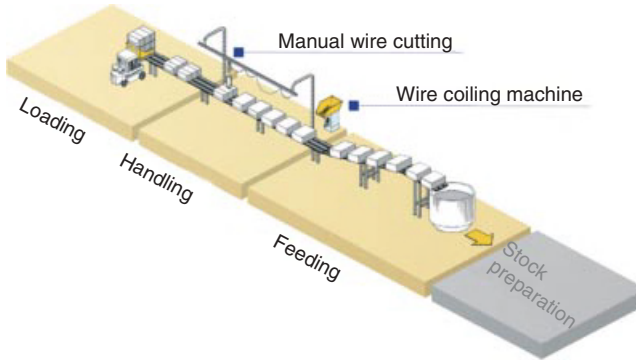


Figure 7.9 Schematic of a single-line handling system for virgin pulp bales. (Source: Voith B + G.)



Unit dewatering machine



Unit destacker

Figure 7.10 Unit dewatering machine and a unit destacker of a virgin pulp handling system. (Source: Voith B + G.)

packaging paper lines), the wires are cut only and needed to build up the tail and to entangle plastic foils, strings, and textiles. In the HC pulp line, after wire removal, the bale structure is opened into a loose material by a bale opener, followed by a leveling drum to equalize the paper flow to the required height. Besides vat pulpers also drum pulpers are often used in HC pulping. To feed a drum pulper, the loose material on the conveyor belt is weighed by a radiometric weighing system. In combination with a conveyor speed control this gives a constant mass flow of fiber material into the repulping unit. The capacity of such a fiber material feeding line for recovered paper bales with one dewiring machine is up to 120 bales per hour, depending on the quality of the recovered paper. Figure 7.11 illustrates the schematic of a complete feeding system for baled and loose recovered paper for HC and LC slushing. Figure 7.12 shows a dewiring machine for recovered paper bales to feed an HC pulping line and a wire cutting machine for an LC pulping. The first one has an integrated coiling device and the second one does not.

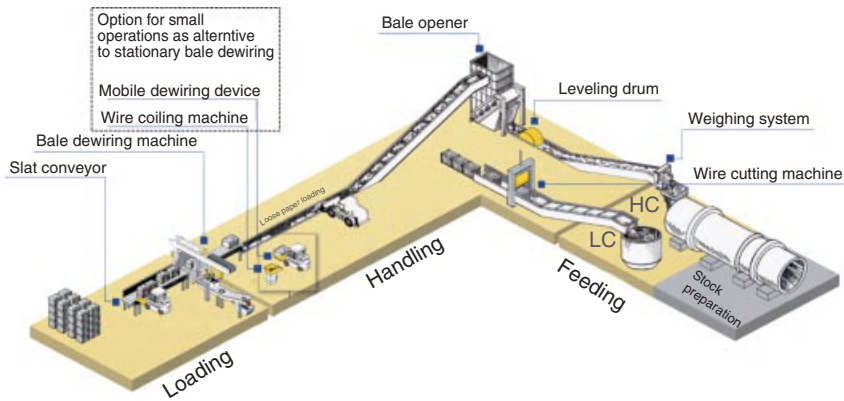


Figure 7.11 Schematic of a handling system for baled and loose recovered paper for high (HC) and low consistency (LC) slushing. (Source: Voith B + G.)



Dewiring machine for recovered paper bales to feed an HC pulping line



Wire cutting machine for recovered paper bales to feed an LC pulping line

Figure 7.12 Dewiring machine for recovered paper bales for an HC and a wire cutting machine for an LC pulping line. (Source: Voith B + G.)

7.3

Disintegration

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7.3.1

Overview and Theoretical Aspects

7.3.1.1 Objectives and General Solutions

The purpose of disintegration (also called *repulping* or *slushing*) is to break down the dried primary fiber pulp or recovered paper into individual fibers, or at least to obtain a suspension that can be pumped (primary disintegration). In the latter case, the remaining flakes have to be broken down in subsequent deflaking machinery (secondary disintegration). Disintegration is needed not only at the beginning of the stock preparation system but also for the wet or dry broke from the paper machine. Disintegration is done either in a pulper (a vat with an impeller) or in a rotating drum. In the paper industry the terms repulping or slushing are used for disintegration as well.

During pulping the applied disintegrating forces have to be greater than the strength of the raw material. Wetting reduces the strength by breaking the fiber-to-fiber hydrogen bonds and loosening the network forces of the entangling fibers. Strength reduction by wetting is about 85–98% for primary fiber pulp and nonwet strength recovered paper, and <60–80% for wet strength recovered paper [1]. For example, the tear strength of a handsheet made of spruce pulp is 1380 N m^{-1} when dry, and is reduced down to 19 N m^{-1} after wetting for 15 s in water [2].

For the purpose of saving energy and for high production, wetting of all of the raw material should be done in the shortest possible time. Recovered wet strength paper grades that are difficult to repulp may be slushed at elevated temperatures of greater than 75°C . Addition of chemicals – acidic or alkaline, depending on the wet strength agent – further assists wet strength reduction. This more-expensive procedure is advisable when the wet breaking length of the stock is higher than about 600 m. Sometimes, higher temperatures and/or chemicals are used for a lower wet strength level down to 300–400 m as well.

7.3.1.2 Some Basics

The relevant forces in repulping are due to viscosity, acceleration, and mechanical clinging. Their magnitude, frequency, and point of location that act on the flakes are different and change during the disintegration process. Viscosity is mainly a matter of suspension consistency and the type of stock; together with the velocity difference it creates shear stress. Acceleration of a particle results in inertia forces. Clinging of a flake, for example, around the rotor of a pulper may induce viscosity, acceleration, or mechanical forces. Theoretically, all three kinds of forces are present during the whole disintegrating process. All these define the minimum size of the flakes obtainable for a given raw material. Wet breaking length seems to be a raw material property most suitable to judge the ability and energy demand of the stock to be disintegrated [1].

The kinetics prevailing in disintegration may be described in analogy to chemical first-order decomposition processes [3]. The flake reduction speed is directly proportional to the flake content itself:

$$\frac{dc}{dt} = -k \times c(t)$$

where $c(t)$ is the flake content in percent or mass unit, t the disintegration time, and k the disintegration constant. The algebraic solution of this equation is

$$c(t) = c_0 \times e^{-kt}$$

or transformed into a logarithmic equation

$$\ln c(t) = \ln c_0 - k \times t$$

with c_0 representing the initial flake content at $t = 0$.

As Figures 7.13 and 7.14 show this equation corresponds well with the practical results of disintegration.

7.3.1.3 Steps in Disintegration

Following are the steps involved in repulping:

- feed the system with a predetermined rate of raw material and water;
- wet the fibrous raw material rapidly and completely;
- apply sufficient force to break the material down into individual fibers;
- discharge the suspension.

In the case of recovered paper repulping further steps may be necessary:

- remove solid contaminants such as foils, stickies, and printing ink from the fibers;

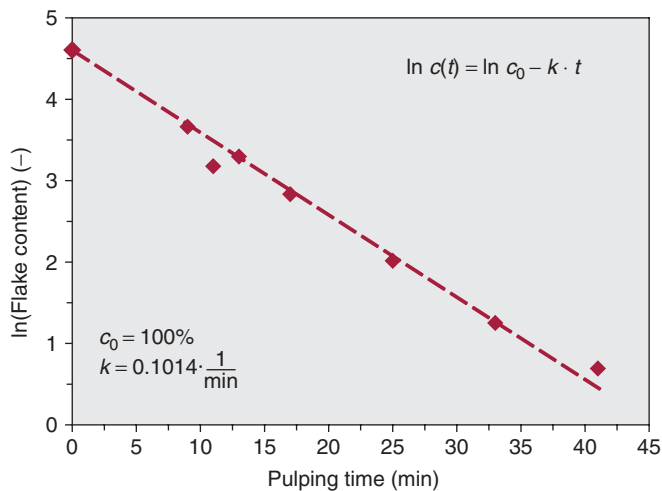


Figure 7.13 Natural log of flake content as a function of disintegration time for a stock containing Kraftliner and corresponding decomposition equation. (Source: Voith.)

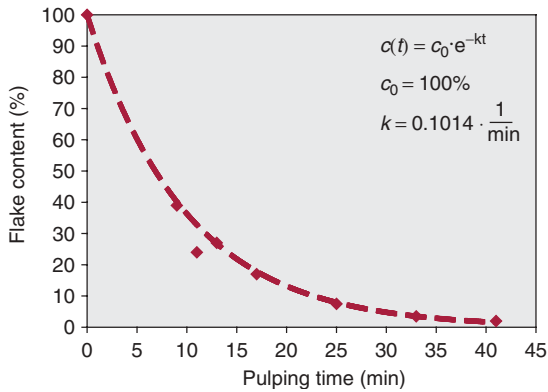


Figure 7.14 Flake content as a function of disintegration time for a stock containing Kraft-liner and corresponding decomposition equation. (Source: Voith.)

- remove solid contaminants from the process at an early stage before they are broken down into too small particles that are difficult to be removed in subsequent machinery
- mix process chemicals (such as deinking and bleaching agents) with the suspension.

Depending on the raw material, the required production, and the amount and kind of contaminants, repulping is done in different types of pulpers or drums at consistencies between <6 and up to 30%. Slushing time is usually between about 5 and 40 min.

The machines for primary disintegration are pulpers (vat with impeller) and drums, which operate continuously (pulper, drum) or discontinuously (pulper). For secondary disintegration, deflakers, disc screens, or some times dispergers are used.

7.3.2

Machines for Primary Disintegration

In the past, machines such as a stamp mill, Holländer (Section 2.5) and Kollergang (edge mill or roller refiner) were used for both disintegration and stock beating (Figure 7.15). These machines had strong limitations with respect to production capacity; hence, with the increasing demands for capacity, pulpers and drums were introduced since the nineteenth century.

7.3.2.1 Pulpers

Pulpers are usually stainless steel vats with a vertical axis. Traditionally, a concentric impeller with vanes is the slushing tool. Vertical elements at the cylindrical wall and guide elements at the bottom redirect the rotating suspension flow to the vat center. The pulper may have a sieve plate at the bottom with round or oval holes. Vat shape, as well as geometry, position, and rotating speed of the impeller have to be adapted



Figure 7.15 Edge mill as an obsolete disintegrating (and fiber beating) machine.

to each other for economic production. For effective slushing the velocity difference between suspension and impeller should be high. Vertical baffles and horizontal bars, as well as an eccentric position of the rotor, increase the velocity difference locally and thus shear forces within the suspension. Figure 7.16 shows a pulper with vat and vertical baffles, screen plate as well as an eccentric rotor with vanes.

7.3.2.1.1 Low Consistency (LC) Pulpers LC pulpers comprise a flat impeller with circumferential speed of about $15\text{--}20\text{ m s}^{-1}$. They operate at consistencies of up to about 6%. At the bottom they have a screening sieve with hole sizes of 6–20 mm for suspension extraction. Operation is either continuous for slushing of recovered



Figure 7.16 View of a pulper for recovered paper with eccentric position of the impeller and with vertical baffles. (Source: Voith.)

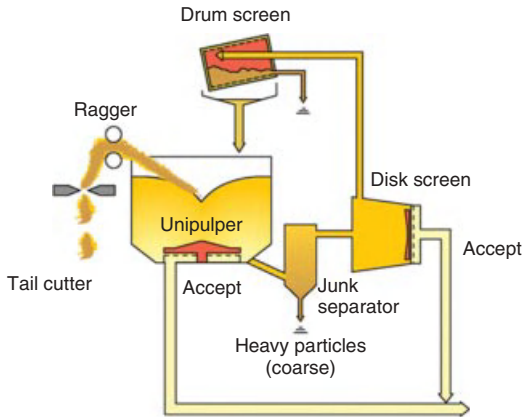


Figure 7.17 Schematic of an LC pulper with trash removal system. (Source: Voith.)

paper (fluting and liner, high wet strength grades) and most of the primary fiber materials, or periodic for certain primary fiber applications. The feed may be loose raw material or opened bales that need to be unwired.

In recovered paper processing ongoing removal of trash has to be ensured in order to prevent excessive trash concentration, which would reduce the production and quality and might even stop the pulper rotor. Figure 7.17 shows a schematic of an LC pulper integrated in a trash removal system for recovered paper with moderate trash quantity. Part of the suspension in the pulper is extracted and fed to a junk separator to remove heavy contaminants. The following disk screen has two functions. It acts as a deflaker to reduce the number and size of the flakes and as a coarse screen for the removal of remaining trash and oversized flakes. The reject is sorted in a drum screen, its accept being recirculated to the pulper and rejects being disposed. In Figure 7.18 a detrashing system for higher trash amount

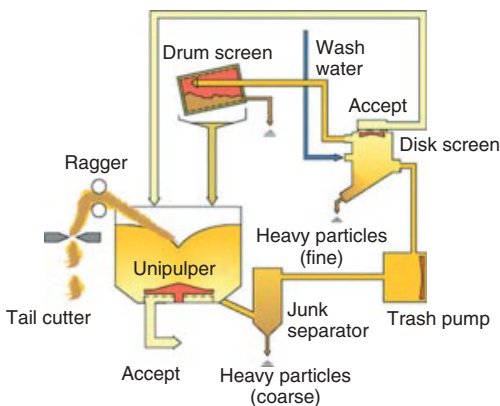


Figure 7.18 Schematic of an LC pulper with trash removal system and washing cycle operation. (Source: Voith.)



Figure 7.19 Ragger for trash removal and trash tail in an LC pulper. (Source: Voith.)

is illustrated. Here, the disk screen is operated with washing cycles. For better consistency control of the whole system, the accept of the disk screen machine is fed back into the pulper. Ragers (Figure 7.19) are used for additional trash removal such as for bale wires, plastic, foils, and textiles. Here, the rotation of the suspension is used to form a ragger rope, which is continuously taken out (up to 100 m h^{-1}). Best ragging is obtained by good rotation at sufficient pulper size and optimized ragger position against the stock feed position.

7.3.2.1.2 HC Pulpers HC pulpers operate at stock consistencies of up to about 19%. This pulper type has a helical rotor (Figure 7.20) and usually no screen plate. Circumferential speed is about $12\text{--}17 \text{ m s}^{-1}$. This pulper generally operates intermittently. One batch comprises the sequence of the following steps: water feed, paper feed, slushing, dilution of the suspension, stock extraction, and, in some systems, washing and extraction of the remaining trash from the pulper vat. Slushing time is about two-third of the batch time. During the batch, the drive torque of the impeller considerably varies. Today, in most systems, the vat is completely emptied and all the trash is removed in a subsequent system.

HC pulpers are used in processing recovered paper such as newspapers and magazines. Figure 7.21 shows an HC pulping system for recovered paper processing, including dumping and dilution water feed system. For each batch unwired bales or loose raw material and water are fed to the pulper. After its reduction to the desired flake content and size at HC – and detachment of ink to a certain degree – dilution water is added. The suspension is then fed to a disk screen with deflaking and coarse screening functions. Its reject goes via a buffer tank to a drum screen, its accept to a dump chest. The reject of the drum screen leaves the system via a dewatering screw, the accept is recirculated.

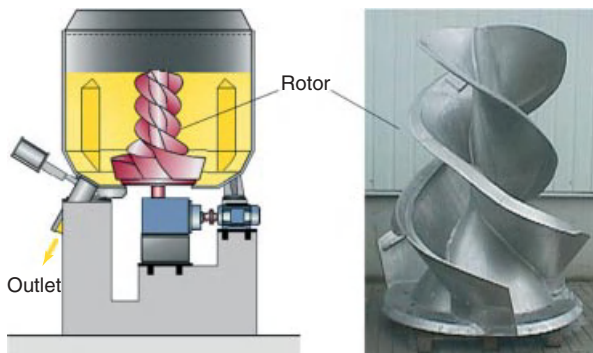


Figure 7.20 HC pulper with a helical rotor. (Source: Voith.)

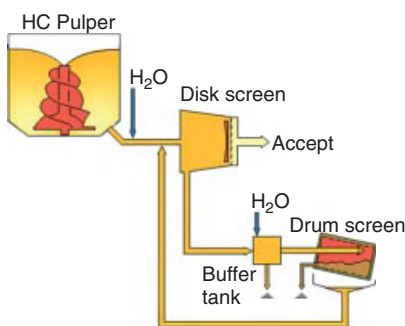


Figure 7.21 Schematic of an HC pulping system. (Source: Voith.)

7.3.2.1.3 Drum Pulpers Nearly forgotten for a longer time drum pulpers got more and more acceptance in the industry since the 1970s. Drum pulpers can operate at consistencies of about 14–30%. The drum is driven on the periphery, the axis is declined to the drum end to move the stock toward the outlet. Drum pulpers are used in repulping of recovered paper of lower wet strength such as newspapers and magazines, fluting and liner, as well as liquid packaging, board. Owing to the lower forces, the size reduction of sensible contaminants such as stickies or thin foils is limited. Drum pulper systems combine the functions of slushing and coarse screening.

There are two types on the market. One (Figure 7.22) has a single drum body with the first zone for slushing and the second zone for coarse screening. The rotation speed is about $100\text{--}120\text{ m min}^{-1}$, the drum diameter is 2.5–4 m, and the length up to 25–40 m, the slushing zone being about two-third of the length. Slushing consistency of this drum principle is up to 20%, accept consistency of coarse screening (hole diameters about 6–9 mm) is about 3–5%. As the drum rotates, the raw material is lifted with the help of lifting baffles mounted along the axial direction. Disintegration occurs mainly by two principles: (i) during lifting part of the material rolls and slides back thus generating shear forces and (ii) the remaining material lifted to higher position falls back to the pond. The resulting impact exerts effective slushing.

FibreFlow® Drum



Figure 7.22 Single drum pulper with slushing and coarse screening in one drum body. (Source: Andritz.)

The second type distributes the two functions of slushing and coarse screening between two individual drums, each operating at different circumferential speeds and consistencies adopted to the different functions (Figure 7.23). Figure 7.24 shows the picture of such a drum pulper. The slushing drum is equipped with a D-shaped “displacement core.” Both displacement core and drum are equipped with bars along the axial direction. The length of the slushing drum is about 7–15 m and that of the coarse screening drum is 7–17 m. The rotation speed of the slushing drum is about 1.5 m s^{-1} and that of the coarse screening drum is about 2.5 m s^{-1} . Consistency in the slushing part is about 23–30% and that in the accept of coarse screening is 3–5%. The filling level of the slushing drum is adjusted to the actual production and should be about 60% of the drum volume to ensure

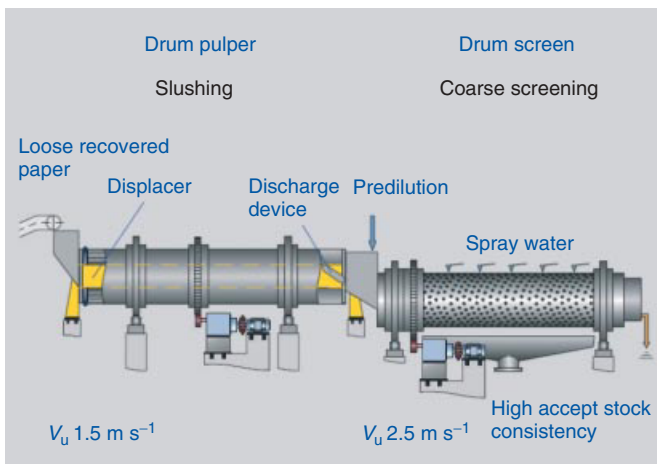


Figure 7.23 Drum pulper with two individual drums for slushing and coarse screening. (Source: Voith.)



Figure 7.24 Photo of a drum pulper with separate slushing and screening drums. (Source: Voith.)

sufficient high dragging effect thus avoiding spinning. As the drum rotates the stock is exposed to shear forces in the upgoing channel between the drum and the fixed displacement core. The impact of the stock falling down from the top further supports effective slushing. Figure 7.25 shows schematically the profiles of both velocity and shear forces of the stock in the drum.

7.3.2.1.4 Broke Pulpers Broke pulpers beneath the paper machine are found at the end of the wire section and the press section where the web is wet and easy to slush. Slushing in broke pulpers in the dryer section, at the size press, or in coating stations needs more energy and time, as the web is dry. (Broke from other places outside the paper machine are treated in pulpers as described earlier.) Broke pulpers extend across the whole width of the paper machine and have to treat the full production. In the case of a web break, the broke pulper located upstream of the break position has to start its full operation almost immediately. Water showers direct the web into the pulper and provide the necessary amount of dilution water. A consistency of 3–5% together with an optimized system of vat geometry and rotor ensures good stock circulation and slushing in the pulper. Circulation energy

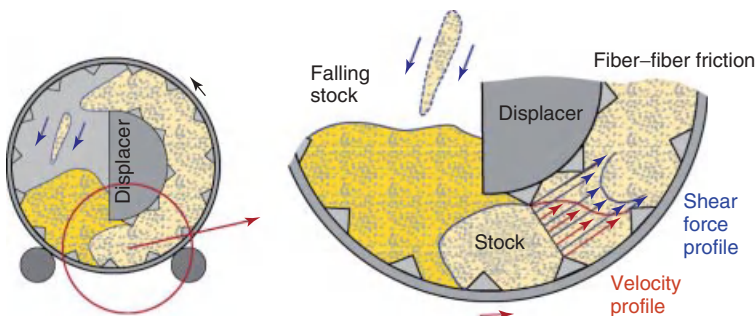


Figure 7.25 Schematic of the velocity and friction profiles in a drum pulper with displacement body. (Source: Voith.)

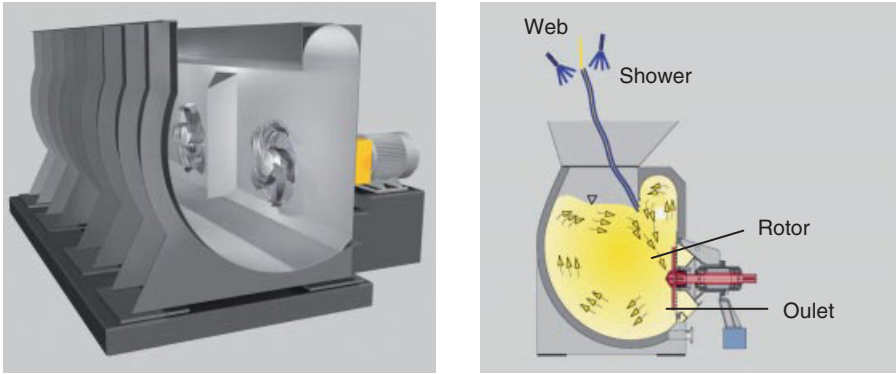


Figure 7.26 Three-dimensional scheme of a broke pulper and cross section of the flow pattern. (Source: Voith.)

and defibering forces are exerted either by agitators with a horizontal axis and propellers mounted on these or by impellers such as those found in pulpers in stock preparation. The disintegrated part of the pulper content is extracted from the pulper through a screen plate. Figure 7.26 shows a three-dimensional scheme of a broke pulper and also a cross section of such a pulper illustrating the flow pattern with the entrapped paper web.

7.3.3

Machines for Secondary Disintegration

The objective of secondary disintegration (deflaking) is to break down small pieces (flakes) of undisintegrated paper or pulp sheets into individual fibers. The residual flake content after the deflaker should be zero, in special cases at least below 5%. Deflaking helps avoid problems related to paper quality, save fiber raw material, and ensure improved operating conditions for the succeeding machines in the process, for example, screening or cleaning.

After slushing the raw material in a pulper or a drum, secondary disintegration is usually carried out in a deflaker in the preparation of recovered paper, virgin pulp, or broke. A remarkable deflaking effect also occurs in disk screens. Cylindrical screens or pumps have a lesser effect.

In the pulper or drum the raw material is disintegrated at least to an extent that the suspension can be pumped. This means that it contains a certain amount of flakes. This holds especially true for sized, coated, or wet strength grades. Here, slushing is interrupted at a certain flake content as it is more economic to do final deflaking in a more suitable machine with a higher energy intensity. Flake content at the inlet of the deflaking machine may vary between 15 and 20% for grades easily to be disintegrated and 20–40% for wet strength grades. Depending on the amount of flakes and the kind and amount of contaminants, different machines are used.

7.3.3.1 Deflaker

A deflaker is a closed machine with a rotor and two stator disks. On each of them teathed fillings are mounted. The circumferential speed is $25\text{--}40\text{ m s}^{-1}$. Deflaking is done at stock consistencies of about 3–5%. The shear forces necessary for disintegration are applied to the fiber bundles and flakes when they pass radially through the filling slots of the intermeshing teeth of the rotor and the stator (Figure 7.27). The peripheral speed of the rotor fillings is $25\text{--}40\text{ m s}^{-1}$. Depending on the entering flake size, flake content, and trash content, coarser or finer fillings for the deflaker are selected (Figure 7.28).

For stocks with low deflaking resistance the specific energy demand is between 20 and 40 kW h t^{-1} . Deflaking is mostly done in a single pass. Two or more passes may be required for stocks that are more difficult to deflake. For flakes with high wet strength even a disperser may be necessary, which can apply higher shear rates.

7.3.3.2 Disk Screen

A disk screen (Figure 7.29) is like a small closed pulper. It works as a coarse screen and serves as a deflaker as well owing to the kind of slushing equipment and the high energy intensity. The deflaking effect is limited but high enough to distinctly reduce the flake content, for example, in the secondary coarse screening stages of systems for packaging papers. Its further advantage is high nonsensitivity with

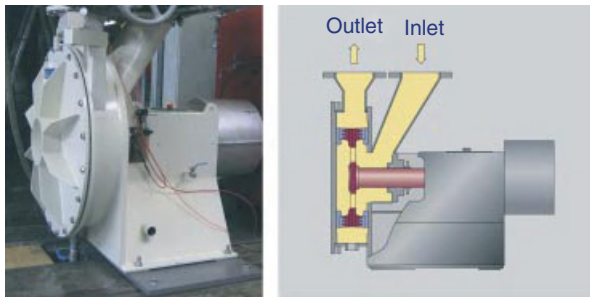


Figure 7.27 Photo and cross section of a deflaker for secondary disintegration. (Source: Voith.)

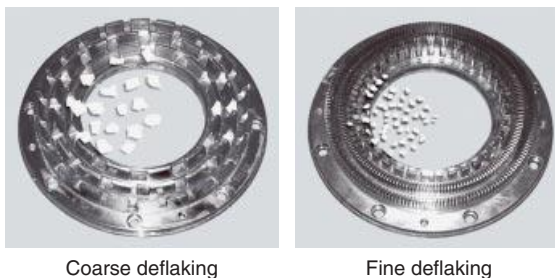


Figure 7.28 Fillings for coarse and fine deflaking. (Source: Voith.)



Figure 7.29 View of an opened disk screen. (Source: Voith.)

regard to mechanical wear by heavy parts and other contaminants. As mentioned before disk screens are also used in the detrashing system. Figure 7.30 shows a disk screen with eccentric arrangement of the rotor in an asymmetric housing enabling safe extraction of the reject to the bottom and avoiding spinnings.

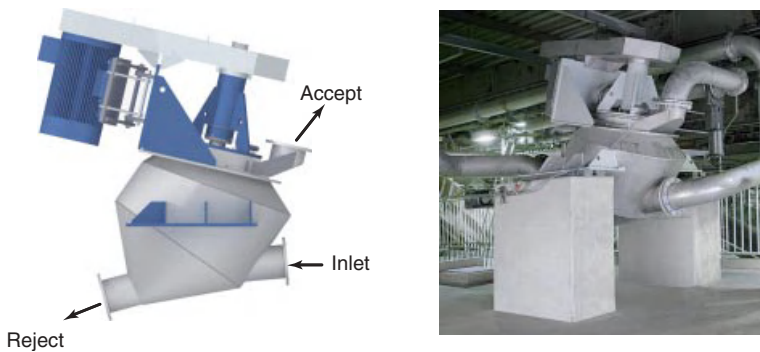


Figure 7.30 Schematic and photo of a disk screen with asymmetric housing. (Source: Voith.)

7.3.4

Operational Principles and Technological Results

7.3.4.1 Continuous and Discontinuous Disintegration

In the case of slushing recovered paper, the removal of contaminants from the pulper vat can be discontinuous or continuous. With the latter the pulper has to be integrated in a detrashing system. In Figure 7.31 the differences between continuous and discontinuous operation is schematically shown with respect to pulper production capacity and amount of contaminants in the pulper over the operating time. After the start of the pulper the production decreases steadily in

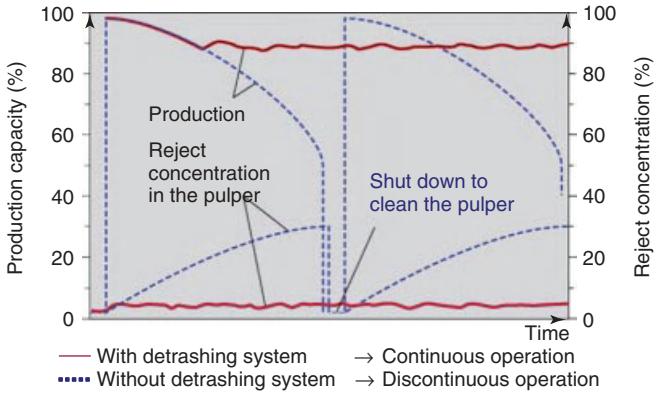


Figure 7.31 Production and reject concentration during continuous or discontinuous operation of pulpers. (Source: Voith.)

both cases. In discontinuous operation it further decreases owing to increasing amount of contaminants and finally the pulper has to be emptied to remove the contaminants; otherwise, production would totally break down. Continuous operation is with detrashing systems as shown in Figure 7.17 or 7.18. Here, the production remains about constant as a certain amount of contaminants is steadily removed from the pulper, which allows high-level production.

7.3.4.2 Flake Content in Primary Disintegration

Disintegration depends on the type of stock and the kind of disintegrating machine. Figure 7.32 gives examples for flake content reduction over disintegration time for wet strength and crepe paper and an easily slushable Kraftliner. The graph shows that the disintegration kinetics varies significantly with different fiber materials.

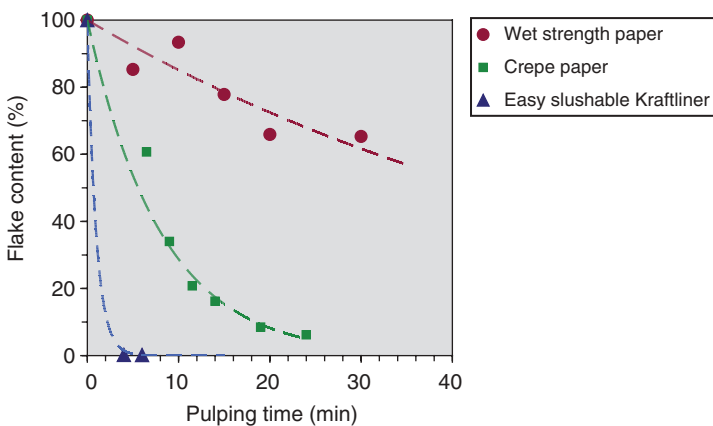


Figure 7.32 Flake content as a function of pulping time for different raw materials. (Source: Voith.)

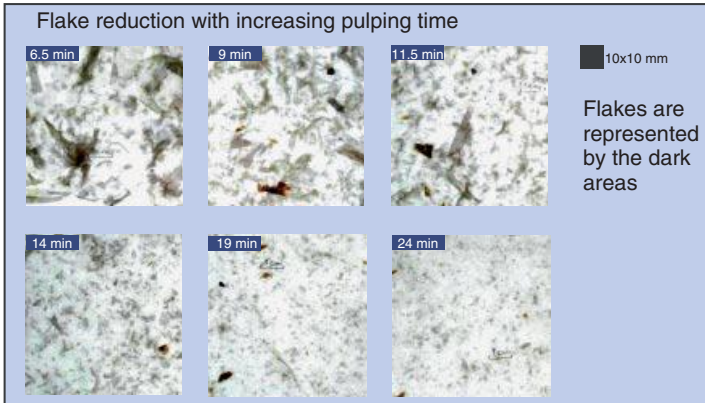


Figure 7.33 Photos of crepe paper in transmitted light technique showing flake reduction with disintegration time. (Source: Voith.)

For example, the disintegration factor k of the easily slushable Kraftliner is eight times the factor of the crepe paper, whereas the factor k of the crepe paper is eight times higher than that of the wet strength paper. Figure 7.33 shows handsheets of the crepe paper in transmitted light technique illustrating the reduction of flakes with increasing disintegration time.

Figure 7.34 illustrates a representative flake spectrum of a label paper of high wet strength after a 90 min pulping time. The MD/CD ratio (2.1) of its wet breaking length (1730 m/820 m) can be found in the rectangular geometry (long to short side) of most of the flakes. For nearly all of the flakes the higher strength was measured in the lengthwise direction. In Figure 7.35 a representative flake sample

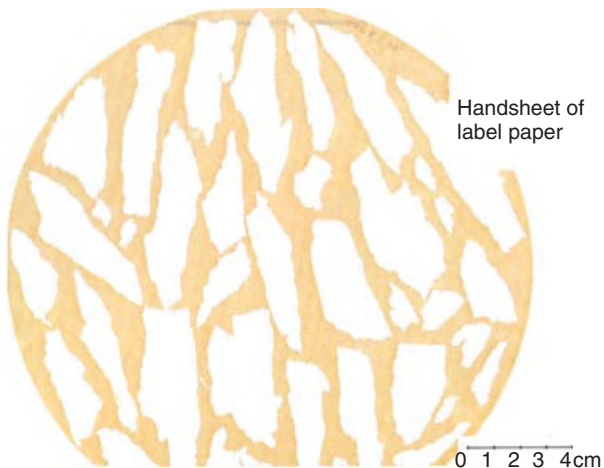


Figure 7.34 Representative flake spectrum of a label paper of high wet strength after 90 min pulping time (wet breaking length in MD 1730 m, in CD 820 m, and MD/CD = 2.1).

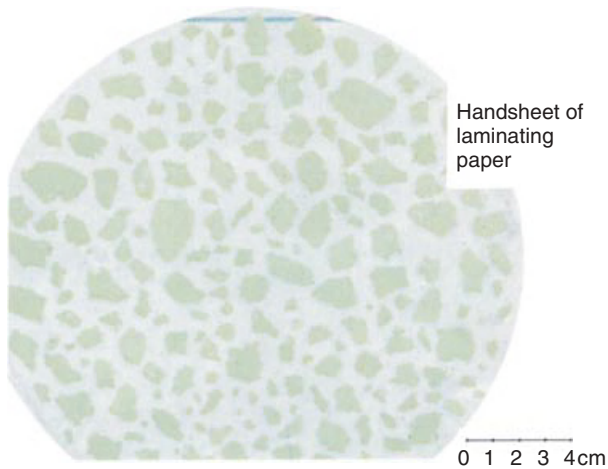


Figure 7.35 Representative flake spectrum of a laminating paper after 90 min pulping time (wet breaking length in MD 650 m, in CD 400 m, MD/CD = 1.6).

of laminating paper is shown, again after 90 min of pulping. The wet breaking length ratio was MD/CD = 1.6 (650 m/400 m). When compared to the label paper samples, here the flakes are smaller (lower wet breaking length) and the shape corresponds to the lower MD/CD ratio. In both cases the forces in the pulper have “calibrated” flakes according to their strength.

7.3.4.3 Flake Reduction in Primary and Secondary Disintegration

It is advisable to limit the time and energy input for primary disintegration. Further energy would not result in significant deflaking and disintegration would not be economic anymore. Dwell-time effects in the dump tower after primary pulping can contribute to further flake reduction. Secondary disintegration can follow in subsequent processes. A disk screen in coarse screening, for instance, can show up to 80% deflaking efficiency. Figure 7.36 gives an example how the change from primary to secondary disintegration using a disk screen in coarse screening can reduce the overall energy demand.

7.3.4.4 Disintegration of a Stock Containing Plastic Foils

In general pulping forces should be high enough for good disintegration but gentle enough to enable low breaking down of the contaminants in the stock. For example, when slushing a stock containing plastic foils the paper should be disintegrated, but the plastic foils should be left in a size that they can be easily screened. In Figure 7.37 the slushing result of a foil-coated food packaging material in an HC pulper is shown [4]. There is already efficient deflaking at moderate specific energy input, but even at very high specific energy the laminate flake content does not decrease significantly as a precondition for good screenability.

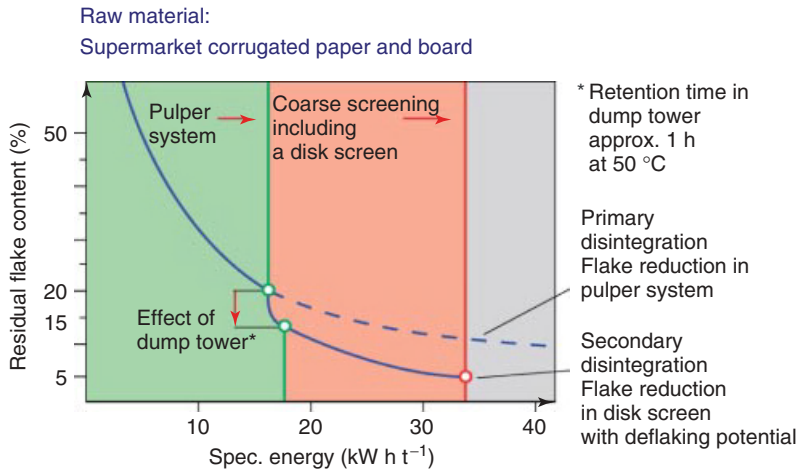


Figure 7.36 Flake reduction in primary and secondary disintegration. (Source: Voith.)

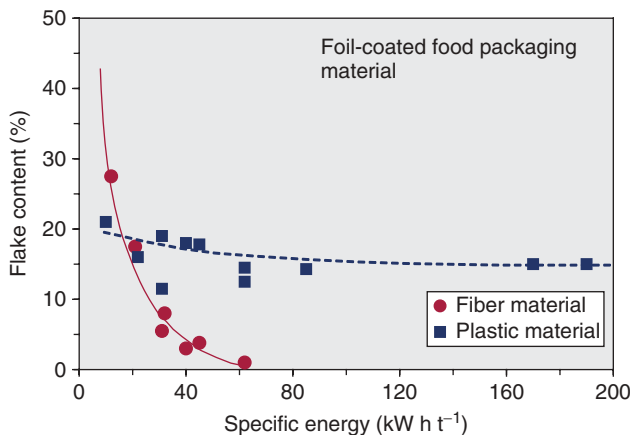


Figure 7.37 Flake reduction during pulping of foil-coated food packaging material in an HC pulper.

7.4

Screening

Harald Heß and Herbert Holik

7.4.1

Overview and Principle Aspects

7.4.1.1 Objective

The objective of screening is to remove the interfering solid substances from the suspension, which differ from the fibers in size, shape, and deformability. These

can be solid nonpaper particles such as plastics, styrofoam particles and stickies or paper flakes, and fiber bundles.

7.4.1.2 Principle Solution

The suspension passes a screen with holes or slotted openings that are larger than the fibers but smaller than most of the particles to be removed. The latter are intended to be retained by the screen and extracted at the reject outlet together with a certain unavoidable amount of fiber suspension. Clearing devices rotate at a small distance over the screen surface generating pressure pulses and thus prevent the sieve openings from plugging. These rotors should not be too aggressive in order to maintain lower strength nonpaper particles in a screenable size. The pressure difference across the screen not only presses the fibers but may also force deformable particles through the screen openings. The cleanliness efficiency for soft stickies, for instance, is therefore lower than that for hard stickies of the same size. Increasing the pressure difference results in further loss of efficiency for soft particles removal compared to that for hard ones.

Fiber loss from the reject of a screen is reduced by rescreening the first-stage reject in the second, third, or even fourth stage. The reject of the last screen (tailing screen) determines the fiber loss and the amount of debris separated from the suspension. Here, a higher reject rate increases the cleanliness efficiency of a screening system, but increases the fiber loss. More stages in one screening system result in lower fiber loss but higher investment costs. All debris particles that are not removed in the tailing screens will be found in the screening systems accept, either directly in “original” size (when the final stage accept is fed forward) or later in smaller size when fed back. Screening is always a compromise between machinery design and system complexity, cleanliness efficiency, fiber loss, throughput, and operating reliability.

Figure 7.38 shows an example of a screen with opened housing, cylindrical screen basket, and foil rotor.



Figure 7.38 Example of a cylindrical screen with opened housing, showing the cylindrical screen and foil rotor. (Source: Voith.)

7.4.1.3 Application

Screening is one of the basic unit processes in stock preparation and is used in both primary and secondary fiber processing. In the latter, screening is done at several positions in the system with different kinds of machines with different kinds and sizes of screen openings. Some kind of prescreening (first coarse screening) step is integrated into the disintegrating systems followed by the actual (second) coarse screening step and fine screening. So more trash is removed step by step, first the coarse and then the finer material. Thus the subsequent screening step can operate more safely and with lower abrasion, even at the high demands of fine screening.

7.4.2

Screening Theory – Some Remarks

The general definitions for separating processes are listed in Section 7.1. Here, some specific remarks related to screening theory are given.

7.4.2.1 Probability of Separation

The debris particles are retained by the sieve according to its size, shape, and deformability as well as to the number of contacts with the screen openings. Typical dimensions for holes are 1–3 mm diameter and 0.1–0.25 mm slot width. As fibers in average have a thickness of about 10–50 μm and length of about 0.5–2 mm, they may easily slip through the openings. If a particle is not deformable and larger in all its three dimensions than the sieve opening, it will always be retained, be it at slots or at holes, both acting as a barrier. A certain probability exists for a particle with one dimension smaller than the opening that it can slip through a slotted sieve as the slots are long in the plane perpendicular to the flow direction. The probability gets higher when the particle is smaller in two dimensions than the slot. The highest probability is given for particles smaller in all three dimensions than the slot or hole openings. The probability always increases further with the number of particle contacts with the opening. Figure 7.39 shows the other way round the

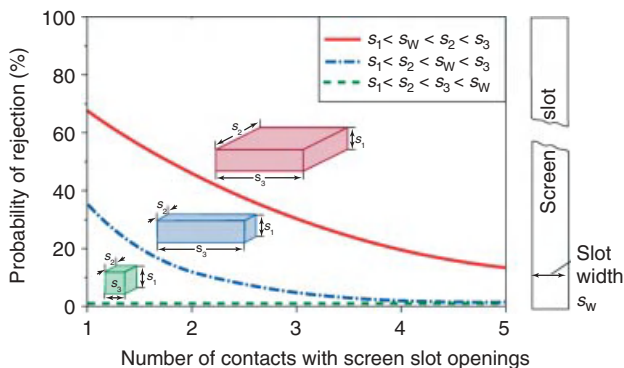


Figure 7.39 Probability of rejection of particles at a slotted screen as a function of their dimension and number of screen contacts [5]. (Source: Voith.)

probability of rejection as a function of particle dimension and the number of contacts with a screen opening [5].

For particles that can be deformed or crushed, the forces acting in the screen are important. These forces may result from the shear forces generated by the rotor and the pressure difference across the sieve.

7.4.2.2 Flow Approaching the Screen Openings

The flow pattern in the vicinity of the sieve opening determines whether and how the particle gets into contact with the opening. Slotted screens usually have a certain profile angle against the tangential direction. Figure 7.40 shows some examples of different geometry. The special geometry directs the stream lines in a way that the point of stagnation for the suspension velocity moves in the flow direction with larger angles. Figure 7.41 shows the flow pattern of an angled screen profile and the stagnation point [6]. The higher the profile angle, the larger are the vortices

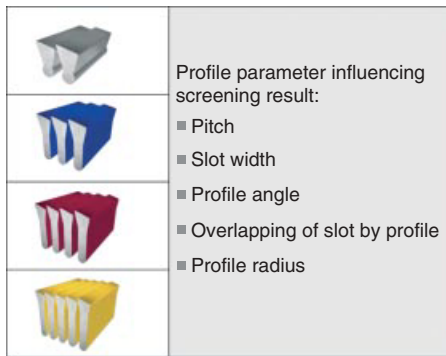


Figure 7.40 Profiles of slotted screen baskets. (Source: Voith.)

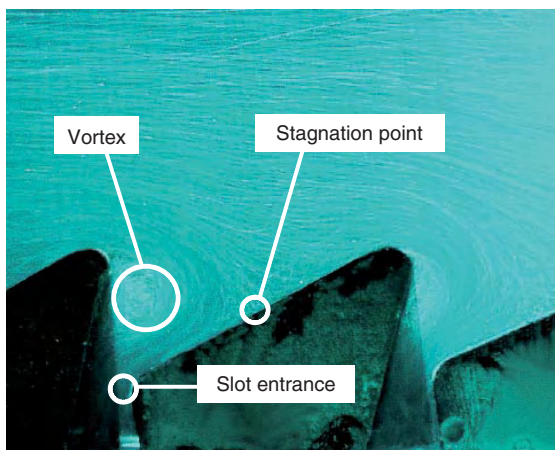


Figure 7.41 Flow pattern of an angled screen profile [6]. (Source: Voith.)

downstream after the bar tip favoring particles passing through the slots. Owing to their inertia, however, the heavy particles cannot easily follow the stream lines into the slot. Same is true for stiff and long fibers (LFs). A steeper angle results in lower screening effect as can be seen from Figure 7.42 [5, 7]. More overlapping of the profile end with the slot improves the screening efficiency.

Figure 7.43 depicts the results of a three-dimensional computational fluid dynamics (CFD) simulation of how model particles are captured in the vortex area of a profiled screen plate. Fibers have been simulated by rods as model particles.

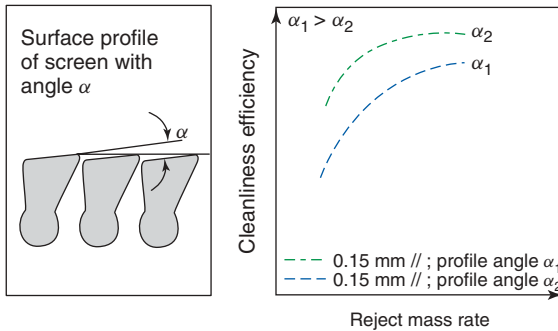


Figure 7.42 Effect of slot width and profile angle on cleanliness efficiency in a pressure screen [6].

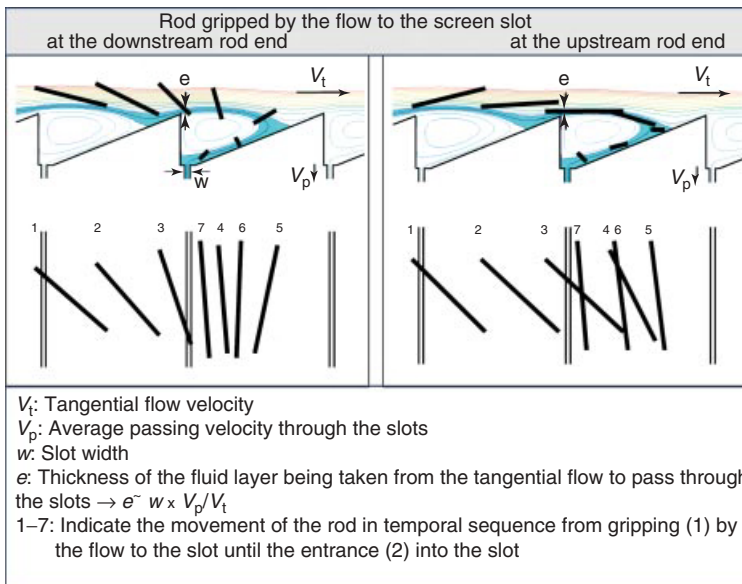


Figure 7.43 Results of a CFD simulation for possible screening mechanism of rods at a slotted and angled screen plate. (After Ref. [8].)

From the results it can be concluded that the fibers are aligned in the vortex axis before entering the slot and passing into the accept side [8].

7.4.2.3 Flow through the Screen Openings

The flow through the screen openings is by far not constant, neither timewise nor locally. Fibers and particles tend to build up a network covering the opening, which reduces throughput. Rotors destroy this network by shear forces and pressure fluctuations (rotor at the same side) or by back-flushing (rotor at the opposite side of the screen). Figure 7.44 shows schematically the change in through velocity for two different rotor types. The curves are based on measurements [5], their results presented here are typified. It can be seen that

- each rotor type has its own characteristic
- there is not only a positive flow through the screen openings but also a certain back flow caused by the suction pulse of the rotor
- the backflow velocity is different for the two rotors and can be a manifold of the through-velocity (foil rotor).

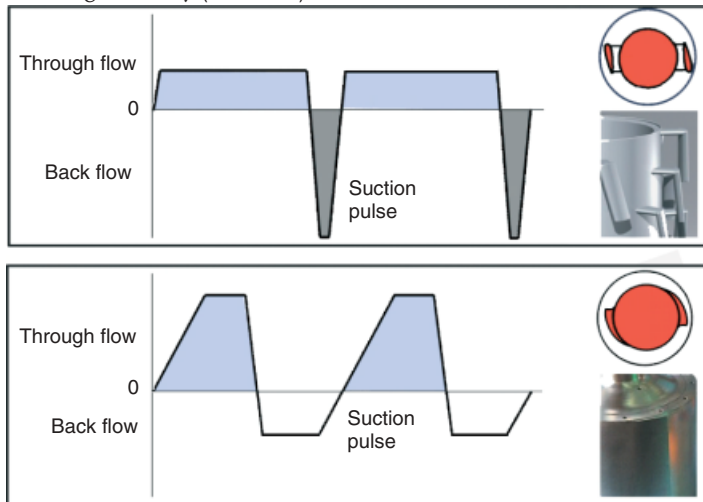


Figure 7.44 Principle suspension velocity through screen openings for two types of rotors. (After Ref. [5].)

Toward the reject outlet the suspension is thickened: It shows higher fiber consistency and higher debris content. This results in faster built up of the network before the openings and higher flow resistance. All this indicates that the calculated average through-velocity often used for comparison reasons does not reflect the operating reality.

7.4.2.4 Flow in the Accept Area

Equal throughput over the whole screen basket area is important for maximum production. According to the amount of suspension passing the screen the accept volume flow increases toward the outlet. With constant flow cross section in the

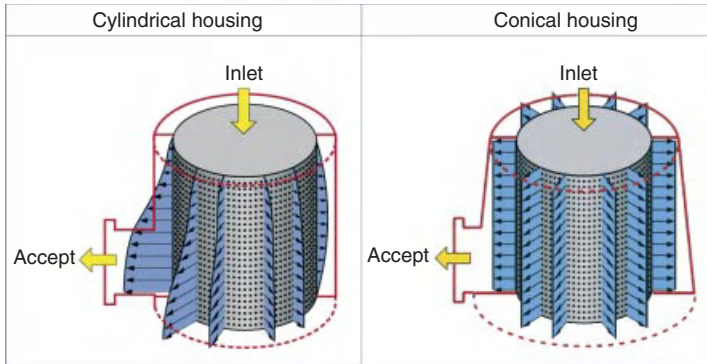


Figure 7.45 Through-velocity field of a cylindrical screen basket with cylindrical and conical screen housing.

accept part of the machine housing, that is, with cylindrical screen basket and housing, the velocity increases toward the outlet and the pressure is reduced according to the Bernoulli equation. As the admissible pressure difference is limited (to prevent plugging) this results in a lower overall capacity, which may be remarkable in compact machine design and at maximum throughput. Figure 7.45 shows schematically the flow conditions through a screen with cylindrical and conical housing, the latter ensuring homogeneous velocity distribution in the accept chamber. Another design uses a rotor with conical body enabling uniform through-velocity over the entire basket area (Figure 7.46).

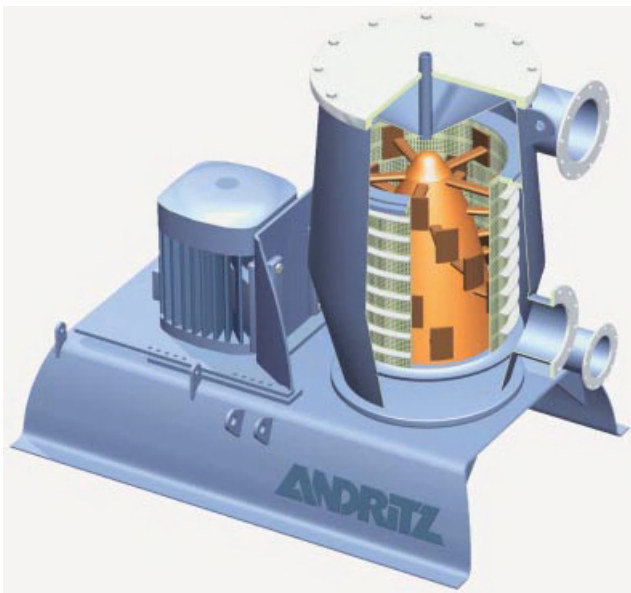


Figure 7.46 Screen with a rotor as “conical” body. (Source: Andritz.)

7.4.3

Screening Equipment and Systems**7.4.3.1 Machine and Operational Parameters Influencing Screening Effect**

Table 7.4 summarizes design and operational parameters for coarse and fine screens, as well as for first and final stage screens.

The main machine parameters for screening are

- the rotor shape and its circumferential speed (influencing the pulse characteristics)
- the rotor position (at the inlet or accept side of the screen influencing the screening characteristics)
- the flow direction through the screen (centrifugal or centripetal)
- the kind and size of the screening apertures (hole, slot, and size)
- the calculated and actual suspension velocity through the screen orifices
- any special configuration to influence the suspension stream lines in the vicinity of the apertures
- the geometry of the housing (for uniform basket throughflow).

The main system parameters are

- type of stock with regard to consistency and fiber type
- kind, size, and amount of debris

Table 7.4 Design and operational parameters for coarse and fine screens.

Criterion/parameter	Unit	Disk screen	Cylindrical screen
Screen apertures			
Hole	mm	2–4	0.08–2
Slot		–	0.1–0.25 (0.4)
Circumferential speed rotor	m s ⁻¹	20–30	10–30
Operating consistency			
MC	%	<5	<4.5
IC		–	<2.5
LC		–	<1.5
Screening effect			
Hole	–	Limited	Good
Slot		–	Best
Thickening			
Hole	–	Low	Mean
Slot		–	High
Specific energy consumption	–	High	Low
Throughput/ screen area	–	Low	High
Acceptable flake content in the inlet	–	High	Low
Flake disintegration	–	High	Low
Contaminant disintegration	–	High	Low
Sensitivity to wear/damage	–	Low	High



Figure 7.47 Opened disk screen for coarse screening. (Source: Voith.)

- through-velocity for the screen apertures given by the required throughput and screen size
- mass flow of reject.

7.4.3.2 Coarse Screening

7.4.3.2.1 Disk Screens In coarse screening both disk and cylindrical screens are used, and both work under pressure. For screening of suspensions with low debris and flake content cylindrical screens are applied and for high loaded suspensions disk screens are used. In Figure 7.47 a disk screen consisting of a conical housing, a screen plate, a vaned rotor, and baffle bars is shown. The screen hole diameters are about 2–4 mm, the peripheral rotor speed is about 20–30 m s⁻¹. Disk screens operate at consistencies below 6%. Owing to their effectiveness in flake defibering, disk screens are also used in the second screening stage of a system with a cylindrical screen in the first stage to reduce loss of paper flakes consisting of valuable fibers, and to ensure safe operation of the system. Owing to its deflaking effect the subsequent stages can be operated reliably as further increase in flake content from stage to stage and thus blocking of the system can be avoided.

7.4.3.2.2 Cylindrical Screens The design principle of cylindrical screens in coarse screening is usually identical or similar to that of fine screens. Cylindrical screens consist of a housing, a rotor with clearing devices, and a cylindrical sieve (Figure 7.48). Depending on the trash content of the suspension different types of rotors may be applied, four of them are shown in Figure 7.49. All rotors are closed, but their surface shape is different. Rotor A usually is applied with hole screen baskets; it stands for high operational reliability, low thickening effect, and high specific throughput. Rotor B can be operated with both hole and slotted

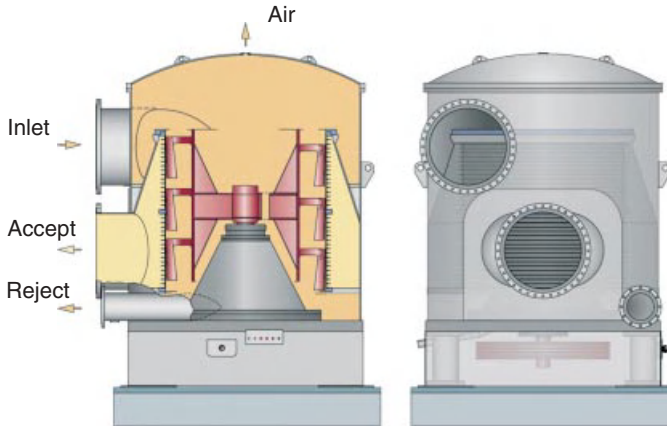


Figure 7.48 Cylindrical screen for coarse screening. (Source: Voith.)



Figure 7.49 Different types of rotors for coarse screening. (Source: Voith.)

screens. Rotor C is used for slotted screens; high screening efficiency, and also more fractionating and thickening can be expected. Rotor D is used for both hole and slotted screens. It has an intensive suction zone and can be used to screen a variety of recycled and primary fiber materials.

The defibering effect of cylindrical screens is generally lower than that of disk screens and depends on the rotor type. Cylindrical screens are used for suspensions with low flake content and operate at consistencies below about 4.5%.

In one machine type the screen rotates whereas the pulsing blades are stationary. Besides the screening function, it comprises an HC cleaning function for heavy particles by centrifugal effects (Figure 7.50). This type of machine is mainly used in coarse screening.

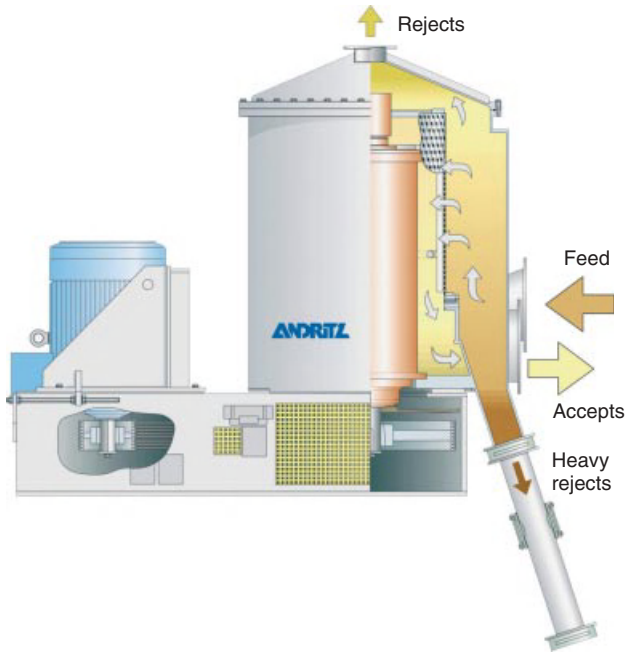


Figure 7.50 Coarse screen with an HC cleaner integrated. (Source: Andritz.)

7.4.3.2.3 Final Stage Screens Final stage coarse screening machines must handle high trash content. On the other hand, low fiber loss and high cleanliness efficiency are required. The machine shown in Figure 7.51 is not pressurized and operates at a consistency of up to 6% in the inlet. Screen hole sizes are about 2–4 mm. Rotors fitted with vanes keep the screen clear and transport the debris such as

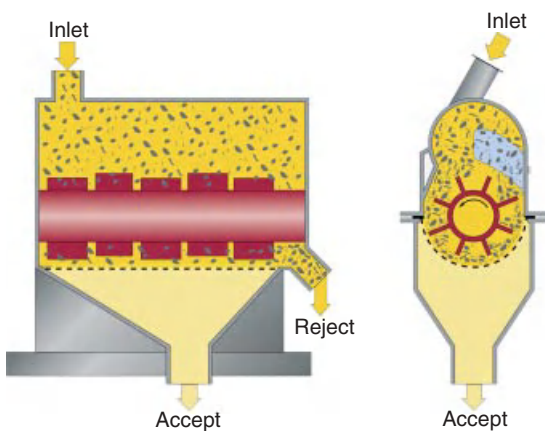


Figure 7.51 Nonpressurized tail screen for coarse screening system. (Source: Voith.)

plastics to the outlet. During the pass through the machine water sprays support the separation of fibers and debris resulting in low fiber content in the reject. Another type of tail screen (Figure 7.52) uses in its lower section a pressurized disk screen whereas the upper part is a nonpressurized cylindrical screen, both usually equipped with holes. These two tail screens have a high deflaking effect and are applied in systems for mixed brown recovered paper processing.

Pressurized cylindrical screens are also used in the last stage but flake and debris reduction may not be sufficient often. Vibration screens with their limited capacity and screening effect are, in most cases, outdated.

7.4.3.3 Fine Screening

7.4.3.3.1 Machine Types For fine screening different types of cylindrical screens are used. They may differ in flow direction (centrifugal, centripetal) and in the position of the rotor relative to the screen basket (inside, outside). Fine screening is done at low stock consistency of below 1.5%. The rotor is adjusted to the requirements of LC screening; its circumferential speed is $10\text{--}30\text{ m s}^{-1}$. Foil rotors are mostly used in LC screening (Figure 7.53). In MC screening rotors such as type A and B (Figure 7.49) are applied. Figure 7.54 shows an example of an LC screen with a foil rotor.

7.4.3.3.2 Screen Basket Types The screen baskets are slotted with widths of $0.1\text{--}0.4\text{ mm}$. Some baskets are milled, where the milling tool defines the slot width and the uniformity of width across the whole basket. Others are bar-type baskets (Figure 7.55) where individual bars are affixed to mountings by welding, brazing, or clamping. The distance between the bars is the slot width. The shape of the bars and the kind of mounting define a profile angle at the slot entrance. Both profile angle and slot width strongly affect the screening result: The smaller the slots and the lower the profile angle, the better the cleanliness effect, and vice versa. On the other hand, finer slots and lower profile angle result in lower throughput and more thickening and fractionation. To maintain the slot geometry as long as possible

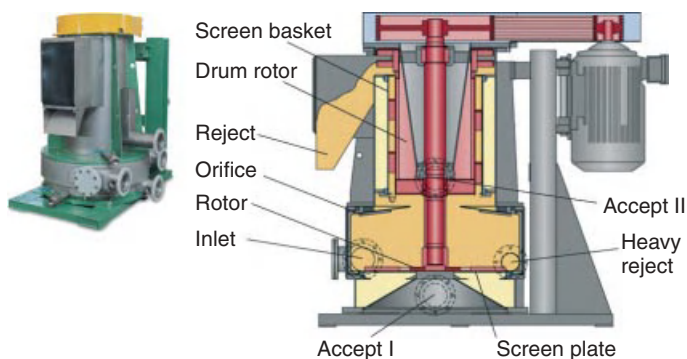


Figure 7.52 Partly pressurized tail screen for coarse screening system. (Source: Voith.)



Figure 7.53 Rotor of a fine screen. (Source: Voith.)

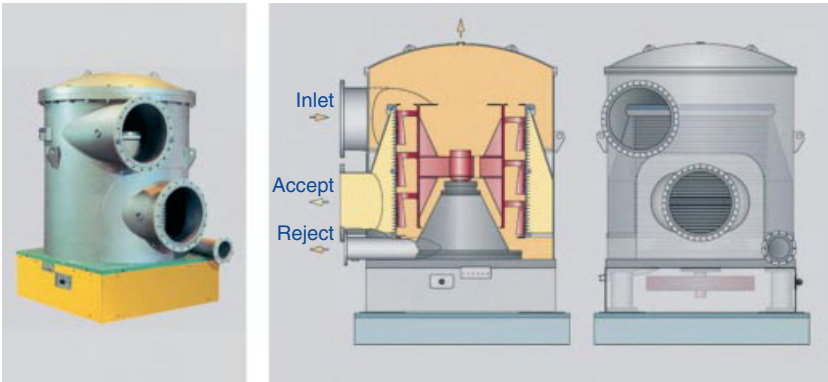


Figure 7.54 LC screen with foil rotor. (Source: Voith.)

during operation, abrasive particles should be removed from the suspension before screening. For that reason recovered paper processing systems mostly comprise LC cleaning ahead of LC screening.

7.4.3.3 Final Stage Screen Final stage screens in fine screening have slotted screen baskets owing to quality requirements. Operation can be either continuous



Figure 7.55 Slotted bar-type screen basket. (Source: Voith.)

or batchwise. Continuous operation of such a screen results in higher cleanliness but with higher fiber loss compared to batch operation. In batch operation, flushing water washes out most of the fibers, but a larger amount of debris passes the screen during the wash cycle. Figure 7.56 shows a final stage screen where part of the reject is recirculated in order to prevent too high a thickening of the reject toward the outlet and to reduce fiber losses.

7.4.3.3.4 Systems Each fine screening system comprises several stages, including a final stage screen. The individual screen accepts and rejects in the various stages are interconnected differently, depending on the requirements. Figures 7.57 and 7.58 show feed forward, full or partial cascade operation schematics. In addition, equations for the overall system separation ratio T as a function of the

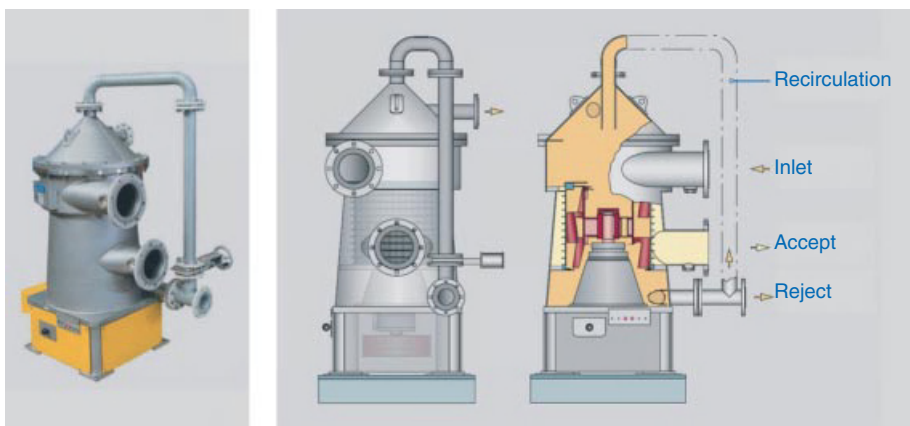


Figure 7.56 Final stage screen in fine screening systems. (Source: Voith.)

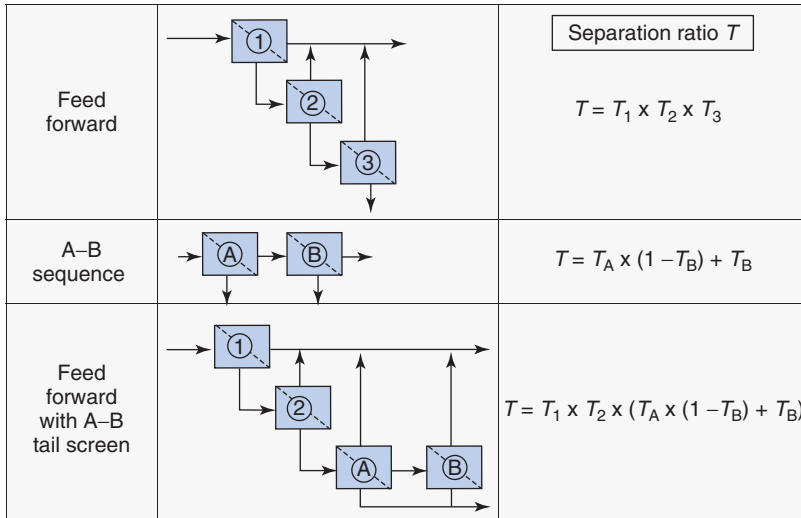


Figure 7.57 Feed forward and A-B sequence fine screening systems.

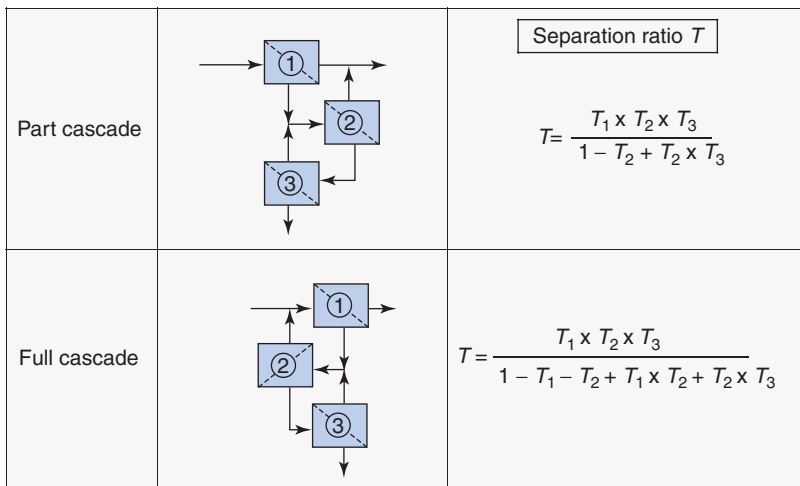


Figure 7.58 Part and full cascade fine screening systems.

separation ratios of the single stages are given. In cascade systems, separation probability is higher. Feed forward may be advantageous when debris particles tend to be easily comminuted in screens or pumps during cascading. An arrangement in series (A-B sequence) provides optimal cleanliness. This sequence can be applied in the primary, intermediate, or final stage. The tail screen defines the amount of debris removed from the system and the fiber loss. Both are important parameters with regard to quality and economy. As the goals are counteracting, a compromise has to be found in each case.

7.4.4

Operational Aspects and Technological Results

The general definitions with respect to evaluation of separating processes such as screening or cleaning are given in Section 7.1.

7.4.4.1 Deflaking Effect

In Figure 7.59 the deflaking effect is explained as the difference in separation ratio between flake reduction and flake retention. One kind of visualization and demonstration of the importance of the deflaking effect in coarse screening systems with high flake content after disintegration is shown in Figure 7.60. Deflaking helps to reduce fiber loss and – even more important – to ensure operation reliability of secondary and tertiary stages. An example based on theoretical calculation demonstrates for a three-stage system how flake content increases in the system for different deflaking effects of the second stage and zero deflaking efficiency of the first and third stages. In all the stages the mass flow split between accept and reject is taken as 70/30 and flake screening efficiency as 80%. It shows how important a good deflaking effect is as the third stage would otherwise not be operable.

7.4.4.2 Screening Gap

There is a risk for screening deficiency, especially for screening systems, when the tailing screen feeds back its accept to the inlet of the previous stage and thereby shows separating characteristics inferior to that stage. This situation is still found in practice. In Figure 7.61 the debris mass flow is plotted qualitatively against the debris particle size. Usually, the debris content decreases with an increase in the particle size. The dotted line characterizes the debris mass flow m_F in the suspension fed to a system with a first- and a second-stage screen. Screen 1 may screen out the particles larger than $d_{p,1}$. The accept contains only particles with

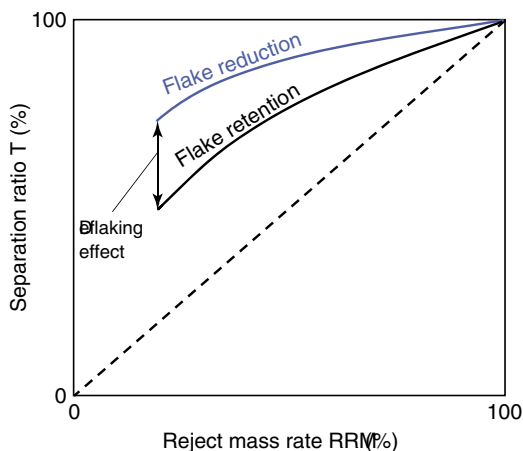


Figure 7.59 Explanation and definition of the deflaking effect.

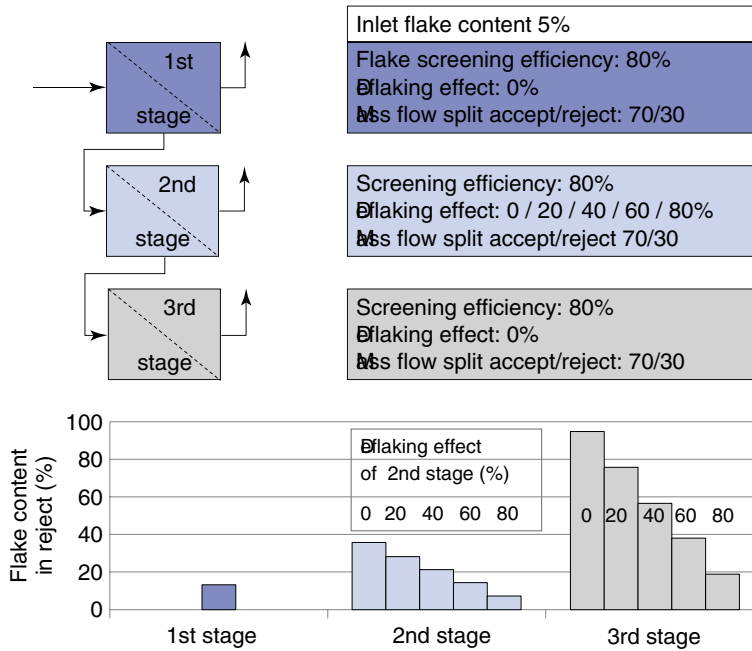


Figure 7.60 Calculated flake accumulation in a three-stage screening system considering deflaking effect in the second stage.

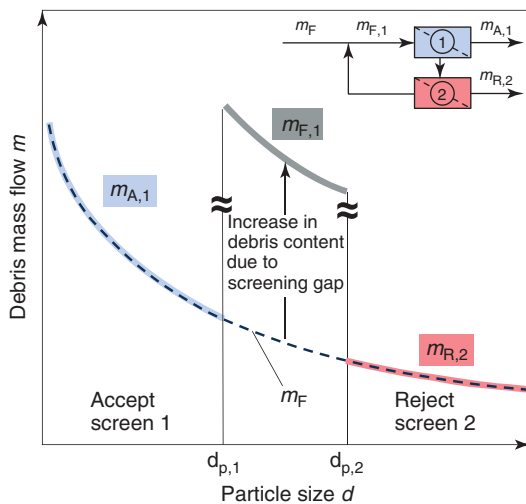


Figure 7.61 Effect of a screening gap on the accumulation of debris particles.

size below $d_{p,1}$. With screen 2 being inferior in its separation effect to screen 1 only particles of size larger than $d_{p,2}$ are separated. In the accept of screen 2 all particles of lower size ($<d_{p,2}$) are found and they are fed back to the inlet of screen 1. Here, the particles larger than $d_{p,1}$ are sorted out again and sent with the reject to screen 2. So the particles of size between $d_{p,1}$ and $d_{p,2}$ cannot escape from this circuit and theoretically are enriched to an infinite extent as represented by the gray curve in Figure 7.61. In practice this can lead to a system collapse. As screens have a certain comminution effect the debris particles are reduced in size during their circulation and after a while will slip through the openings of screen 1 into the accept. This increases the debris content in the accept of the screening system; the maximum debris size is defined by screen 1.

7.4.4.3 Thickening Factor

In screens the reject is thickened depending on equipment and operating conditions. As it may raise problems in the next stage thickening should be reduced as far as possible. On the other hand, higher thickening is accompanied by better screening efficiency. More thickening occurs in fine screening, for example, with smaller slot widths, lower through-velocity of the suspension through the screen openings, lower reject rates, and with a furnish containing a high portion of stiff, long, and thick fibers. From Figure 7.62 the dependency of the thickening factor on slot width can be understood. Increasing slot through-velocity reduces thickening (Figure 7.63). In the further stages of a screening system the stiff, long, and thick fibers accumulate, resulting in higher thickening for the same operating conditions (Figure 7.64).

7.4.4.4 Screening Efficiency

Usually, a higher thickening factor means also higher cleanliness efficiency. This is shown in Figure 7.65 where sticky area reduction as a measure for cleanliness

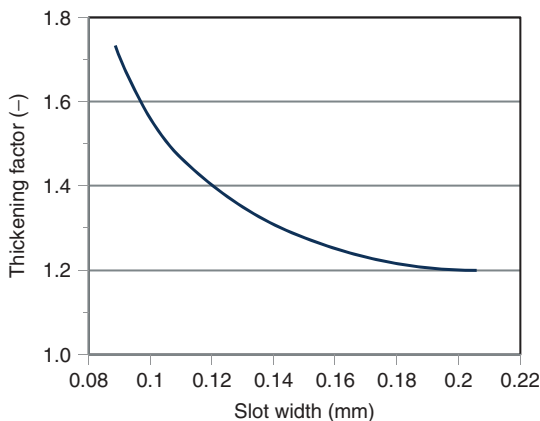


Figure 7.62 Reject thickening factor as a function of slot width. (After Ref. [9].)

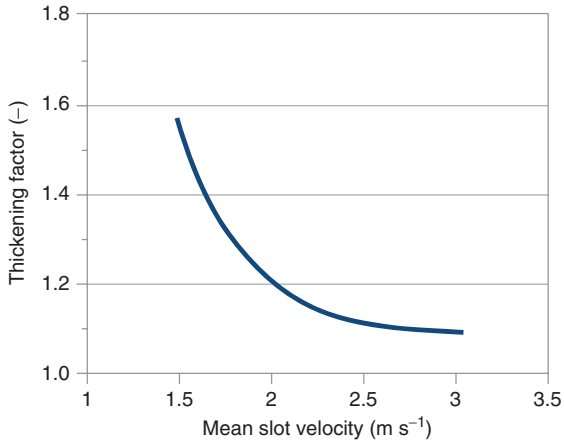


Figure 7.63 Effect of calculated mean suspension velocity through the screen apertures on reject thickening. (After Ref. [10].)

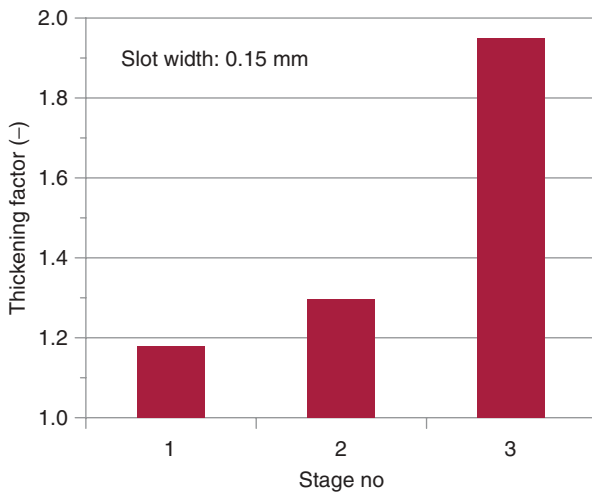


Figure 7.64 Reject thickening factor in the different stages of a screening system. (After Ref. [11].)

efficiency in LC screening is plotted against the thickening factor. Slot widths between 0.9 and 0.15 mm are used for the same screen in this case. In Figure 7.66 the influence of slot width on sticky area reduction is given. Steeper profile angle of slotted screens increases the specific production and reduces the cleanliness efficiency. Thus for worn slotted screen baskets production decreases, but the cleanliness efficiency and thickening increase.

Consistency has a strong influence on the cleanliness efficiency. This is due to differences in machine and operating conditions in MC and LC screening. For

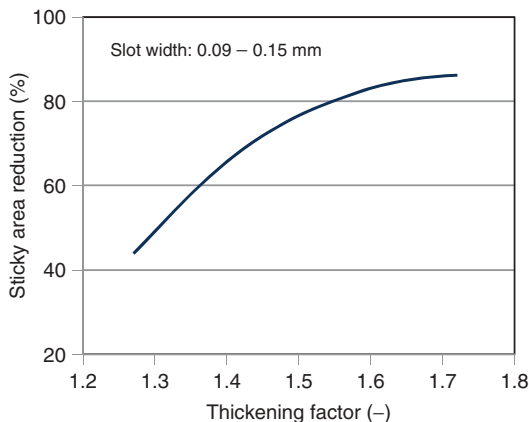


Figure 7.65 Stickies area reduction versus reject thickening factor. (After Ref. [9].)

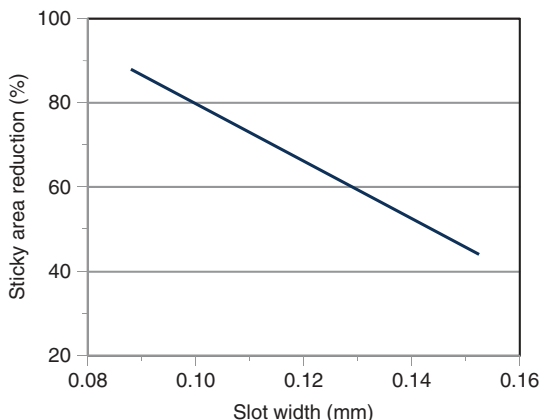


Figure 7.66 Influence of slot width on sticky area reduction. (After Ref. [9].)

example, for stickies, screening the probability of disintegration in MC is much higher than that in LC screening.

The internal design conditions such as suspension flow direction and rotor position also affect the screening result. Centripetal flow may reduce wear of the screen baskets. The rotor placed at the accept side means lower capacity and less wear by heavy particles, but long debris particles such as hair can pass more easily. The rotor placed at the feed side results in better screening and higher throughput, and in more wear, especially in the case of centrifugal flow.

Figure 7.67 gives an overview of the effect of total area offered for screening per 100 tons of daily production on the cleanliness efficiency. Included are MC and LC screens with holes and slots, and systems operating in MC and LC range or only in LC [11]. It shows a certain band with typical tendencies:

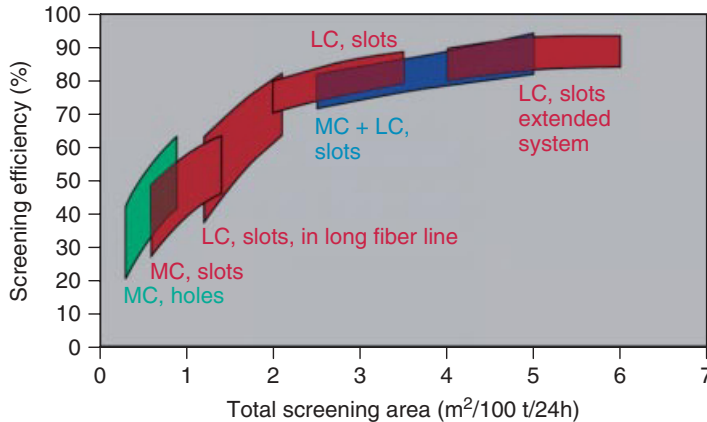


Figure 7.67 Effect of specific total area offered for screening per 100 tons of daily production on screening efficiency. (After Ref. [11].)

- Screening with slots has higher cleanliness efficiency than screening with holes and needs more screening area for the same production.
- Screening in an LC system is more efficient than with a combined MC–LC system, which is still better than a pure MC system.
- For further increase in the cleanliness efficiency it needs an overproportional outlay of machinery and energy for operation as cleanliness efficiency tends to follow an asymptotical curve when plotted against the specific screening area.

7.5

Centrifugal Cleaning

Centrifugal cleaning is used in many industries to separate solids from gas, liquids from gas, and solids from liquids. The principle is also effective in separating, for example, solids of different properties from a suspension. This ability is used in the paper industry when certain undesired components have to be separated from the fibers. The tools used are called *hydrocyclones* or *cleaners*. In stock preparation centrifugal cleaning complements other separation methods such as screening owing to its different physical separation principle. In contrast to screening, hydrocyclone cleaning does not tend to deform softer particles.

7.5.1

Overview

7.5.1.1 Objectives

The objective of centrifugal cleaning is to remove from the suspension particles that negatively affect the paper quality or cause either excessive wear or plugging in subsequent processing machines. For their efficient removal, the particle density

must differ from that of water. The density and/or their size and shape should also differ from those of the desired suspension components.

7.5.1.2 Principle Solution

All hydrocyclones (Figure 7.68) consist of a cylindrical pipe mostly ending in a conical one. The suspension enters the cyclone tangentially at high velocity, which makes the suspension rotate. In this centrifugal field acceleration is generated ranging from 10 to 1000 times the gravity. The heavy particles are forced to the outer wall, whereas the light ones are driven to the center. Corresponding types of cleaners are called HW (heavy weight) and LW (light weight) cleaners.

The flow in a hydrocyclone is a three-dimensional two-phase flow. The circumferential component generates the centrifugal force, the axial component moves the solid particles toward the cleaner outlet, and the radial component of the suspension flow proceeds them from the outside toward the center and vice versa.

The flow streams where the heavy or light particles are accumulated are separated from the cleaned stock stream. This separated stream still contains a certain amount of valuable components such as fibers and fines. Therefore, several cleaner stages are installed for further separation.

7.5.1.3 Applications

Hydrocyclones are used in stock preparation of virgin pulp and of recovered paper where they are even more important. Different hydrocyclone types exist for operation at various consistencies depending on the location in the process. There are cleaners operating at HC (3–6%) after disintegration of the stock or along the process line and toward the end of stock preparation, as well as in the approach flow system at LC (0.5–3%). HW cleaners may remove metal, glass, and sand of particle

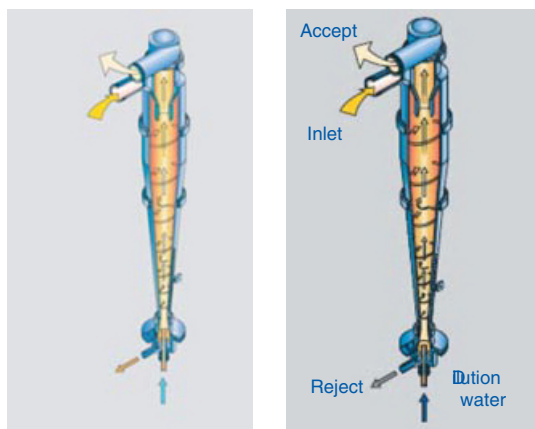


Figure 7.68 Low consistency cleaner as an example of a hydrocyclone in stock preparation. (Source: Voith.)

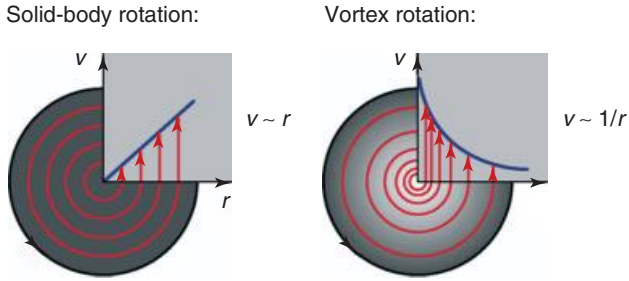


Figure 7.69 Solid-body rotation and vortex rotation.

sizes from 50 μm up to 8–20 mm depending on the type, whereas LW cleaners are effective for light particle removal such as wax or plastic foam of similar size range.

7.5.2

Theoretical Aspects

7.5.2.1 Basics of Hydrocyclones

7.5.2.1.1 Flow Principles There are two rotational flow principles present in cleaners, the solid-body rotation where the tangential velocity v_t is proportional to radius r

$$v_t = \omega \times r$$

with ω as the angular velocity, and the vortex rotation where theoretically the velocity v_t is proportional to $1/r$

$$v_t = \frac{\text{const}}{r}$$

In Figure 7.69 these two flow patterns are illustrated.

Owing to friction and turbulence effects, v_t is usually calculated as

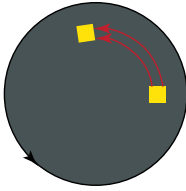
$$v_t = \frac{\text{const}}{r^n}$$

with $n = 0.5$, often used in practice.

In solid-body rotation only negligible shear forces occur within the cyclone, which allows the suspension to flocculate. This is detrimental for the separation efficiency as the particles to be separated may be caught in the fiber flocks. In vortex rotation the shear forces are higher, which supports fluidization of the fiber network (Figure 7.70).

Figure 7.71 shows that at a certain radius a change from solid-body rotation to vortex rotation takes place in a hydrocyclone [12–14]. The outlet of the cleaners is placed in the cleaner center in the vicinity of the solid-body vortex.

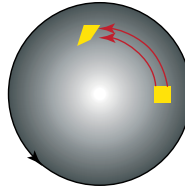
Solid-body rotation:



No distortion of elementary volume:

- No internal shearing action
- Formation of fiber flocks

Vortex:



Distortion of elementary volume:

- Internal shearing action
- Fluidiation of fiber networks

Figure 7.70 Effects of shear forces in (a) solid-body and (b) vortex rotation.

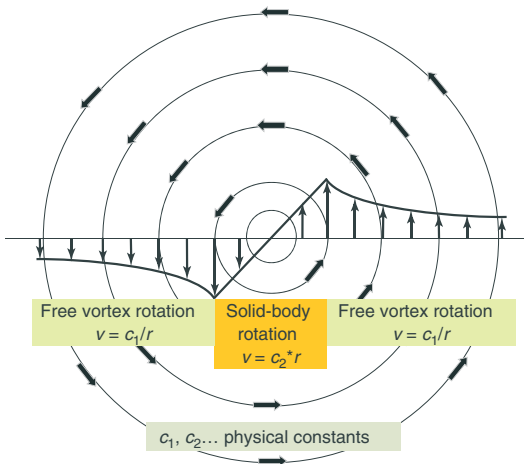


Figure 7.71 Local tangential rotation velocity in a hydrocyclone.

7.5.2.1.2 General Remarks with regard to Efficiency of Hydrocyclones Hydrocyclone efficiency generally increases with the following:

- Increased centrifugal acceleration, obtained by high tangential velocity and a small diameter of the hydrocyclone. The velocity is dependent on the pressure differential between the inlet and the accept.
- Lower stock consistency, as the fiber network may restrict particle motion at elevated consistencies.
- Appropriate reject flow removal without remixing of reject and accept streams.
- Particles with
 - large density difference compared to water
 - large size at comparable density
 - favorable hydrodynamic shape ($c_w \times A$) at comparable density and size (with the flow resistance coefficient c_w and the projected area A).

7.5.2.1.3 Some Definitions and Equations Centrifugal acceleration a_c due to tangential velocity v_t at radius r is

$$a_c = v_t^2/r$$

Centrifugal force F_c acting on a particle of volume V_p and density ρ_p moving with velocity $v_{t,e}$ at radius r is

$$F_c = V_p \times \rho_p \times a_c$$

Force due to buoyancy F_b in a fluid of density ρ_f is given as

$$F_b = V_p \times \rho_f \times a_c$$

Flow resistance force F_{fr} against radial movement of the particle with the radial velocity v_r in a fluid [15, 16] is as follows:

$$F_{fr} = \frac{c_w A_p \rho_f}{2v_r^2}$$

The flow resistance coefficient c_w depends on the Reynolds number Re_p

$$c_w = \frac{24}{Re_p}$$

with

$$Re_p = \frac{v_r d_p \rho_f}{\eta_f}$$

where d_p is the equivalent diameter of the projected area and η_f is the dynamic viscosity of the fluid. As the fiber suspension is a non-Newton fluid η_f should to be seen as an apparent viscosity [17].

7.5.3

Cleaner Types and Systems

7.5.3.1 General Remarks

7.5.3.1.1 Design Principles According to the flow directions of the reject and accept relative to the inlet, hydrocyclones are called either *counterflow* or *unidirectional flow cleaners* (Figure 7.72). In counterflow, inlet and accept or reject are at the top and reject or accept at the bottom. Unidirectional flow is defined by the reject and accept connections being opposite to the inlet.

Usually, hydrocyclones have three connections (three-way with inlet, accept, and reject of HW or LW particles). Some LC cleaners operate as four-way cleaners (inlet, accept, reject of heavy, and reject of lightweight particles) or even five-way cleaners with an additional air outlet (Figure 7.73).

The overflow may work against the ambient pressure or against the controlled overpressure. It is operated continuously or discontinuously and with or without back-flushing water.

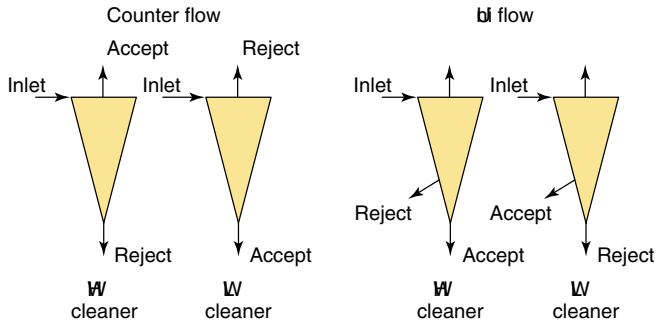


Figure 7.72 Counterflow and unidirectional flow in hydrocyclones for HW and LW cleaning.

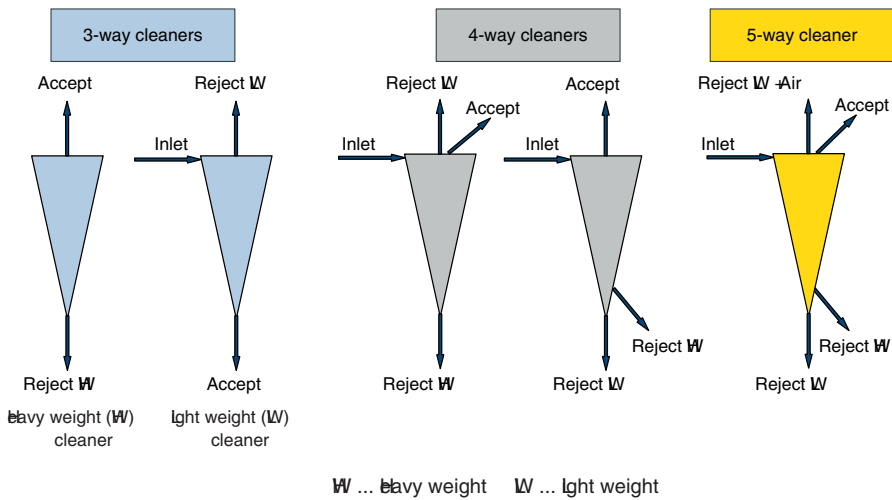


Figure 7.73 Principles of cleaners with different number of ways.

Usually, the centrifugal field is built up just by the entrance velocity of the suspension. In the case of an HC cleaner (Section 7.5.3.2), an additional means for generating rotation may be used.

7.5.3.1.2 General Rules for the Selection and Operation of Hydrocyclones A smaller cyclone diameter results in higher efficiency. On the other hand all openings and connections must be of such a size that plugging is avoided. Furthermore, smaller diameters result in a higher number of cyclones to be installed in a system.

A higher pressure difference across the cyclone improves the efficiency, but increases pump energy consumption.

Three-way cleaners are more efficient and easier to operate than four- or five-way cleaners.

The throughput should be close to the layout conditions. Increased throughput increases centrifugal forces, but reduced dwell time for a particle in the cleaner

and higher turbulence may decrease the efficiency. A too low throughput reduces the centrifugal acceleration and thus also the particle sedimentation efficiency.

The reject rate should be optimized as higher reject rate results in a cleaner stock but also in more losses of valuable components.

LC increases separation efficiency as the particles can move more freely. Higher consistency due to only higher filler content is of low influence. On the other hand, LC increases the required pump energy as a result of higher flow rate needed to ensure the required production capacity.

Higher flake content also reduces the movability of the particles and should be reduced by disintegration ahead of the cyclone.

Back-flushing water should be kept as low as possible as it reduces the consistency in the system. On the other hand, losses of valuable material are increased with less back-flushing.

Increased suspension temperature reduces water viscosity, which allows the particles to move easier. A large temperature change may influence the removal efficiency of certain particles with densities close to that of water as temperature changes its density so that there is no sufficient difference left anymore between the particle and water density.

7.5.3.2 High Consistency (HC) Cleaners and Systems

HC cleaners are positioned after slushing and operate at consistencies of about 3–5%, sometimes up to 6% and also lower than 3%. They are the largest cyclones used in the paper industry. They are used for precleaning to remove heavy particles of more than 1 mm in size. Their density has to be significantly higher than 1 g m^{-3} . These particles may plug, wear, or damage subsequent machinery and therefore they have to be removed. HC cleaners are also known as HD (high-density) cleaners. They are mostly based on the counterflow principle (Figure 7.74). In single-stage mode reject discharge is batchwise, and, in the case of a two-stage system, the discharge in the first stage is continuous, whereas reject removal is discontinuous in the final stage. In the latter case the HC cleaner reject of the first stage is diluted, optionally passes a sedimentation tank and then is finally cleaned. The second-stage cleaner operates at consistencies of about 2.5%. The sedimentation tank protects this cleaner from abrasion and plugging to a great extent. The reject is extracted periodically and is about 0.1–1.0% of the total mass flow of the system. The system is shown in Figure 7.75.

7.5.3.3 Low Consistency (LC) Cleaners and Systems

LC cleaners operate at consistencies of 0.5–2% and even up to 3%. In the consistency range of 2–3% they are also known as *IC cleaners*. LC cleaners are smaller than the HC cleaners (Figure 7.68). Usually, they are of the three-way type. Owing to the low operating consistency and high centrifugal forces (small diameter and high circumferential velocity) the removal effect is high. On the other hand, the pump energy demand per ton of stock is high due to the high flow rates. Reject outlet is continuous.

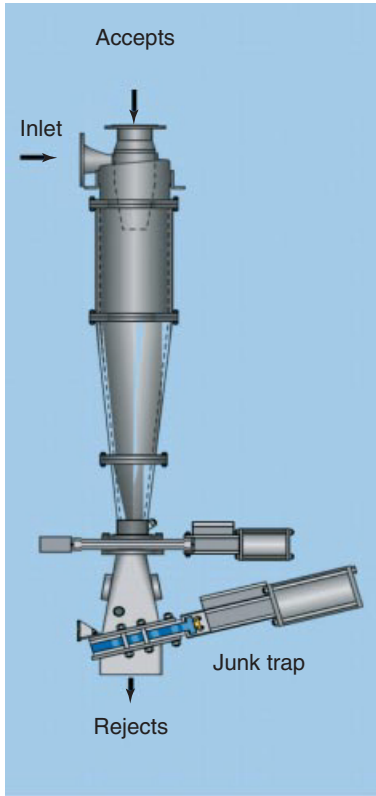


Figure 7.74 High consistency cleaner. (Source: Voith.)

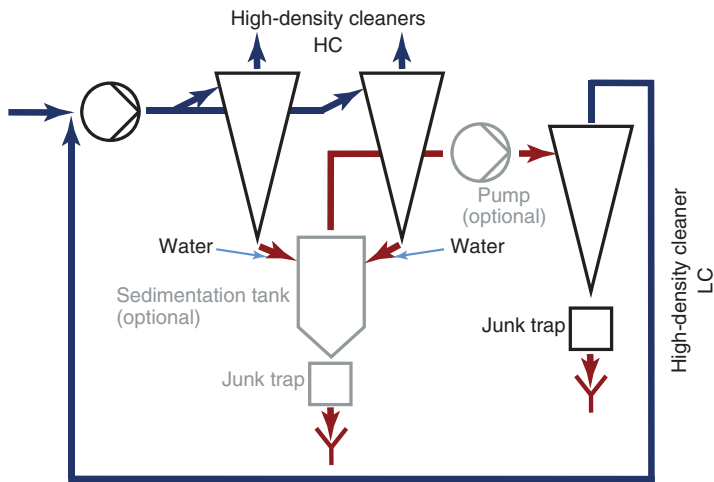


Figure 7.75 High consistency cleaner system. (Source: Voith.)

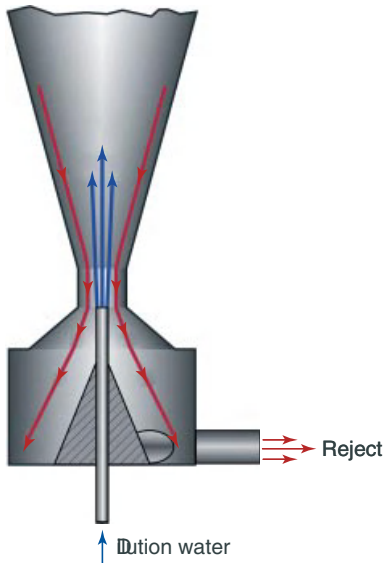


Figure 7.76 Details of the reject area of a heavy weight LC cleaner. (Source: Voith.)

By removing fine sand particles HW LC cleaners protect the fine, slotted baskets of the screens from wear and sand accumulation. During cleaning the suspension thickens, consistency is higher near the wall. Here, the heavy particles accumulate. To prevent the reject outlet from plugging and to reduce fiber content in the reject, dilution water is added at this position. However, the cleaner design must ensure flow conditions in the reject outlet area that the dilution water does not remix the separated heavy particles with the cleaned stock. Figure 7.76 shows details of the reject area of an HW LC cleaner. High abrasion at the inner cleaner surface occurs due to high circumferential velocity and high acceleration of fillers and sand, especially at the inlet and the cone; hence, the surface has to be protected by ceramic material or rubber.

LW LC cleaners, nowadays, are recommended mainly for wax and plastic foam removal. They can also be advantageous when particles such as soft stickies may be deformed or reduced in size in a screen. A precondition is that their density should be lower than that of water. In Figure 7.77 an HW cleaner with unidirectional flow scheme is shown.

7.5.3.3.1 System A cleaner system consists of as many as five stages. The reject of the first stage is diluted and cleaned in the second stage; its accept is fed back to the inlet of stage one and its reject is diluted and cleaned in the third stage; and so on. This type of system configuration is called a *cleaner cascade system* (Figure 7.78). The consistency in the reject is higher than that in the inlet. This thickening mainly results from the concentration of debris and fillers. Thickening factor of HW LC cleaners is 3–5 with the reject outlet acting against the ambient pressure and 1.5–3



Figure 7.77 Light weight cleaner with unidirectional flow principle. (Source: Voith.)

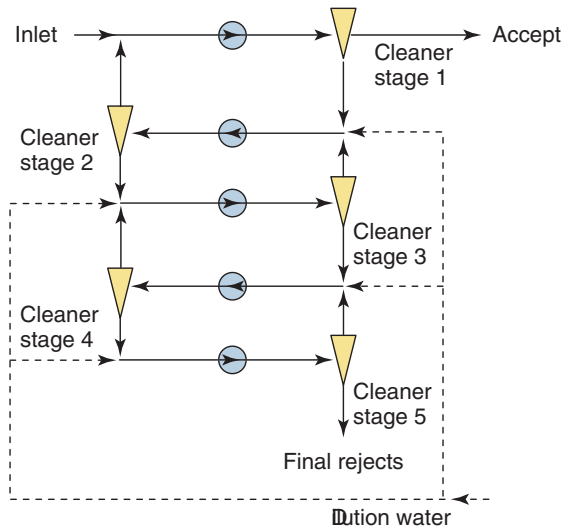


Figure 7.78 Cascade system with LC cleaners.

when acting against overpressure. Before the reject enters the next stage it has to be diluted with water of low fiber content. The capacity of the next stage is only about 30–45% of the preceding one.

Individual cleaners of one stage are connected to form cleaner batteries with a common distributor feeding the inlets of all cleaners of the stage. Their accepts and rejects flow to the collector pipes (Figure 7.79).

7.5.3.4 Cleaner with Rotating Housing

Centrifugal cleaner is a special type of equipment, which has rotating housing and central inlet at one end and outlets for the cleaned suspension and the low-weight particle stream at the other end (Figure 7.80). Owing to high centrifugal acceleration and controlled flow conditions, the cleaner can remove light particles with a density close to that of water.

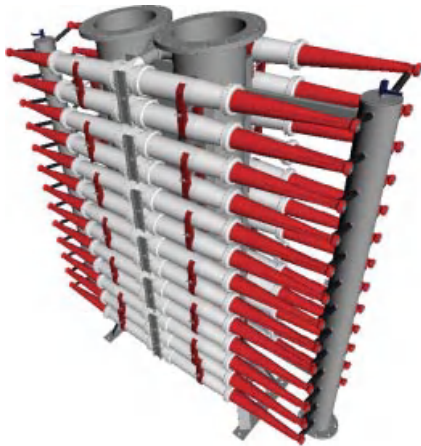


Figure 7.79 Cleaner battery. (Source: Andritz.)



Figure 7.80 Cleaner with rotating housing. (Source: KADANT Inc.)

7.5.4

Operational and Technological Results**7.5.4.1 Overview on Design and Operational Conditions**

Table 7.5 gives an overview on typical design and operational parameters of HC and LC cleaners. The throughput of a single HD cleaner ranges up to 14 000 l min⁻¹. Pressure drop usually is 1.0–1.5 bar. With LC cleaners, pressure drop normally is between 0.7 and 2 bars. The reject rate is significantly higher with LC cleaners. It ranges from 5 to 30% depending on the cleaner type, the operation mode, and the cleaner position in a multistage cleaner system.

7.5.4.2 Typical Technological Results

For evaluation of the separating effect the definitions given in Section 7.5.1.1 are valid. The separation efficiency of HD and LC cleaners is shown in Figures 7.81

Table 7.5 Overview of typical design and operational parameters of cleaners used in the paper industry.

Characteristic	Cleaner type			
		HC cleaner	LC cleaner	
			HW	LW
Preferred flow principle	–	Counterflow	Counterflow	Unidirectional flow
Consistency range	%	(2.5) 3–6	0.5–3	0.5–1.5
Throughput per cleaner	l min ⁻¹	Up to 14 000	100–1000 (2000)	100–500 (5000)
Specific energy demand/stage	kW h t ⁻¹	0.5–3	2–10	2–50
Pressure drop inlet-accept	Bar	0.5–1.5 (1.8)	0.7–2 (4)	0.8–2
Approx. g-factor	–	<60	<1000	<1000
Diameter (maximum) reject opening	mm	300–700	75–300	110–450
Reject rate by mass/stage	%	80–120 0.1–1.0	10–40 5–30	40–60 3–20
Reject thickening (not final stage)	–	–	1.5–5	0.2–1.0
Reject discharge mode				
Not final stage	–	Continuous	Continuous	Continuous
Final stage	–	If any: batch	Continuous/batch	Continuous

and 7.82 for the separation of sand particles of varying sizes. Efficiency improves with increasing particle size. Figure 7.81 shows results from a HD cleaner system. Efficiency is better when operating two stages compared to only one stage. As expected efficiency also improves if the pressure drop is increased. Figure 7.82 additionally illustrates the influence of the stock consistency in LC cleaning. It

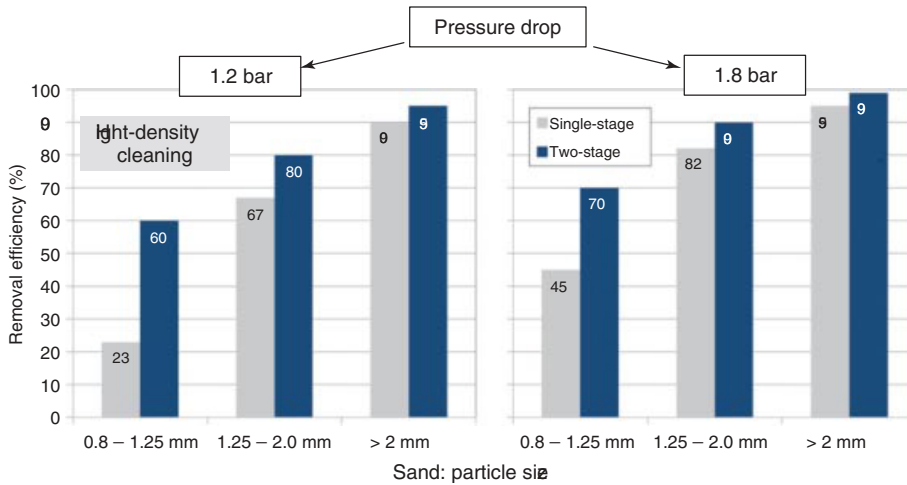


Figure 7.81 Separation efficiency of high-density cleaners with respect to sand particles. (Source: Voith.)

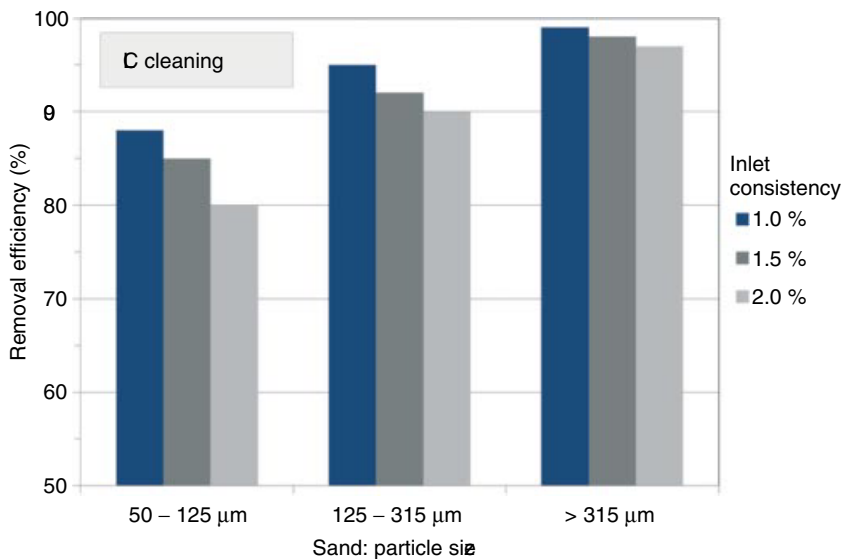


Figure 7.82 Separation efficiency of LC cleaners with respect to sand particles. (Source: Voith.)

can be seen that the fiber network at higher consistencies obstructs the movement of the particles and thus reduce the separation efficiency. However, LC cleaners can be operated up to 3% consistency with still acceptable removal efficiencies (Figure 7.83). Good fiber-flock fluidization throughout the whole cleaner and optimum flow regime at the cleaner outlet are required to make an LC cleaner work at that HC. In Figure 7.84 some examples of rejects from HD cleaning of an OCC stock are given for the first and second cleaner stages. The average size of the heavy particles is higher in the first-stage rejects. Figure 7.85 shows reject samples of LC cleaners. It can be seen that the smaller cleaner diameter is more effective in sand removal.

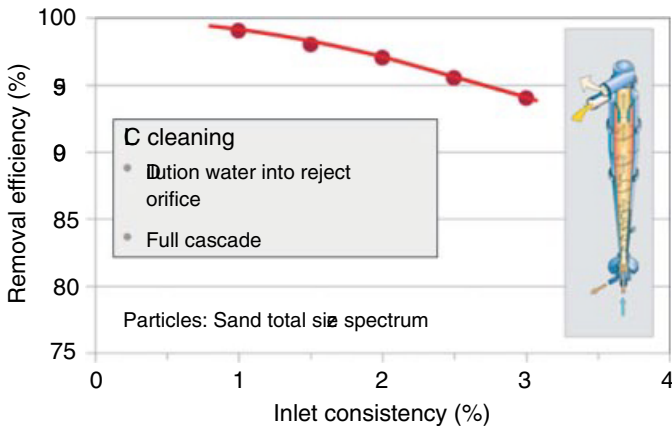


Figure 7.83 Sand removal efficiency of an LC cleaner cascade system as a function of inlet consistency. (Source: Voith.)

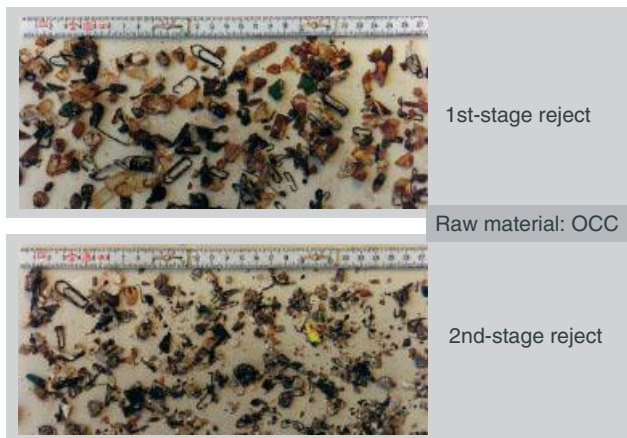


Figure 7.84 Rejects of the first and second stage of a high-density cleaning system. (Source: Voith.)

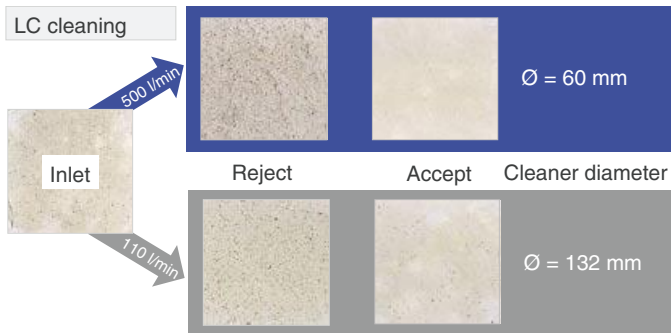


Figure 7.85 Influence of cleaner diameter on the removal efficiency in LC cleaning. (Source: Voith.)

7.6 Selective Flotation

Flotation is a separation process. Its principle is used either for selective or for nonselective separation of solid particles from the suspension. Selective flotation shall remove contaminants (solids–solids separation), whereas nonselective flotation shall remove all solids (solid–water separation). First attempts for flotation deinking started in the second half of the 1950s in Austria and Germany. In 1965, the production with the first deinking cells specially developed for the paper industry started in Germany; it was an impeller flotation cell, followed by a lot of further cell principles. In North America wash deinking was the favored process for a long time to take out water-based ink particles. This kind of process was introduced in Europe for removing other fine and disturbing particles such as ash, fines, and microstickies; hence high-speed washers have been developed, the first one was started in the industry in 1981. As wash deinking results in high solid losses the application was and is limited in Europe. Here, it is mainly used today for deashing of stock for sanitary products.

7.6.1

Overview and Theoretical Aspects

7.6.1.1 Objectives

Selective flotation is used in stock preparation systems for recovered paper processing. The objective is to remove certain contaminants from the suspension, such as printing ink, stickies, fillers, coating pigments, and coating and ink binders. “Deinking” of the stock is the main purpose of flotation in recovered paper processing: Removing the ink particles increases brightness, whereas removing dirt specks enhances cleanliness. Particles larger than $50\ \mu\text{m}$ are usually called *dirt specks* and are visible to the naked eye.

7.6.1.2 Principle Solutions

In selective flotation air is injected into the suspension generating bubbles that are mixed with the suspension. Such an air bubble may catch one or more particles. The particles remain attached to the bubble and are carried to the surface of the suspension by buoyant forces acting on the bubbles. The resulting foam containing the dirt particles is then withdrawn from the suspension. The selection criterion in flotation is the different surface wettability of the fibers to be retained and the particles to be removed. The surface of these particles is or has been rendered hydrophobic (water repellent). The size of the particles that can be removed by selective flotation with at least reasonable effectiveness is limited to a range of about a minimum of 5–10 μm up to a maximum of 250–500 μm .

7.6.1.3 Main Prerequisites for Good Flotation Results

The following are the main prerequisites for a good deinking result:

- The particles have to move freely in the suspension: they have to be detached from the fibers.
- The particles must have a floatable size and shape: larger particles have to be reduced in size, too small particles have to be agglomerated into larger ones, and flat particles should be reshaped to cubic ones.
- The particles should be hydrophobic to a certain extent by nature; if not, this can be accentuated by applying suitable chemicals to the suspension.
- The air bubbles have to move freely: the fiber consistency should not be too high so that bubbles can freely ascend. Thus the development of bubble nests can be avoided which may break through to the suspension surface without contributing to foam generation but even destroying the existing foam layer.
- A sufficient number of air bubbles of convenient size (in the 1 mm range) should be uniformly distributed in the suspension: effective bubble generation and mixing of bubbles and suspension have to be ensured.

7.6.1.4 Two-Phase Flow in Flotation

Flotation is done in so-called cells. Their design has to ensure bubble generation, collision of the ink particles with the bubbles, transport of the ink–bubble aggregate to the suspension surface, and foam removal.

7.6.1.4.1 Bubble Generation There are different principles to generate bubbles in a suspension. In any case the resulting bubbles sizes depend on the surface tension of the suspension as well as on the energy input when mixing the air in the suspension. Of course also the ratio of air volume related to the total suspension volume influences the bubble size. A simple way to produce bubbles is to press air through a permeable body such as perforated metal sheeting or ceramics. Here, the bubble size also depends on the air injection openings. Dynamic mixers have rotating impellers with air outlets fed by compressed air. Static mixers make use of natural aspiration for air supply and of the kinetic energy in the fluid for mixing. The smaller the bubble diameter, the higher is the number of bubbles produced

for a given amount of air. Small bubbles can transport only small particles, for larger particles it needs larger bubble diameters. So a mixture of different bubble diameters should prevail to take into account the size spectrum of the solid particles to be removed. The relative air load (total air volume flow to total suspension volume flow) is mostly about 300%, in some cases even more than 500%.

7.6.1.4.2 Collision of the Dirt Particles with the Bubbles Collision is a matter of probability and can only happen by relative movement of bubble and particle. Using a permeable body for bubble generation without forced mixing needs a longer residual time – and thus ascending path length – of the bubbles in the suspension to increase the collision probability. With dynamic mixers collision of bubbles and particles is intensified in the vicinity of the rotating mixing body. In static mixers the complete streams of both suspension and air pass through the mixing element and undergo an intensive mixing with high collision probability.

7.6.1.4.3 Transport of Particle–Bubble Aggregate to the Suspension Surface As soon as a particle has been attached to the bubble its detachment has to be avoided. Detachment may occur by too high-shear forces owing to turbulence, buoyancy, and gravity. Buoyancy and thus ascent velocity of larger bubbles is higher than that for smaller bubbles. The risk of too high-shear forces suggests that one should make the ascending path length as short as possible. On the other hand, a higher suspension level may be advantageous as collision probability is increased when the bubble ascends a longer distance. This is especially important in designs where the collision probability at the moment of bubble generation is lower. Depending on the operating principle of the different cells either longer or shorter path lengths help to calm the suspension surface in order to enable effective foam removal and to avoid remixing of the foam with the suspension. It should be born in mind that bubble swarms induce ascent velocity, which may result in a highly turbulent surface. Figure 7.86 demonstrates that bubble size and particle size should have a suitable size ratio in order to ensure collision and to avoid detachment. Another important factor is the degree of microturbulence in the vicinity of bubble and particle.

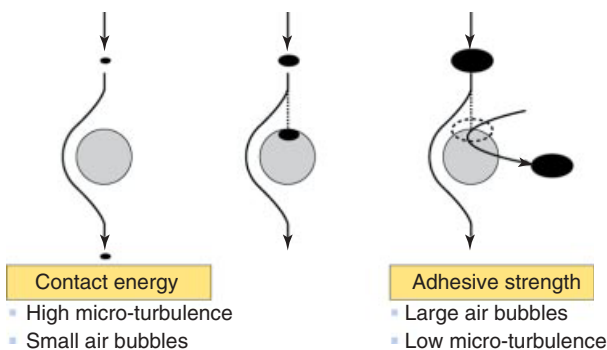


Figure 7.86 Adequate sizes of particles and bubbles and suitable level of microturbulence.

7.6.1.4.4 Foam Removal Foam discharge is done, for example, by free overflow over a weir. A scraper may support the removal. In other designs the foam is discharged through sucking pipes by pressure difference, either by the outside vacuum or by the pressure inside the cell.

7.6.2

Chemistry in Flotation

In many cases additional chemicals are needed to make flotation work efficiently. The fatty acid soap is used very often especially with furnishes containing old newspaper and magazines. Synthetic surfactants and silicone derivatives are two further chemical groups employed in deinking. Usually, caustic soda is used to improve ink detachment by fiber swelling and cracking the ink binders, and the fatty acid system itself also requires a certain amount of caustic soda (see also Section 6.9).

7.6.2.1 Fatty Acid Soap

Fatty acids are organic carboxylic acids having a long alkyl chain. The chain length of the products for deinking usually is from 13 to 18 carbon atoms. There are saturated fatty acids and the so-called oleoic acids that contain unsaturated double bonds. In the presence of caustic soda, saponification takes place in the first step. The resulting sodium soap acts as a surfactant and undesirably stabilizes the single ink particle in the suspension. This is due to the hydrophobic ends of the soap molecules covering the hydrophobic ink particles and the hydrophilic ends extending into the liquid phase. The sodium soap itself develops foam but counteracts ink removal by the ink dispersing effect. In the next step the sodium soap reacts with the Ca ions mostly present due to the prevailing water hardness. The resulting Ca soap is the basic molecule to make the chemical system work in terms of ink removal. Figure 7.87 summarizes the chemicals participating in fatty-acid-based ink removal. In Figure 7.88 the dispersing effect of sodium soap is illustrated.

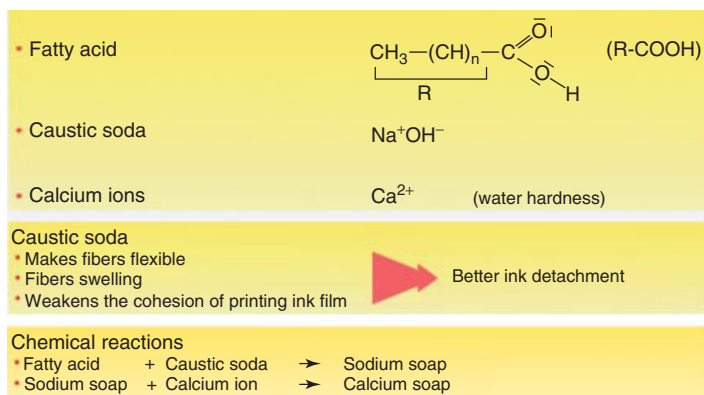


Figure 7.87 Chemical system for fatty-acid-based ink removal.

There are several approaches to explain the mechanism of fatty-acid-based ink removal [18–20]. One approach says that the nonsoluble Ca soap molecules form flocs in the size range of 0.5 μm . The flocs are hydrophobic thus trying to cover the ink particles and increasing their hydrophobicity. So, smaller particles can aggregate to larger ones, which can be more easily captured by the air bubbles. The aggregation is called *collecting effect* [19]. Figure 7.89 schematically illustrates the mechanism of ink particle collection. Figure 7.90 shows toner particles attached to an air bubble at the end of a vertical needle in a test apparatus [20].

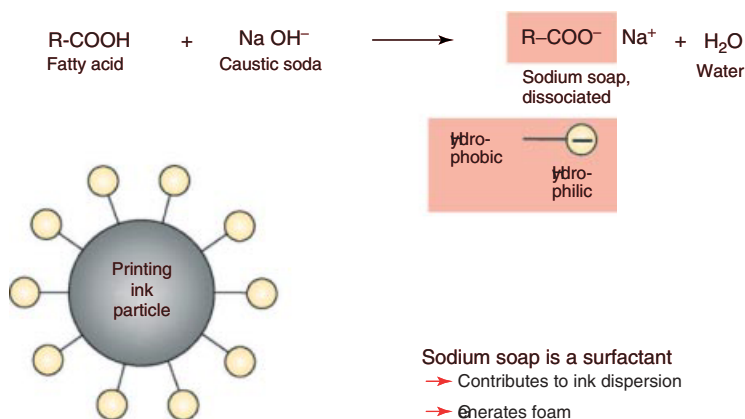


Figure 7.88 Dispersing effect of sodium soap.

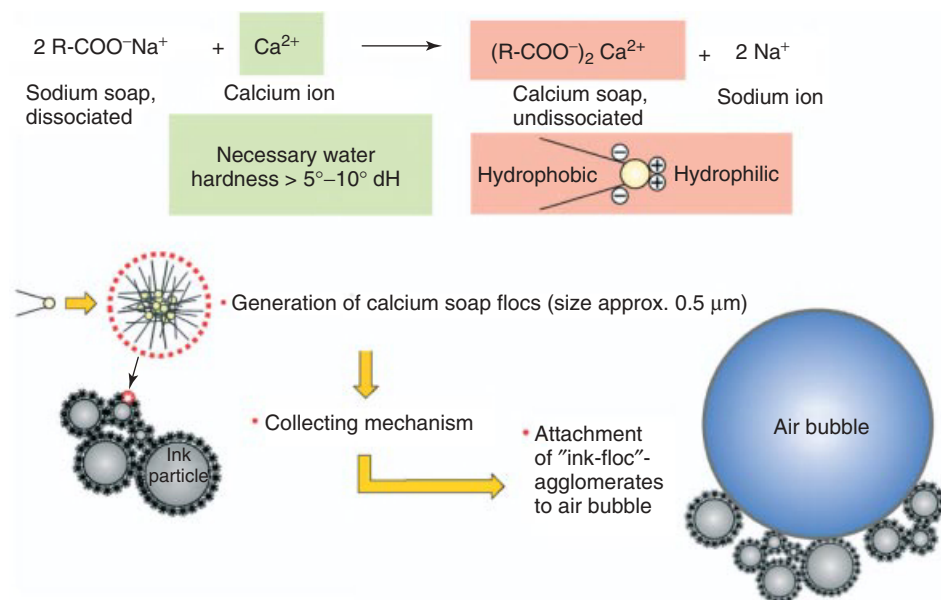
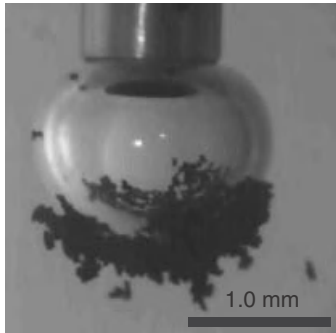


Figure 7.89 Collecting mechanism of a fatty-acid-based deinking chemistry.



- Stationary air bubble at the end of an inverted needle
- Toner particles in fatty acid based chemistry (Calcium oleate) → 75–150 μm

Figure 7.90 Attachment of toner particles to stationary air bubble at the end of an inverted needle [20].

7.6.2.2 Synthetic Surfactants

The advantage of synthetic surfactants is that they do not need other chemicals to start their effect in flotation. They decrease the surface tension of water thus showing good foaming activity but have a limited collector effect. The mechanism of synthetic surfactants is shown in Figure 7.91. They are mostly used with woodfree furnishes. Here, the ink particles are larger (dirt specks) and the strong foaming activity favors the entrainment of these particles into the foam layer.

7.6.2.3 Silicone Derivatives

Silicone derivatives have hydrophobic and hydrophilic molecular components as well. They act as collectors similar to the Calcium soap [21]. Silicone derivatives are based on polysiloxane with special functional groups to generate the ink collection ability. At comparable overall flotation losses and brightness gain, ash removal can be higher with silicone derivatives compared to fatty acid soap [22].

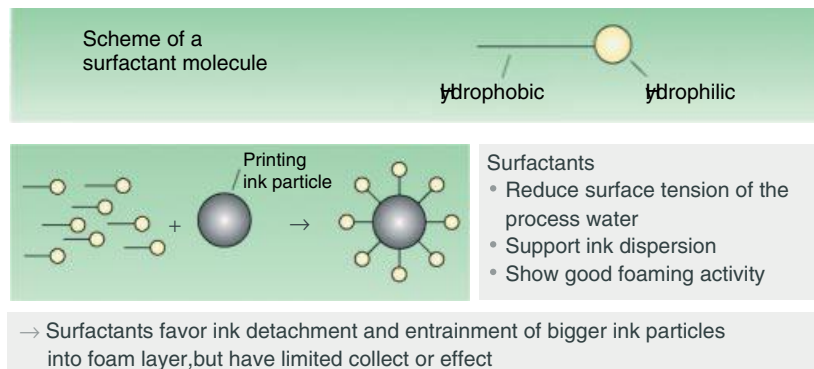


Figure 7.91 The mechanism and characteristics of synthetic surfactants.

7.6.3

Equipment and Systems**7.6.3.1 Flotation Cells**

In the past a large variety of flotation cell designs were used. The cell body can be of open design, but nowadays the cells are usually closed for environmental reasons. The closed cells can be pressurized or operated under a slight vacuum to avoid exhausts. One flotation line usually consists of several flotation steps where the accept stream of the preceding step is the inlet flow of the following one. There is repeated aeration of the suspension in the individual steps. The arrangement of these steps can be different: individual cells for each flotation step connected by pipes to a complete line, individual cell compartments that are aligned in horizontal or vertical direction in one overall cell body, and column-like cells with internal recirculation. A special case is a vertical cyclone-shaped cell where the ascent of the bubbles is mainly due to the centrifugal forces and is directed to the center.

Figures 7.92–7.95 show schematics or photographs of five of the numerous cell designs, each of them working after a different principle. They also differ in the arrangements of the individual flotation steps. Figure 7.92 shows an impeller cell. An air-dispersion rotor is used for aeration and mixing of air and suspension. Several units are arranged in line. In Figure 7.93 a closed, rectangular cell is shown. The bubbles are provided by a half moon air pipe and are dissipated by a turbine rotor. The suspension is recirculated and re-aerated several times. The foam is removed over a weir using a scraper. The circular cell in Figure 7.94 is closed and pressurized. It is divided into three to five superimposed elementary cells. The suspension flows from top to bottom and is aerated after each elementary cell before being fed to the next lower one. Aeration is achieved by static mixers with self-aspiration. The bubbles injected in each elementary cell ascend through the upper cells to the foam layer at the top. The foam is removed through pipes by overpressure against the ambient pressure. The Comer Cybercell is another tower-type cell with static mixers. Bubble distribution is improved by a mechanical agitator. The suspension flows top down against the direction of the ascending

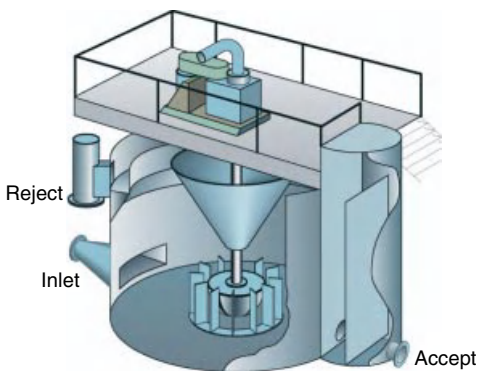


Figure 7.92 Example of an impeller flotation cell. (Source: Ahlström.)

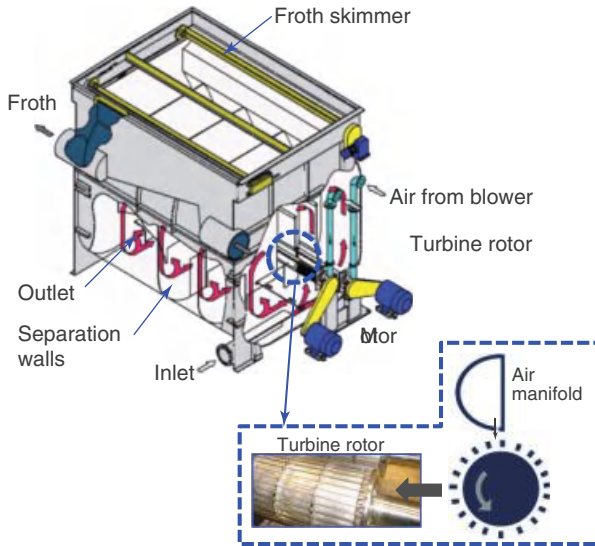


Figure 7.93 Example of a flotation cell with a dynamic mixer. (Source: Voith IHI.)

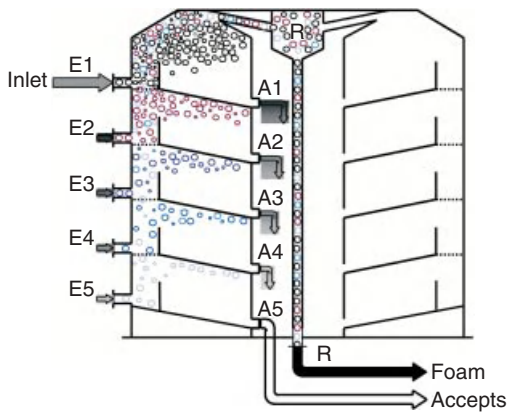


Figure 7.94 Example of a flotation cell with the cells arranged vertically. (Source: KADANT Inc.)

bubbles. Part of the suspension is aerated again and lead back to the lower and middle part of the cell. The foam is paddled off over a weir at the top.

The cell type in Figures 7.95 and 7.96 consists of an elliptical tube that contains individual cells arranged in line. In each cell the suspension is aerated by a self-aspirating static mixer working on the step diffuser principle. The foam flows over a weir and is collected in a common channel. Overflow is controlled by a combined control of both the suspension level in the cell chamber and the level in the foam channel. The flotation cell in Figure 7.97 is of cyclone type. A static mixer

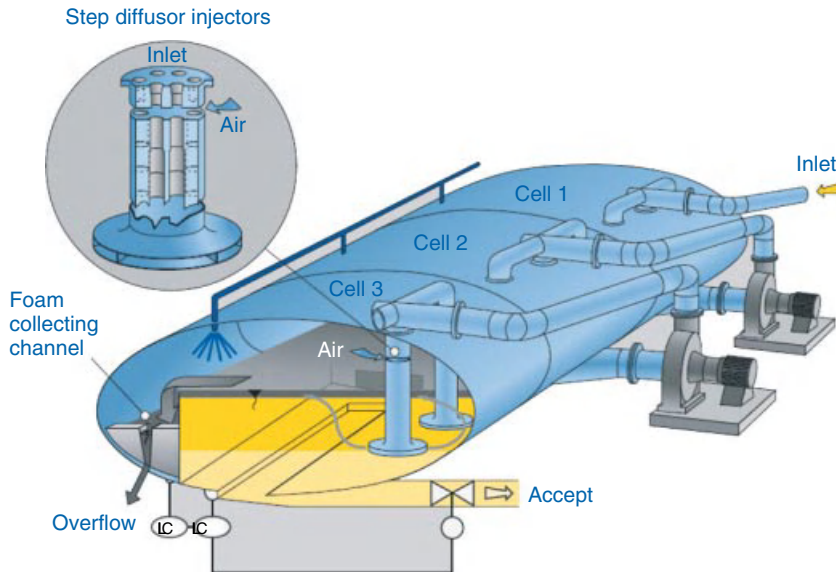


Figure 7.95 Schematic of a flotation cell with horizontally arranged cells. (Source: Voith.)



Figure 7.96 Photo of a flotation cell with horizontally arranged cells. (Source: Voith.)

arrangement supplies air by natural aspiration to the cell. Owing to the centrifugal force the air bubbles flow to the cell center. The foam is removed at the top.

Other cells still found in the industry in some installations are the Beloit PDM 2 flotation cell (horizontal tube with static mixer) and the Kvaerner flotation column (vertical tower).

Recent developments in flotation focused on the reduction of the specific energy input, and improving the selectivity of the flotation process and operational stability. Lowering specific energy consumption requires optimized fluid dynamics as well as aeration elements and process pumps with good energy efficiency [23]. Selectivity is improved by running the flotation at higher ink concentrations. This is done by recirculating at least part of the overflow. Corresponding flotation systems can be selected from a variety of different flotation circuits possible. The process stability

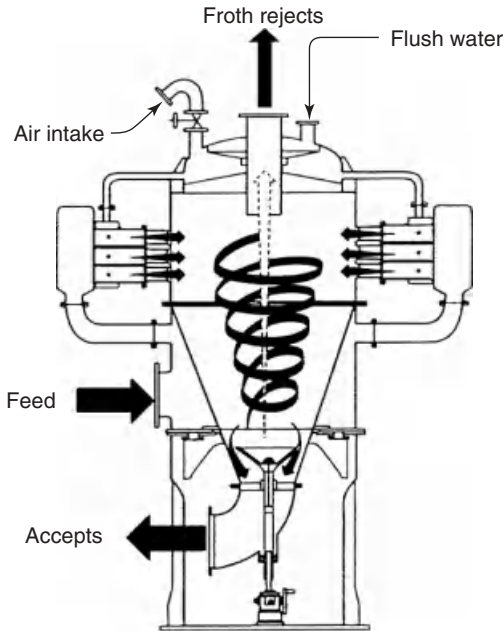


Figure 7.97 Example of a flotation cell working as a cyclone. (Source: Shinhama.)

improves by suitable control of the flotation overflow, and by reliable mechanical foam deaeration.

7.6.3.2 Flotation Systems and Flotation Selectivity

The foam from the flotation line contains – besides the particles to be removed – some fiber material, mainly short fibers and fines as well as fillers. Selectivity improves if this loss in valuable raw material is minimized. On the other hand, reducing the amount of reject foam is limited as this negatively influences brightness and cleanliness.

Figure 7.98 shows different flotation system configurations. The resulting selectivity can be seen from Figure 7.99. Here, accept brightness is plotted against total solids loss. A simple flotation system is the arrangement of several cells one after the other in a single stage. At a given brightness target the losses are highest here because the total overflow is rejected without any posttreatment. In a single-stage system with partial foam recycling the foam of the last few cells is fed back to the flotation inlet and only the foam of the first cell is rejected. By this kind of foam recirculation selectivity improves because the collision probability of the ink particles with the air bubbles increases as a result of higher ink concentration. The two-stage flotation system is state of the art since many years. The overflow of the primary stage is floated again in a secondary stage. This is to recover valuable materials such as fibers, fines, and some fillers from the primary overflow in order

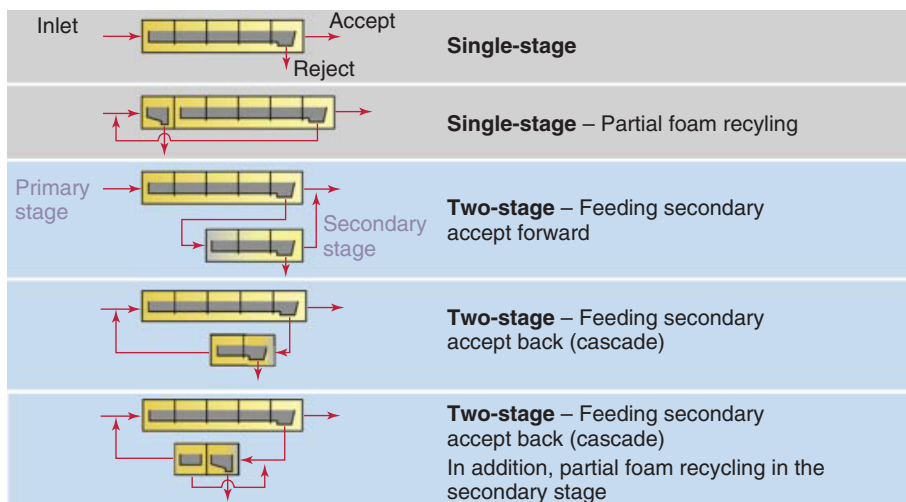


Figure 7.98 Single- and two-stage flotation systems.

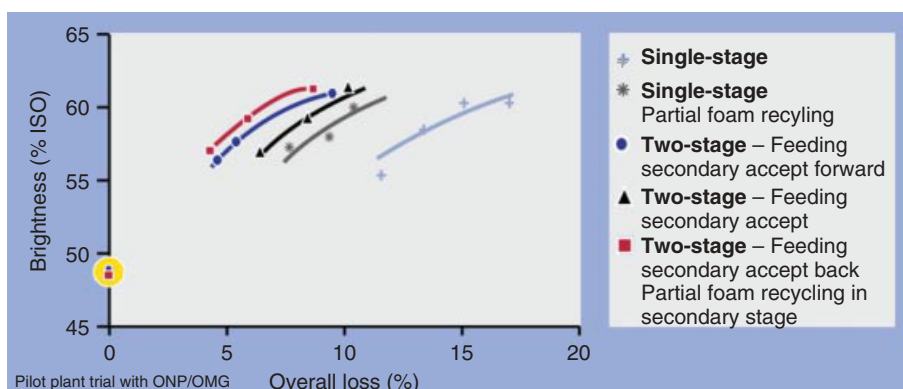


Figure 7.99 Brightness as a function of total solid losses with single- and two-stage flotation systems.

to make the flotation process more economic. Regarding selectivity feeding back the secondary accept to the inlet of the primary stage is superior compared to the feed-forward mode. Highest selectivity can be achieved if the two-stage system is additionally equipped with partial foam recirculation.

7.6.3.3 Foam Handling

The reject of the primary cells contains large quantities of air. Deaeration of the reject is necessary to ensure stable operation of the secondary cells. This can be done, for example, in a deaeration cyclone mounted on a foam tank (Figure 7.100). Alternatively, a foam pump deaerating and pumping the foam at the same time is used (Figure 7.101). In this case foam tanks for further deaeration are not required.

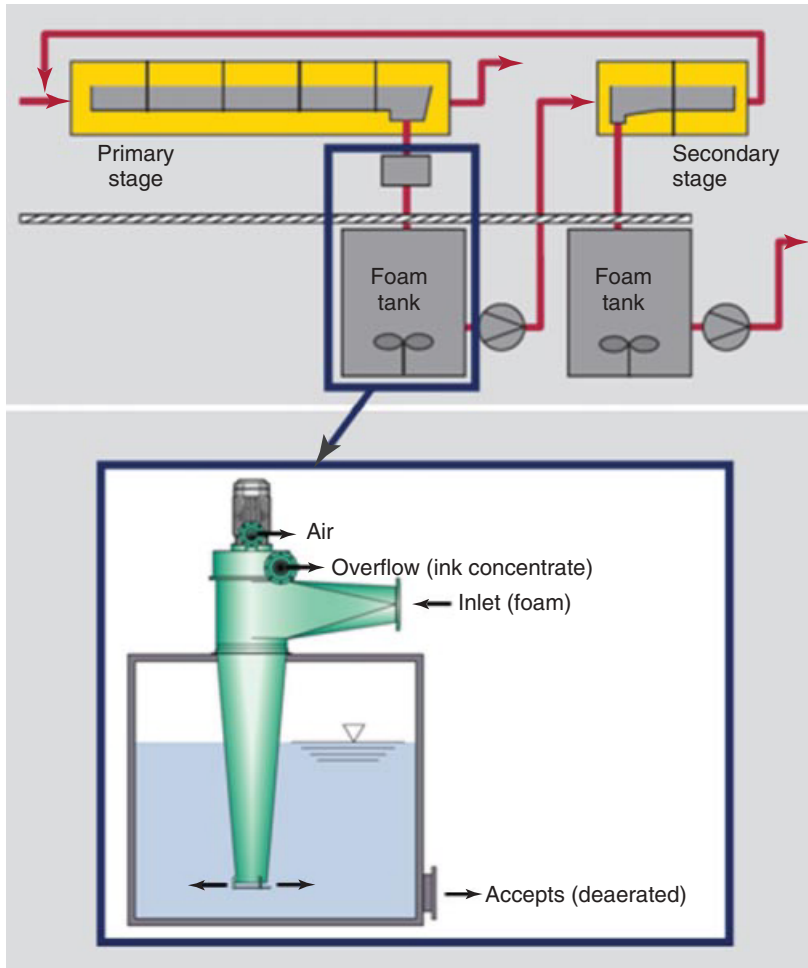


Figure 7.100 Flotation line with secondary stage and deaeration cyclone for primary overflow.

7.6.4

Operating Conditions and Technological Results

7.6.4.1 Operating Conditions

The capacity of a flotation line today ranges from 50 to 1200 tons per day. Depending on the recovered paper mixture and on the product demands, up to three flotation lines may be installed in different process loops of a stock preparation system.

Typically, flotation lines operate at stock consistencies of 0.8–1.5% and temperatures of 40–70 °C, neutral to slightly caustic suspension conditions (pH 7–9) and water hardness above 5–10 dH.

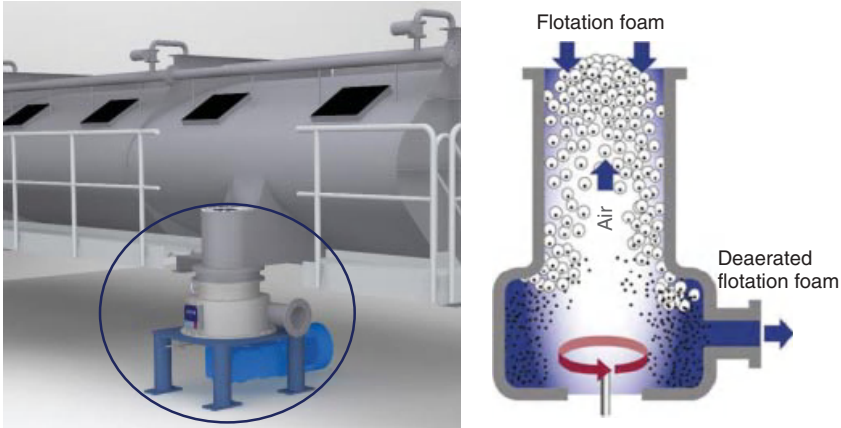


Figure 7.101 Deaeration foam pump. (Source: Voith.)

Energy is consumed for pumping the suspension within the flotation line and for foam deaeration and in certain cases for air compression. The specific energy consumption is between 13 and 30 kW per ton.

7.6.4.2 General Technological Results

7.6.4.2.1 Brightness Brightness increases during flotation in a nonlinear way. The increase in brightness in the following cell is less than that in the cell before as the amount of dark particles in the suspension, which are not yet removed, decreases from cell to cell. This is shown in Figure 7.102 where the brightness development is plotted against the number of cells for a mixture of old newspapers and magazines.

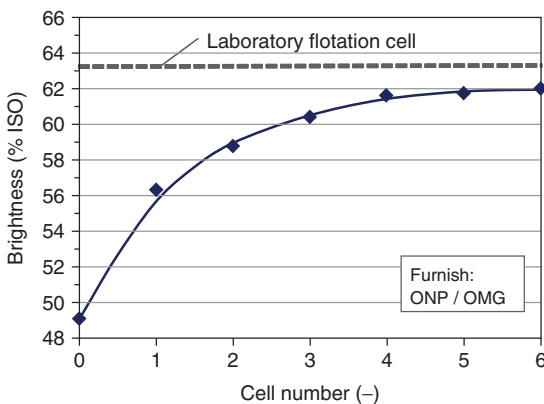


Figure 7.102 Brightness development versus number of cells for a mixture of old newspapers and magazines.

Laboratory flotation tests are often used to predict the upper limit of brightness gain or dirt specks reduction. In Figure 7.102 the corresponding brightness limit is included. Figure 7.103 shows an example of a laboratory flotation cell commonly used in the paper industry. In Figure 7.104 brightness is plotted over flotation time in a laboratory cell. The maximum brightness potential of the stock was reached after 12 min. When a suspension with high ratio of mechanical pulp and high amount of fillers undergoes flotation for a very long time the brightness may



Figure 7.103 Example of a laboratory flotation cell.

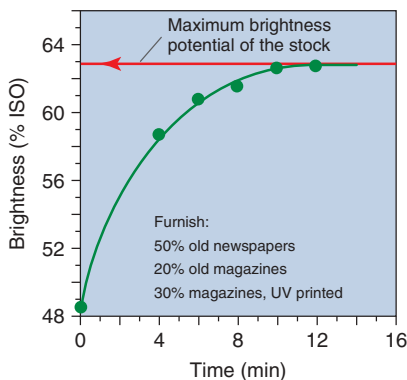


Figure 7.104 Brightness development versus flotation time in a laboratory cell for a mixture of old newspapers and magazines.

even decrease for a certain time and then increase again. At the beginning, the removal of a large amount of ink particles strongly increases brightness. Later on the removable dark dirt particles become less, but a certain amount of bright fillers and pigments is removed, so brightness may decrease. At the end lower brightness mechanical pulp fines are removed, which results in increasing brightness again.

There are various laboratory flotation cells on the market differing in many aspects. So standardizing laboratory flotation tests is difficult. In general the operation parameter of laboratory cell should be chosen in such a way that the laboratory test is technologically equivalent to the full-scale flotation system.

7.6.4.2.2 Dirt Specks In Figure 7.105 dirt speck reduction is plotted against the number of cells for a mixture of old newspapers and magazines. The curve is similar to that of brightness gain. The size of dirt specks has a strong influence on the flotation result. Figure 7.106 shows for different raw materials how the

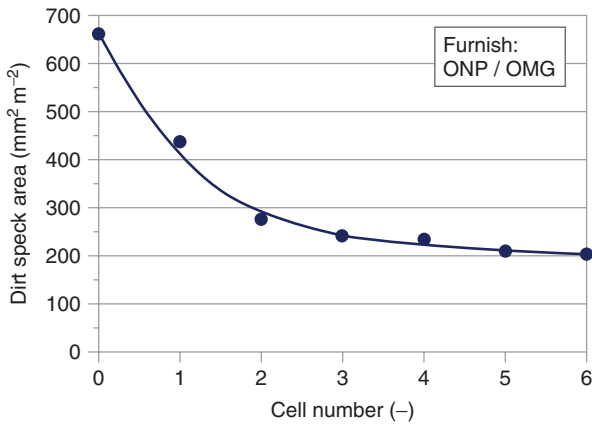


Figure 7.105 Dirt speck reduction versus number of cells for a mixture of old newspapers and magazines.

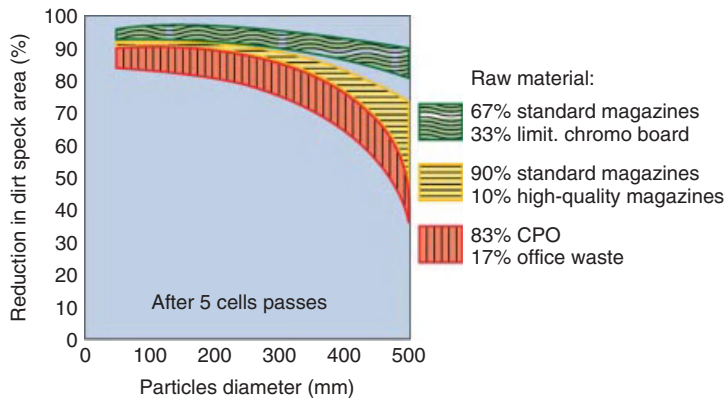


Figure 7.106 Efficiency of dirt speck reduction versus particle diameter.

efficiency of dirt speck reduction depends on particle diameter. Between 5 and 350 μm particle diameter the efficiency is high, clearly decreasing for larger sizes. The curve ends at 50 μm as is the usual limit of lab tests (40–50 μm can be seen with naked eye).

7.7

Nonselective Flotation (Dissolved Air Flotation DAF)

7.7.1

Overview and Theoretical Aspects

7.7.1.1 Objectives

Nonselective flotation is used for process water clarification in water loops. The objective is to dispose of all the undesired water components that cannot be removed by mechanical separation, such as anionic trash, fines, or microstickies. These components would negatively affect the efficiency of the production process and/or the product quality. Nonselective flotation works as kidneys in the loops allowing the reduction of fresh water consumption at low freights of these materials. The clarified water may also be used for spray nozzle operation, which requires certain cleanliness. Furthermore, DAF is also used for wastewater clarification (see Chapter 9).

As nonselective flotation is based on bubbles generated by depressurizing air-saturated water this unit process is called *dissolved air flotation*.

7.7.1.2 Principle Solution

The different steps involved in nonselective flotation are as follows:

- **Generating flocs:** Flocculants (cationic polymers) are added and mixed with the water to be clarified. As a result the fine particles agglomerate to flocs [24]. In addition coagulants can be added before dosing the flocculant to transfer colloidal material (“anionic trash”) into microflocs in order to make it accessible to flocculants. The solid content of the suspension in the inlet is in the range of 0.01 and 0.5%.
- **Bubble generation:** First a side stream of the untreated water (sometimes also clarified water) is air saturated in a tank at about 6 bar. All remaining nondissolved air is removed as these larger bubbles would negatively affect the further process. By depressurizing the water small air bubbles finely distributed in the water are generated (Figure 7.107). The bubble size depends on the pressure before throttling, the saturation degree, and on the nozzle type.
- **Flotation:** The side stream of the aerated water is mixed with the main stream of unclarified water and fed into a flotation tank. The fine air bubbles (about 50–200 μm) generated by depressurizing adhere to the flocs and rise to the surface where they form a stable layer of sludge. For good flotation results flow turbulences in the tank have to be kept to a minimum.

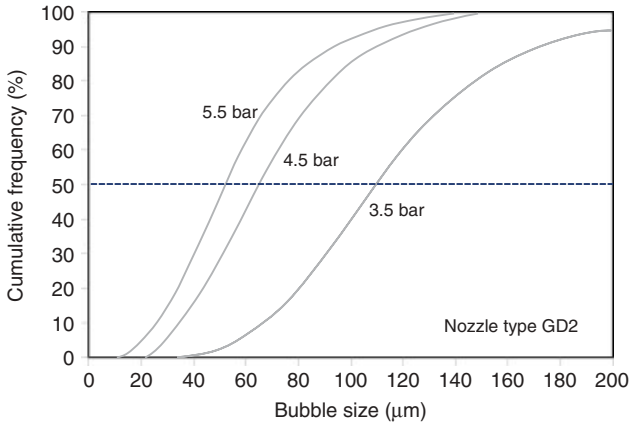


Figure 7.107 Cumulative frequency of the diameter of air bubbles after depressurizing a system of water with dissolved air from different pressure levels to ambient pressure (modified after Ref. [25].)

- **Sludge removal, clarified water outlet:** The formed stable sludge is removed from the water surface by paddles or screws or just by overflow and discharged. The clarified water exits from the bottom of the tank.

7.7.1.3 Solubility of Air in Water

The amount of a gaseous component i , which can be dissolved in water, follows the Henry law and is proportional to the partial pressure p_i of this gas component above the water level:

$$c_i = k_{H,i} \times p_i$$

where c_i is the volumetric concentration of the gas i in the water and $k_{H,i}$ is the Henry law constant of this gas component in water. $k_{H,i}$ is a function of the water temperature. In the atmospheric air the main components are nitrogen N_2 and oxygen O_2 . Depending on the temperature, k_{H,O_2} is about twice k_{H,N_2} . On the other hand, the partial pressure of nitrogen in the air is about four times higher than that of oxygen. So the concentration ratio between nitrogen to oxygen changes from 4 : 1 in air to about 2 : 1 when dissolving the gases in water. The concentrations of the individual gas components can be superposed linearly. For air the solubility in water is illustrated in Figure 7.108. It decreases with raising temperature. At 15 °C and 6 bar about 125 l air can be dissolved in 1 m³ water. After expansion to 1 bar about 105 l air will become free and usable for DAF. Dissolved substances in the water can reduce the solubility.

7.7.2

Equipment

In Figure 7.109 the system for nonselective flotation is shown with the tank for aeration of the suspension under pressure and the piping leading to the flotation tank. The clarification tank is the largest equipment in DAF. It can be circular,

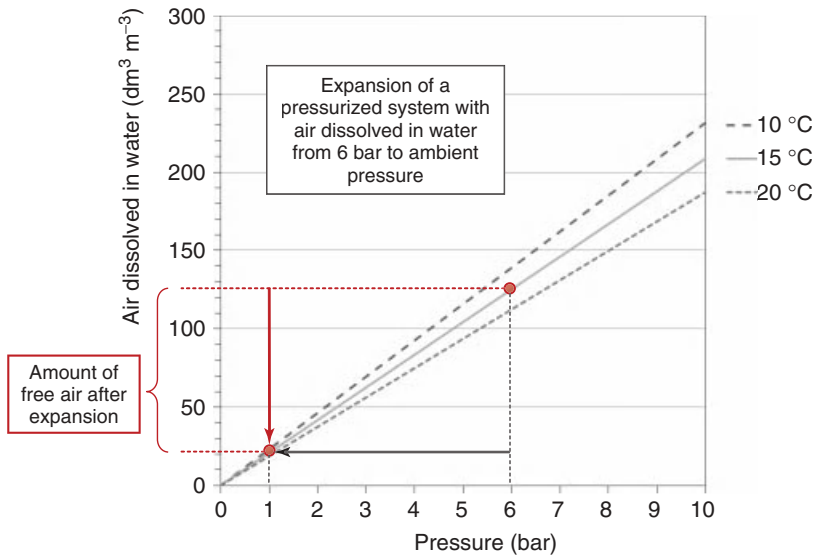


Figure 7.108 Solubility of air in water.

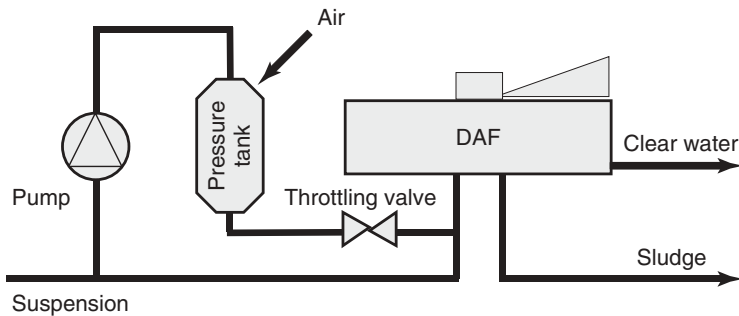


Figure 7.109 System for nonselective flotation (DAF).

rectangular, with or without built-in elements for flow guiding, and made of metal or concrete. The design depends, for example, on the requirements placed on the quality of the clarified water, the position in the process, and the quantity of water to be clarified. Figures 7.110 and 7.111 show a schematic and a photo of a circular tank for DAF. They show the central feed of the mixed streams of aerated and unclarified water, the sludge removal by a paddle, the discharge to the tank center by a feeding screw, and the extraction of the clarified water near the bottom at the periphery. The tanks can have diameters of up to 25 m and throughputs of up to $2500 \text{ m}^3 \text{ h}^{-1}$.

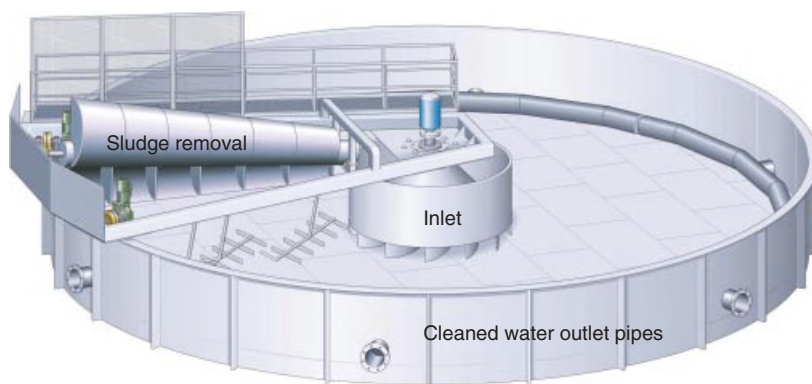


Figure 7.110 Schematic of a circular tank for dissolved air flotation (DAF).



Figure 7.111 Photo of a tank for dissolved air flotation (DAF).

7.7.3

Technological Aspects

7.7.3.1 Cleanliness

For good clarifying results the particle sizes should be in the range of 1–100 μm . Smaller particles such as colloidal substances have to be agglomerated, and the larger ones should be removed before; significant larger particles resulting from flocculation can also be removed in DAF. During DAF the chemical, physical, and process parameters have to interplay correctly. Dual dosing can minimize costs at high cleaning effect (Section 6.11). Typically, the removal of the solid particles lies between about 85 and 98%. The kind of use of the clarified water defines the required cleanliness. On the other hand, cleanliness should only be as high as necessary and for economic reasons not be overdone. Cleanliness of the clarified water is in the range of 50–200 ppm and depends on the application, the furnish, and the final paper quality to be produced. Typical applications lying in this cleanliness range are the clarification of

- back water in the stock preparation loops to allow to further close the water circuits
- wastewater

- washer filtrates (see Section 7.10)
- process water to be used as spray water for the showers in the wire and press section.

7.7.3.2 Sludge Handling

The dryness of the DAF sludge is between 1 and 6% depending on the system. Usually, sludge is today a well accepted source of energy. For best thermal efficiency the sludge has to be dewatered in one or two steps before it is used in incineration (Chapter 8).

7.8

Fractionation

7.8.1

Objectives and Principle Solutions

The objective of fractionation is to separate certain fractions of fibers from each other, differing in their morphological characteristics. Special demands put on fractionation can be

- to obtain an LF fraction in the reject stream with the lowest possible short fiber (SF) content
- to get a high SF content in the accept stream with the lowest possible LF content
- to separate flexible, thin and thin-walled fibers from stiff, thick, and thick-walled fibers for example, early wood from late wood fibers
- to obtain an R14-reduced fraction in the accept stream.

Recovered paper is mostly a mixture of different kinds of fibers. Here, fractionation offers advantages such as the following:

- Separate refining of the LF fraction gives energy savings and better influence on specific stock properties.
- The separated fraction streams (accept and reject) can be used for the different plies in multi-ply paper and board production. The thin-walled fibers are used in the outer layers to provide a smooth surface for good printing characteristics. The thicker, stiff fibers are advantageous for the middle layer as they provide bulk and thus higher bending stiffness.
- The increasingly competitive situation in biomass application fractionation may be helpful when separating fibers of high value for paper making from others usable for energy generation.

7.8.2

Basics

Basic principles used for fractionation are screening and centrifugal field application. To separate thin-walled early wood fibers from coarse- and thick-walled late

wood fibers hydrocyclones or other sedimentation equipment can be used. The separation principle makes use of the varying sink velocities of these fibers in the centrifugal field when apparent density and fiber shape differ [26].

By far more common is fractionation according to fiber length and stiffness. In this case, separation is mostly done in screens. In [27] it is explained why screens are specifically suited for fiber length fractionation. The long fibers are hindered from passing the screen openings owing to several effects such as the influence of the fluid velocity field in the boundary layer, the inertia of the fibers, and the kind of fiber impact at the downstream edges of the openings. Figure 7.112 shows that the passage ratio through the screen opening decreases significantly when the fiber length increases [28]. Fiber stiffness has also an influence on fractionation result. So a certain differentiation between CTMP and Kraft pulp can be seen.

The general separation theory as described in Section 7.1 can be analogically applied to fractionation. Here, the separation ratio is expressed as the mass flow rate of, for instance, the long fibers in the long fiber fraction related to the total mass flow rate of the inlet. The fractionation coefficient of the long fibers Q_{LF} is a characteristic figure:

$$Q_{LF} = 1 - c_{LF,A}/c_{LF,R}$$

$c_{LF,A}$ and $c_{LF,R}$ are the long fiber concentrations in the accept and the reject, respectively. Separation ratio S is

$$S = \frac{RRM}{(1 - Q_{LF} + Q_{LF} \times RRM)}$$

with RRM being the reject mass flow rate.

$Q_{LF} = 0$ corresponds to the diagonal line in Figure 7.113 and means that the feed is just split into accept and reject without any enrichment of the long fibers

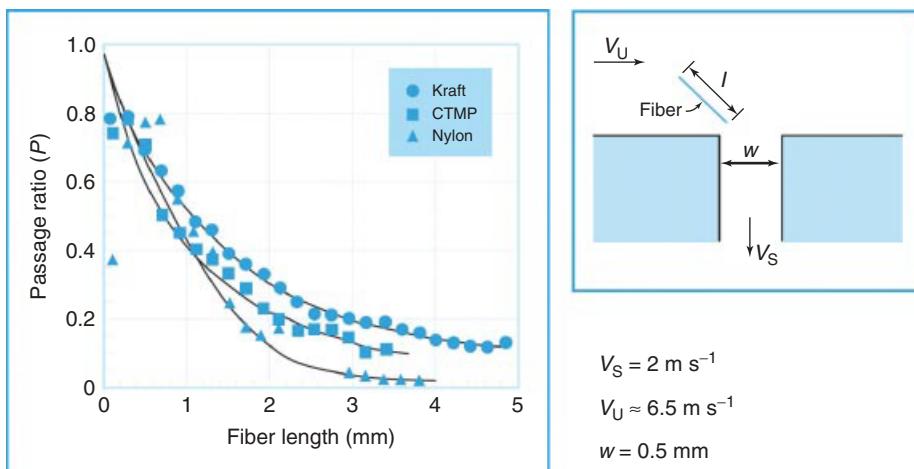


Figure 7.112 Effect of fiber length on passage ratio through slots for a range of fiber types [28].

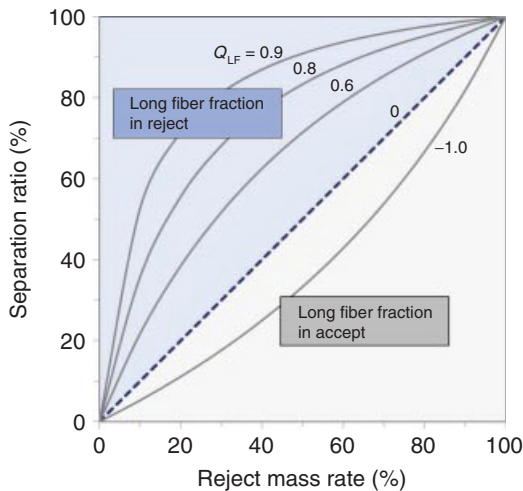


Figure 7.113 Illustration of separation characteristics in fractionation.

neither in the reject nor in the accept. $Q_{LF} > 0$ describes the situation when the long fibers are enriched in the reject. For good fractionation, the Q_{LF} curve in the reject field should be as far as possible from the diagonal (high enrichment factor of LF). Maximum theoretical enrichment in the reject is reached at $Q_{LF} = 1$. In this case no long fiber would be in the accept anymore.

Hence, fractionation aims to separate fiber classes of different morphology from each other, for example, LFs and SFs. In contrast to that, in screening only the debris should be shifted to the reject and, in principle, fiber fractions in the accept and the feed should be the same.

7.8.3

Machinery

The screens for fractionation are both flat and cylindrical screens as used for screening. But there are some differences with respect to operating conditions and machine parts. Figure 7.114 shows an example of a cylindrical screen fractionator.

Machinery parameters that improve the fractionating effect are, for example, smaller openings (holes or slots), lower or zero profile angles of slotted screens, or an even more special profile. For flat screens the hole diameters are 1.5–2.5 mm. For cylindrical screens hole diameters are 1–2 mm and the basket has a smooth surface. Slotted baskets have a slot width of 0.15–0.2 mm, the profiles show a low or zero angle.

Sometimes, specially designed cleaners are also used for improved overall fractionation effect in addition to screening. The cleaners are of special design.

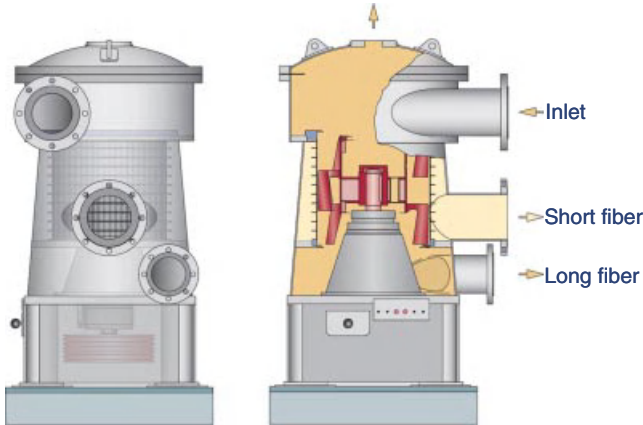


Figure 7.114 Screen-type fractionation machine. (Source: Voith.)

7.8.4

Operational and Technological Remarks

The mass flow split in screening is about 5–25%, whereas in fractionation it is distinctly higher with 30–60%, depending on the production requirements. Higher consistency and lower through-velocity of the suspension through the screen openings improve the fractionation effect.

With fractionation in screens the main debris flow goes with the stream enriched with long fibers. So this stream has to undergo a separate screening step for removing the debris from the fibers.

The fiber length distribution is often analyzed in laboratory with the Bauer McNett classifier [29] and Chapter 29. This consists of a series of chambers each with a progressively smaller screen mesh. The standard set of screens ranges from 14 (16) to 200 mesh. The fiber fractions R16 and R30 retained on the corresponding meshes contain the longer fibers. Figure 7.115 shows for these fiber classes the fractionation results from a cylindrical screen with a hole screen basket [30]. The concentration of the R16 class is 2.6 times higher in the reject than that in the accept. With the R30 class this factor drops down to 1.2 and accordingly a higher amount of the R50 fraction is found in the accept than that found in the reject. This shows that separation of long and short fibers is far from being complete, many long fibers are found in the short fiber fraction and vice versa, only a certain enrichment of long fibers in the reject or short fibers in the accept is possible.

Using cleaners for fractionation stock consistency may not exceed 0.5–0.6% in order to make benefit of the different sinking behavior of the various fiber types or of fiber and fiber bundles [12, 26, 31]. Figure 7.116 shows the effect of a two-stage cleaner system on the fractionation of mechanical pulp fibers [32]. The fractionation effect is discernable from the photos but again by far not complete; hence, more development work has to be done in the future.

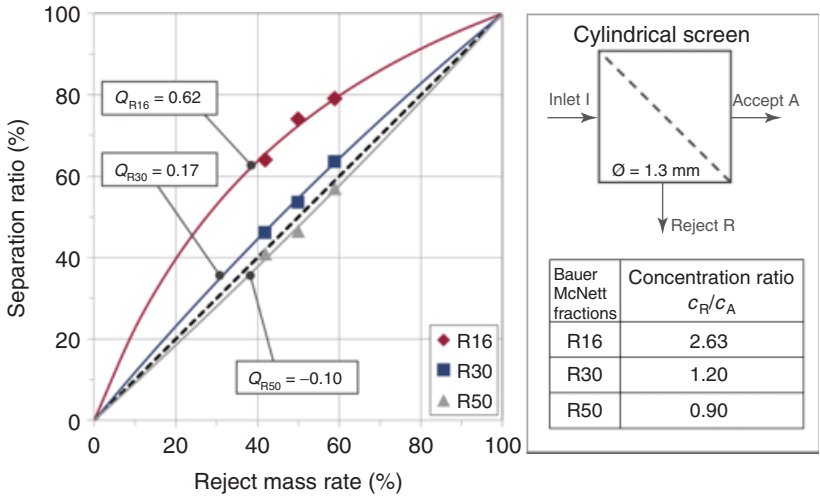


Figure 7.115 Hole screen fractionation characteristics of different Bauer McNett fiber fractions from a mixture of recovered paper of 1.02 and 1.04 according to EN [30].

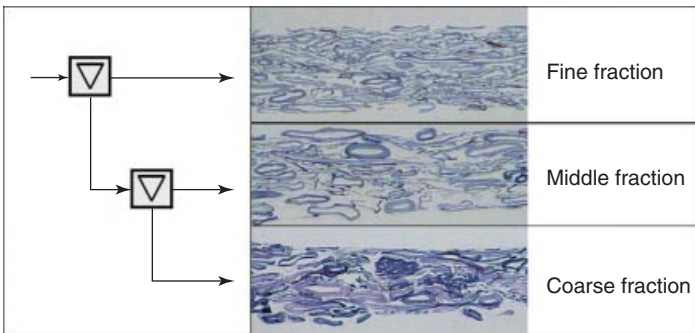


Figure 7.116 Effect of a two-stage cleaner system on the fractionation of mechanical pulp fibers [32].

7.9

Dewatering

7.9.1

Overview and Theoretical Aspects

7.9.1.1 Objectives

The objective of dewatering a fiber suspension in stock preparation is to separate the solids in the suspension from water and dissolved ingredients. Reasons for dewatering the suspension are technological and economic. They are mainly

- to separate the water loops with regard to chemical and contaminant load as well as temperature

- to adjust stock consistency to a defined level required by specific unit operations such as dispersing or bleaching
- to recover fibers from the white or wastewater
- to increase consistency to the highest possible level when making wet laps or at discharge of the rejects.

7.9.1.2 Basics and Principle Solutions

Dewatering is a filtration process where a suspension stream of consistency c_I is divided by a filter into a thickened part with a consistency of c_T and a filtrate stream of consistency c_F (Figure 7.117). At the start of filtering, retention of the solids on the filter is low. With time, the mat thickness increases and so does retention, which means that the solid content in the filtrate decreases (Figure 7.118). An extra layer of LFs applied to the filter at the beginning of filtration helps to increase retention. Dewatering usually aims for zero consistency in the filtrate, which in practice is not reached as retention is never 100%. In contrast, washing takes advantage of this effect for solid/solid separation.

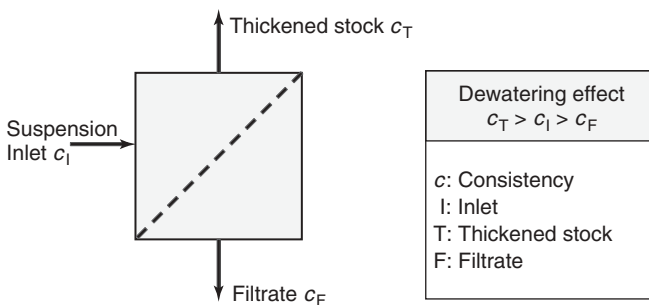


Figure 7.117 Basic model of filtration.

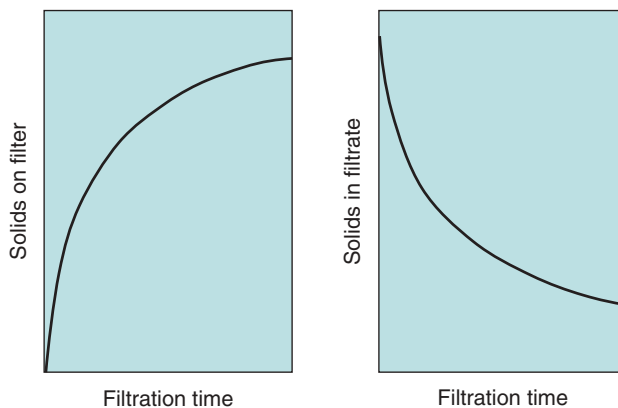


Figure 7.118 Increase in retention over filtration time.



Figure 7.119 Curved screen as an example of a static filter. (Source: Andritz.)

Various types of machines are used for dewatering in stock preparation: drum filters, belt filters, twin-wire presses, disk filters, and screw presses, as well as static filters such as inclined and curved screens (Figure 7.119). They can differ in several aspects such as

- the driving forces for dewatering, for example, gravity, vacuum, wire tension over a curved surface, and mechanical pressing in a nip
- the maximum admissible inlet consistencies (from 0.5 up to 12% for fiber suspensions or even more in the case of sludge applications) or the kind of stock impurities of the entering suspension for ensuring safe operation
- the obtained outlet consistencies of a minimum of 3% up to more than 30%
- the filtrate consistency which may vary between parts per million and percentage numbers.

Machinery selection is done according to technological and economical requirements.

7.9.2

Machinery

7.9.2.1 Drum Thickeners

Drum thickeners (or slushers/deckers) comprise an open roll covered with a filter wire, rotating in a vat filled with suspension (Figure 7.120). The feed consistency may vary between about 0.5 and 2.5%. A slusher is used when the required discharge consistency is not more than about 3–4%. For higher outlet consistencies of about 5–6%, a decker, which comprises an additional roll to press and further dewater

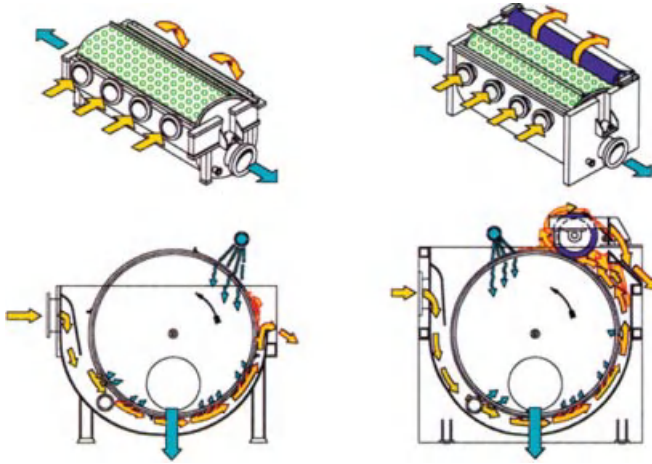


Figure 7.120 Drum thickeners. (Source: Voith.)

the filter mat before discharge, is used. As the cylinder rotates a mat is built up on the outside of the filter drum. Here, dewatering is governed by the differential head between the suspension level in the vat and the filtrate level inside the drum. In the case of a slusher the thickened stock overflows into a chute and in the case of a decker the mat is removed from the couch roll by a doctor blade. The filtrate in the drum is extracted from the inside through a hollow shaft. A special variant of a drum thickener is shown in Figure 7.121. The drum is in cylindrical folded design in order to increase the drum surface and thus dewatering capacity.

7.9.2.2 Belt Filters, Twin-Wire Presses

Here, in principle, the suspension is fed onto a horizontal moving wire and dewatered by gravity or additionally by a vacuum placed under the wire. Dewatering capacity can be further increased by a second wire covering the suspension and the bottom wire. By guiding this sandwich over roll(s) of different diameter(s) D under a tension S of the outer wire a dewatering pressure p is exerted: $p = 2 S/D$. The highest dry content of the thickened stock is obtained when additional dewatering is done in one or several press nips. Twin-wire presses (Figure 7.122) obtain high consistencies of about 25–50% and make use of all of the three principles described above.

7.9.2.3 Disk Thickener

The filtering elements in disk thickeners are hollow disks covered on both sides with wires. Numerous disks are mounted closely and equally spaced on a hollow shaft. The length of the machine is up to about 10 m with about 2.5–4 m disk diameter. The filter disks are immersed about halfway in the suspension in a trough. The driving force for dewatering is the head differential between the suspension height in the trough and the filtrate level that can be adjusted. As the filter disks rotate (at 5–20 m min^{-1} at the circumference) a fiber mat builds up,



Figure 7.121 Photo of a drum thickener with a cylinder in folded design. (Source: Voith.)

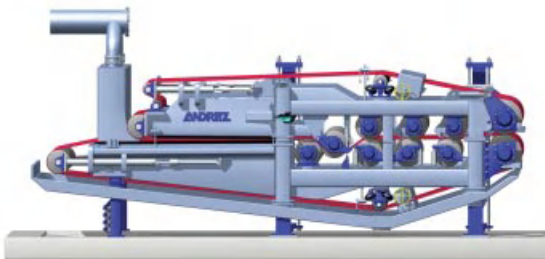


Figure 7.122 Twin-wire press. (Source: Andritz.)

which continuously falls back to the trough owing to gravity and flow forces. Thus the trough consistency increases and the thickened suspension exits over a weir. The filtrate is removed through the hollow shaft. Its consistency is high as the fiber mat is continuously removed resulting in low retention. Figure 7.123 gives a view on a partly opened disk thickener.

7.9.2.4 Disk Filters

Compared to disk thickeners disk filters additionally apply vacuum to further increase the consistency, production, and retention. They are used for white water

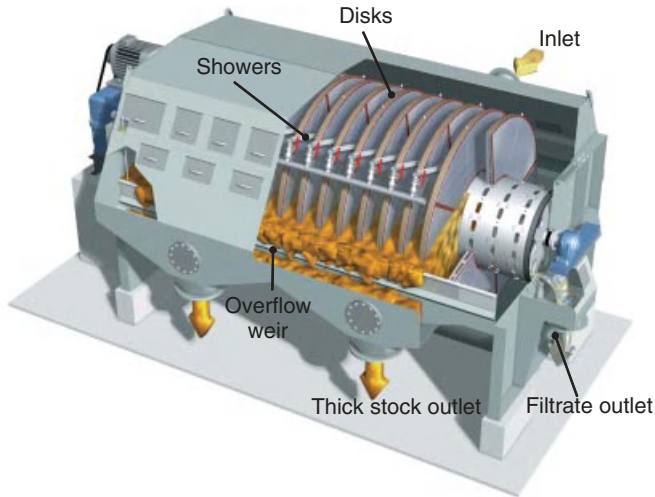


Figure 7.123 View of a partly opened disk thickener. (Source: Andritz.)

cleaning in the paper machine water circuit (save-all) and for dewatering of pulp suspensions in pulping. The length of the machine is up to about 17 m with approximately 3–6 m disk diameter. Typical consistencies are between 0.4 and 1.5% at the inlet and depending on the technical principle even higher and up to 8–18% at discharge. The filter disks are similar in design to those in disk thickeners. A filter mat builds up during rotation at the filter disk surface supported by the vacuum generated by a “barometric leg” governed by the differential head of filtrate level in the filter and the outlet to the ambiance. Owing to the vacuum the mat remains fixed to the filter disks and is further dewatered after having emerged from the suspension (“drying zone”). The thickened stock is removed from the disks in the upper quadrant by knock-off showers and collected in a conveyor via chutes between the disks. The disks are then cleaned by oscillating cleaning showers before the filter area is reimmersed into the suspension, and filtration starts again. In the beginning filtration takes place by gravity and the filtrate consistency is high (cloudy filtrate) due to the thin fiber mat. Consistency decreases with increasing filter mat thickness (clear filtrate) when a vacuum is applied. The filtrate is divided into two streams by separating means in the filtrate zone – the cleaner one, for example, being used for shower water. Sometimes, a third stream (super-clear filtrate) is drawn off. In Figure 7.124 the principle is illustrated. Figure 7.125 shows the view of a partly opened disk filter. The individual disk consists of several segments being mounted on the central shaft with each segment covering a circumferential sector of the disk. Disk sectors with undulated surfaces to increase dewatering area are well established in the market (Figure 7.126). Figure 7.127 shows an installation of disk filters in a mill.

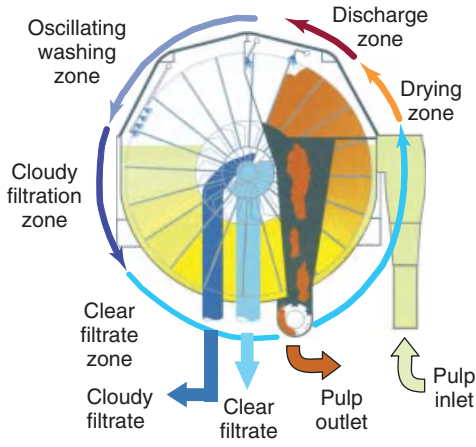


Figure 7.124 Principle of a disk filter. (Source: Voith.)

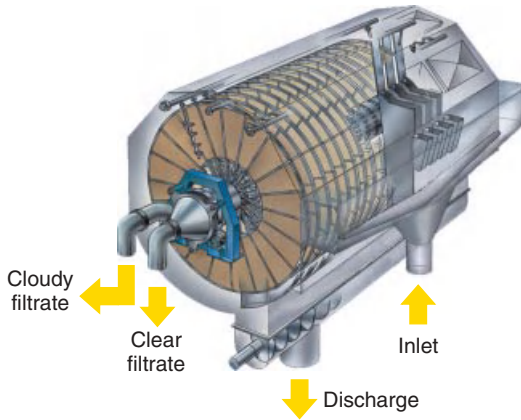


Figure 7.125 View of a partly opened disk filter. (Source: Voith.)



Figure 7.126 Disk sectors with undulated dewatering surface. (Source: Voith.)



Figure 7.127 Mill installation of disk filters. (Source: Andritz.)

7.9.2.5 Screw Presses

Screw presses comprise a housing, perforated (round holes or slots) screens, and a rotating screw (Figure 7.128). The stock is transported by the screw to the outlet, being dewatered en route. The free volume between the screw body and the screen basket, available during the transport, decreases in the axial direction and thus the dewatering pressure increases. Reduction in the free volume can be achieved by decreasing the screw pitch angle and increasing the screw rotor shaft diameter. As the filter mat is continuously removed from the screen cylinder high stock consistency and dewatering capacity are achieved. On the other hand, the filtrate consistency is highest compared to all other dewatering methods. Outlet consistency is a direct function of the applied torque. Automatic torque control regulates the screw speed to keep discharge consistency high and constant (Figure 7.129). Screw presses are also used for dewatering in reject handling systems.

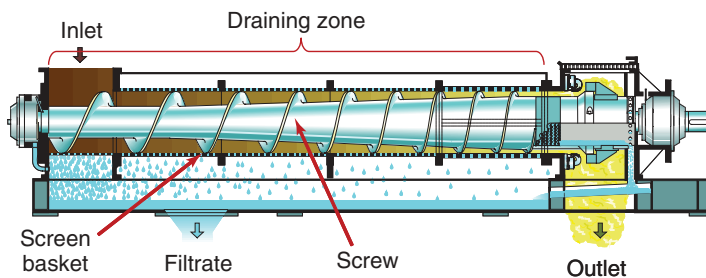


Figure 7.128 Screw press. (Source: Voith.)

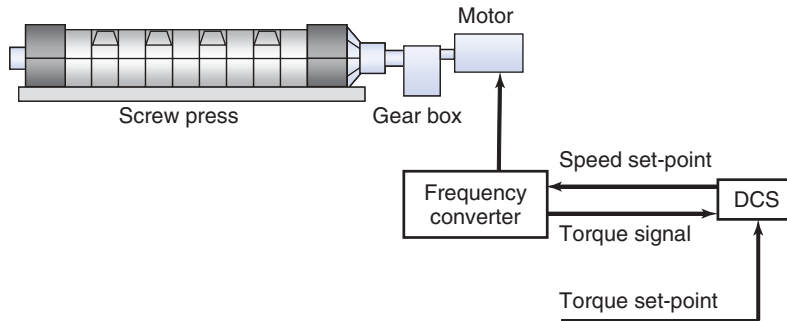


Figure 7.129 Control principle of a screw press. (Source: Voith.)

7.10

Washing

7.10.1

Overview and Theoretical Background

Washing is applied in stock preparation systems for recovered paper processing. Here, the objective of washing is to remove solid and/or dissolved substances that may negatively affect the papermaking process or the finished product quality from the fiber suspension. Dissolved and colloidal contaminants include, for example, organic and inorganic substances contributing to COD and anionic trash. Solid particles comprise fillers, coating and ink particles, microstickies, and fines. Removal of ink particles by washing (wash deinking) has been quite usual in the United States.

Washing is a filtrating–thickening process mostly used to separate solids from solids. To be washed out the particles have to be free of the fibers and smaller than about 30 μm . The smaller the particles, the lower the consistency at the washer inlet, and the higher the outlet consistency of the thickened suspension

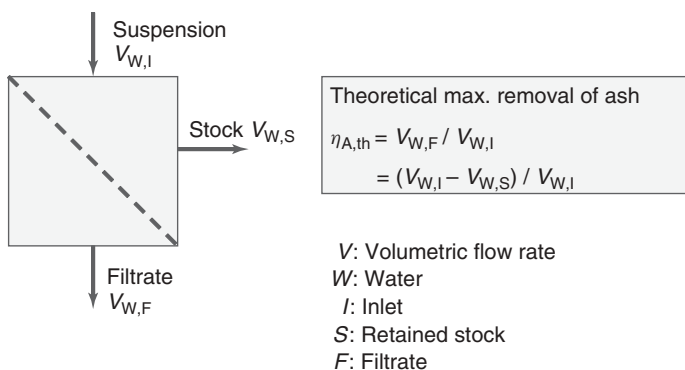


Figure 7.130 Definition of the theoretical maximum washing effect.

mat, the greater is the washing effect. The maximum theoretical washing effect is given by the ratio of filtrate flow/inlet flow, which is shown in Figure 7.130. This theoretical number cannot be obtained in practice as more particles are retained in the fiber mat than would correspond to the above ratio due to a certain filtering effect. Depending on the kind of substances the washing effect also differs for ash (anorganic) and fines (organic). In Figure 7.131 the definition of ash removal and the total solids removal efficiency is given.

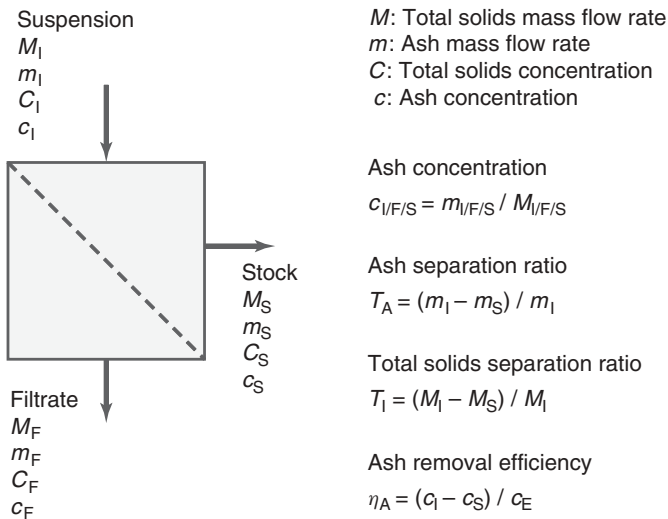


Figure 7.131 Definition of ash removal and total solids removal.

The application of a washing unit and the kind and amount of substances to be washed out depends on the raw material, the other unit processes applied in the stock preparation system, and the finished product requirements. A washing stage in a system requires effective cleaning of the filtrate, usually by nonselective flotation. This in turn means high solid loss from the system. If desired the washing effect and thus the solid loss can be adjusted, for example, by cleaning only part of the filtrate or adjusting the washer itself if possible.

7.10.2

Machinery

The machinery used for washing consists mainly of disk thickeners and high-speed belt filters. Static filters such as inclined and curved screens, spray filters, and pressure-screen-type washers are also found. Disk thickeners are described in Section 7.9. Figure 7.132 illustrates the operating principle of a high-speed belt filter. A headbox distributes the inlet suspension in cross-direction and feeds it into the gap formed by the center roll and the wire. The filtrate is collected and a doctor scrapes off the washed stock from the center roll [33]. These machines operate

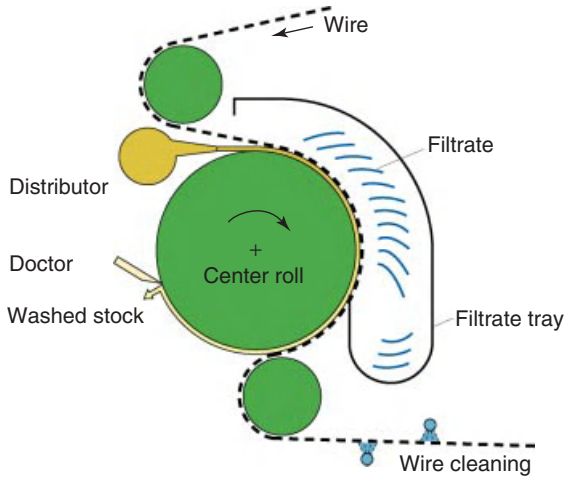


Figure 7.132 Operating principle of a high-speed belt filter. (Source: Voith.)



Figure 7.133 Example of a high-speed belt filter with two center rolls. (Source: Voith.)

at speeds of about $350\text{--}1000\text{ m min}^{-1}$. Inlet consistency is about $0.7\text{--}1.5\%$. The suspension is dewatered under the pressure exerted by the wire tension. The stock leaves the center roll with a consistency of about $5\text{--}10\%$. Examples of a high-speed belt filters are shown in Figures 7.133 and 7.134.

7.10.3

Technological Aspects

The washing effect can be adjusted over a wide range by the fiber mat thickness, that is, by its basis weight. The higher the basis weight the lower the washing

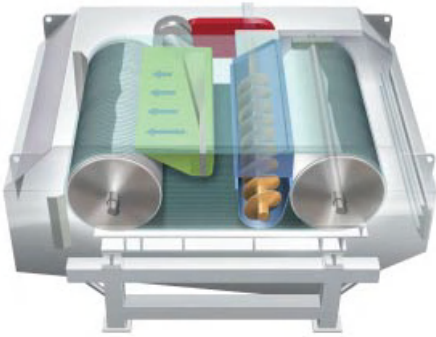


Figure 7.134 Example of a high-speed belt filter with two rolls for pre- and final dewatering of the same stock. (Source: Kadant.)

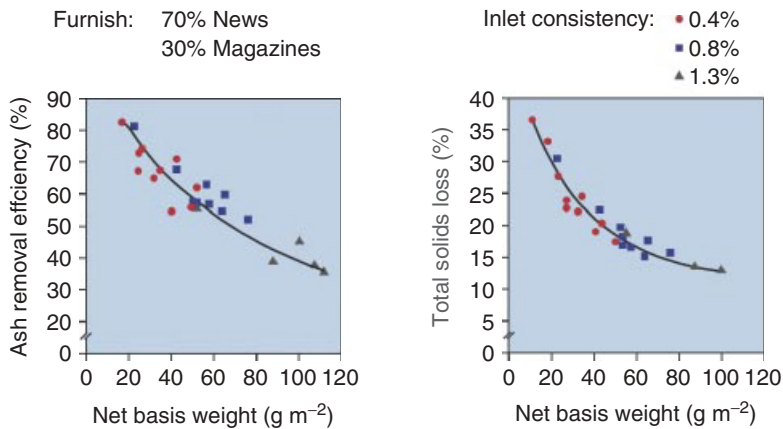


Figure 7.135 Ash removal efficiency and total solids loss as a function of net basis weight for a high-speed belt filter. (Source: Voith.)

effect. Figure 7.135 shows ash removal efficiency and total solids loss (total solids separation ratio) as a function of net basis weight for a high-speed belt filter [33, 34]. The proportion of ash and fines in the filtrate also depends on the basis weight as larger particles (as fines are, on an average, compared to fillers) are better retained than fillers when changing, for example, from very low basis weights of 20–40 or 50 g m⁻². This is shown in Figure 7.136 for a high-speed belt filter. It can be seen that selectivity for ash removal compared to organic fines removal rises when the basis weight of the filter mat is increased. As ash particles are smaller they have the chance to leave with the filtrate even at a thicker filter mat.

Figure 7.137 indicates different levels for ash removal efficiency and total solids loss with various washing principles. This is due to different thicknesses of the filter mat and dewatering pressures.

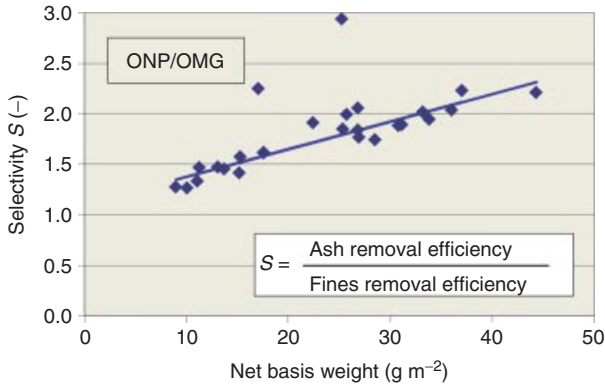


Figure 7.136 Results from practice showing the different washing effect for fillers and fines as a function of basis weight for a high-speed belt filter. (Source: Voith.)

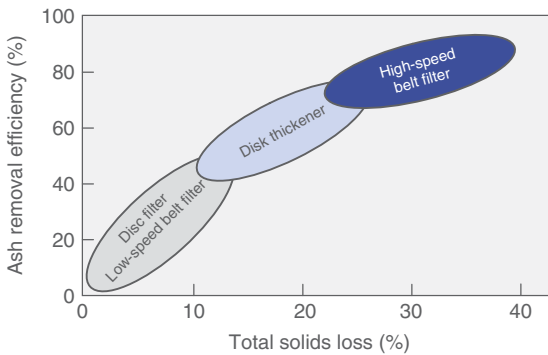


Figure 7.137 Range of washing effect as a function of total solids loss of different washing principles.

7.11 Mixing and Storing

7.11.1

Overview

In stock preparation various components are mixed or stored at many places. Mixing and storing usually follow different goals. Mixing means that different components should be brought into a highly uniform suspension. Examples are mixing thick stock with water, or different fiber stocks with each other, or chemicals with stock or fiber suspensions. The objective of storing is to stock up fiber suspensions and prevent them from demixing. It should be avoided that solids float to the top of the suspension or settle at the bottom and excessive flocculation of the solid material in the suspension should be counteracted. Another purpose can be to give the fibers enough dwell time for soaking or for chemical reactions such as bleaching.

7.11.2 Mixing

Mixing has to ensure that all individual component flows entering a mixing apparatus have been uniformly distributed in the exiting stock flow. In stock preparation mixing is done, for example, in a pulper or drum (water and fiber material, stock, and chemicals), in the disperger (stock and chemicals), or in chests. When mixing is done in a chest its whole volume has to be agitated continuously. This requires relatively high energy input. Different stock components are often premixed in a static mixer before they are finally mixed in a subsequent chest.

Mixing of suspensions in chests is usually done at stock consistencies of 3–5%. The geometry of mixing chests should have an approximate 1:1 up to 1:1.6 diameter-to-height ratio for minimum energy demand and good mixing effect. The suspension is agitated by a chest mixing propeller similar to a ship's propeller as shown in Figure 7.138. Their diameter can be up to 2200 mm with an installed power of up to 200 kW.

Specific energy demand is $0.2\text{--}0.5\text{ kW m}^{-3}$, depending on the size and geometry of the chest as well as on the stock type and consistency. The mixing effect can be adjusted either by the angle of the propeller wings or by speed control, which is standard today. Unbleached sulfate pulp requires the highest energy, followed by bleached long fiber pulp, mechanical pulp, and hard wood pulp. Energy demand decreases with lower consistency and with rising temperature.

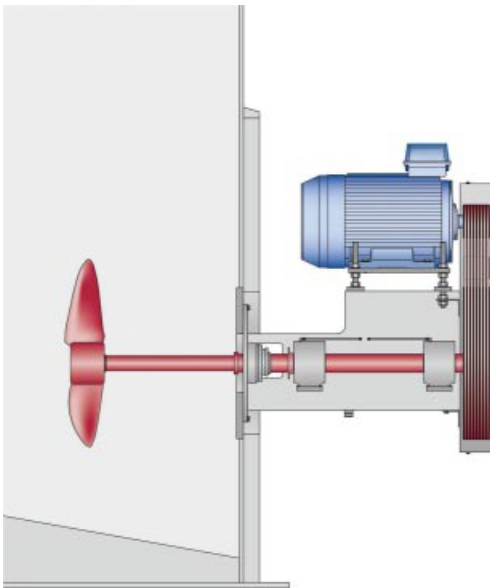


Figure 7.138 Chest mixing propeller with horizontal axis. (Source: Voith.)

7.11.3

Storing7.11.3.1 **Storing at Low Consistencies**

During storage of a suspension, demixing of water and fibers and other components may occur at low and medium consistencies. This has to be avoided. Stirring only a small part of the suspension at regular intervals at different positions in the storing chest is sufficient to hinder or correct separation and reflocculation. Thus the energy demand is low.

Vertically suspended stirrer shafts with pairs of propeller blades at several levels of the shaft are used to prevent demixing. At the bottom the shaft can have a fix guiding, a balancing weight or can be freely movable. In larger diameter storing chests the shaft rotates epicyclically, or a pair of stirrer shafts is used for very large units. The kind of equipment shown in Figure 7.139 is applied at smaller and medium storage volumes. The type of curvature of the propeller blades should be so as to avoid spinning parts in the stored stock to cling to the blades. The energy demand is about $0.02\text{--}0.1\text{ kW m}^{-3}$. The time for one revolution is adjusted to the stock type, for example, 20 s.

For large storage volumes, towers are used with reduced diameters at the bottom. Only this lower part is agitated by a mixing propeller. In this case the stock can also be stored at higher consistencies, even above 10%.

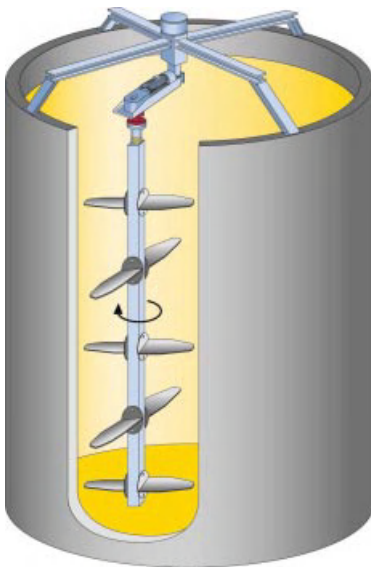


Figure 7.139 Storage chest with a vertical stirrer shaft to prevent demixing. (Source: Voith.)

7.11.3.2 Storing at Medium and High Consistencies

There is no distinct definition for medium and high consistency. Anyhow a range of 8–18% and 18–35% might meet the common understanding of medium- and high consistency, respectively. In storing at medium and high consistency, demixing of the stock is usually no problem. But the stock has to flow through the tank uniformly from top to bottom as a plug flow avoiding stagnant zones where the stock may decay. The crucial requirement is the continuous removal of the stock from the storage tank. For that the stock is diluted close to the outlet. Large units above 500 m³ often have a conical bottom end.

Figure 7.140 shows an example of a medium-consistency tower with a rotating spreader at the top entry for evenly distributing the stock over the tower cross section in thin layers [35]. The goal is not only to let air easily escape from the stock but also to prevent channeling and stagnant zones in order to make maximum use of the tank volume. Inlet consistency is typically 10–12% and the outlet consistency is about 4%. Dilution takes place in the bottom zone, where one or several agitators

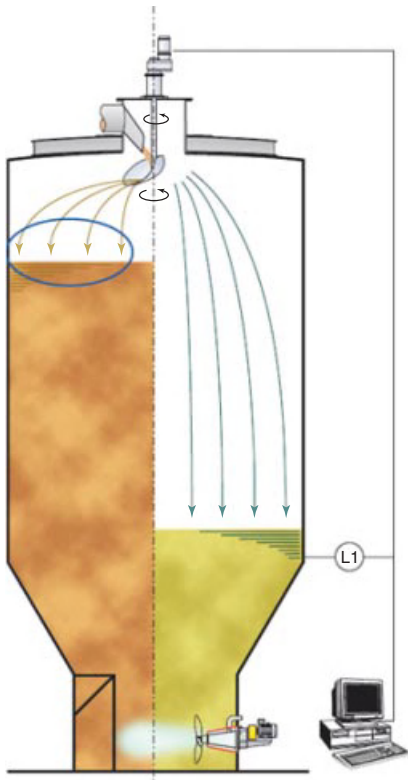


Figure 7.140 MC storage tower with top entry spreader. (Source: Sulzer.)

are operated to prevent sedimentation and to minimize consistency variations in the exiting pulp.

In Figure 7.141 an example of an HC tower used for bleaching is illustrated. The dilution concept is separately pointed out here. Most of the dilution water is led behind the agitators: one part is distributed by a baffle device in the center of the bottom zone and other small part is led to the suction side of the discharge pump. Typical inlet consistency is 30% and consistency after dilution is 4%. The tower is conically shaped to ensure good flow from top to bottom. There is also a rotating spreader at the top entry enabling maximum and nonvarying retention time. This is especially important in bleaching where chemical reactions have to take place. Bleaching technology with bleaching towers or bleaching pipes is separately dealt with in Section 7.12.

The required storage volume depends on the stock consistency. Stock with a consistency of 10% requires only half the storage volume compared to a consistency of 5%. Lowering the storage volume by increasing the consistency is limited, however. For example, a crumbly stock of 30% consistency has about the same storage density and thus needs the same storage volume as a stock with 10% consistency.

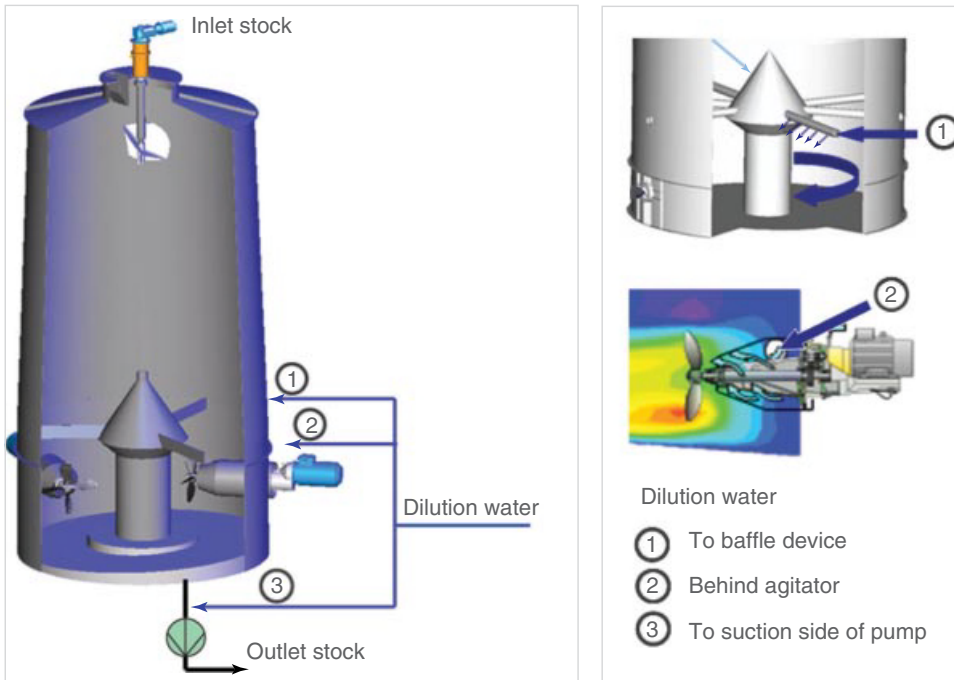


Figure 7.141 HC bleaching tower and dilution system of the exiting stock. (Source: Sulzer.)

7.12

Bleaching of Secondary Fibers

7.12.1

Objectives and Principles

With bleaching in stock preparation systems for recovered paper the optical properties of secondary fibers are improved: the brightness of the stock is increased and a possible color shade is reduced.

There are two different bleaching principles:

- Oxidative bleaching, mainly with peroxide as the bleaching agent, for brightness increase by fiber lightening.
- Reductive bleaching, with either (sodium) dithionite or FAS (formamidine sulfinic acid) as the bleaching agent, for color value correction and brightness increase by color stripping and fiber lightening.

Table 7.6 summarizes the process conditions of the different bleaching principles. The main parameters influencing the bleaching result are the type of chemical, its dosage, pH value, temperature, and retention time. Depending on the requirements of the finished stock either one or both bleaching types are integrated in a stock preparation system. The amount and type of bleaching agents have to be adjusted fiber composition of the stock (woodfree wf or wood-containing wc) and to the desired properties of the finished stock.

Table 7.6 Process parameter of the different bleaching principles.

Bleaching type	Oxidative		Reductive	
		Hydrogen peroxide	Sodium dithionite	FAS
<i>Chemical dosage</i>				
Bleaching agent	%	1–2	0.4–1	0.2–0.6
Sodium hydroxide	%	0.3–1.2	–	0.5 × FAS dosage
Sodium silicate	%	1–2	–	–
<i>Process parameter</i>				
Stock consistency	%	25–30	10–15	10–15 25–30
Reaction temperature	°C	60–95	60–95	60–95 120
Retention time	min	30–60 wc	15–60	15–30
wood-containing/woodfree		30–90 wf		
Start pH	–	10–11	6–7	9–10
End pH	–	8–9	6–7	7–8

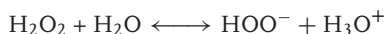
FAS, formamidine sulfinic acid; wc, wood containing; wf, woodfree.

Chemical dosage as percentage of the 100% active chemical mass related to the oven-dry pulp.

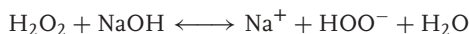
7.12.2

Peroxide Bleaching

Peroxide bleaching is usually done with hydrogen peroxide H_2O_2 and is carried out in the presence of sodium hydroxide, sodium silicate, and sometimes chelating agents at elevated temperatures. Under these conditions the peroxide acts as a lignin-preserving bleaching agent, that is, the colored structure of mechanical pulp is eliminated without any substantial dissolution of wood material [36]. The bleaching mechanism of peroxide is based on the oxidative effect of the per-hydroxyl anion HOO^- which is created when peroxide dissociates in water [37]. Owing to dissociation peroxide is weakly acidic.



Alkaline conditions favor the formation of the per-hydroxyl anion.



As sodium hydroxide itself leads to fiber yellowing, an optimum dosage ratio of hydroxide and the peroxide has to be chosen to ensure the best possible bleaching effect at the lowest chemical costs. Sodium silicate and chelating agents are used to prevent the peroxide from catalytical decomposition at the elevated temperatures and alkalinity, especially in the presence of metal ions such as iron, manganese, or copper [37].

Peroxide bleaching efficiency increases with stock consistency even up to values of 30% (Figure 7.142). Hence, a combination with the dispersion system that operates at high consistencies and temperatures is advisable, using the disperger to admix the bleaching agents to the stock. Dosage of peroxide is about 1–2% of 100% active peroxide based on the oven-dry pulp. Dosage of sodium silicate is about the same. After mixing, the stock is fed into a bleaching tower (downflow) to ensure sufficient retention time, about 30–60 min for wood-containing and 30–90 min for woodfree stock, at elevated temperatures of about 60–95 °C and a pH of 10–11 at the beginning of the bleaching reaction. The brightness gain is about 4–11%

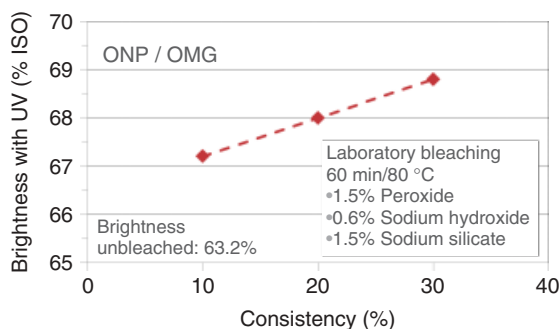


Figure 7.142 Brightness increase in peroxide bleaching as a function of stock consistency [37].

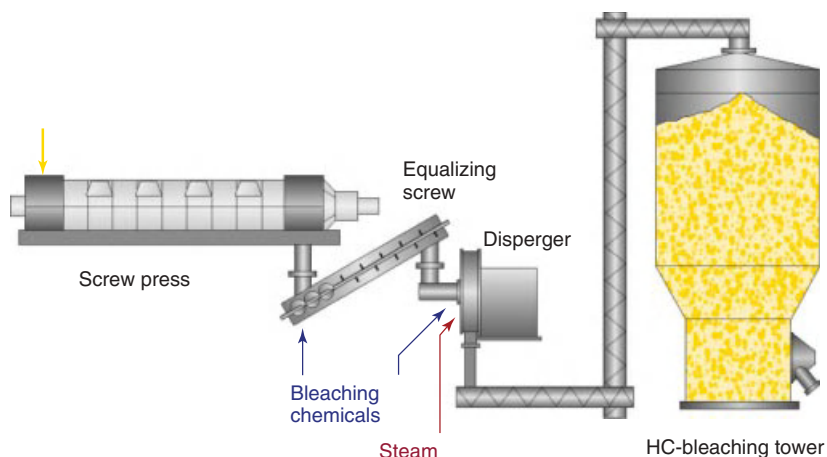


Figure 7.143 Peroxide bleaching system. (Source: Voith.)

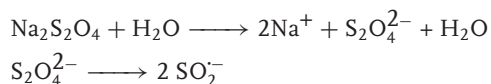
ISO for woodfree stocks and 2–5% ISO for wood-containing stocks. These values depend strongly on the kind of raw material and the bleaching conditions. A system for peroxide bleaching is shown in Figure 7.143.

7.12.3

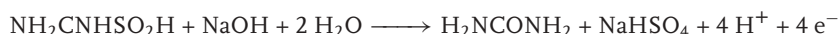
Reductive Bleaching

Economic reductive bleaching of secondary fibers requires an oxygen-free stock as dithionite is sensitive to oxygen present in the air. Therefore, the stock has to be deaerated, which can be done sufficiently at a medium consistency of about 10–15%. FAS is less sensitive, thus operating consistency can be as high as 30% and a disperger may be used for admixing of FAS. Best results are obtained when operating the disperger under pressure and at temperatures up to 120 °C. Both agents are usually fed to the inlet of a medium-consistency pump and admixed to the stock in the pump. Dithionite and FAS as well preserve the lignin.

Dithionite is used in form of sodium dithionite ($\text{Na}_2\text{S}_2\text{O}_4$). It is assumed that the sulfoxylate anion radical ($\text{SO}_2^{\cdot-}$) is the bleaching active agent [37, 38]. This radical is obtained by dissociation of the dithionite ion:



With FAS $\text{NH}_2\text{CNHSO}_2\text{H}$, the reductive bleaching effect is based on the following chemical equation [37]:



Dosage is 0.4–1.0% for sodium dithionite and 0.2–0.6% in the case of FAS. The chemical reactions are much faster than those with oxidative bleaching and hence reductive bleaching can be carried out in a bleaching pipe or a smaller tower

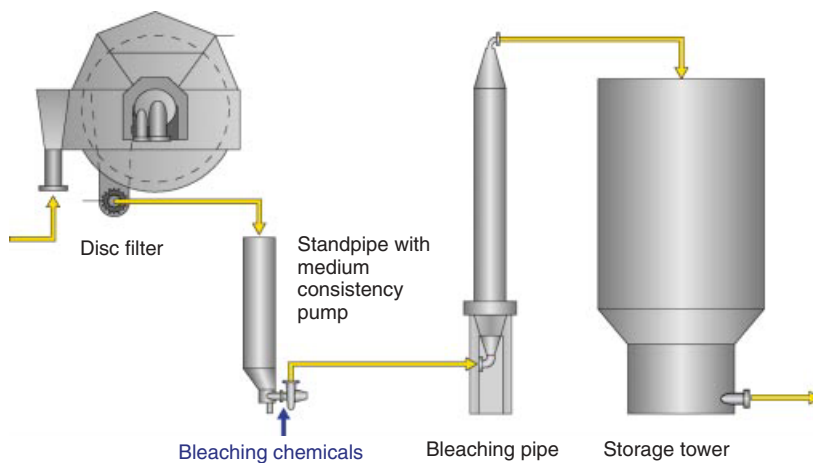


Figure 7.144 Reductive bleaching system. (Source: Voith.)

(upflow) with a retention time of 15–60 min for dithionite and 15–30 min for FAS. The temperature is 60 (minimum) to 95 °C, pH 6–7 (dithionite) and 9–10 (FAS) at the beginning of the reaction. A system for reductive bleaching is shown in Figure 7.144.

7.13

Refining

Herbert Holik and Oliver Lüdtkke

7.13.1

Overview

7.13.1.1 Objectives

The objective of refining or beating is to “design” the fibers to match the requirements of the paper making process and the desired properties of the finished paper. For example, good dewatering characteristics of the stock are desired in the forming and press sections as well as a high potential for good formation quality in the forming section. Sufficient web strength is required for safe web transfer in the press and dryer sections when the paper web is still wet. Desirable paper properties may include certain strength properties (tensile, tear, burst, fold, and Young’s modulus), bulk, air permeability, opacity, or printability. During refining all stock and paper characteristics are more or less affected, so optimization of the refining parameters has to ensure a sound compromise of the resulting stock and paper properties.

Refining is very important in stock preparation for virgin chemical pulp. For mechanical and recycled fibers refining has lower importance. The refining of

recycled fibers usually aims for strength increase at low Schopper Riegler (SR) increase as well as for shive elimination or reduction.

7.13.1.2 Principle Solution

By refining, the shape of the fibers is changed. They may be shortened, split lengthwise, collapsed, or fibrillated. Refining is done either at LC (virgin fibers, secondary fibers) of about 3–6% or at HC (mainly reject refining) of about 30% and more. Refining is done by means of refiners of different housing shape (conical, cylindrical, or disc-like). Stator and rotor of the refiners are equipped with fillings that are fitted with bars. In refining the fibers pass through the very small gap between the bars of the rotor and stator fillings.

The operating parameters influencing the result in LC refining are

- geometry (and material) of the fillings
- net refining energy
- specific edge load (SEL).

7.13.2

Basics

In Figure 7.145 a segment of a disc filling with bended bar design is shown. The angle between the bars of the rotor and the stator (cutting angle), the bar width, and bar edge sharpness are the main influencing parameters of the fillings. As the bars are subjected to wear during operation the bar edges develop a shape that depends on the bar material and the load applied.

The net refining energy is the amount of power transferred to the pulp. There are two common definitions for the net power. One definition considers no-load power with pulp, the other definition with water. The meaning of no-load power is the share of power that is required for pumping. To measure the no-load power a certain flow of either pulp or water is fed through the refiner at an open refining gap position. Typically the no-load power with pulp is higher than that with water.



Figure 7.145 Segment of filling for a disk refiner. (Source: Voith.)

Furthermore, the no-load power with pulp depends on pulp type and consistency, which is a weak point of this kind of definition.

The refining energy transferred is controlled by the force pressing the stator and rotor together. The SEL is calculated from the net refining power P_{net} divided by the cutting edge length per second (CEL). The CEL refers to the length formed per second by the edges of the bars as they move past each other.

$$\text{SEL} = \frac{P_{\text{net}}}{\text{CEL}}$$

$$\text{CEL} = Z_R \times Z_S \times l \times \frac{n}{60}$$

with Z_R as the number of rotor bars; Z_S , the number of stator bars; l , the length of the bars; and n , the rotating speed.

Compared with fibrillation, cutting reduces the fiber length far more, which results, for instance, in lower fiber flexibility, less fines generation, and subsequent easier dewatering. Owing to the reduced fiber length it helps to improve formation quality. On the other hand, with cutting the strength potential of the fibers, especially tear, will not be fully developed. Shortening of the fibers is more pronounced using fillings with a small cutting angle, small bar width, and sharp bar edges. Furthermore, refining should be done under high SEL as less energy is needed to increase the SR value of a stock.

In contrast, for fibrillation of the fibers the bars of the rotor and the stator should have a larger angle and the SEL should be low. This results in, for instance, better utilization of the strength potential of the furnish. On the other hand formation cannot be improved and the sheet is more dense, which reduces dewatering speed. Fibrillating refining needs more energy to increase the SR value of a stock. Figure 7.146 shows microscopic pictures of pine-kraft pulp before and after fibrillation refining.

7.13.3

Historical Review

Since the beginning of paper making, fiber treatment was, besides sheet forming, a key process. In former times stamping mills prepared the textile fabrics to a fine stock for the handmade paper. Another machine to prepare the stock is working

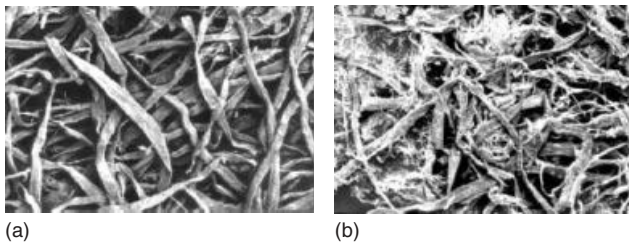


Figure 7.146 Microscopic pictures of pine-kraft pulp (a) before and (b) after fibrillation refining.

in the higher consistency range. This machine is called *roller refiner* (or edge mill or Kollergang), combining pulping, deflaking and refining in one step. The latest development before the continuously operated LC-refiner was the Hollander beater, which is still in use in some smaller paper mills for special treatment like cutting–refining of linters. The installed power on the large Hollander beaters was up to approximately 100 kW, production was about 100 tons per day. The first continuously operated LC-refiners were the conical types from different suppliers such as Jordan, Claffin, or Escher Wyss. On the basis of the angle of the cone these machines are divided into steep cone refiners and flat cone refiners. Flat cone refiners have a maximum installed power of about 400 kW and a maximum production of about 150 tons per day. With the double disk refiner a capacity in the order of magnitude of 1000 tons per day is reached, the maximum installed power is about 2500 kW. In Figure 7.147 the historical chain of refining machinery is shown.

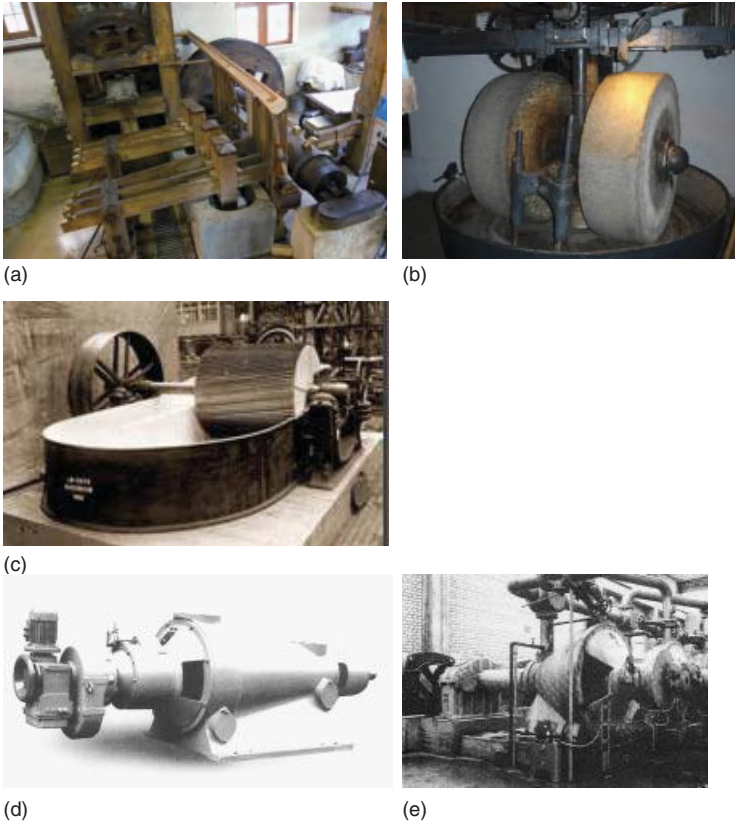


Figure 7.147 Historical review of refining machinery. (a) Stamp mill (b) Roller refiner (c) Hollander beater (d) Flat cone refiner (e) Steep cone refiner.

7.13.4

State-of-the-Art Refining Machines**7.13.4.1 Low Consistency (LC) Refining**

Today's refiners for LC refining are double disk refiners, or refiners with conical or cylindrical geometry of the rotor/stator unit. Figure 7.148 shows a double disk refiner in cross section. Both sides of the rotor are equipped with fillings acting against the stator fillings of the front side (with loading device) and the backside (with drive). The front stator is moved by the loading device, the rotor can slide along the center shaft when loaded or unloaded. The peripheral speed of the rotor is about 25 m s^{-1} . The double disc refiner is globally the most successful refiner design since it combines economical operation and easy maintenance with a large variability of available patterns. Numerous research projects confirmed that importance of the refiner fillings design is higher compared to different machine designs such as disc, conical, and cylindrical geometry. Figure 7.149 shows a double disk refiner with open lid. The change of fillings can be done from a single person without lifting device in short time.

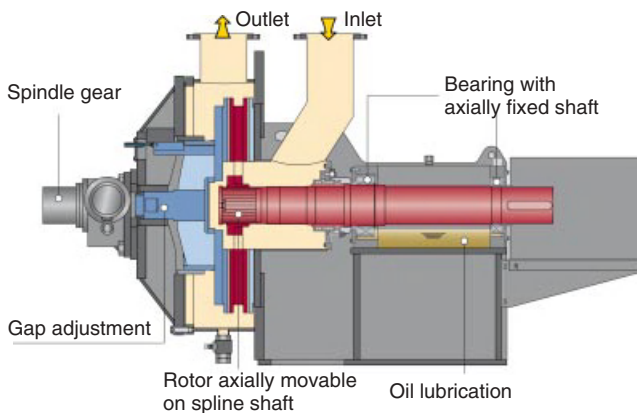


Figure 7.148 Cross section of a double disc refiner. (Source: Voith.)



Figure 7.149 Example of a double disc refiner opened showing the fillings. (Source: Voith.)

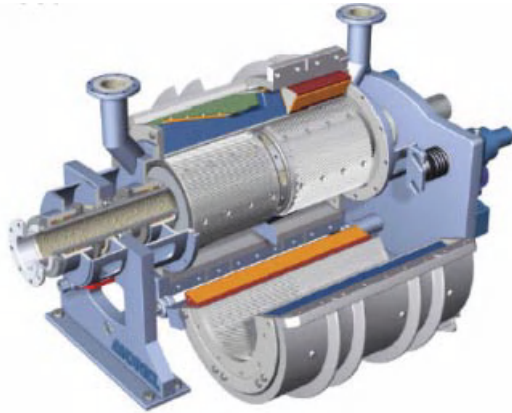


Figure 7.150 Cylindrical refiner with center feeding. (Source: Andritz.)

In Figure 7.150 a refiner with cylindrical rotor/stator geometry is shown. The stock enters the center of the machine via the hollow center shaft and is refined during its helical horizontal path to the two stock outlet pipes. The refining energy is controlled by the gap between the rotor and the stator which is adjusted by cone-shaped means.

In a more recent refiner design (Metso) the pulp is fed into the refining zone through holes in the rotor. After treatment the fibers leave the refining zone through holes in the stator. With this forced fiber flow, which is vertical to the grooves in the filling, the probability to treat the fibers is different from that of the hydraulic self-adjusted refiners such as conventional disc, conical or cylindrical refiners where the pulp flow is in the direction of the groove.

7.13.4.2 High consistency (HC) Refining

HC (30% and more) refining is mainly based on the shear force effect between the fibers. This is why HC of the stock is required, which in turn necessitates its dewatering. To save costs HC refining is best placed in a system position where the stock is already dewatered for other purposes, for example, in order to separate the water loops (see Chapter 8).

HC refining preserves fiber length to a high degree, resulting in high dynamic strength properties, high elongation, and porosity. HC refining is done either in special HC refiners or with disk dispersers, which is described in Section 7.14. Here, the disk disperser is operated without steam heating. Figure 7.151 shows a refiner plate for HC refining.

7.13.5

Operational and Technological Aspects

Canadian Standard Freeness (CSF) or SR value is often used to check the effect of refining. Unfortunately, this value can only partly characterize the actual properties



Figure 7.151 Refiner plate for HC refining. (Source: Andritz.)

of a stock. The properties of papers made from the same original stock but with a different kind of refining may vary in a wide range in spite of the same measured number of CSF or SR value. The same is true for the behavior of the stock in the paper machine. It needs additional measurements such as fiber length distribution, specific surface, or flexibility of the fibers to obtain a better picture of a refined stock.

The refining resistance of a stock depends on different fiber properties. One example is the type of pulp bleaching. As shown in Figure 7.152 more energy

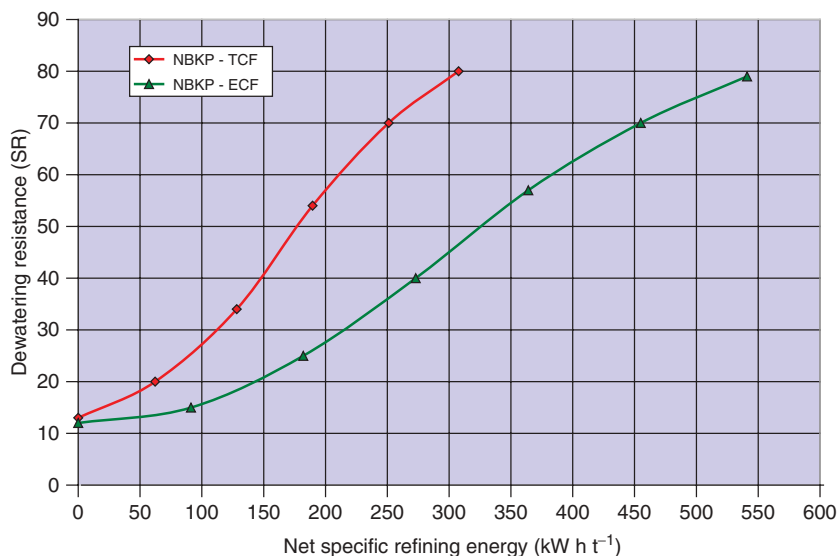


Figure 7.152 Influence of the net specific refining energy and the kind of bleaching on the dewatering resistance for needle-bleached kraft pulp (NBKP).

is required to refine elementary chlorine-free (ECF) pulp that has been bleached without Cl_2 but using a chlorine compound that is most common, chlorine dioxide (ClO_2). On the other hand, the totally chlorine-free (TCF) bleached pulp where peroxide (H_2O_2) and ozone (O_3) are used for bleaching shows significant lower energy demand to reach certain refining target expressed as SR value. In this example, the raw material is needle-bleached kraft pulp (NBKP) from Scandinavian origin. The higher refining resistance of ECF pulp is related to the more selective reaction of typically used chlorine dioxide at ECF bleaching to the lignin. This results in low decomposition of the cellulosic structure which remains stronger after bleaching.

As fiber length is of high importance for paper properties one should know the influence of refining parameters on the development of fiber length. Besides the bar angle of the used fillings, the SEL is the most relevant parameter. Figure 7.153 shows that higher SEL leads to more fiber length reduction for the same filling type.

The main target of refining, usually, is to develop the strength properties to the required level. Commonly accepted is to describe the strength properties of different pulp types by the tear–tensile diagrams. Typically, NBKP pulp reaches a maximum of tear-strength at low transferred refining energy where only low tensile strength is obtained. Further refining increases tensile strength and reduces tear strength. Leave bleached kraft pulps (LBKPs), usually, show an increase of both

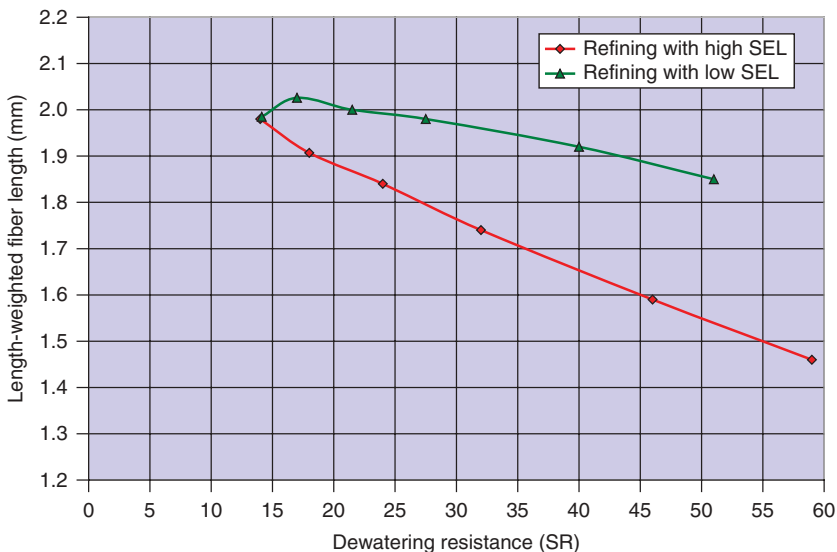


Figure 7.153 Influence of specific edge load (SEL) on the development of fiber length and dewatering resistance for needle-bleached kraft pulp (NBKP).

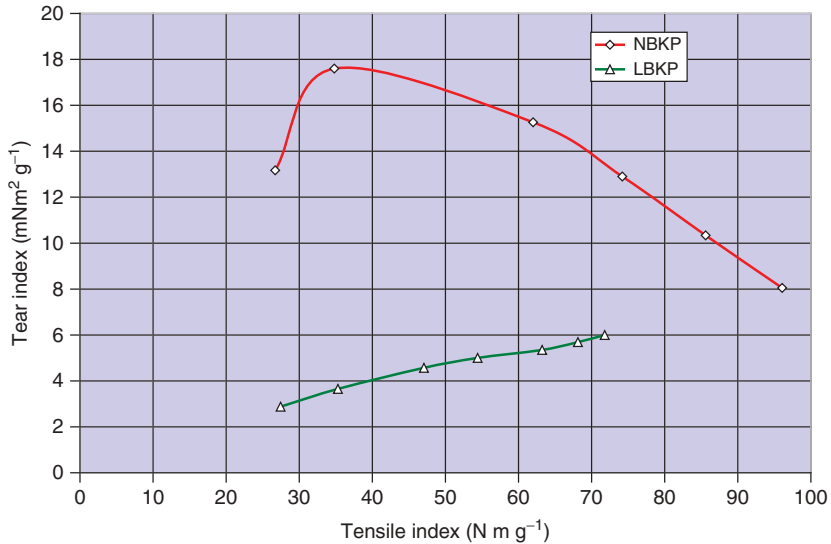


Figure 7.154 Development of strength properties (tear index and tensile index) for two different kinds of fiber material (needle-bleached kraft pulp, NBKP, and leave-bleached kraft pulps, LBKP).

tear and tensile strength with more refining. But the strength level is on a distinctly lower level compared to NBKP pulps (Figure 7.154).

The refining energy required to increase the SR value is about $0.5\text{--}2.5 \text{ kW h t}^{-1}$ per SR. This value is influenced by the type of stock processed, the SR value and the refining conditions.

7.14

Dispersion

Harald Heß and Herbert Holik

7.14.1

Overview and General Aspects

7.14.1.1 Objectives

Depending on the furnish quality as well as on the requirements of the finished product, the tasks of a dispersing system vary widely. They are, as follows:

- reduction of the size of dirt specks below the limit of visibility
- reduction of the size of stickies
- breaking down coating and sizing particles
- distribution of wax finely
- detachment of ink or toner particles from fibers
- disintegration of fiber bundles

- treatment of fibers mechanically and thermally
- mixing in bleaching agents
- decontamination of the stock with regard to microorganisms.

Table 7.7 summarizes the tasks of dispersion in stock preparation for different paper grades.

7.14.1.2 General Aspects

Dispersion is used in secondary fiber processing. Dispersing is not a separation process. It only enables subsequent process stages to remove certain debris particles. For example, flotation can remove ink particles only when they are detached from the fibers. Nevertheless, one of the tasks of dispersion is called *reduction of dirt specks and stickies*. But this only means that their size should be reduced under certain size limits, for example, of visibility or measurability.

Dispersion is located at the point of water loop separation where the suspension is dewatered up to a consistency of about 22–35%. Often bleaching is done in combination with dispersing. For high quality demands two dispersing steps may be required in the process.

During dispersing high-shear forces are applied to the debris particles to be dispersed and also to the fibers. The shear forces have to exceed the strength of these debris particles in order to reduce their size or to detach them from the fibers. Hence, the dispersers have to be operated at high stock consistencies mentioned above in order to ensure the transfer of the required amount of dispersing energy, and the temperature has to be elevated to reduce the strength of the debris particles.

Table 7.7 Tasks of dispersion in stock preparation for different paper grades.

Task	News-print	SC paper	LWC paper	Tissue	Test liner	Board (filler)	Board (top liner)
Dispersion of							
Dirt Specks	+	+	+	+	+	+	+
Makro-stickies	+	+	+	+	+	+	+
Wax					+	+	
Coating grids	+	+	+	+			+
Detachment of							
Ink	+	+	+	+			+
Toner	+	+	+	+			+
Bleaching agents/stock mixing	+	+	+	+			+
Microbial decontamination	+	+	+	+	+	+	+
Increase of							
Strength		+	+	+	+		
Bulk				+		+	

7.14.2

Equipment and Operational Aspects7.14.2.1 **System**

A dispersing system consists of three major process steps:

- dewatering the suspension from 4 to 10% up to the required consistency of about 22–35%
- heating the dewatered stock to a temperature of about 85–90 °C (at ambient pressure) or higher (up to 130 °C under pressure)
- applying shear forces to disperse the stock.

Dewatering of the suspension is done in a screw press – in some systems in a twin-wire press. The required stock temperature during dispersing is obtained by direct steam heating which may be done by steam either in a separate heating screw or by direct feed of the steam into the disperser. Figure 7.155 shows an example of a dispersing system with the heating steam directly fed into the disperser. Dispersing itself is done either in a high-speed disk disperser (Figure 7.156), in a cone disperser

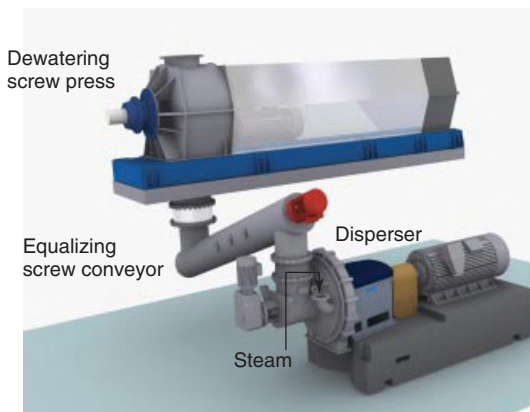


Figure 7.155 Dispersing system with dewatering screw press and direct heating in the disperser. (Source: Voith.)



Figure 7.156 Disk disperser opened to show the fillings on rotor and stators. (Source: Voith.)



Figure 7.157 Disperser with conical fillings. (Source: Metso.)

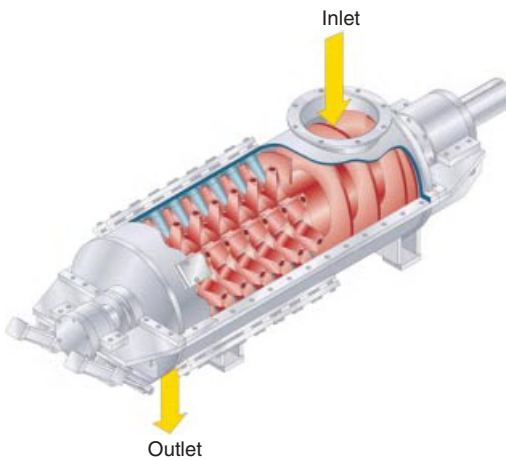


Figure 7.158 Single-shaft kneading disperser. (Source: Voith.)

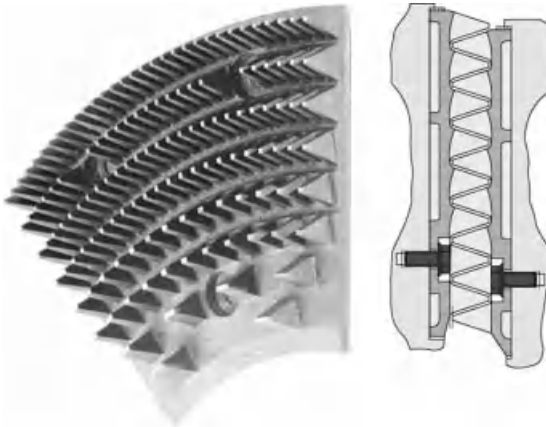
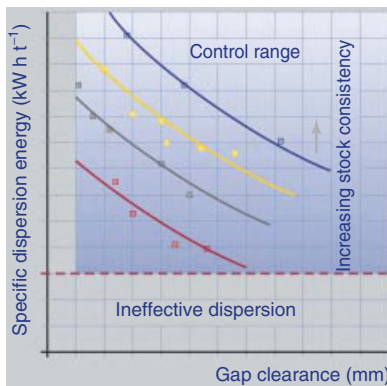
(Figure 7.157), or in a slow-running kneading disperser (Figure 7.158). Table 7.8 indicates operational parameters of disk and kneading dispersers.

7.14.2.2 Disk Disperser

7.14.2.2.1 Principle Design and Operating Parameters The fillings of a disk disperser (Figure 7.159) usually have intermeshing teeth or sometimes refiner-type bars. The rotor/stator element spacing is 1 mm or less and the peripheral speed is about 50–100 m s⁻¹. When increasing the circumferential speed above a certain maximum the dispersing effect can only be slightly improved. The specific energy demand is 30–80 kW h t⁻¹, in certain cases up to about 120 kW h t⁻¹ or more. The specific energy is controlled by adjusting the spacing of the rotor/stator elements after having preset a favorable inlet consistency [39]. Figure 7.160 qualitatively shows the effect of gap clearance and stock consistency on transferable specific energy. Disk dispersers are always operated at elevated temperatures otherwise the loss in

Table 7.8 Operational parameters of disk and kneading dispersers.

		Disk disperser	Kneading disperser
Inlet consistency	%	25–35	22–35
Outlet consistency	%	4–7/15–35	15–35
Inlet temperature	°C	60–130	40–95
Circumferential speed	m/s	50–100	7–13/0.5–1.5 Single shaft/twin shaft
Spacing	mm	0.5–1.5	~ 10
Specific energy demand	kW h t ⁻¹	30–80 (120)	30–80 (120)
Installed power	kW	300–4500	400–2500
Production	t d ⁻¹	30–1000	30–700

**Figure 7.159** Fillings of a disk disperser. (Source: Voith.)**Figure 7.160** Qualitative dependency of specific dispersion energy on gap clearance and stock consistency in a disk disperser. (Source: Voith.)

stock freeness would be considerable. However, this effect may have use for HC refining of recycled fibers. Main stock flow of a disk disperser is in radial direction.

Another type of high-speed disperser has conical fillings (Figure 7.157). For the same diameter a longer working zone and thus a larger number of impacts between stock and fillings can be provided [40]. The filling design combines a cone and a flat disc ring at the periphery.

7.14.2.2.2 Model of Dispersion Mechanism in a Disk Disperser In a disk disperser the stock is pumped by centrifugal forces supplied by the rotor speed. For continuous stock transportation all voids in the fillings and in between have to be completely filled with stock: The first rotor ring pumps the stock in the radial direction into the spacing between rotor and stator and from here through the channels in the subsequent stator ring, and then the space between stator and the next rotor ring is filled up. This rotor ring can now accelerate the stock and further pump it to the next stator ring, and so on.

The stock velocity curves in the space between the stator and rotor rings are not really known. They mainly depend on the distance between stator and rotor rings as well as on the shear behavior of the stock. The schematic shown in Figure 7.161 shows a small part of two rotor rings and one stator ring. The stock velocity curves are assumed and are estimated from some facts:

- the stock exiting the radial rotor channels has circumferential velocity of the rotor
- the stock entering the radial stator channel has zero circumferential velocity
- in between the circumferential velocity is decreased to a certain degree by the friction of the stock at the stator ring, at a larger distance from the rotor down to about zero in the vicinity of the stator
- the stock leaving the stator has zero circumferential velocity

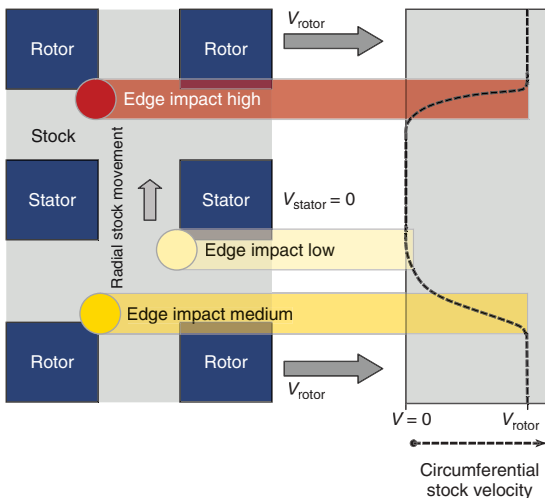


Figure 7.161 Principle mechanism of shear generation in high-speed disk disperser.

- this stock is rapidly accelerated later on by friction at the rotor ring surface, but only in its very vicinity
- the radial velocity of the stock is very low compared to circumferential velocity of the rotor.

The higher the velocity gradient, the greater the shear forces are. Highest velocity gradient and thus highest shear stress can be expected at the inlet of the rotor ring channels. Shear stress at the outlet of the rotor must be somewhat lower due to smaller velocity gradient. A zone of distinctly lower shear may be at the inlet of the stator ring channels. Shear stress in all other zones, especially in the filling channels, is supposed to be negligible. The reliability of this approach to describe the shear force pattern depends, however, on the gap clearance between the stators and the rotors and on the stock characteristics.

Stock treatment is forced as all stock has to go through the shear zones. It is repeated depending on the number of rotor and stator rings. The impact of the particles on the edges of rotor and stator rings is a matter of probability and may have a limited influence on the dispersing result. In the literature, different models are used to describe the physical operating conditions in a disperser [41].

7.14.2.3 Kneading Disperser

7.14.2.3.1 Principle Design and Operating Parameters The fillings in a kneading disperser are much coarser than those in a disk disperser (Figure 7.162). The stock is transported in axial direction by rhomboidal cogs fixed on the rotor working as impellers. Cylindrical teeth fixed inside at the horizontal housing work as resistance elements. The rotor/stator spacing is about 10 mm and the peripheral speed is 5–13 or 0.5–1.5 m s⁻¹ depending on the design that may be single- or twin shaft. Energy input for kneading dispersers is usually between 30 and 80 kW t⁻¹, in special cases up to 120 kW t⁻¹. The transferred dispersing energy for the kneading disperser is controlled by adjusting the entering stock consistency and by throttling the outlet. The latter can be done either with a valve or with a discharge screw. Kneading dispersers can be operated unheated at normal process temperatures without noticeably decreasing freeness of the stock.



Figure 7.162 Filling of a kneading disperser. (Source: Voith.)

7.14.2.3.2 Assumption of Dispersion Mechanism in a Kneading Disperger The mechanism of shear generation is not really known. One approach is that during transportation along the kneading chamber the stock is squeezed again and again through the spacing built up by the rotor and stator cogs. During squeezing some kind of plug flow may occur with high-shear zones at the cog edges resulting in an intense fiber-to-fiber friction. In kneading, stock treatment seems to be a matter of probability even when stock-“squeezing” is repeatedly applied.

7.14.3

Technological Aspects

The most important influence of both disk and kneading dispergers on the dispersing effect is the specific energy consumption [42, 43]. In Figure 7.163 the stickies area reduction is plotted against specific energy consumption and Figure 7.164 shows dirt speck reduction against specific energy consumption for two different furnishes.

It is known for the disk disperser that it needs a certain minimum specific energy to get any macrostickies reduction. Trials show that with an increase in the circumferential speed above a certain maximum only a slight further improvement of the dispersing effect can be obtained [43]. Elevated temperature reduces the strength of stickies and thus improves the reduction of stickies.

The effects of the two disperser types in general are mostly similar. In Table 7.9 the tendencies of technological results and preferable application of disk and kneading dispersers are listed. The main differing tendencies are:

- the disk disperser may be advantageous when good sticky and dirt speck reduction are required
- the kneading disperser is recommended when high porosity and bulk of the finished product are a priority.

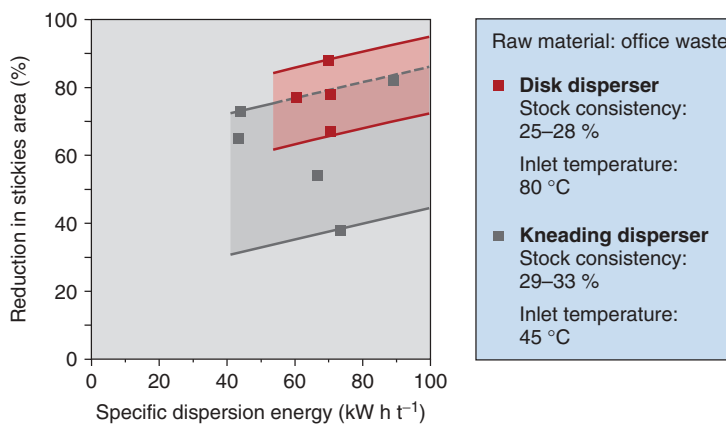


Figure 7.163 Reduction in macrostickies depending on the specific energy applied in a disk disperser and a slow-running kneading disperser. (Source: Voith.)

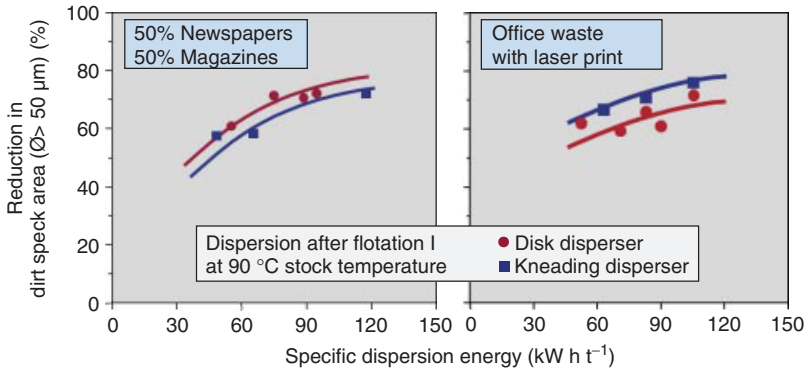


Figure 7.164 Reduction in dirt specks depending on the specific energy in a disk disperser and a slow-running kneading disperser. (Source: Voith.)

Table 7.9 Tendencies of technological results and preferable application of disk and kneading dispersers.

	Disk disperser	Kneading disperser
Dirt specks	Good reduction, especially conventional inks	Good reduction, especially toners
Macrostickies	Good reduction	Less good reduction, stickies remain better screenable
Strength	Moderate increase with heating Strong increase without heating	No or low increase
Beating degree (SR)	Moderate increase with heating Strong increase without heating	No or low increase
Positioning in a system with		
One disperser	Before postflotation Optionally in long fiber line of packaging grades	Before postflotation
Two dispersers	Before postflotation and second disk disperser at end of system	Before postflotation combined with a disk disperser at end of system

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8

Systems for Fiber Stock Preparation

*Oliver Lüdtké and Andrea Stetter**

8.1

Objectives

The target of fiber preparation systems is to modify the raw materials for paper production so that the stock suits the requirements of the paper machine as well as those of the finished paper or board. Raw materials are virgin fibers from different sources such as chemical pulps from hard- or softwood or mechanical fibers such as stone groundwood (SGW), pressure groundwood (PGW), thermo mechanical pulp (TMP), or chemi thermo mechanical pulp (CTMP). The largest portion of raw materials today is recovered paper which is processed into secondary or recycled fibers. The recovered paper grades differ a lot as regards fiber composition and cleanliness levels. Therefore, the processing systems have to take into account these differences as well as the various quality requirements of the finished stock.

The development of stock preparation systems is driven by the following requirements:

- low furnish cost
- low energy demand
- reduced quality of recovered paper
- increasing paper machine speeds
- lower basis weights of the produced paper
- low fiber loss
- high production capacity
- few effluents.

8.2

Historical Review of Stock Preparation Systems

Stock preparation has always been a central process in paper production. Without the suitable furnish the papermaker cannot produce the desired paper quality. In earlier times old textiles were found to be suitable. This shows that from the

* Contributed to the First Edition.

beginning, recycling and reusing of raw materials was quite usual. But it needed a few steps before this raw material could be used as furnish for paper-making. First the old textiles were sorted manually, and unsuitable parts such as buttons were removed. After precleaning, the textiles were treated by a chemical process in a digesting sump to enhance the defibering that was finally done in a subsequent stamp mill. The available amount of textiles for papermaking was limited and could not meet the increasing demand.

In the nineteenth century, mechanical and chemical processes were developed to produce virgin pulp from wood. The system for the final preparation of these pulps for papermaking was very simple and mainly consisted of slushing and refining/beating.

Later in the twentieth century, the usage of postconsumer recycling paper grew more and more because of the economic and environmental reasons. Today, the usage of virgin pulp and recycled fibers is well balanced and on a global scale both fiber resources are essential as raw material for papermaking.

With increasing usage of recovered paper the systems had to be adapted, and suitable machines for specific purposes had to be developed. Figure 8.1 displays the important developments in the evolution of equipment that resulted from new challenges in recovered paper preparation as regards the raw material as well as the quality requirements [1].

Printing colors had to be removed from the fibers and suspension in order to make use of printed recovered paper for higher grades. So the deinking cell was developed. First attempts started in the second half of the 1950s, and in 1965, the first industrial deinking cell specially developed for the paper industry started operation in Germany. In North America, wash deinking was the favored process.

The next challenge in Europe in the late 1960s was bitumen when recovering the packaging boxes of fruits and vegetables from overseas. During this time, a lot of patents were granted based on mechanical, thermal, and chemical processes. Standard procedure finally became hot dispersing of the remaining bitumen particles, which had not been able to be screened out.

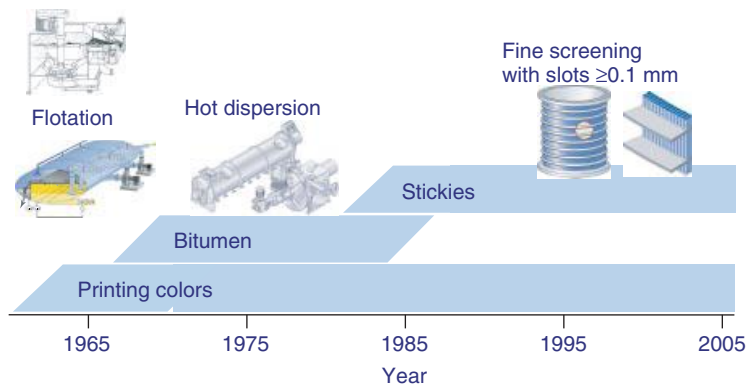


Figure 8.1 New machines for secondary fiber preparation because of upcoming challenges.

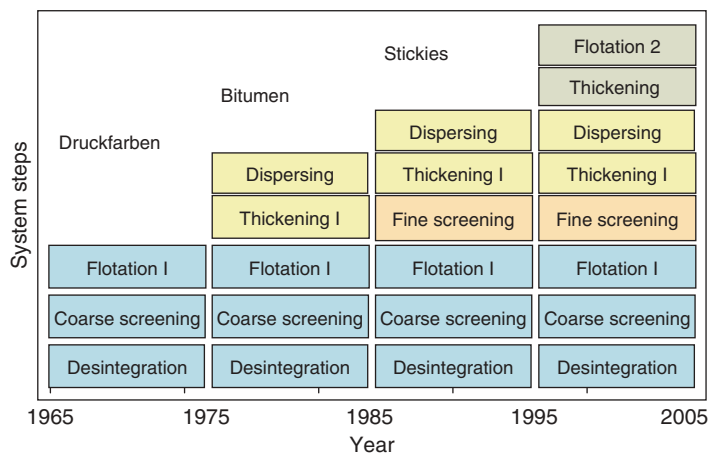


Figure 8.2 Development of stock preparation systems for white grades.

In the 1980s, the “career” of the stickies began. The main progress in stock cleanliness was reached by fine screening with slots down to a slot width of 0.1 mm. The production of these screen baskets requires a high precision technique, and system solutions have to prevent these high-tech parts from damage and excessive wear.

With the new machines, the stock preparation systems got more effective. Because of the increased use of recovered paper as well as increasing quality requirements, the systems also became more extensive. In Figure 8.2, the development of stock preparation systems for white grades on the basis of recovered paper is shown.

In the 1960s and 1970s, a deinked pulp (DIP) system consisted of three steps: disintegration, coarse screening, and flotation. During the mid-1970s thickening and dispersing were added to meet the quality requirements put on the secondary fiber stock. About 1985, fine screening had been introduced as a step in between to sort out the stickies. Only the unscreenable stickies should be reduced by dispersion to a size which no longer disturbed the process and the product. Since about 1995 a system with a second flotation and a second thickening stage became standard for high quality requirements.

An important step was the consequent separation of the water circuits between stock preparation and paper machine. But during the stock preparation, thickening ahead of dispersing gave the opportunity to extract undesired fine particles from the water and the system. A further advantage of thickening was that bleaching (oxidative and reductive) could be done effectively at the given high stock consistency.

Another important recycling process as a “short circuit” within the paper mill was and is the use of broke. Broke comes up at several steps during paper production, as wet broke on the first part of paper machine and as dry broke later on the paper machine as well as in converting and upgrading steps. As broke is usually clean,

Table 8.1 Overview on stock preparation systems.

Stock preparation system for	Typical kind of raw material	Typical source	Typical use	Typical spec. energy demand (kWh t ⁻¹)
Virgin pulp	Chemical pulp	Pulp mill	High grade papers	50–500
	Mechanical pulp	Pulp mill		0–150
Wood-containing deinked pulp	Wood-containing recovered paper	Wood-containing mixed office Household	Wood-containing graphical grades	150–250
Woodfree deinked pulp	Woodfree recovered paper	Woodfree mixed office	Woodfree graphical grades, market DIP	200–300
Packaging grades	Old corrugated containers	Ware houses	Packaging papers	100–200
Packaging grades with fractionation	Old corrugated containers	Ware houses	Packaging papers multi layer	100–200
Broke	–	–	–	20–400

it is handled in a simple stock preparation system with slushing and defibering as the key functions.

Table 8.1 gives an overview of today's systems indicating the typical kind of raw material, source and use, as well as the typical specific energy demand. The latter excludes the energy demand for the actual chemical or mechanical pulp production. The numbers include the energy consumption of the fiber processing machinery as well as pumps. Some examples can explain the wide range of the energy demand. Preparation of virgin pulp for tissue may need much less energy (starting at about 20 kWh t⁻¹) than for cigarette or transparent papers (several 100 kWh t⁻¹). Some systems for packaging papers from OCC may work without dispersing or refining which are main energy-consuming process steps. The energy demand of broke systems for easily slushable papers may be as low as 20 kWh t⁻¹, whereas for wet strength broke difficult to disintegrate, several deflaker passes – and even a dispersing stage – are needed and up to 400 kWh t⁻¹ may be required.

8.3 Systems for Primary Fiber Preparation

The systems for primary fiber preparation are less complex than a recovered paper processing system because of the much lower level of impurities and contamination in virgin fiber pulps. Depending on the paper type produced and the availability of the various fiber types, a paper machine, or especially a multilayer board machine, may be fed by several different fiber qualities, each of them treated in separate lines with different process steps.

Integrated paper mills have their own chemical and/or mechanical pulping plants. Here the fibers usually are not dried before they are supplied for fiber preparation. In nonintegrated mills typically market pulp in form of bales is used. There are two common types of bales: one bale type is produced by stacking dry pulp sheets, the other type is formed by pressing dry pulp flakes (flash dried). In both cases the bale size is similar and weight is 200–250 kg.

The fiber preparation in an integrated mill usually simply consists of refining (of mainly chemical pulp), whereas nonintegrated mills have to use more extensive systems including slushing, removal of contraries and impurities ahead of deflaking, and/or refining. Figure 8.3 shows a conventional system for virgin fiber preparation of chemical pulp.

The virgin pulp in bales must be placed individually on a conveyor belt. The wires holding the bales together are cut and removed by hand or automatically. The bales reach the LC pulper – which can be operated continuously or in batches – via a weighing device. Slushing takes place at a consistency of 5–7%. After a certain pulping time, the slushed pulp is pumped to a dump chest where further fiber swelling takes place. The high density (HD) cleaning stage – a hydrocyclone device – operates at about 5% consistency and removes heavy particles such as bale wire pieces, and small stones in order to protect the following deflaking and refining machines from mechanical damage. The optional intensive deflaking that follows breaks down the remaining flakes. It also has to prevent the so-called fish-eyes in the final paper, which are caused by nondisintegrated fiber bundles when flash-dried pulps are used. Subsequent refining achieves the desired fiber properties in order to meet the quality parameters of the final product. Owing to the wide variety of virgin fibers, refining has to be adapted to each raw material and each paper quality target. By refining, strength properties, formation, and special demands such as electrical insulation or grease proofness of the paper to be produced are influenced. The same is true for machine runnability.

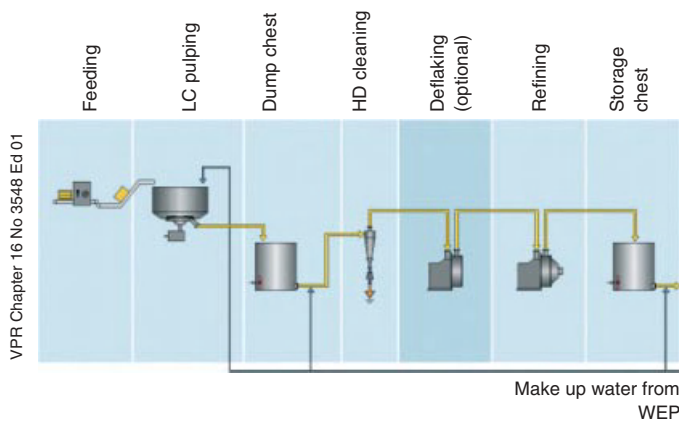


Figure 8.3 System for virgin fiber preparation from chemical pulp.

8.4

Systems for Secondary Fiber Preparation

Secondary fiber preparation systems are extremely diverse. This is because of the wide variety of recovered paper grades with their different paper components and quality levels, the quantity and type of nonfiber components such as fillers, debris, and other detrimental substances, the varying production ranges, and especially the requirements of the paper machine and the final product. Furthermore, governmental regulations on wastewater, waste disposal, and noise levels also have to be considered. On the other hand, it is possible to get to an appropriate paper quality at lower production costs by using recycled fibers rather than virgin fibers.

8.4.1

Systems for Graphic Paper Grades

The raw materials for graphic paper grades mainly comprise graphical postconsumer recovered papers and smaller portions of unprinted or printed preconsumer grades. Wood-containing recovered paper is generally called *deinking material* and consists of old newspapers (ONPs) and old magazines (OMGs). Woodfree recovered paper consists of mixed office waste (MOW) and other coated woodfree and uncoated woodfree (CWF and UWF) printing papers. In these grades, unbleached chemical fibers and mechanical fibers have to be avoided because in systems for white paper grades, high demand is put on optical properties.

The product from a secondary fiber preparation plant for white grades is usually called *deinked pulp* as there is at least one process step for ink removal integrated in the system. In most of the cases this deinking step is done by selective flotation. Washers may be used for deinking in special cases when very finely dispersed printing inks (like water-based flexo inks) are present in the recovered paper or when not only the ink but also the major share of the ash content needs to be removed, as is true, for example, for tissue grades.

The main parameters characterizing the quality of a DIP are brightness, stickies content, dirt specks, and ash content. Depending on the application, namely the recovered paper grades used and the paper grades produced, different requirements are imposed on the DIP quality and thus on the system layout and efficiency.

8.4.1.1 System for Wood-Containing Graphic Papers

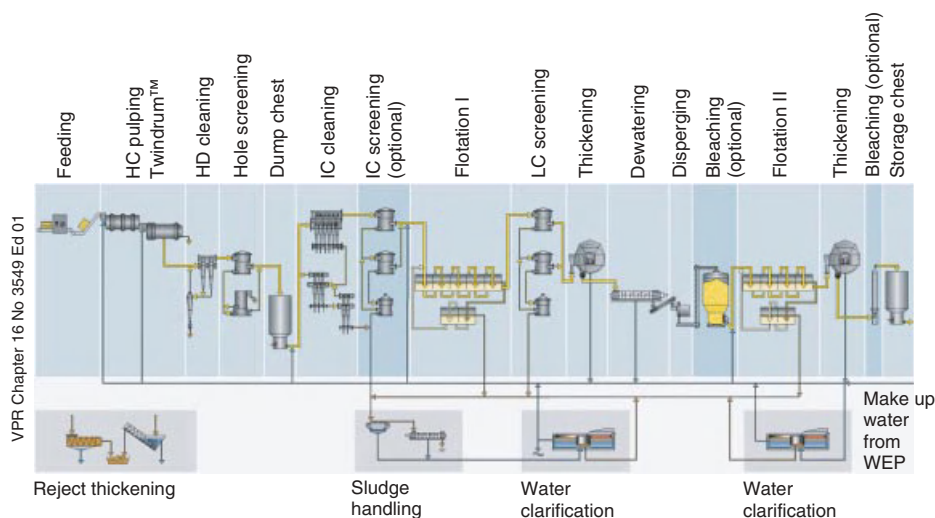
The graphic paper grade with the highest secondary fiber content today is newsprint. There are a great number of paper mills producing newsprint, improved newsprint, or even SC-B as well as some lightweight coated (LWC) grades based on 100% recycled fibers, especially in middle Europe. High grade SC-A and LWC papers may also contain up to 30% recycled fibers. The main recovered paper source for these grades is the so-called deinking grade (European grade classification: 1.11) which represents a mix of 40–60% ONP and 60–40% OMG. The significant quality parameters of this raw material and of the DIP for graphic paper grades are shown in Table 8.2.

Table 8.2 Quality parameters of European ONP/OMG mix and DIP for different wood-containing graphical paper grades.

Grade	DIP brightness (%ISO)	DIP dirt count > 50 μm ($\text{mm}^2 \text{m}^{-2}$)	DIP stickies ^a ($\text{mm}^2 \text{kg}^{-1}$)	DIP ash content (575 °C) (%)
Recovered paper (Mix ONP/OMG)	45–48	1500–3000	4000–8000	20–25
Newsprint	60–62	100–200	<200	12–16
Improved newsprint	65–68	100–200	<200	12–16
Supercalendered (SC)	65–68	50–100	<100	12–16
Lightweight coated (LWC)	68–72	50–	<100	9–13

^aAccording to TAPPI T277 (measurement with Somerville laboratory screen with 0.15 mm slotted screen plate).

A fiber preparation system for white paper grades consists of the process steps shown in Figure 8.4. Recovered paper is delivered in bales or loose and is fed to a conveyor belt where the wires holding the bales together are cut and automatically removed. The raw material gets to the pulping stage via a weighing device. From the measured weight, the necessary amount of water for slushing and dilution, as well as the necessary amounts of deinking chemicals, are calculated and fed to the high consistency (HC) pulping stage. Pulping is done at a minimum consistency of 15% (and up to 28% in drum pulpers) for gentle fiber–fiber friction and a low degree of contaminant break down. Operation is either batchwise in a HC pulper or continuous in a drum pulper. For good ink detachment, in wood-containing

**Figure 8.4** Fiber preparation system for deinked pulp production.

systems pulping is done in an alkaline environment. Sodium hydroxide assists the ink detachment; sodium silicate avoids redeposition of the ink on the fibers and stabilizes hydrogen peroxide, which is added to compensate for the alkaline-induced yellowing of mechanical fibers. Deinking additives such as soap and/or surfactants can also be added in the slushing stage.

After slushing, the larger contaminants are removed from the suspension by coarse screening at a consistency of approximately 4.5% in detrashing machines and/or sorting drums. Hole sizes here can vary from 4 to 16 mm. HD cleaning removes major heavy contaminants such as glass, stones, or staples. The following medium consistency screening is carried out with hole baskets with a minimum hole diameter of 1.0 mm. These are especially effective for reduction of flat particles. Medium consistency refers to a level of 3.5% in this area in the first screening stage and dilution in the subsequent stages.

For high quality demands, an intermediate consistency (IC) slot screening stage (with slot width a minimum of 0.20 mm) follows at 2% consistency as the next step for removal of stickies and other cubic or round particles. This stage is protected against mechanical damage by a cleaning stage for sand removal which also operates at IC.

Deinking flotation represents the “heart” of the whole deinking plant. It follows after dilution down to a low consistency (LC) of approximately 1.2%. The main target of the flotation stage is the removal of printing inks but small lightweight particles, stickies, and ash are also removed in the deinking cells when these particles are hydrophobic. As mentioned earlier, the deinking chemicals such as soap and/or tenside are added either in the pulper or directly before the deinking stage, but sometimes the soap dosage is split between both stages.

The multistage fine screening system operates with slot widths of approximately 0.15 mm. If the fine screening stage is the only slot screening stage in the system, a cleaner plant ahead of it for sand removal is recommended for protection against wear.

Fine screening is followed by thickening of the suspension with disk filters and subsequent dewatering by wire or screw presses to a consistency of about 30%. This is the precondition for dispersing. Dispersion takes place at elevated temperatures. The temperature increase is realized by steam injection, either in a heating screw or directly in the disperser. In the dispersion stage, further ink detachment as well as reduction of the size of dirt specks and stickies takes place.

In addition, if bleaching of the fibers is necessary to meet the brightness targets, the dispersion stage is the optimum dosing point for oxidative bleaching chemicals (e.g., peroxide), because of favorable consistency and high mixing efficiency. If bleaching chemicals are added, a HC bleaching tower for adequate retention time at 30% consistency is installed after dispersion.

All the process stages described earlier can be installed in the first water loop of a wood-containing DIP system. State-of-the-art DIP systems for high quality requirements comprise two loops, where, in the second loop, the residual ink, as well as ash, stickies, and other hydrophobics are removed by a second flotation stage. The stock is then thickened again in disk filters to a consistency of approximately

12%. For the highest quality demands of supercalendered (SC) or LWC papers, it is dewatered once more to 30% consistency, heated, and sent to a second dispersion stage for further break down of stickies, printing inks, and dirt specks to sizes under the visibility limit. Optional reductive bleaching is involved either after the disk filter or, if installed, after the second dispersion stage. Chemicals used for reductive bleaching are hydrosulfite/sodium dithionite or FAS.

Finally the stock is pumped into the storage tower. As a summary, Table 8.3 shows the effect of the process stages on the quality parameters [2–6].

For high-grade DIP, an additional fiber design stage, consisting of a minimum one low-consistency refining stage is often implemented between the storage tower and the approach flow system of the paper machine. This is to modify the fiber characteristics in order to improve the final paper quality, namely strength and surface properties.

Brightness and dirt specks are the most relevant quality parameters of DIP. The subsequent figures show how these parameters developed during the stock preparation process. The figures are an example from the production of SC paper with a system similar to that shown in Figure 8.4.

From Figures 8.5 and 8.6, it can be seen that flotation in combination with dispersing and bleaching are the key processes to increase brightness and reduce dirt specks. Dispersing reduces dirt speck area and brightness at the same time. In fact this notice can lead to misunderstanding because dispersing does not remove anything from the pulp. The truth is that dispersing reduces, at least partly, the size of dirt specks below the limit of visibility. Therefore, the smaller dirt specks are no more detected by the measuring device. On the other hand, a great many bigger dirt specks are transformed into a lot of smaller dirt particles that have a larger total surface, thus reducing brightness.

8.4.1.2 System for Woodfree Graphic Paper Grades and Market DIP

Woodfree recovered paper, such as MOW, CWF, and/or UWF, is used as raw material to produce woodfree DIP grades for tissue, woodfree graphic paper grades, or market DIP as a chemical pulp substitute. Table 8.4 shows the raw material quality parameters and the quality demands on woodfree DIPs for named applications.

A typical fiber preparation plant for woodfree DIP production basically uses nearly the same process stages as a plant for wood-containing DIP (Figure 8.7). The main differences from the wood-containing process in Figure 8.4 are found in the thickening stages. In order to be able to achieve the required low ash contents of 2% in tissue production, a washing stage is used instead of the otherwise standard disk filter in both loops for thickening. The washer filtrates contain a large amount of ash and fines. These solids are removed from the filtrate in a subsequent dissolved air flotation unit (DAF) and the ash is thereby removed from the process. Of course in these applications, the yield will be significantly lower than the wood-containing DIP. For woodfree graphic papers or as a chemical pulp substitute, the DIP should not have more than 5% ash content and a maximum of $20\text{--}40\text{ mm}^2\text{ kg}^{-1}$ stickies (according to TAPPI T277, measured in a Somerville laboratory screen

Table 8.3 Effect of the process stages on quality parameters of wood-containing DIP.

Quality parameters process stage	Brightness	Dirt specks content	Stickies content ^a	Ash content	Debris content	Fiber design
Pulping coarse screening	Detachment and dispersion of smaller printing ink particles	Detachment and dispersion of larger printing ink particles	Saving screenability	-	Removal of coarse contaminants	-
HC cleaning	-	-	-	-	Removal of heavy particles	-
MC hole screening	-	-	Reduction	-	Removal of flat particles	-
IC cleaning	-	-	-	-	Removal of sand and debris	-
IC screening	-	-	Reduction	-	Removal of cubical/round particles	-
Flotation 1	Increase by removal of printing inks	Reduction	Reduction	Reduction	-	-
HW cleaning	-	Reduction	-	-	Removal of sand, debris and dirt specks	-
Fine screening	-	Reduction	Reduction	-	Removal of cubical/round particles	-
Washing/thickening/dewatering	Increase by removal of printing inks ^b	-	-	Reduction ^b	-	-
Dispersion 1	Reduction by detachment and dispersion of smaller printing ink particles	Particle size reduction	Particle size reduction	-	-	-
Flotation 2	Increase by removal of printing inks	Reduction	Reduction	Reduction	-	-
Dispersion 2	Reduction by detachment and dispersion of smaller printing ink particles	Particle size reduction	Particle size reduction	-	-	-
Oxidative bleaching	Increase (fibers)	-	-	-	-	-
Reductive bleaching	Increase (fibers and color stripping)	-	-	-	-	-
Refining	-	-	-	-	-	Increase of strength properties and fiber flexibility

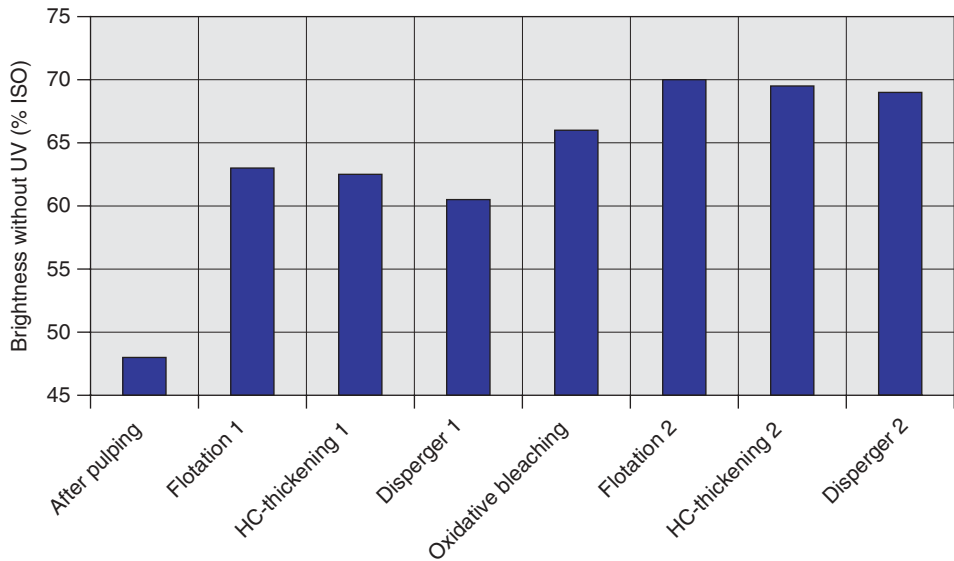
^a According to TAPPI T277.

^b Only, when filtrates are clarified.

Table 8.4 Quality parameters of European MOW/UWF/MWF mix and DIP for different woodfree graphical paper grades.

Grade	DIP brightness (%ISO)	DIP dirt count > 50 μm ($\text{mm}^2 \text{m}^{-2}$)	DIP stickies ^a ($\text{mm}^2 \text{kg}^{-1}$)	DIP ash content (575 °C) (%)
Recovered paper (Mix MOW/UWF/CWF)	60–70	1000–5000	5000 – 20000	15–25
Tissue	80–90	<150	<200	<2
Market DIP as substitute of chemical pulp	80–90	<100	<20–40	<5

^aAccording to TAPPI T277 (measurement with Somerville laboratory screen with 0.15 mm slotted screen plate).

**Figure 8.5** Development of brightness of the pulp during stock preparation of DIP for SC paper production.

with 0.15 mm slotted screen plate) and 100 $\text{mm}^2 \text{m}^{-2}$ dirt count (> 50 μm). This is achieved by installing at least one washing and a second dispersion stage [2–6].

8.4.2

Systems for Packaging Paper and Board Grades

For packaging paper and board grades, recovered paper is the main fiber source with a share of about 60% worldwide. In Europe, most of the mills produce packaging

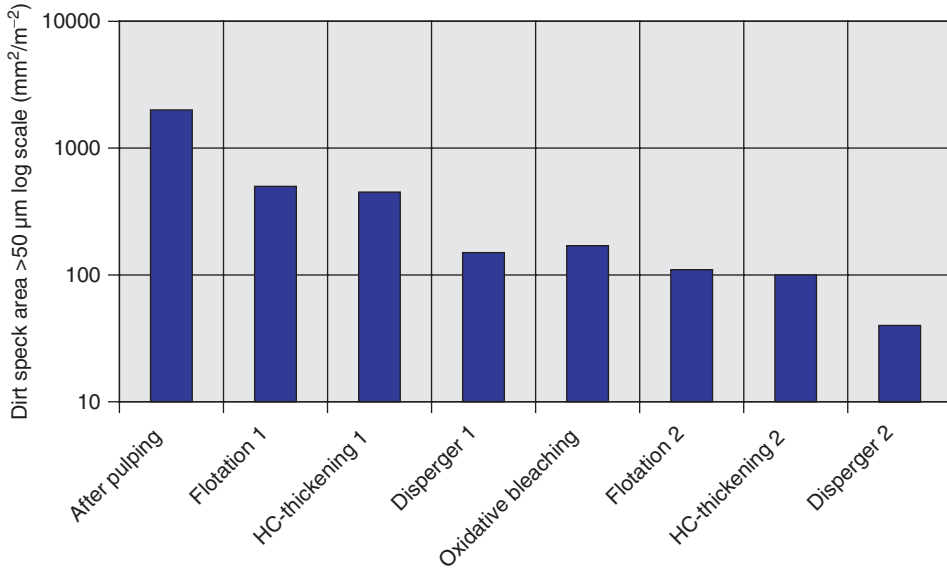


Figure 8.6 Development of dirt speck area of the pulp during stock preparation of DIP for SC paper production.

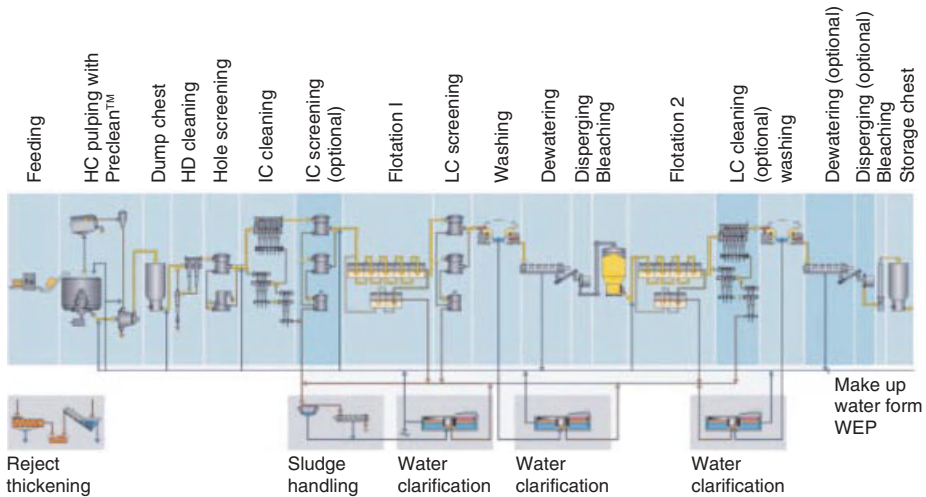


Figure 8.7 Fiber preparation system for woodfree deinked pulp production. (Source: Voith.)

papers based on 100% recycled fibers. The main recovered paper qualities for the packaging grades are mixed recovered paper from households and supermarkets, the latter mainly being old corrugated containers (OCCs). The recovered paper qualities for packaging grades contain much more debris than “white” recovered paper grades.

The recovered paper quality in general, and especially for the “brown” grades, tends to steadily decrease. At the same time the production costs, the stock quality demands concerning the paper machine runnability, as well as the final product properties put high demands on the fiber preparation systems. This results in these more sophisticated systems than they used to be in earlier times. The major objectives in stock preparation systems for packaging grades are cleanliness, strength characteristics, and high yield. The importance of optical characteristics is steadily increasing as packaging material is often printed.

Many of the packaging paper and board grades are multilayer products, meaning that they consist of different layers using more often different recycled fiber types, and also virgin pulp. Therefore different individual fiber preparation systems are often needed. In the case of 100% recycled fiber-based production with multi-layer or multi-ply paper machine forming sections one completely separate fiber preparation plant is installed for each layer. Or, as is also state-of-the-art, different recycled fiber qualities are produced, starting with one fiber preparation line and then separating the stock flow into lines of different qualities by fractionation. These fractions can then be used either separately for each layer on the paper machine or they can be remixed in desired proportions [2, 3].

Figure 8.8 shows a state-of-the-art fiber preparation system for packaging grades without fractionation. The recovered paper, delivered in bales, is put on a conveyor belt where the wires are cut, but not removed, and sent to a continuously operated LC-pulper working at a consistency of 4.5–5.5%. In the pulper wires, strings and other spinning contaminants are removed by the ragger. As various other types of contaminants accumulate in the pulper, an efficient detrashing system is one of the key components of a fiber preparation plant for packaging paper. The slushed stock, after HD cleaning, can still contain up to 20% flakes. It is fed into a dump chest

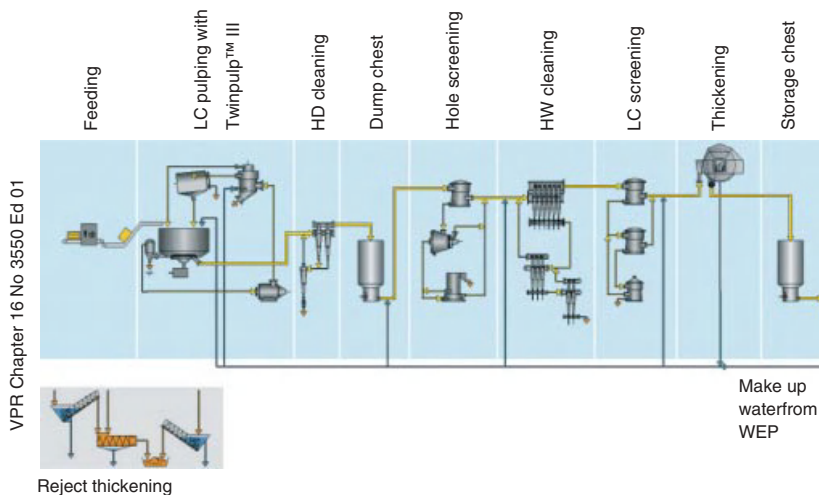


Figure 8.8 Fiber preparation system for packaging grades without fractionation.

chest with a certain retention time, to assist the defiberation of the flakes further down in the process.

After the dump chest the stock is treated in a hole-screening stage at a consistency of approximately 3.5%. The design of this stage depends to a high degree on the flake content of the stock. For high flake contents, disk screens (hole sizes 2.4 mm) are recommended, at least in the second stage, as they are more robust and they have a distinctly higher deflaking potential than cylindrical screens (hole sizes 1.6 mm). The first and second stages are fed forward.

After hole screening, the flake content should not exceed 4% to ensure a good runnability of the following cleaning and fine screening stages. Heavyweight cleaning is done after dilution of the stock and is followed by the fine screening with slot widths of 0.25 – 0.15 mm. Here the major part of the stickies and other contaminants is removed from the process. After that, the stock is thickened in a disk filter for separation of the water circuits of the fiber preparation and the paper machine and to reduce the volume of the following storage tower.

In the case of a fiber preparation line with fractionation (Figure 8.9), the stock after hole screening is fractionated by screening at slot widths of 0.20 – 0.15 mm. The accepted fraction represents the so-called short fiber fraction and is treated further by removing sand through heavyweight cleaning and thickening before storage. The “rejected” fraction is called the *long fiber fraction* and is treated much more intensively than the short fibers. This fraction contains, besides the longer fibers, an increased amount of contaminants and most of the remaining flakes. Therefore it needs to be treated, as a minimum, by a heavyweight cleaning stage and a fine screening stage. If the demand on optical cleanliness is very high, a dispersion stage is used for homogenization. If the recovered papers potentially contain waxes, as in American OCC grades, lightweight cleaners in both fractions as well as a dispersion unit in the long fiber fraction should be installed. For applications,

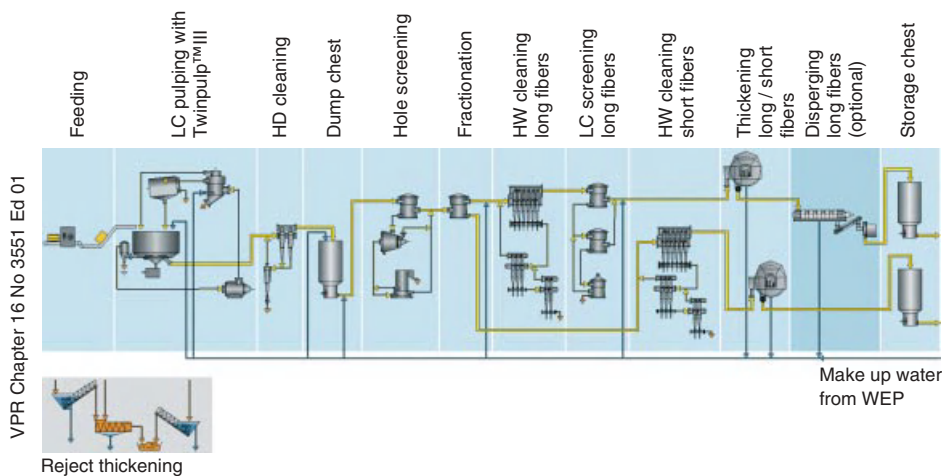


Figure 8.9 Fiber preparation system for packaging grades with fractionation.

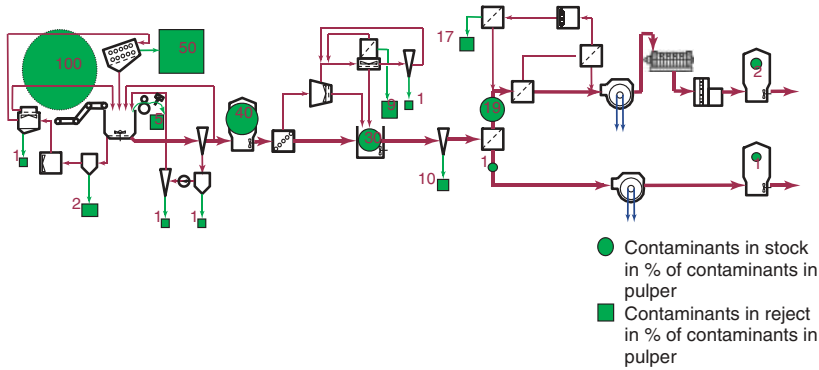


Figure 8.10 Development of stock cleanliness and reject discharge in a stock preparation system for packaging and board grades.

where the recovered fibers still show a potential for strength development, refining of the long fiber fraction is also recommended [2, 3].

As yield is besides specific power consumption, the most important precondition to economic operation every single machine has to be adapted to the requirements and the process. Figure 8.10 shows where the reject is discharged and how the cleanliness of the stock is developed during the stock preparation process. The tail stages in screening and cleaning have the task to separate fibers from undesired material with high efficiency. Tail screening machines therefore need a certain deflaking potential or an additional deflaking device has to be installed.

8.5 Systems for Broke Treatment

Broke is an important stock source and occurs on a continuous basis as trims from the wire as wet broke and from the winders as dry broke. It can also occasionally occur as reel slab-offs, in the finishing room or during breaks in the paper machine or coating equipment. Usually all broke is fed back to the process in the approach flow system. Broke treatment starts with slushing in different pulpers. These pulpers are installed under the machine and dimensioned according to the paper machine width such as couch pit pulpers for wet broke and size-press and reel pulpers for dry broke. Alternatively, they are installed separately such as winder, finishing room, and broke roll pulpers for dry broke. The design of a broke treatment system depends on the requirements of the paper machine and can contain several stages such as thickening, screening, cleaning, and deflaking or can be very simple and consists only of a slushing stages. Sufficient buffer capacity for the broke is also important because it should be fed back in controlled portions as it has different properties from fresh stock because of drying, chemical content or, in coated paper production, too high filler content. In specialty paper production, for example, of wet-strength papers or impregnated papers, broke has

either to be further treated (e.g., by mechanical dispersion, increased temperature through steam injection, or the use of special chemicals for repulping) or be taken out of the paper-making process. In colored paper production, dry broke has to be used immediately or, if this is not possible, stored until the same color is produced again. Paper grades developing wet strength after production should be repulped in time as well [7].

8.6

Peripheral Systems in Secondary Fiber Preparation

In secondary fiber preparation, peripheral systems are very important for the runnability of the whole plant as well as for cost minimization and environmental issues. Peripheral plant components are the reject system, sludge treatment, and water handling. Coarse rejects from the pulping section, heavy particle separation, and hole screening are dewatered to a dry content of approximately 60%. If thermal treatment is involved for these rejects, metal components have to be removed and the particle size adapted to the burning process by means of shredding.

Fine rejects and sludges from the flotation stages and the DAFs are also drained to approximately 60% dry content and either sent to energy recovery or used in the concrete or brick industry [4]. Water handling is another key element as it affects – besides costs and environmental issues – various quality parameters of the finished product such as brightness, cleanliness, or odor.

8.7

Process Engineering and Automation

Presently, advanced process engineering and automation are – because of the complexity of the plants – the basic requirements for fiber preparation systems. Engineering provides the right connection of all the described process stages by planning the process layout and selecting adequate pump, pipe, and chest designs and sizes for low energy consumption and economic investment. State-of-the-art is a nearly chest-free stock preparation system between pulper, dump tower, and storage tower, where fan pumps (like in the paper machine) have widely replaced chests.

The main field of automation in a fiber stock preparation system lies in the control of those operational parameters which are important for every stage in the process, for example, consistency, flow, pressure, level, power consumption, and temperature. It also includes programs in the distributed control system (DCS) for automated startups and shutdowns of the different subsystems or even the whole fiber preparation system. Advanced automation concepts ensure, in the case of production (i.e., oven-dry tonnage) changes, that each subsystem is simultaneously adjusted to the new production requirements. Here, a production set point is entered by the operator or automatically controlled as a function of paper machine

production or the level of the storage tower. The production control value for each subsystem is then calculated, whereby the losses of the individual subsystems are taken into account [8].

Another advanced approach in automation for fiber preparation systems is the introduction of quality control systems. As an example, the operator chooses the desired brightness value of the final stock in the storage tower. The so-called model predictive controls calculate the necessary bleaching chemicals according to the actual conditions measured ahead of a bleaching stage(s) to control the brightness on a feed-forward basis instead of the conventional feedback control strategy. This reduces dead times significantly and leads to more constant quality as well as to reduced costs for bleaching. An additional cost-control module for multistage bleaching processes calculates the most quality- and cost-efficient dosage of bleaching chemicals for each individual bleaching stage [9].

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9 The Integrated Recycled Paper Mill (IRPM)

9.1 Environmental Aspects and Profitability

Lucas Menke

Using recycled paper as raw material has been state of the art for several decades. However, in the last few years, the focus has changed. Aspects such as “sustainability” and “environmental interfaces” that were considered important from the regulatory angle, have gained greater importance from a different point of view. Paper-producing companies have had to look for an improved image or follow tougher regulations, but now they are also aware that these “environmental interfaces” have become significant economic factors. It can be expected that in the future these environmental aspects will become even more important – the rate of change depending on geographical and political situations. Discussions regarding the introduction of sustainability ratings for paper mills and making these ratings available to the public are already on. The labeling of paper products with special benchmarks for sustainability and environmental friendliness might be a next step.

What should be considered as “environmental interfaces?”

New mills should be planned and installed for minimum impact on nature and the environment. Here, the operational environmental interfaces are highly important:

- Use of water resources, energy, consumables, and chemicals
- Discharge of wastewater, rejects, and residuals
- Secondary reuse instead of final discharge and disposal- value to value (V2V)
- Optimized logistics and transport of raw materials, residuals, and the paper products.

The investigation of environmental interfaces is a precondition for any new plant installation, and often a precondition for the start of official permission and validation procedures from authorities.

A special challenge is that every paper mill has individual parameters and boundary conditions that will determine ROI (return on investment) and TCO (total cost of ownership) of appropriate environmental technologies and resource

management. Therefore, to achieve best economic and ecological results, the processes involved need to be individually designed and engineered.

A “typical north European recycled paper mill” is selected as an example to illustrate the economic importance of environmental interfaces (based on figures of 2010):

- Production: 1450 t day⁻¹ of lightweight packaging paper
- Raw material: 100% recovered paper, yield 90%
- Disposal costs for rejects: €75–105 per t
- Disposal costs for sludge (dewatered to 55–60%): €45–65 per t
- In-house freshwater preparation, conventional effluent treatment.

To explain the significance of environmental interfaces, the different costs are shown as percentage of total production costs in Figure 9.1. Costs for environmental interfaces amount to 13.5%, which is a substantial part of the total operational costs.

There are good opportunities to reduce costs and thus improve profitability:

- Reduce freshwater consumption and wastewater discharge by enhanced water reuse.
- Avoid disposal fees by secondary use of residuals, for example, generate replacement fuel (RPFL).
- Use own and third-party RPFLs for energy generation.
- Produce biogas and reduce energy consumption and costs for sludge disposal of the wastewater treatment plant (WWTP) by changing to anaerobic wastewater treatment.

In principle, the operational costs and ROI for environmental interfaces for “greenfield paper mills” can be calculated quite accurately. On the other hand, these costs depend on many factors and might vary continuously. For “upgrade projects”, there are additional challenges such as limitations within the existing

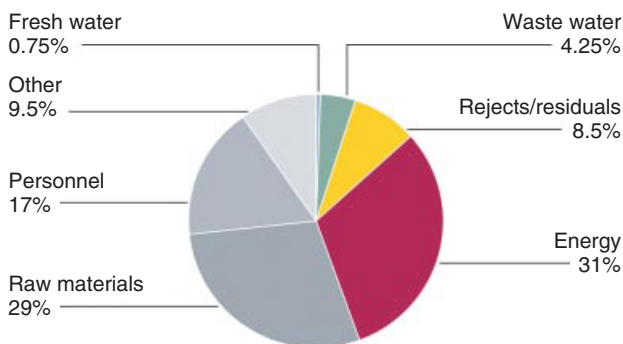


Figure 9.1 Example for the cost distribution in a typical north European paper mill using recovered paper as raw material.

infrastructure and equipment. For a Greenfield- or upgrade- project, the following should be considered for best profitability and sustainable environmental interfaces:

- Creating a team of economical and technical experts from the mill
- Creating a business calculation model, which considers all costs for resources and operation
- Investigating applicable possibilities and technologies and defining target projects
- Verifying possible funding and support from authorities
- Verifying possible projects with industrial partners, for example, secondary use of residuals
- Verifying ROI and TCO of target projects and verifying soft factors, for example, image.

9.2

Subsystems and Peripheral Systems of the Integrated Recycled Paper Mill

Lucas Menke

9.2.1

Overview

In the past and even at present, in many paper mills, all processes other than stock preparation and paper and board production are considered as peripheral and thus of secondary importance. Consequently, attention is paid only to a certain extent to their process design, operational performance, and efficiency. Cross-process synergies are not used often. The approach of the integrated recycled paper mill (IRPM) is to integrate peripheral processes in order to reduce interfaces, save resources, improve operation and profitability, and gain sustainability.

The IRPM includes three process categories (Figure 9.2):

- The core process which comprises stock preparation as well as paper and board production on the paper machine
- The WSR subsystem (water, sludge, reject) involving
 - creation of internal water loops around the paper machine and stock preparation, which are directly connected and significant to the core processes, for example, through selective clarification
 - prethickening and pressing of sludge to remove nonproductive solids and contaminants allowing filtrate reuse
 - safe handling of mostly discontinuous reject streams, which are separated into secondary usable material streams and conditioned, for example, they may be shredded and pressed, to allow subsequent use as RPFL.
- The integrated peripheral systems (IPS), which allow the continuous operation of the core and the WSR processes. Their modules are
 - Automatic material handling of recovered paper: bale opening and recovered paper conditioning as well as feeding to the pulping process

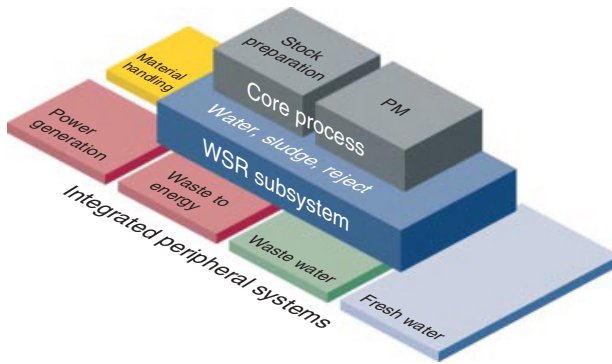


Figure 9.2 The three processes in an integrated recycled paper mill (IRPM).

- Freshwater preparation from own or external sources
- Freshwater management and conditioning for different process purposes such as steam generation, water sealing, and preparation and supply of chemicals for high-pressure felt showers
- Wastewater treatment with pretreatment, anaerobic biological treatment for biogas generating, and aerobic and secondary treatment for clarified water recirculation
- Preparation of process chemicals used, for example, in stock preparation, water treatment, and dewatering, and on the paper machine
- Fuel storage and conditioning to feed incinerators with fuels from own residuals and/or external supply as, for example, biomass, RPFLs, MRF (multiple recyclable furnish), or garbage
- Power generation, for example, by incineration.

9.2.2

Technical and Operational Aspects of the Integrated Recycled Paper Mill

The IRPM makes use of all process synergies between the core and WSR process and the IPS for operational and economical efficiency.

The following lead technical principles are applied here:

- **Complete and better use of raw materials:** In earlier years, the use of recovered paper as raw material was meant to be just a substitute for that of virgin fibers in paper production. In the IRPM, residuals from stock preparation are the input into a secondary value chain (V2V principle). Reject and residual streams are treated by different technologies to get “value fractions” such as high-caloric RPFL from plastics and low-caloric RPFL from sludge, which is used, for example, in brick production or incineration, and recycling metals which came as trash with the waste paper. Some IRPM operators have already started management of external waste stream logistics to secure their recovered paper raw material sources. In the future, waste stream management by IRPMs may be

primarily done to ensure sufficient fuel supply for the mill's incineration power plant to secure energy production in the future.

- **Energy saving and energy production:** Energy savings can be achieved by better optimized processes with improved scalability, taking into account the different production types, start-up and shutdown scenarios, and integration of WSR and IPS as far as possible. Energy can be produced from converted rejects and residuals and external RPFL or biofuels, as well as from biogas from effluent treatment.
- **Water quality management and specific water consumption:** Good water quality management aims for lowest amounts of water consumption and only “good enough” water quality as really needed for the different processes. For example, freshwater should be used only for high-pressure felt showers, sealing, or preparation of chemicals and steam. Continuous control can ensure lowest possible water consumption in stock preparation, for example, by a smart loop design. The principle of “biokidneys” by IPS anaerobic/aerobic water treatment allows bio water recirculation in order to reduce freshwater consumption. This has to be controlled by the limiting factors conductivity and salinity, using recycled biowater in the mill, biocide dosing and lime removal are important factors to achieve good operating conditions.
- **Avoidance of residuals:** Residuals have to be uncompromisingly reduced or avoided. Lowest discharge is ensured by best fiber recovery, dynamic and accurate fines, and ash control. Besides, the higher yield, less sludge saves disposal cost or lowers the portion of low-caloric RPLF in incineration. Anaerobic treatment reduces the organic load (chemical oxygen demand, COD) without generating large volumes of aerobic excess sludge in case of conventional biological (aerobic) treatment. Disposal of aerobic sludge is costly and dewatering, difficult. The use of low dryness biological sludge as RPFL is harmful even when mixed with other RPFLs, as storage is difficult (bad odor), and conveying and feeding of this sticky sludge creates technical problems.
- **Integrated control systems:** An integrated control system for the core, WSR processes and the IPS allows integrated operation and data storage. Besides better integrated operability, important cost-relevant process information goes hand in hand with production data and allows the use of operational synergies and optimization. The main relevant areas are, for example, water management, RPFL, power generation and logistics.
- **Industrial status:** The status of an IRPM allows better perspectives in industrial classification compared to a conventional recycled paper mill, which produces paper from recovered paper and generates rejects, residuals, and wastewater without their further internal use. In contrast to that, the IRPM converts recovered paper and follows the V2V principle, dividing into different streams of valuable resources:
 - recycled fibers;
 - different categories of RPFLs;
 - other recyclable furnishes.

The IRPM can be seen as green sustainable plant that improves the value chain when combined with energy production, using RPFL and biogas from the WWTP, or even using third-party RPFL or municipal recyclable furnishes.

Some newer IRPM projects could even get funding or credit line supports, depending on location and geographical area. Figure 9.3 shows the modules of an IRPM.

9.2.3

Boundaries and Ownership Alternatives

New greenfield recycled paper mills or bigger upgrade projects currently offer some interesting opportunities for investment and operational partnerships and funding. In the last years, many different projects have been executed. As sustainability and environmental friendliness are a main focus, industrials, investors, operators, and public/municipal operations may find new synergies here. In the following, some models are explained.

- IRPM with shared peripheral systems

If multiple industrial producing businesses are situated close to each other, for example, in a business park, there are good preconditions to share certain peripheral systems and use synergies such as

- combined heat and power generation;
- reuse of residuals and biogas for power generation;
- common freshwater preparation and/or combined effluent treatment.

Substantial improvements in sustainability and economics require the investment of time and engineering (Figure 9.4).

- IRPM and build–own–operate (BOO) models

In these models, all peripheral systems (or part of them) are owned or operated by third parties. These systems may include power generation, freshwater and wastewater treatment as well as chemical supply and/or operational dosing (Figure 9.5). The paper company owns and runs just its core business, “paper production.” The BOO model contract typically defines parameters, for example, “tons/of paper produced” on which specific operational costs are based. For new paper mills, these IRPM advantages and synergies should be included in the BOO contract. A BOOT (build–own–operate–transfer) contract may allow the transfer of ownership and operation of the peripheral systems to the mill in later years.

- IRPM and private–public shared peripheral systems (PPP)

In this special form, a part, or all IPS, are owned and may be operated by public authorities, for example, for power generation using municipal waste and paper production residuals. Municipal wastewater especially could be combined with (anaerobic) pretreated paper mill wastewater. It is essential that, for such PPP projects, the IRPM engineering and process principles continue to be applied for better overall efficiencies and economical synergies. PPP

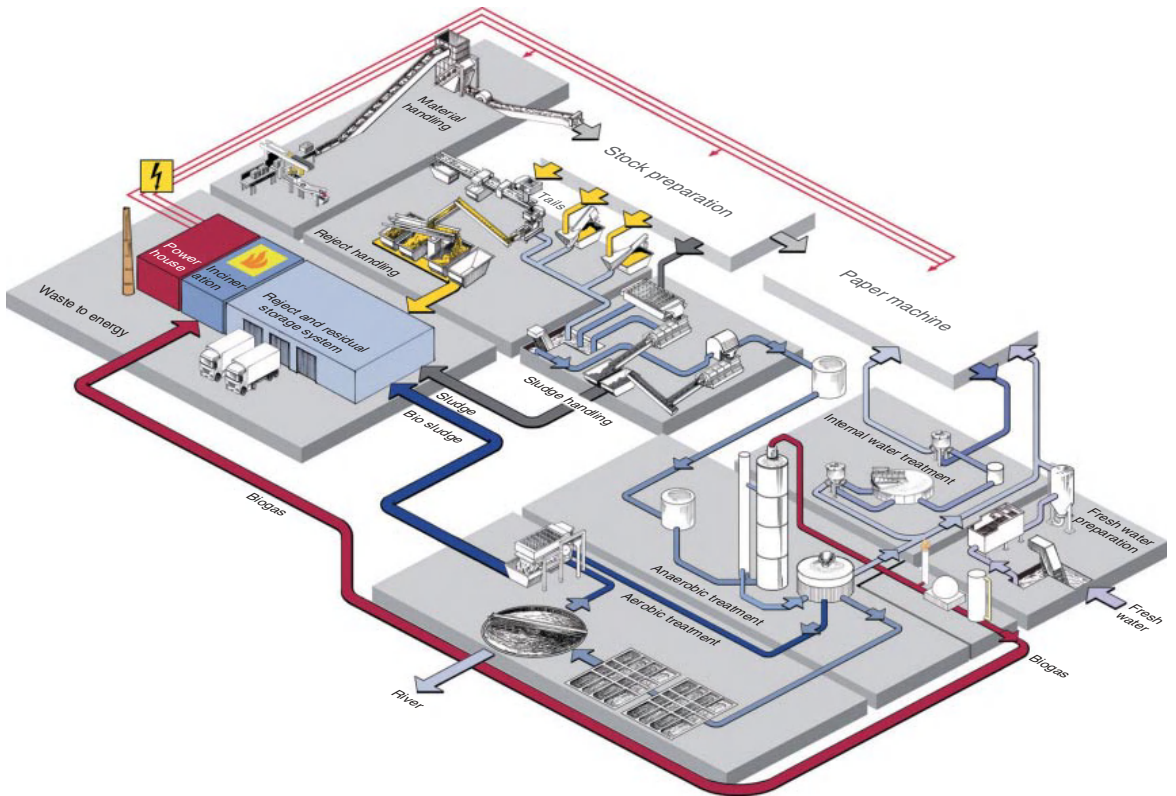


Figure 9.3 The modules of an integrated recycled paper mill.

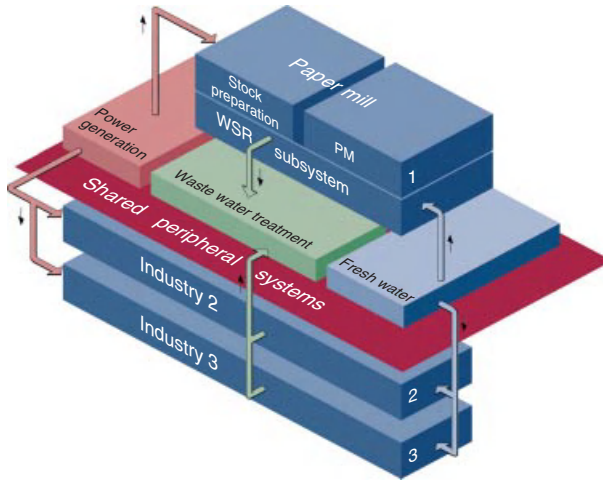


Figure 9.4 IRPM with shared peripheral systems.

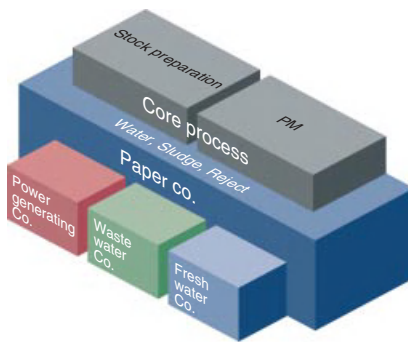


Figure 9.5 IRPM BOO (build-own-operate) and similar models.

projects in some case could be considered as “public infrastructural funding” securing long-term sustainability, which generally is well supported by public opinion.

9.2.4

The Urban Mill Model

It can be expected that sustainability and resource management in the context of paper production will be the “driving or breaking” factor toward new projects in the future.

The outlook is to combine and integrate the IRPM further into a life-cycle-oriented value chain and to bring sustainability to a further level, in the so-called “urban mill projects” (Figure 9.6):

- Combine the logistics for MRF, recovered paper, and municipal waste, securing the shortest possible ways, and avoid intermediate storage as far as possible.

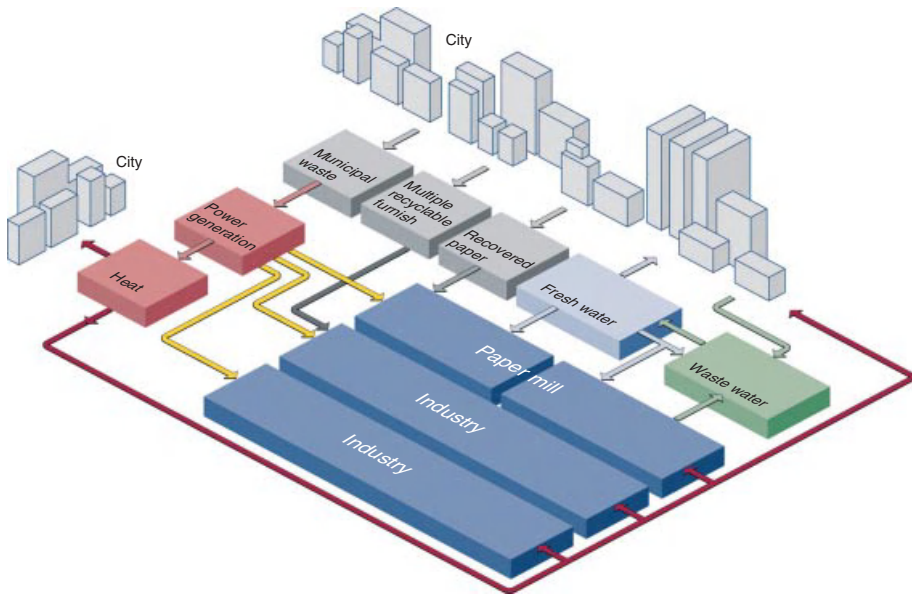


Figure 9.6 The “urban mill model” as an integrated paper mill, which gains advantages through synergy.

- Use residuals and waste to produce energy, which can be reused at its maximum in the form of electrical, power, steam, and heat transfer for public heating.
- Minimize the use of freshwater and wastewater discharge by intelligent water management through, for example, “cascaded water reuse,” not only within the IRPM but over the urban and different industrial water processes.

9.3

Subsystems for Water, Reject, and Sludge (WSR)

Lucas Menke

The WSR subsystems are directly connected to the main production processes, stock preparation, and paper machine. The subsystems are connected to each other as well. Filtrates from rejects and sludge dewatering are discharged to the water subsystem. The water subsystem clarifies water streams by removing nonusable fibers and solids as well as contaminants in the form of organic matter, be it colloidal or dissolved. Water clarification generates sludge, which in turn must be dewatered in the sludge system again.

Figure 9.7 shows the interconnection between the WSR process blocks and the importance to consider cross effects and interconnection of loops. This gives an overview of these systems, whereas WSR treatment technologies are explained in detail in the following chapters.

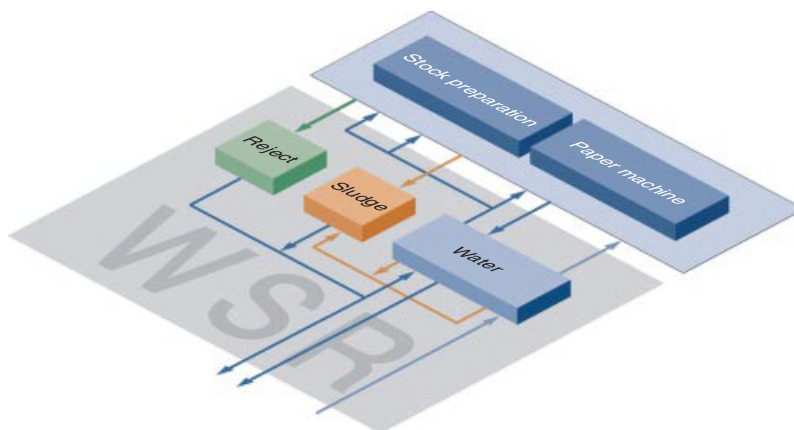


Figure 9.7 Water sludge reject (WSR) subsystem.

9.3.1

Water Subsystems

The aim of water subsystems is to secure good enough water quality when the water is looped and reused. To secure adequate water quality for the main process, water clarification must eliminate all solids that are not useful for paper production, such as fiber fragments, fines, ash, and contaminants. Contaminants appear in many different forms, for example, they may be colloidal or partially dissolved, and might require special preconditioning before they can be separated. With good water management and water clarification, freshwater consumption can be brought to a minimum at reasonable costs. Expensive techniques such as membrane filtration, which can remove ultrafine or dissolved matter are not necessary usually, and hence would not pay off.

9.3.2

Sludge Subsystems

Sludges are considered as residual solid streams without coarse contamination. They must be preconditioned and dewatered to a dryness level that allows handling, pressing, and transporting in the sludge subsystem. In case the sludge is considered for secondary use, for example, for incineration, stable and high final dryness is essential.

Sludge streams are mostly homogeneous; they contain nonusable fibers, ash, ink and fillers, or substances from water clarification. The source of sludge streams are deinking flotation, water clarification, low-consistency (LC) cleaning, and fine screening. The difference between sludge and rejects is defined by the level of coarse and inert contamination, and how continuous or discontinuous the discharge from the main process is. Compared to sludge from water clarification and flotation, some “fine rejects” from cleaning and screening can be considered and treated as

sludge as well, as long as the level and type of contamination is not harmful for the sludge handling equipment. Critical contaminants can be, for example, sand, glass, and broken stone, or small plastics.

9.3.3

Reject Subsystems

Reject systems treat residuals separated during pulping, screening, and cleaning in stock preparation and at the paper machine. Rejects can be differentiated by size, type, occurrence, and heat value into two groups:

- Coarse rejects are bigger in size. They appear during pulping, and during coarse or hole screening, and contain mainly plastics. These rejects have a high secondary value (heating). Depending on the type of pulping system, trash and heavy coarse rejects, for example, bigger metals, are already sorted out or need to be sorted out. Coarse rejects are reduced to a smaller size, metals are further separated, and the reject is then dewatered to highest dryness before it is used as valuable RPFL for incineration.
- Fine rejects are of smaller size originating from high-consistency (HC) cleaning, LC cleaning, and fine screening, which in most cases require different types of conditioning of these streams. Generally, the secondary value of fine rejects is comparably lower, some streams cannot be reused at all, and others have to be dewatered quite well to be reused as low-caloric RPFL. Some fine reject streams can be directly forwarded to the sludge subsystem if permitted; this depends on their type and level of contamination.

9.4

Water Circuits

*Lucas Menke and Andrea Stetter**

9.4.1

Introduction

Water is, besides fibers, the key component in pulp and paper manufacturing and fulfills numerous functions in the process. It is used as a transport medium, for cleaning and cooling, as a lubricant and finally as the “binding agent” for forming hydrogen bonds between the fibers within the paper sheet. In earlier times, paper was produced with a high specific freshwater consumption in the range of $500 \text{ l (kg paper)}^{-1}$. In the last few decades, for economic as well as ecological reasons, the average water consumption has been reduced to less than $10 \text{ (kg paper)}^{-1}$ or lower as state of the art depending on the type of paper produced. This dramatic reduction was only feasible owing to the increasing closure of the in-house water circuits and also because majority of the former freshwater consumers are now being fed by clarified circuit water [1].

* Contributed to the First Edition.

9.4.2

Freshwater

Depending on the availability and local conditions, surface water and, to some extent, groundwater are the usual sources of freshwater in a paper mill. Surface water, in particular, does not meet the required quality parameters and therefore has to be conditioned by filtering and/or chemical coagulation and flocculation and subsequent sedimentation before use. For boiler house use and in specialty paper production, for example, production of photographic base paper or cigarette paper, the freshwater is softened and/or desalinated. With the limited amount of freshwater available nowadays, this resource must be used efficiently. In general, the freshwater taken into a mill is first used for cooling; then it is distributed to its process consumers, either directly or after further heating. There are only a few freshwater consumers in modern mills, such as chemical preparation and dilution systems, sealing water consumers (mainly vacuum pumps), and some high-pressure sprays for felt conditioning.

9.4.3

Process Water

Most of the water used in a paper mill is process water, that is, water that is recycled in the different water loops of the water circuit of the system before disposal. The process water is “produced” in the thickening and dewatering stages of the papermaking process. Owing to its content of solid, colloidal, and dissolved substances, the quality of process water is lower than that of freshwater.

9.4.3.1 **Detrimental Substances**

Major process changes in paper production in the last two decades have been

- a strongly increased use of recovered paper;
- the change from acid to neutral systems in the paper machines;
- the reduction in freshwater consumption.

These changes have led to steadily growing problems because of an increased content of the so-called detrimental substances in the water loops. Detrimental substances stem from wood components as resin or lignin derivatives, from freshwater as humic acids, from broke and recovered paper as coating binders, glues, and adhesives, from additives as fatty acids or silicates, starch, and others. Table 9.1 shows the composition and origin of detrimental substances in the process water [2].

Detrimental substances can cause a lot of problems throughout papermaking process, some examples being reduced efficiency of additives, reduced optical and strength properties, poor sizing, bad odor, negative effects on drainage and drying, and therefore reduced paper machine speed. These substances are the main reason for deposits and foam generation causing defects in paper as well as resulting in paper web breaks. Detrimental substances include anionic oligomers and polyelectrolytes as well as nonionic hydrocolloids [3]. Their content in the

Table 9.1 Composition and origin of detrimental substances.

Chemical compound(s)	Origin
Sodium silicate	Peroxide bleaching, deinking, recovered paper
Polyphosphate	Filler dispersing agent
Polyacrylate	Filler dispersing agent
Starch	Coated broke, recovered paper
Humic acids	Freshwater
Lignin derivates, lignosulfonates hemicelluloses	Chemical and mechanical pulp
Fatty acids	Mechanical pulp, deinking

water circuits is usually measured with the help of some parameters as the so-called anionic trash, measured as cationic demand by polyelectrolyte titration in a streaming current device or as COD.

The presence of inorganic dissolved substances, that is, salts, is measured in terms of increased conductivity in the water circuit system. Salts are detrimental to the process performance and potentially to the paper properties. Electrolytes reduce the swelling potential of fibers and chloride especially leads to corrosion of machine parts [4]. The content of detrimental substances in paper mill water circuit systems depends on the input of raw materials, on the output by bleeding through wastewater disposal as well as by the degree of transfer to the final paper, on the loop design, and on the presence of “kidney” technologies in the mill.

For different applications, such as sprays in the paper machine, solids (mainly fibers, fines, and fillers) in the process water are also disturbing and have to be removed before the water is used.

9.4.4

Typical Paper Mill Water loops

All processing cycles in paper production are connected directly or indirectly by water loops. The objectives of the water circuit system are to offer the required volume rate and quality of water for each consumer and to treat and/or bleed out water containing detrimental substances. A water circuit system of a paper mill usually includes different water loops (Figure 9.8):

- Paper machine loop including the approach flow system and the white water systems I and II (WW I and II)
- One or two (in special cases, such as market DIP (deinked pulp) production, sometimes even three) water loops in the stock preparation.

End-of-pipe treatment for bled-out water is carried out in WWTPs, which are either owned by the mill or the public. In a few cases, mills have completely closed their water circuits, meaning there is no wastewater produced at all and freshwater therefore is only fed at the same volume rate (approximately $1.5 \text{ l (kg paper)}^{-1}$) as

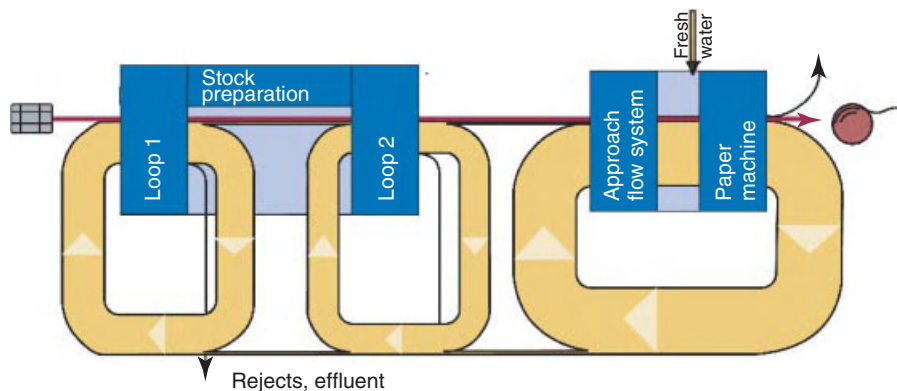


Figure 9.8 Water loops in a paper mill.

it is removed by evaporation in the dryer section of the paper machine and with the rejects leaving the mill.

Owing to the challenges mentioned earlier, water management is an absolute must for every modern paper mill. Some important principles have to be followed in order to manage the water circuit system successfully:

- efficient loop separation, that is, transferring stock from one process loop to the following one should be done only at high consistency (preferably 30%), that is, at low water content, in order to avoid transferring detrimental substances from one water loop to the next to the greatest possible degree;
- application of countercurrent flow, that is, freshwater is added only at the paper machine; excess water from each loop must only be sent backward and wastewater is disposed of only from the first loop in fiber preparation (lowest quality water);
- no mixing of water from different production lines in mills where more than one paper machine is operated;
- no mixing of water from different fiber preparation lines and/or pulp preparation plants;
- use of kidney technologies for removal of solids and/or detrimental substances;
- adequate sizing of the water buffers for each water loop in accordance with the stock storage volumes for avoiding uncontrolled overflows in start-up, shutdown, or paper machine sheet break situations.

9.4.4.1 White Water Circuit System

The white water circuit of a paper machine, also called the paper machine loop, consists of the WW I and II and the save-all unit. WW I, coming from the wire section, is used to directly dilute the main stock flow after the machine chest in the approach flow system and for profile control in the headbox. WW II originates also from the forming section and additionally from the press section (after removal of felt hairs, usually with a bow screen), from broke thickening and from the overflow of WW I. WW II is sent to a buffer tank and from there it is used at the end of stock preparation to dilute stock from high consistency (12–30%) to storage

consistency (4–12%) and for slushing and diluting broke. A defined amount of WW II, preferably the majority of it, plus the trimmings from the forming section are fed to the save-all unit. Save-alls have a dual function: stock recovery and water clarification. Most of the modern paper machines are equipped with a disc filter save-all unit treating a certain volume of WW II by filtering it through a fiber mat. This mat is formed by adding a so-called sweetener stock to the WW II filter. For sweetener stock, usually the best dewatering stock component used at the paper machine is selected in order to limit the size of the disc filter. In addition to cloudy and clear filtrate, disc filter save-all applications also produce a super clear filtrate with very low solid content. This superclear filtrate is used as a freshwater substitute for spray applications in the paper machine. The clear filtrate is stored in a buffer tank. The cloudy filtrate is usually fed directly back to the inlet of the disc filter, the “used” sweetener, including the recovered stock, is fed back to the thick stock in the approach flow system. DAF (dissolved air flotation) type save-alls are used in older machines and nowadays when a certain degree of ash and fines removal from the process is demanded. In this case, the sludge of the DAF is rejected. The advantages of a disc filter save-all compared to a DAF save-all are higher filtrate quality, no chemical consumption and less space requirement.

There are two reasons that there is always an excess of water present in the paper machine loop. First, the paper machine loop is continuously fed with freshwater used for spraying and chemical dilution. Second, the incoming water content of the stock is higher (consistency 12–30%) than the water content in the sheet after the press section (consistency up to 50% and more). This excess water is sent, in the form of clear filtrate, backward from the save-all unit, as makeup water, to the stock preparation, thus following the countercurrent principle. This makeup water is often additionally treated in a DAF with coagulation and flocculation chemicals in order to remove detrimental substances before feeding it backward.

9.4.4.2 Water Circuit Systems in Stock Preparation

In some cases, the water circuit system of a paper mill consists of only one water loop, for example, when chemical pulp is the only fiber source or in lower quality packaging paper production. For systems using mechanical fibers and/or recovered paper, the strict separation of the water loops in stock preparation from the paper machine loop is essential in order to meet high runnability and quality demands, because this strategy keeps detrimental substances from the paper machine. Depending on the required quality of the prepared fiber stock and thus on the design of the stock preparation system, the water circuit system in the stock preparation can consist of from one to three water loops. The loops are separated by the thickening/dewatering process stages (disc filter and wire press or screw press). The filtrates of these stages are sent backward for dilution purposes in the same loop; the excess water (usually clear filtrate from the disc filter) replenishes the preceding loop. A water buffer tank, usually fed by clear filtrate from the disc filter in loop I, avoids uncontrolled overflow to the WWTP. Wastewater is disposed of from the first water loop as filtrate from reject and sludge thickening, as these filtrates are of low quality. Usually, they are treated chemically or mechanically in

a DAF unit. Depending on the freshwater consumption, a certain amount of this treated filtrate can be recycled into the process.

To reduce the content of detrimental substances within a water loop, DAF units are used as the so-called kidneys for circuit water cleaning, usually in the second loop of the stock preparation. In this case, a combination of coagulants and flocculation aids are added to part of the clear filtrate from the disc filter in loop II in order to precipitate and flocculate detrimental substances into a floatable form and subsequently remove them from the process in the DAF. High ash content in recovered paper is also problematic for some paper grades. Here, washing stages in the stock preparation only make sense when large amounts of ash need to be removed. Therefore nowadays, the filtrates of screw presses are often de-ashed in order to achieve a reduction in ash content in the final stock. Usually, the screw press filtrate is precalibrated in a spray filter for fiber saving and the fiber-free but ash-containing filtrate is then also sent to a DAF unit after the addition of flocculation aids.

9.4.4.3 Examples of Millwide Water Circuit Systems

Three examples show in detail, how the different water circuits for the various paper grades are designed.

9.4.4.3.1 Water Circuit System for Graphic Papers

Water Circuit System in a DIP-Based Newsprint Mill Figure 9.9 shows the water circuit system for a modern newsprint mill using DIP as the fiber source.

The system consists of three water loops, two in stock preparation (because of the combination of flotation–dispersion–flotation) and one in the paper machine.

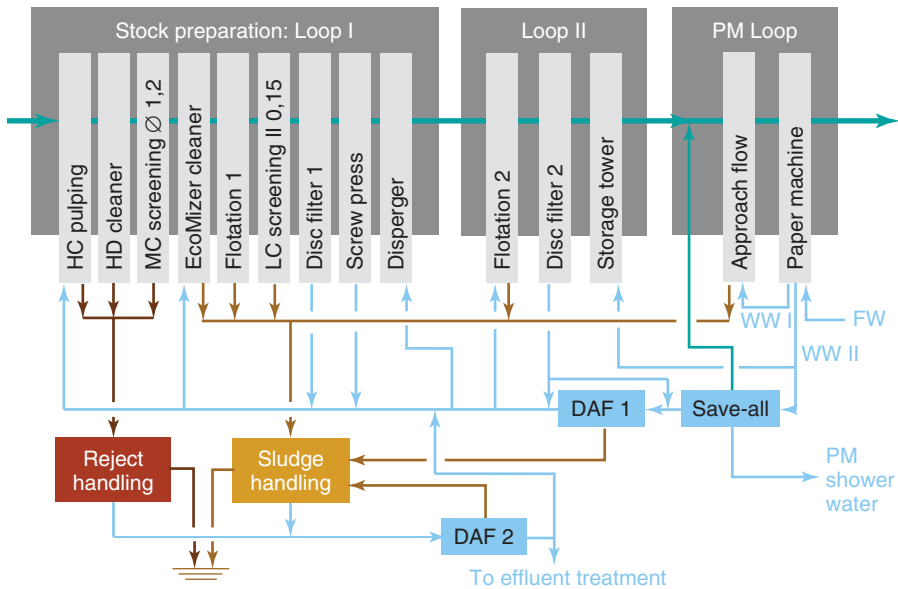


Figure 9.9 Water circuit system in a DIP-based newsprint mill.

The water circuit design follows the previously mentioned principles of counter current flow and thereby allows the freshwater to be used to the maximum effect. In addition, the save-all is followed by an additional DAF unit. DAF 1 is used as a kidney for removal of detrimental substances, treating the makeup water from the paper machine (clear filtrate) together with part of the clear filtrate from the disc filter in loop II. DAF 2 treats the filtrates from reject and sludge dewatering. The clarified water is partly recycled back into loop I, the rest being sent for effluent treatment.

Water Circuit System in a DIP-Based LWC Mill Figure 9.10 shows the water circuit system for lightweight coated (LWC) paper also using DIP as the fiber source.

There are again three process water loops and the countercurrent principle is consequently used. Compared to the newsprint, LWC based on DIP requires a higher DIP quality. The lower ash content required in the final stock and the higher demands on brightness, justifying two bleaching stages, necessitate bigger efforts also in the water circuit system, that is, in kidney technologies. Therefore three DAF units are installed. DAF 1 is used for removal of detrimental substances from the paper machine makeup water. DAF 2 provides the necessary ash removal from the filtrates of the screw presses in loops I and II after precalibration and treatment of the disc filter filtrate in loop II. DAF 3 clarifies filtrates from reject and sludge treatment, which are then partly recycled, the rest being sent for effluent treatment.

Water Circuit System in a Mill for Packaging Paper The configuration of water loops in systems for packaging grades is less complex than for graphic paper grades. Older or lower quality packaging paper systems are often single-loop systems. Modern systems with an integrated LC screening in the stock preparation plant use a thickening stage before storage and therefore consist of two water loops, one

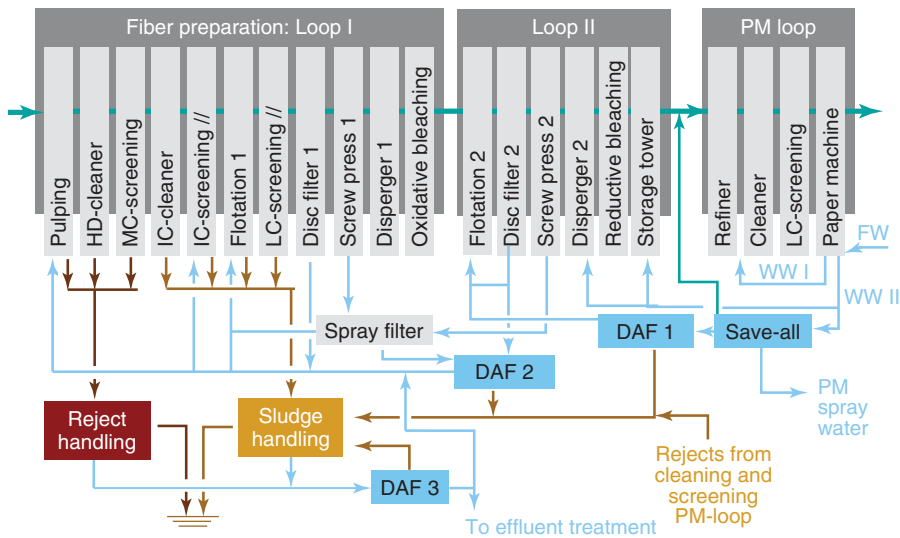


Figure 9.10 Water circuit system in a DIP-based LWC mill.

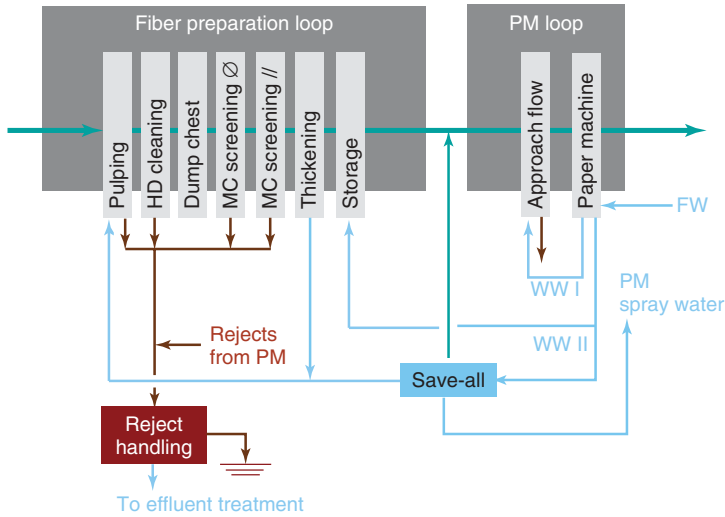


Figure 9.11 Water circuit system in a mill for packaging paper (testliner and fluting).

for the paper machine and one for the stock preparation system. Figure 9.11 shows such a water circuit system in a modern mill producing testliner and fluting.

Again, the freshwater is added only at the paper machine. WW II is used for redilution after thickening in the stock preparation plant. The save-all clear filtrate is used for makeup in the fiber preparation system. Filtrate from the thickening stage in the fiber preparation system is the main source of water for slushing and dilution. Wastewater is sent as filtrate from reject handling to the end-of-pipe effluent treatment system.

9.4.4.4 Current Limits on Circuit Closure

The maximum reuse of the water employed is limited by the various detrimental substances in the process water. Their concentration, measured as COD concentration in the water (in parts per million), increases at a disproportionate rate when reducing the specific effluent (l (kg paper)^{-1}). The higher the water circuit system is closed, the more COD ($(\text{kg COD})(\text{t paper})^{-1}$) is loaded into the paper instead of being bled into the wastewater (Figure 9.12) [5]. This leads to a disproportionate increase in various problems because of the detrimental substances, as mentioned earlier. Therefore, the state-of-the-art systems are limited to certain specific (l (kg paper)^{-1}) effluent volume rates with respect to a certain minimum freshwater consumption as shown in Table 9.2.

Consequently, the multiloop systems for graphic paper grades nowadays follow the countercurrent principle and partly use circuit water cleaning according to the kidney principle. So it is possible to reduce the specific water emissions down to $8\text{--}10 \text{ l (kg paper)}^{-1}$. Further closing would lead to increased amounts of detrimental substances. This would negatively affect product quality, for example, decreased optical properties and increased stickies and dirt content as well as

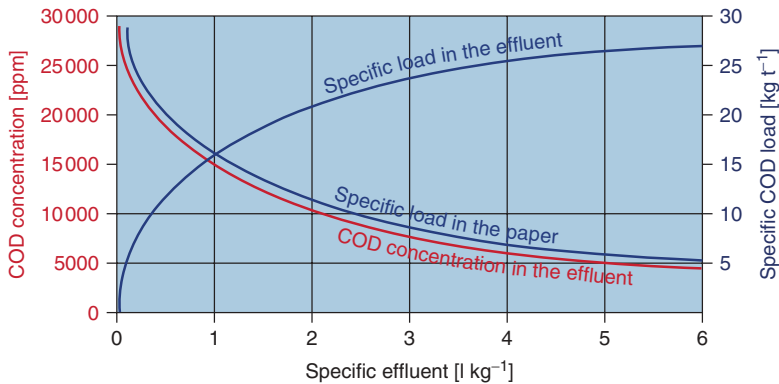


Figure 9.12 Effect of loop closure on COD values.

Table 9.2 Recent limits of system closure.

System application	Specific effluent	Disturbing effects limiting further closure
	Volume in l kg^{-1} paper	
<p><i>Graphic paper grades</i></p> <ul style="list-style-type: none"> • Several water loops • Countercurrent flow • Circuit water cleaning (kidney) 	8–10	<ul style="list-style-type: none"> • Decreasing product quality • Felt/shower plugging • Lower particle retention • Scaling • Slime
<p><i>Board and packaging grades</i></p> <ul style="list-style-type: none"> • Single or two loops • Water treatment only for showers 	3–5	<ul style="list-style-type: none"> • Odor problems (water and product) • Corrosion • Deposits

runnability problems on the paper machine, such as felt and shower pluggings, reduced retention, scaling, and slime formation. The typically simpler board and packaging-grade systems with their somehow lower demands on water management can work with specific effluent volume rates of a minimum of $3\text{--}5 \text{ l (kg paper)}^{-1}$. Further closing these loops without using additional internal circuit water cleaning could lead to odor problems both in the mill and in the paper itself, as well as corrosion and deposits, and the paper machine runnability would be significantly reduced.

9.4.4.5 Zero-Effluent Systems

Reducing the effluent volumes to zero means that freshwater consumption is reduced to $\sim 1.5 \text{ l (kg paper)}^{-1}$. Here problems would arise from the extremely high

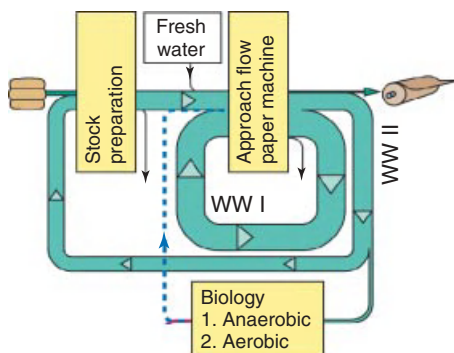


Figure 9.13 Zero effluent concept for a packaging paper mill.

amounts of detrimental substances, which will be bled out of the process only by transferring them into the paper. The only solution to these problems is to remove the detrimental substances from the process with suitable highly efficient kidney technologies. These include, in addition to circuit water cleaning by coagulation and flocculation with subsequent removal in a DAF unit, anaerobic/aerobic combinations of biological treatment, different membrane filtration technologies such as micro-, ultra-, or nanofiltration down to reverse osmosis or evaporation [6, 7].

Some packaging paper mills in central Europe currently run with zero-effluent systems (Figure 9.13) using a combination of anaerobic/aerobic biological treatment as kidney technology for COD reduction [6].

The driving forces for reducing the effluent to $0.1 \text{ (kg paper)}^{-1}$ for these mills, were unique to each mill. In one case, there was high cost-saving potential by completely avoiding effluent fees for disposal into a public effluent treatment plant (ETP). In another, the reason for complete water circuit system closure was the lack of available freshwater because of the local conditions when installing additional production capacity [7].

The other mentioned kidney technologies, that is, membrane filtration and evaporation, are mainly known as *pilot-scale applications* as they are quite cost intensive and still not proven state of the art [7].

9.5

Reject Systems

Lucas Menke

9.5.1

Definitions

Solid substances, which cannot be used for papermaking are of different types, for example, waste, trash, residuals, rejects, and sludge. The following definitions have been established and are now used in the industry.

9.5.1.1 Waste

Waste refers to all nonusable items that can appear in other comparable industries but have nothing to do with paper recycling, paper producing, and paper related processes. Examples under this category are oil bins, chemical containers, special packaging material (e.g., polystyrol), composite residuals (e.g., felts and wires), and others. Furthermore, the word “waste” is not used in combination with paper recycling and paper producing industry. In reality, paper industry uses recyclable “value material” and converts it to primary value material as paper and secondary value material such as RPFL.

9.5.1.2 Residuals

Residuals are rejects and sludge and stand for residual secondary value materials appearing from the papermaking process, which can be used in different process steps or industries.

Rejects are

- solids of smaller or larger inhomogeneous size;
- solids that appear mostly discontinuous in different daily quantities;
- solids that are a composition of very different materials.

Rejects appear from “separating process stages.” In most cases, they are wet with about 10–30% consistency.

Special rejects are biomass residuals such as

- bark
- wood broke
- sawdust.

Sludges are

- solids of smallest size appearing as a suspension;
- solids that appear on a continuous basis, typical with consistencies of 1–10%;
- solids that, in general, do not contain larger-particle-size contamination.

9.5.1.3 Trash

Larger waste objects that might appear occasionally in reject streams, but must be considered as nontypical “accident type” objects or matter in raw material streams, are considered as trash. Typical examples are larger steel pieces, mechanical items, or bulk garbage. Figure 9.14 shows an amount-related flowchart.

9.5.1.4 Reject Systems

In the following, only rejects that come from paper mills using recovered paper to a high percentage as raw material are considered. Rejects from virgin paper mills, for example, based on groundwood as raw material are not in focus here as such rejects are mainly biomass products. They are in most cases ready for use as biomass fuel or secondary industrial products.

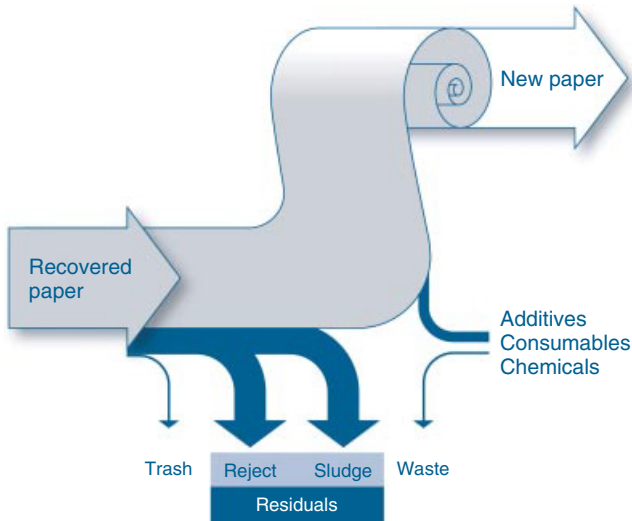


Figure 9.14 Typical amount-related flowchart of residuals.

In recycled paper mills, reject systems are the combination of multiple transport and process stages. They allow the conditioning and separation of the reject streams for subsequent reuse as secondary value materials, efficiently handle and economically dispose of these rejects, or use them as landfill.

Reject systems are individually designed, depending on the following factors:

- Reject rate in percentage to be expected with recovered paper intake in tons per day
- Equipment used for pulping, detrashing, and hole screening
- Determination of reject fractions and respective requirements, for example, when used as secondary value fuel, in separate or mixed fractions
- Transport and logistics requirements and operational conditions, for example, storage
- Requested performance (tons per day, particle size, dryness, fraction contents)
- Required operational availability, for example, for maintenance during operation.

For the planning of reject systems, it is recommended to involve external partners such as transportation and logistics companies, or companies who will use secondary value materials (e.g., BOO partners) as early as possible to secure all cross synergies possible.

9.5.2

Types of Rejects from Different Process Stages in Stock Preparation

The process modules in stock preparation plants differ depending on the type of paper produced and the required stock quality. So plants for recycled paperboard,

newsprint, or tissue have completely different residual or reject profiles, that is, quantities and qualities of the single reject streams are different.

However, the type of rejects and the way to treat them depends on the process blocks and the installed equipment. Therefore, in the following, the reject system modules are described depending on the main process equipment installed.

9.5.2.1 Coarse Rejects

9.5.2.1.1 Rejects from Pulping and Detrashing Three different pulping systems must be considered, each of which discharges rejects in different manner and of different quality:

- Drum pulping
- Continuous conventional LC pulping
- Discontinuous HC pulping.

Rejects from Drum Pulping Currently, drum pulping is used for old corrugated containers (OCC) and white grades. The difference is the cleanliness of the recovered paper fed. As the drum pulper rotates slowly and has no cutting edges, the reject is more or less washed out in a state as found in the input (Figure 9.15).

The fiber reject separation happens in a large sorting drum that might bundle the rejects in spin-ups, and in the worst case, in ropes. The reject is mostly discharged continuously, but in some cases discontinuous dumping is seen as well, when big, coarse, trash pieces that had entered the drum pulper they are unloaded into the reject system. When the pulping process is (re)started, water and fiber flush outs can be expected.

The following has to be considered for a drum pulper reject system:

- The reject is discharged mostly continuously but high volume dumps appear.
- The reject is bundled in spin-ups, and in the worst case, ropes have to be expected.



Figure 9.15 Typical rejects from drum pulper.

- Coarse trash is unloaded as it enters the drum pulper.
- Start-up conditions might be critical because of flush out of water and fiber.

Compared to other pulping systems, drum pulping requires a more sturdy and sophisticated reject system. Reject handling simply by hand and man power as seen in early years will be no option in the future for health, safety, and environmental reasons.

Rejects from Low-Consistency Pulping LC pulpers are typically operated in conjunction with junk separation, detrashing, and a sorting drum. The stock flows through an extraction plate with holes on the pulper bottom and the rejects are typically removed continuously through a lateral discharge. The reject stream runs through a junk trap or junk tower, for heavy-part separation, and is then pumped by a detrashing system to a sorting drum. Riggers or ropes are used for additional trash and reject removal. In older installations, grippers are used for direct trash removal.

Reject systems for an LC pulper should take into consideration that lightweight coarse reject, mainly plastics (Figure 9.16).

- is discharged nearly continuously from the sorting drum mostly fiber-free;
- is free from coarse trash and metals;
- has a consistency of 15–25% (after predewatering);

whereas heavyweight coarse reject (trash, metals, stones)

- is discharged dumpwise, in wet condition from an automated junk trap containing fiber suspension;
- removed by a gripper from an intermediate junk tower and dumped mostly dry.

Rejects in the form of ropes from the rigger are

- steel wire spin-ups containing plastics, tapes, and bundled lightweights;
- discharged rope pieces of selected length (1 m).
- Special safety precautions are required in rope handling in many cases.

Rejects from High-Consistency Pulping HC pulpers are typically used in processing higher qualities of recovered paper (newspaper, magazines) to produce white



Figure 9.16 LC pulping reject.

grades. They are operated intermittently. After pulping and dilution, the suspension is run through a detrashing system with a screen-sorting function. The rejects flow to a sorting drum. A heavy coarse reject discharge is installed in some systems and might be combined with the detrashing pump.

Reject systems for a HC Pulper should consider the following:

- Lightweight coarse reject (mainly plastics), which
 - is discharged nearly continuously from the sorting drum, and is mostly fiber-free;
 - has a (predewatered) consistency of 15–25%;
 - may contain heavy coarse particles (small to medium size) when no junk removal or heavy discharge system is installed;
 - can be critical for the installation of reject handling modules in older systems as they may have low-positioned sorting drums.
- Heavy coarse rejects (small to medium trash, metals, stones), which
 - are discharged discontinuously from heavy outlets of the detrashing system or pump-screening devices, if the respective equipment is installed.

Rejects from High-Consistency Cleaning HC cleaning is installed after pulping to remove smaller heavy coarse particles typically from 1 to 10 mm by cyclone separation. HC cleaner reject discharge is wet and their removal is batchwise, depending on their characteristics:

- Small heavy parts such as sand, stones, glass and staples, hard plastics.
- Staples that might have built up chains, which require special handling (Figure 9.17).
- Depending on HC cleaner operation, rejects might be discharged as a suspension with higher fiber content that might require special handling.



Figure 9.17 Rejects from HC cleaning.

Rejects from Coarse Hole Screening Coarse hole screening use holes typically in a range of 2–5 mm of diameter, depending on the screen design (disk or cylindrical or a combination). Some screens have special heavy discharge outlets. Reject discharge can vary depending on screen design or equipment used. In general, the lightweight reject stream appears continuously with higher consistencies of 15–25%. Some hole screens discharge with very low consistency and therefore require different reject treatment. Heavy rejects from hole screens contain small particles, which are typically treated by centrifugal cones (Figure 9.18).



Figure 9.18 Rejects from hole screening.

For hole screening rejects the following should be considered:

- Lightweight reject (mainly plastic foils)
 - is discharged nearly continuously from screens;
 - has a (predewatered) consistency of 15–25%;
 - might be discharged as low as 1–5% by special equipment.
- Small heavies discharged from screens are forwarded to special centrifugal cones for HC cleaning.

9.5.2.2 Fine Rejects

9.5.2.2.1 Differentiation between Fine Rejects and Sludge In principle, the differentiation between “fine rejects” and “sludge” is fluent and depends on the perspective from which it is seen. Fine rejects are distinguished from sludge by the level of coarse and inert contamination and require separate treatment compared to sludge only when

- the type or level of contamination is harmful for the sludge dewatering or pressing equipment
- sludge dewatering does not exist in the WSR subsystem, because typical “sludge generators” such as water clarification, flotation, or effluent pretreatment are not installed or are located far away.

In the case that reject disposal is inexpensive, and coarse and fine rejects can be dewatered together, the compromise of lower final dryness may be acceptable.

9.5.2.2.2 Fine Rejects from Low-Consistency Cleaning LC cleaning is operated in two different ways, as

- heavyweight LC cleaning to remove fine sands, clay type solids, and so on;
- lightweight reverse cleaning to remove lightweight matter such as wax, plastic foams, or polystyrol.

LC cleaning is always operated as multistage cascade system. The rejects are discharged continuously with low consistencies of 1–3% (Figure 9.19).

For handling of LC cleaner rejects, the following should be taken into consideration:

- Prethickening is required and fibrous materials can be expected.
- Heavyweight LC cleaner rejects are abrasive and may cause mechanical wear in subsequent installed equipment.
- Heavyweight LC cleaner rejects will cause sedimentation in nonstirred chests or tanks.
- Lightweight LC cleaner rejects can be sticky and may deposit on surfaces and wires.

9.5.2.2.3 Fine Rejects from Slotted Fine Screening Fine screening is typically installed as multistage cascade system and removes contaminants such as stickies, glue agglomerates, melts, and resin residuals. Rejects are discharged with a low consistency of around 1% on a continuous basis.

For handling of fine screening rejects, the following should be considered:

- Prethickening is required, the reject contains fibrous materials.
- Fine screening rejects can be sticky or slimy.



Figure 9.19 Rejects from LC cleaning.

Table 9.3 Amounts of reject and sludges dependent on recovered paper grade and the paper produced.

Produced paper	Recovered paper	Amount of total waste (% by dry weight)	Amount of waste (% by dry weight)			
			Rejects		Sludges	
			Heavy weight and coarse	Light weight and fine	Flotation deinking	White water clarification
Graphic paper	News, magazines	15–20	1–2	3–5	8–13	2–5
	Superior grades	10–25	<1	≤3	7–16	1–5
Hygienic paper	Files, office paper, ordinary, medium grades	28–40	1–2	3–5	8–13	15–25
Market DIP	Office paper	32–40	<1	4–5	12–15	15–25
Liner, fluting	Sorted mixed recovered paper, supermarket waste	4–9	1–2	3–6	–	0–1
Board	Sorted mixed recovered paper, supermarket waste	4–9	1–2	3–6	–	0–1

Typical amounts of rejects and residuals for different types of recovered paper and board productions are shown in Table 9.3.

9.5.3

Technology of Reject Handling Systems

The term *reject handling systems* covers a wide range of technical solutions for reject handling. In the simplest case, these are systems that consolidate the various rejects of residues and dispose of them, largely untreated, possibly following dewatering only, in stores such as bunkers or containers.

However, the term *reject handling systems* is also used to define complex systems that produce replacement fuels (RPFLs) which as well are called , refuse-derived fuel (RDF) from rejects and residues.

The complexity of a reject system mainly depends on the recycling and/or disposal methods used. The recycling or disposal method defines the required reject quality. To reach the required reject quality, various handling stages, in addition to the straightforward transport function, are required in most cases.

The following are typical reject handling stages:

- Predewatering (removal of free water)
- High-pressure dewatering, that is, pressing to the highest possible stock consistency
- Single-stage or multiple-stage crushing to attain a required particle size
- Detection and separation of large particles and coarse contaminants

- Detection and separation of large metal particles
- Separation of reject fractions according to size
- Magnetic separation of metal particles that contain iron
- Separation of nonferrous metals
- Mixing of different individual reject flows.

Special requirements also exist for reject conveyance:

- Reliable conveyance must be possible, even with fluctuating reject mass flows or under difficult conditions such as in surge water.
- The controlled split of the reject mass flow is often required, which makes special conveyors necessary.
- Rejects may have to be conveyed over long distances and in closed conveyor systems, for example, because of odors.

Another major challenge in reject handling is the fact that it involves material flows, the composition, quality, and accumulation quantities of which can vary greatly in the short term. Contaminants in waste streams often have very unusual characteristics and sizes.

In addition to the challenges for designing new reject systems, the required operational standards are often relatively high, particularly in terms of operating efficiency:

- Maximum availability for operation 24 h a day, seven days a week:
 - Upsets or failure in the reject system must never lead to a plant shutdown.
 - Bypass circuits must be provided for use during breakdowns and maintenance.
 - In bypass mode, provision must be made for the reprocessing of partially treated reject.
- Low operating costs in association with the
 - lowest possible energy consumption;
 - high resistance to wear (high durability and the lowest possible costs for wear parts);
 - low servicing and maintenance costs (good accessibility for maintenance, easy installation and removal of wear parts, etc.).

In the past, reject systems were often not included in the overall planning of new material processing until at a very late stage. Special attention is now paid to the reject handling system as early as in the preplanning stage. In many cases, reject handling must be planned in association with the relevant logistics, such as collection and disposal, and must therefore be included in the layout plans at an early stage.

Modern reject systems usually consist of conveying systems that bring together individual flows. Steps such as shredding or high-pressure dewatering will follow this process.

Figure 9.20 shows examples of a block diagram and layout of the various reject handling stages.

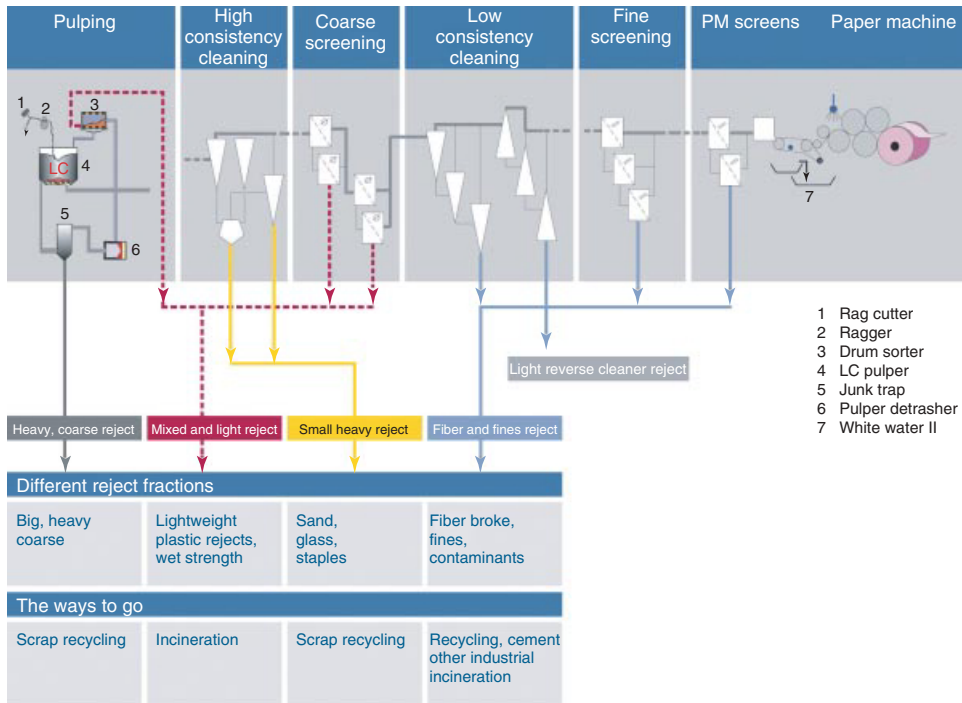


Figure 9.20 Example of a block diagram and layout of the various reject handling stages.

9.5.3.1 Coarse Reject Handling

Coarse reject handling from pulpers is a major issue in all material processing involving recovered paper. Reject accumulation and quality can vary greatly depending on the configuration of the pulper system and the kind of raw material processed.

9.5.3.1.1 Drum Pulper Coarse Reject Handling Drum pulpers are usually fed with recovered paper, either loose or as de-wired bales. With drum pulper rejects, the following assumptions can be made:

- Reject generally accumulates continuously.
- Reject may contain large contaminant particles (unlike conventional pulpers, as drum pulpers do not have a size-limiting detrashing system).
- Pulper ropes may form, particularly if dewiring quality is poor. Pulper ropes are critical for all reject systems; they must be removed as soon as they are detected; this usually is done manually.
- With drum pulpers, larger water surges or pollutant discharges can be expected, for example, during start-up or during grade changes.

Figures 9.21 and 9.22 show a schematic and a photograph of a typical drum pulping reject system.

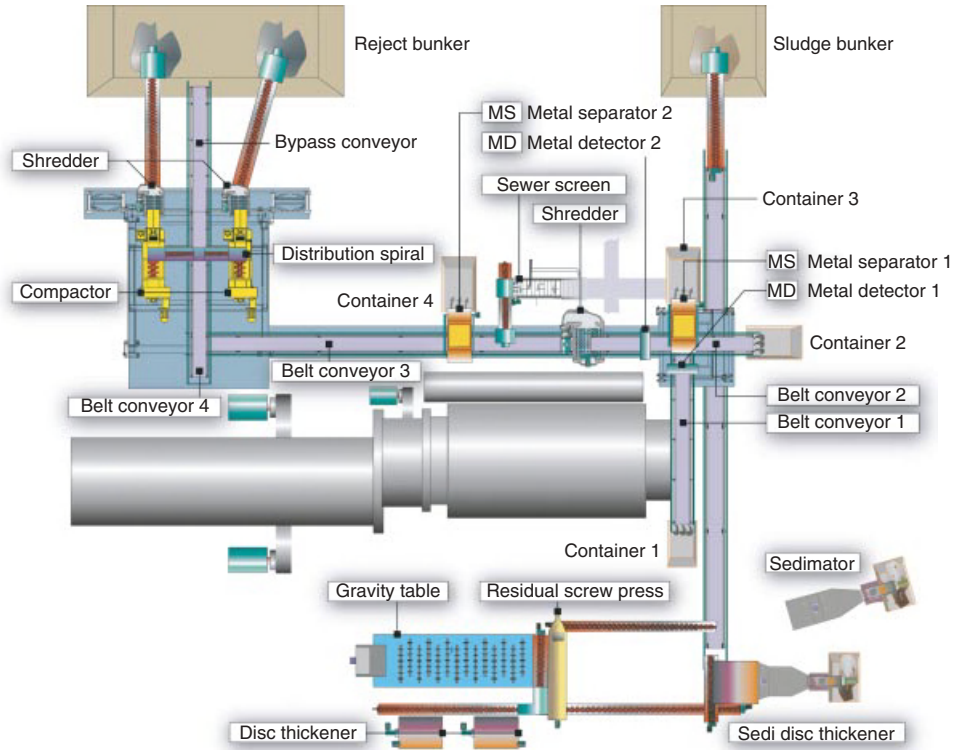


Figure 9.21 Typical drum pulping reject system.

9.5.3.1.2 Conventional Pulper Reject Handling A distinction is made in principle between HC and LC pulpers.

HC pulpers usually work intermittently. Dewired recovered paper bales are loaded and pulpers are equipped with a heavy particle sluice. Reject is drawn off discontinuously via an appropriate waste disposal system. The reject is usually fed into a sorting drum. A timing system allows the reject to accumulate intermittently in batches in predewatered condition. The following are the typical characteristics of the reject:

- Reject is predewatered.
- It undergoes timed accumulation in batches.
- Reject particles may be light or large.

LC pulpers operate continuously. Wires usually are not removed, but are used for spinning the pulper rope. The reject is removed continuously or at short intervals via a waste disposal system and dewatered in a sorting drum. The pulping rope is pulled by means of a winch and cut into long pieces. The characteristics of the reject are as follows:

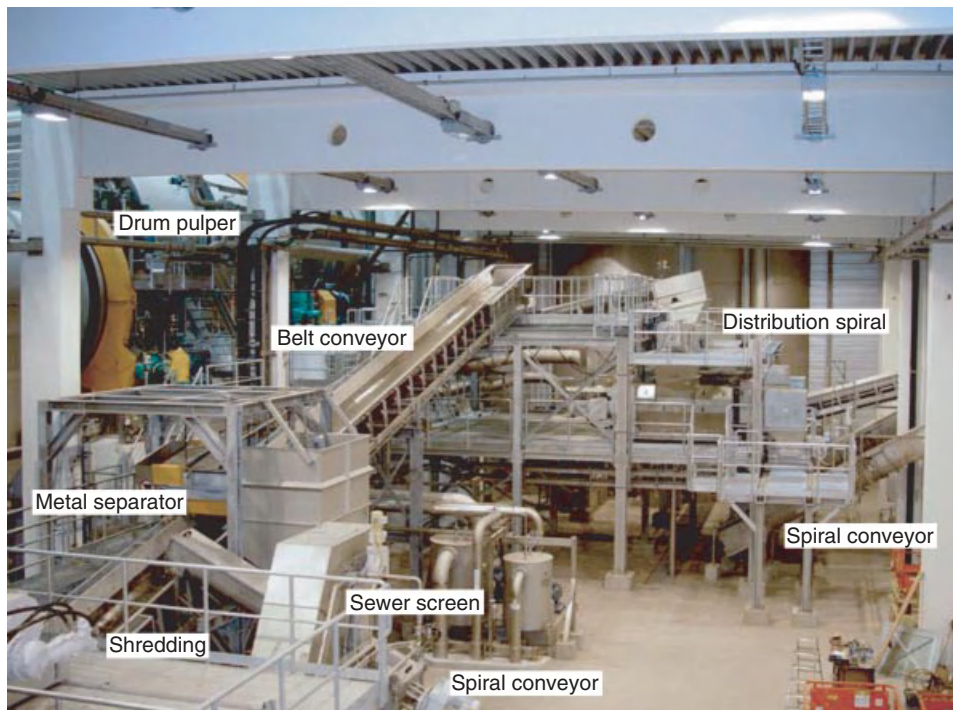


Figure 9.22 Photo of a drum pulping reject system.

- Reject is predewatered.
- Accumulation is uniform.
- The pulping rope requires special handling and/or separate disposal.

Figures 9.23 and 9.24 show the schematic and a layout of a typical HC pulper reject system.

9.5.3.1.3 Handling of Ropes The handling of pulper ropes is critical. On the one hand, there is a high risk of injury, and on the other hand, it is difficult to find alternative disposal methods. Disposal of nonprocessed pulper ropes is very expensive. For this reason, pulper rope separation into the basic metal and plastic reject fractions became prevalent, particularly in Europe. The required standards for this type of processing plant are high, and special processing equipment that can handle hydraulic rope shredding is needed. The ropes are shredded in several stages; metal parts are removed by means of magnetic separation (Figure 9.25).

9.5.3.1.4 Lightweight Reject Handling Lightweight reject handling is a process in which smaller plastic and foil parts are separated by means of coarse hole screening. Depending on the hole screening system, this reject accumulates

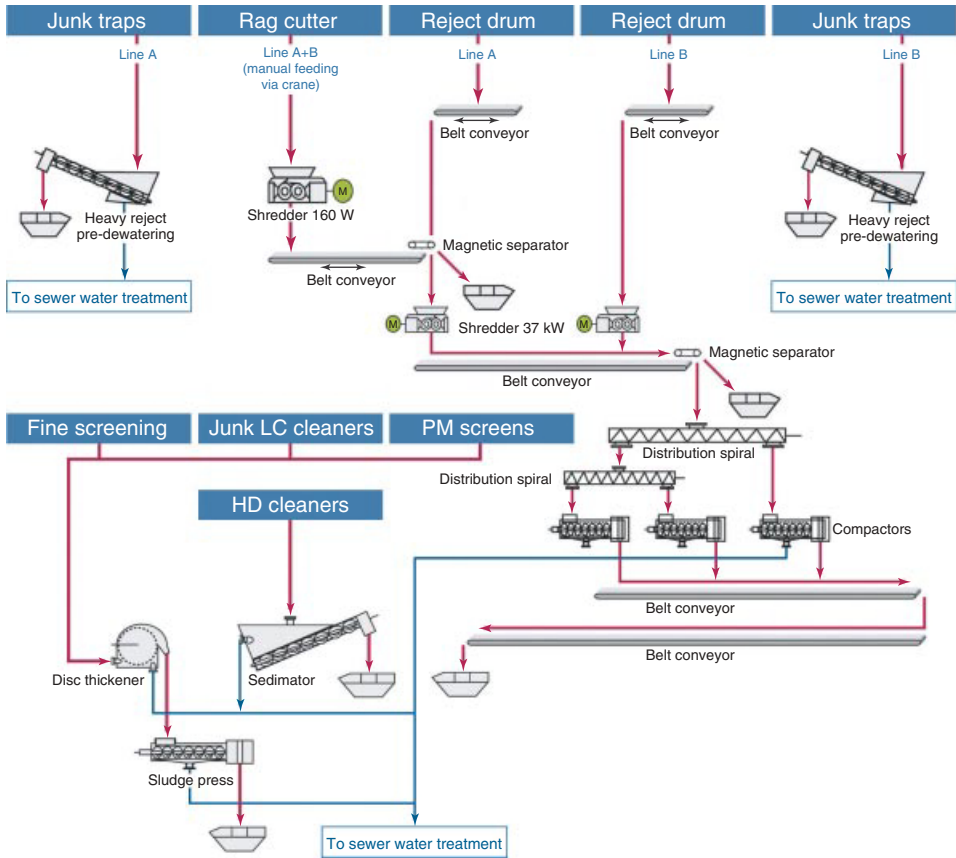


Figure 9.23 Schematic of typical HC pulper reject system.

either continuously or intermittently, usually in predewatered condition. The only significant distinctions are fiber content and dryness. In most cases, this reject can be added directly to high-pressure dewatering systems.

9.5.3.2 Fine Reject Handling and Combined Systems

The selection of the appropriate process stage depends on the degree of contamination of the fine reject. In almost all cases, fine reject accumulates with a very low material consistency, that is, predominantly in the liquid state, and must consequently be dewatered in one or two stages.

When the degree of contamination with inert materials (sand, glass, staples) is low, fine rejects can be dewatered together with sludge. The inert materials (sand, glass, staples) from HC or LC cleaners are usually initially separated from fine rejects using sedimaters, conveyed out of the overflows into containers, and separated from other solids such as fine materials or reject fibers, in water treatment stages.

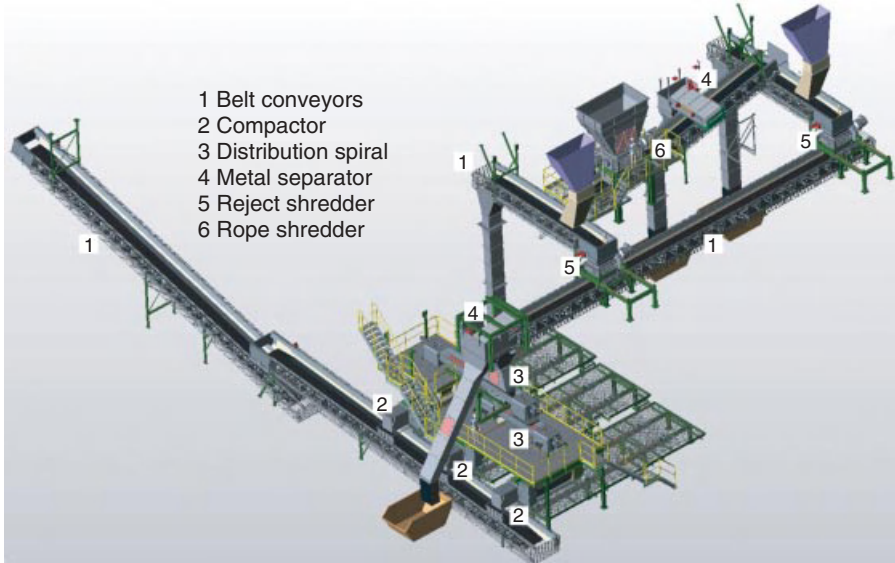


Figure 9.24 Layout of a typical HC pulper reject system.

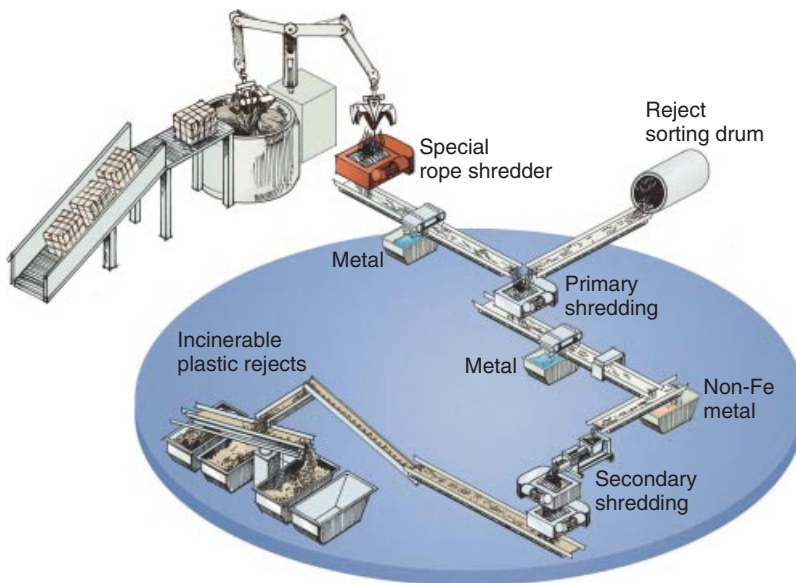


Figure 9.25 Typical rope shredding system.

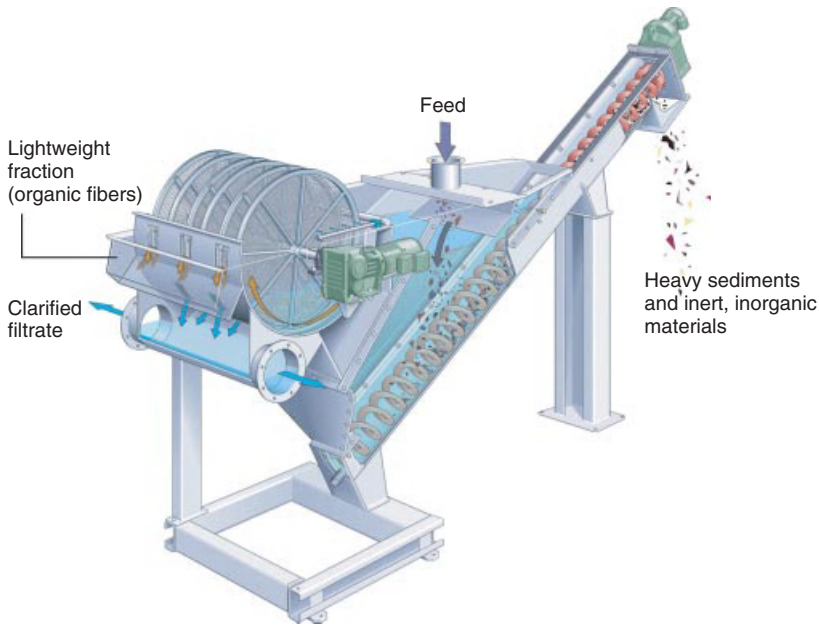


Figure 9.26 Three-phase separating device.

Sometimes a three-phase separation process is applied, separating small, heavy, and inert rejects from lightweight rejects and fiber suspension, while simultaneously cleaning the water (Figure 9.26).

9.5.4

Reject Conveying and Storage Equipment

9.5.4.1 Reject Shredding

Shredders are usually used for crushing rejects. The important criteria for the selection of the machine type are the particle size that can be achieved as well as the resistance to wear and the serviceability. Low-speed, twin-shaft machines for which the wear parts (blades) can be reconditioned economically have proved to be advantageous (Figure 9.27).

9.5.4.2 Reject Dewatering – Reject Pressing

Screw presses are established in high-pressure reject dewatering, particularly where high dry contents of around 60–65% need to be reached and where high availability is important (Figure 9.28).

Hydraulic punch presses tend to be mechanically more fragile and achieve significantly lower dry content levels (40–50%).

Simple press containers are used in some regions, in particular when the final dry content plays a subordinate role because of the disposal situation (low costs) and at the same time small reject quantities are handled.

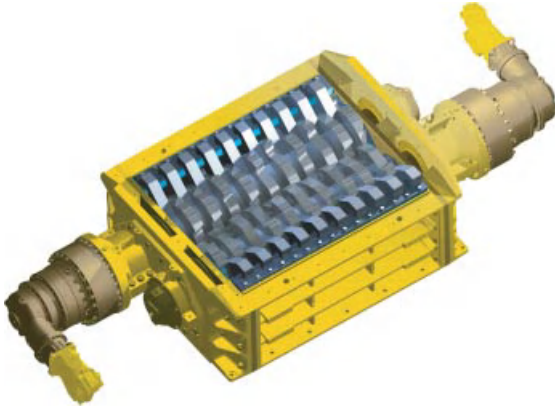


Figure 9.27 Typical shredding device.

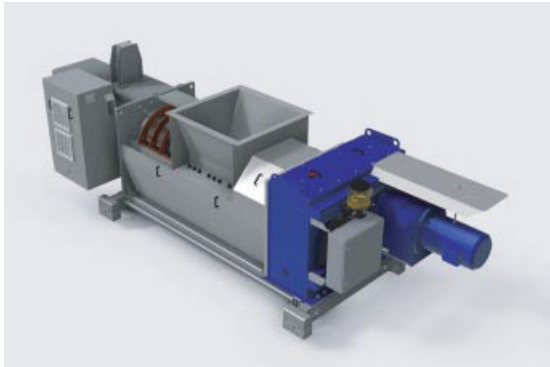


Figure 9.28 Reject screw compactor.

9.5.4.3 Metal Detection and Magnetic Separation

Capacitive metal detectors are used to detect large metal parts. These devices can usually be programmed and can detect metal parts of a specific critical size. These can then be removed, for instance, by reversing the conveying elements.

Magnetic belt separators are used to separate ferrous metals. Correct arrangement plays a major role in achieving high efficiency with this type of equipment.

9.5.4.4 Reject Conveying Systems

Many different conveying elements are used in reject conveying systems. The selection of these mainly depends on the following parameters and criteria:

- The particle size of the reject to be conveyed and the type of contamination
- Whether the reject is wet or dry
- Quantity to be conveyed and conveying distance
- Pitch of the route
- Open or closed conveyor route.



Figure 9.29 Pocket conveyor for long distance pickup at multiple locations allowing complex routing.

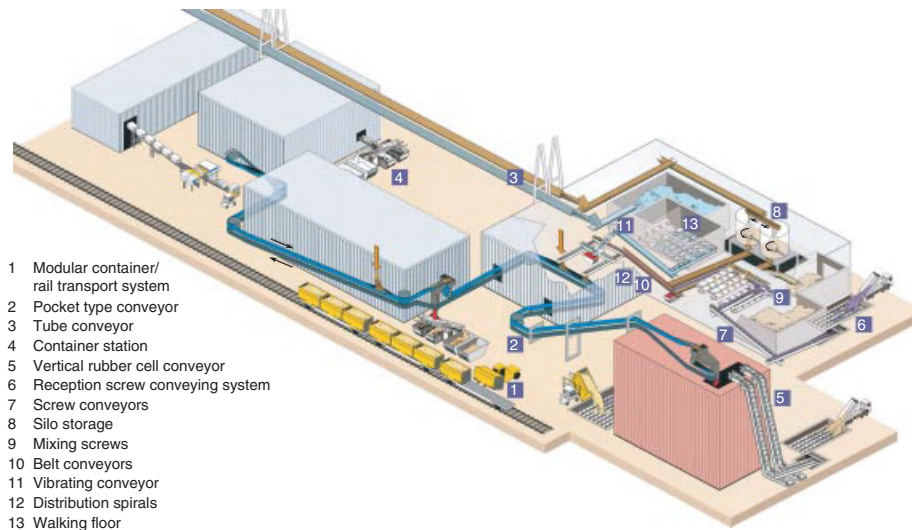


Figure 9.30 Example for mill conveying systems.

The correct dimensioning of conveyor units plays a major role, largely because of discontinuous accumulation. Reject places specific requirements on all conveying equipment, particularly if the reject is wet and high contents of plastic foils are expected. Both special belt conveyors and screw conveyors are available.

More recent, long-distance conveying technology permits different locations to accommodate various reject streams. This means that the reject and residues can be brought together economically (Figure 9.29). To cover all mill internal transport requirements, human power should be avoided for economic reasons. Recent millwide conveying systems (Figure 9.30) provide typically fast ROI depending on regional wages.

9.5.4.5 Reject Storage Systems

The design of reject storage systems largely depends on the required storage capacity. Containers are particularly suitable for smaller reject quantities. Automatic container filling stations are available for these systems.

Bunkers are usually used for storing large reject quantities for which special feeding systems are available. Wheel-type loaders, which load trucks directly, can usually be used to empty bunker systems economically.

For temporary storage of larger reject volumes because of logistical reasons, crane systems with claw buckets in combination with moving floors are used in most cases. The reject can then be bagged in a controlled way. However, the reject particle size has to be reduced accordingly (Figure 9.31).



Figure 9.31 Typical storage system for high- and low-caloric residuals feeding incineration, using cranes, live bottoms, and special conveying equipment.

9.6 Sludge Dewatering Systems

Lucas Menke

Sludge dewatering systems are an important component of WSR subsystems. Efficient sludge dewatering is essential for low disposal costs, while feedback of previously cleaned dewatering filtrate plays an important role when optimizing specific water consumption.

Besides dewatering, chemical and physical processes are also carried out during the sludge dewatering process. Chemical conditioning by adding polymers ensures high dewatering levels and good filtrate quality.

9.6.1

Sludge from Different Process Stages and Their Characteristics

In recovered paper processing, several sources of fine rejects, depending on the type, quantity, and quality are considered as process sludge.

9.6.1.1 Sludges from LC Cleaners and Slotted Screens

Sludges and fine rejects from LC cleaners and slotted screens usually accumulate in the form of thin fluids with stock consistencies of 1–3% and can only be fed into sludge dewatering if the proportion of inert contaminants, such as sand or fine broken glass, is very low. Otherwise, inert contaminants can lead to excessive wear, for example, of screw presses and centrifuges, or can significantly shorten the service life of belt filter presses.

Sludges and fine rejects from LC cleaners and slotted screens can usually be dewatered effectively. The rejects of slotted screens usually contain a high proportion of structural fiber-type material, which allows efficient dewatering in screw presses. Cleaning of the filtrate is recommended if it is returned to the process.

9.6.1.2 Deinking Sludges

Sludges from deinking cells usually accumulate with a stock consistency of 1–2%. The high percentage of fine materials and ash, with little structural material, is characteristic of these. For this reason, mixing with other sludge streams is recommended in most cases for dewatering in screw presses. The filtrates of deinking sludge dewatering must be processed accordingly, so that ink residues and contaminants are eliminated.

9.6.1.3 Sludge from Microflotation or Circuit Cleaning

Sludge from microflotation usually contains fine materials, fiber debris, and concentrated contaminants from circuit cleaning. Stickies are often characteristic of this sludge. These stickies also limit the choice of dewatering units, as belt filter presses and centrifuges are less suitable because of adhesion problems.

9.6.1.4 Sludges from Washing Process Stages

Washing process stages are used to eliminate ash and fine materials. These fine materials in the filtrates are usually concentrated by means of microflotation. The resulting sludge can be dewatered effectively in most cases, but it contains little structural material. Mixing with other sludges is therefore recommended.

9.6.2

Integration of Peripheral Sludge Systems with Primary and Biosludge

In modern paper production plants, the aim is to ensure that all sludge that accumulates is processed in an integrated sludge dewatering system. This includes the treatment of sludge that accumulates internally from the WSR subsystem and sludge from the effluent plant as well as primary and biological excess sludge.

Integrated sludge dewatering offers both operational and logistical advantages, and in most cases, it even offers lower investment costs.

Stringent requirements must be placed on filtrate treatment control in this process in order to prevent impurities and biological contaminants when the filtrate is returned to the production process.

Another challenge is the changing quantity, composition, and characteristics of the sludge to be treated. This is especially important during start-up and shutdown of production. For example, if there is no production sludge (WSR) to treat, and as a result, the percentage of organic sludge increases greatly, dewatering in screw extruders may be significantly less effective.

9.6.2.1 Sludge Predewatering

In current technology, two-stage dewatering is commonly used as it provides better control of the dewatering process and usually also of the separation of filtrate flows.

Sludge predewatering is used for preconditioning very thin sludge that accumulates with a stock consistency of 0.5–3% and is dewatered to approximately 8–16%.

There are different dewatering systems used in the paper industry.

- **Rotating-drum sludge thickener:** Rotating-drum sludge thickeners are mainly suitable for small and medium quantities of sludge (up to 10 t day^{-1}). The low investment costs generally conflict with higher consumption of chemicals, because during dewatering, the rotation of the drum leads to high shear forces.
- **Gravity table:** Gravity tables currently offer the most effective solution. Preconditioned sludge is applied to a horizontally running wire. Here, gentle dewatering takes place without shear forces. Plows are used to optimize dewatering. Gravity tables can be configured with different belt widths and/or lengths and achieve outlet consistencies of 10–20%. The low consumption of chemicals and good filtrate quality are typical advantages. The only technical limitations for gravity tables are that the belts are sensitive to mechanical contaminants and coarse particles (Figure 9.32).
- **Disc thickener:** Disc thickeners can very effectively handle varying quantities and qualities of sludge. Disc thickeners are insensitive to mechanical impurities and can even separate out heavy particles. They achieve good filtrate qualities and thickening is up to 8–14%. Another advantage is the compact design and ease of maintenance.

In many cases, disc thickeners can also be used as “smart loop modules” in primary treatment. In this case, the wastewater stream is fed directly to the disc thickener, which is then used simultaneously for filtration. Sludges can also be surrendered simultaneously for thickening (Figure 9.33).

- **Centrifuges:** Centrifuges offer the advantage of good controllability. However, they are usually only recommended for small quantities of sludge, as well as in cases that only single-stage dewatering is being used. Centrifuges reach final dry content of 30–45%, even from thin feedstock consistencies, depending on the nature and composition of the sludge. They offer advantages in dewatering of sludges that have a high biological proportion. In comparison with other

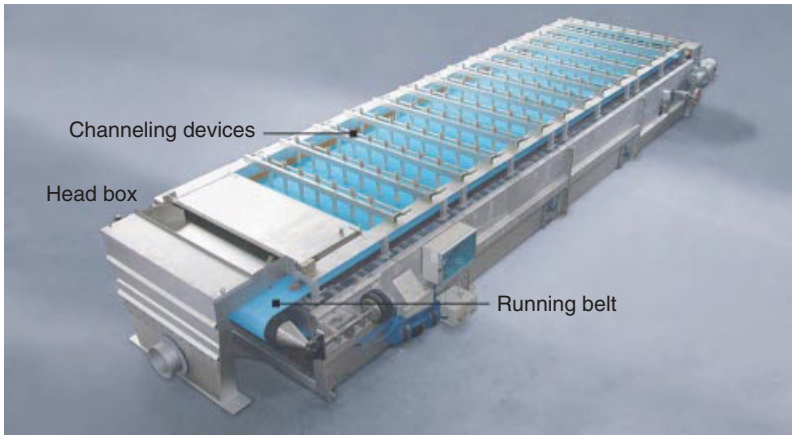


Figure 9.32 Gravity table.



Figure 9.33 Photo of disc thickener.

processes, the energy costs are higher. Centrifuges can also be sensitive to mechanical wear and inert impurities.

9.6.3

Sludge Pressing

After dewatering, mechanical pressing usually achieves the highest possible final dry content at the lowest possible disposal costs (based on weight) or, in the case of thermal recycling, the highest calorific values because of the lower moisture content.

State-of-the-art screw presses have prevailed over belt filter presses in high dry content dewatering (Figure 9.34). The following are the advantages of screw presses:

- High dewatering capacity per machine – up to 100 t day⁻¹ and more
- High final dry content – up to 60%

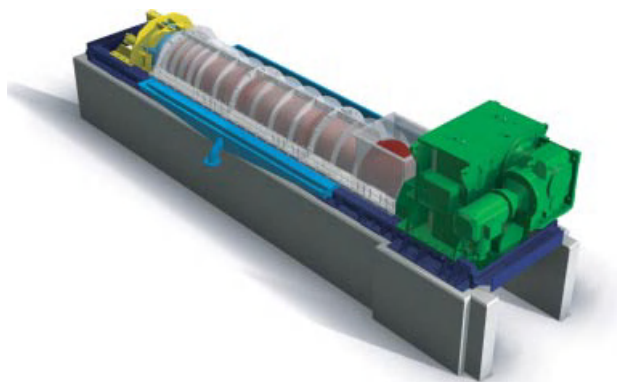


Figure 9.34 Typical screw press for sludge dewatering as used in paper industry.

- High availability and relatively low maintenance
- Space-saving installation.

Screw presses are limited only to the extent that they require a minimum of structural material in the sludge. Belt presses may in some cases offer advantages in this respect.

Belt presses are generally used for smaller flow rates and offer a good alternative, especially in terms of investment costs. Various configurations are available for belt presses (roll layout, number of rolls, and press nips). Depending on the type of sludge to be dewatered, belt presses can also achieve dry contents of up to 50% and produce 40 t day^{-1} or more per machine.

9.7

Wastewater

*Lucas Menke and Udo Hamm**

9.7.1

Introduction

The paper industry has a high demand for freshwater. At the beginning of the twentieth century, about $500\text{--}1000 \text{ m}^3$ of water was required for the production of 1 t of paper. Currently, the specific freshwater demand is much lower. The German paper industry, for instance, has succeeded in reducing the specific freshwater consumption to $9 \text{ m}^3(\text{t paper})^{-1}$, which corresponds to a wastewater volume of about $\sim 11 \text{ m}^3(\text{t paper})^{-1}$, for board and packaging paper mills this values are even 60 % lower as per the year 2012. In an international comparison, the performance in sustainable use of water resources and of wastewater treatment in the Central European paper industry is of a high technical standard. In the following, data from the Central European pulp and paper industry is presented.

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9.7.2

Characterization of Wastewater9.7.2.1 **Overview**

The pollution in the wastewater of a paper mill depends on the type of raw material, the type and amount of fillers and chemical additives applied, and on the specific water consumption. Effluents from mills that largely or exclusively process chemical pulps have a lower contamination than those from mills in which mechanical pulp or recovered paper is used as raw material. The use of starch or other organic additives results in a relevant increase of organic contamination, measured as BOD₅ (biological oxygen demand) or COD.

Dyes and fillers can lead to color and/or turbidity of effluents. Effluents from paper mills have a low content of nitrogen and phosphorus compounds. For this reason, these elements must be added as nutrient salts (e.g., urea and phosphoric acid) to feed microorganisms during treatment in biological purification plants. The closure of the water circuit within the mill results in an increase in the concentration of the effluent contamination.

For recycled paper mills, the base figure for sizing an ETP is the COD that is taken into the plant by each ton of recycled paper as raw material. Up to 10% leave the mill with the produced paper, 90% leave the mill with the wastewater or residuals.

9.7.2.2 **COD as a Parameter for Characterization of Wastewater**

Biological processes can eliminate nearly 100% of biologically degradable organic substances in the wastewater of paper mills. Considering the amount of organic substances determined as COD, the level of elimination is 80–95%.

A distinction must be made between total COD, dissolved COD, anaerobic degradable COD, aerobic degradable COD, total inert COD, and dissolved inert COD. Figure 9.35 shows a schematic explaining the relation of the different COD values.

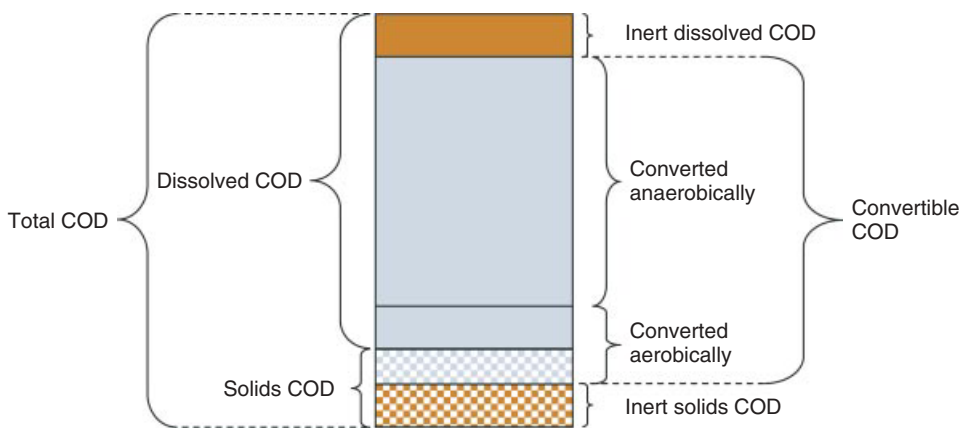


Figure 9.35 Relation of the different COD values.

9.7.3

Wastewater Treatment

The type of treatment selected depends on the type of paper produced, raw material used, and specific water consumption. Typically, the following parameters should be available for design and sizing of an ETP:

- Flow in cubic meter per hour as nominal and maximum flow
- Load in BOD₅ and COD
- pH level of calcium carbonate (mg l⁻¹), or hardness
- Suspended solids in milligrams per liter
- Temperature
- Total organic carbon (TOC), organic halogens subject to absorption (AOX value).

Currently, most of all ETP are designed as a combination of multiple stages combining chemical, physical, and biological treatment stages. Depending on the requirements for final discharge quality, many different concepts and technologies can be applied; the most used are listed in the following

- Primary treatment
 - sedimentation
 - DAF
 - filtration, screening.
- Secondary treatment
 - aerobic treatment, single or as cascade
 - aerobic moving-bed bioreactors (MBBRs), which use carriers for biomass growth (not applicable for high calcium content)
 - anaerobic biological treatment (expanded granular sludge bed reactors, EGSBs) or high rate reactors
 - bio solids removal (obligatory) by means of sedimentation (standard), DAF, or filtration.
- Tertiary treatment
 - precipitation, coagulation, flocculation in combination with
 - * sand filtration, DAF, or wire filter
 - * membrane filtration (only for special applications)
 - * Fenton process (combined precipitation, coagulation, and oxidation process)
 - Fenton's reagent is a solution of hydrogen peroxide and an iron catalyst that is used to oxidize contaminants in wastewater.

Figure 9.36 shows typical treatment technologies applied for different paper grades as regards COD load and specific water consumption.

9.7.3.1 Removal of Suspended Solids

Effluents from paper mills contain solids and dissolved substances. Solids (fibers, fillers) are mostly removed from the effluent in a chemomechanical clarification process by support of flocculants. The degradation of dissolved organic substances is performed in aerobic and anaerobic biological treatment plants.

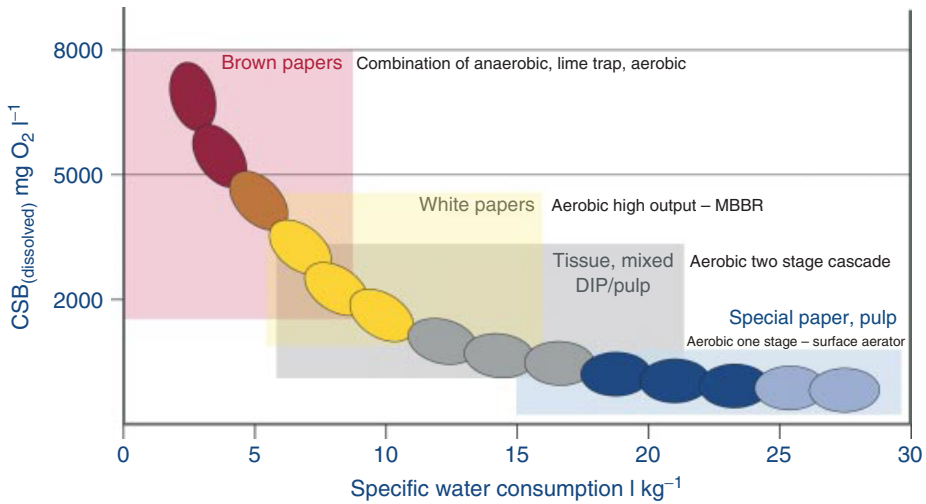


Figure 9.36 Typical treatment technologies for different COD loads over specific water consumption related to paper grades.



Figure 9.37 Circular sedimentation clarifier.

For chemical–physical clarification (solids removal) of effluents, sedimentation (round and rectangular basin with bottom sludge removal), or DAF are used. Screens and rakes for the separation of coarse material and sand traps are applied only when required. Figure 9.37 shows a circular sedimentation clarifier.

9.7.3.2 Biological Treatment

Primarily, activated sludge processes are used for aerobic biological treatment. Anaerobic treatment has become established especially in paper mills processing recovered paper.

9.7.3.2.1 Aerobic Treatment The activated sludge processes applied are single-stage processes, systems with recycled sludge aeration, cascade systems, and two-stage processes as well. Atmospheric oxygen transfer is employed, using surface aerators (roll aerator or gyratory aerator) or submerged pressure aerators. The clarification capacity or efficiency of activated sludge plants can be improved by using foamed plastic carriers in the activated aeration basin (MBBRs). Biological treatments with activated sludge process are exclusively fed with mechanically preclarified wastewater (total solids suspended (TSS) $<200 \text{ mg l}^{-1}$). The addition of nitrogen and phosphorus compounds is required. The BOD_5 efficiency attainable with activated sludge processes is usually in the range of 90–98% and the COD efficiency between 80% and 95%. For final clarification after the aeration tank, horizontal (rectangular and round basin)- or vertical-flow (hopper basin) sedimentation basins are preferred. Sand filters in combination with precipitation/coagulation or, occasionally, membranes, are used as further clarification (tertiary) stages. Third-stage treatment processes for the elimination of nitrogen and phosphorus compounds are usually not required.

9.7.3.2.2 Anaerobic Treatment Anaerobic processes are used for the treatment of higher loaded effluents ($\text{COD} >2000 \text{ mg l}^{-1}$). Anaerobic bacteria in the form of biopellets are used for the conversion of dissolved COD in to methane (biogas). Anaerobic technology in most cases is best for brown (board and packaging) recycled paper mills. The following are their advantages over aerobic treatments:

- much lower energy consumption;
- production of valuable biogas, which can be used in the mill boiler for steam production, or converted into electrical energy using gas engines;
- very low production of anaerobic excess sludge, which occasionally can even be sold;
- much smaller installation area required compared to aerobic treatments.

Figure 9.38 shows the difference in COD conversion between aerobic and anaerobic treatments.

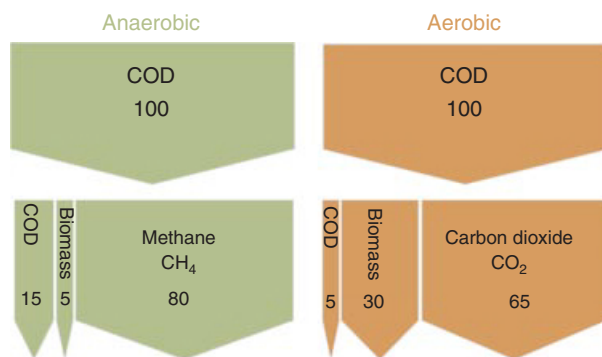


Figure 9.38 Difference in COD conversion between aerobic and anaerobic treatment.

However, those advantages comprise higher initial investment cost in equipment (20–30%), which, in some cases, are compensated by lower civil construction cost, for example, for aeration tanks. The operation of anaerobic plants definitely requires good, skilled and well-trained personnel, and is more demanding than the simple operation of most aerobic plants. Anaerobic operation can become critical if the wastewater contains high contents of calcium carbonate ($>350 \text{ mg l}^{-1}$); in such cases, special process steps or reactor designs have to be selected.

Currently, in the paper industry, two different types of anaerobic reactors are mainly used:

- EGSB reactors operate within a tank of 10–15 m of height, and use a small footprint compared to the volume. These reactors operate as single-stage reactors achieving good mixing of granular anaerobic sludge and wastewater, using a one-stage three-phase separator for gas, water, and biomass separation and retention.
- Multiple-stage EC (external circulation) or IC (internal circulation) reactors, which typically have very small footprints compared to the volume, ranging from 20 to 30 m. The slim design combines two stages, one on top of the other, with good mixing of wastewater and biopellets in the lower area. The upper area is used as a calm zone to allow good biomass retention. Some reactors allow the combination of internal and external recirculation. Special reactors have additional features for heavy biomass removal, such as calcium carbonate-crustrated pellets.

Figure 9.39 shows a typical EGSB reactor.



Figure 9.39 Typical expanded granular sludge bed reactor (EGSB reactor).

9.7.4

Biological Sludge

The biological excess sludge generated in ETP must be dewatered and disposed and cannot be returned to the papermaking process. Belt presses or centrifuges are used for dewatering. The dewatering characteristics can be improved by the addition of chemicals (e.g., coagulants and polymers). Typical final dryness is between 20% and 27% TSS if biosludge is dewatered without being mixed with other sludges. The high content of residual water depends on the cell structure of the biomass. Disposal costs of biosludge are high because of the low TSS even if mixed with other, easier-to-be-dewatered process sludge (fine rejects from stock preparation or primary ETP sludge). In some cases, thermal sludge drying is applied.

9.7.5

Closed Water Circuit

A closed water circuit is achieved when no wastewater leaves the paper mill. The process water is then almost 100% utilized. Only evaporation losses and the water content in the paper and in the residual matters must be replaced by freshwater ($1-2\text{ l (kg paper)}^{-1}$).

Figure 9.40 shows a schematic of a closed water circuit. The essential requirement for reusing biologically treated water is a quality suitable for the operation of sensitive systems in the paper mill (e.g., showers, trim showers), which in most cases requires a tertiary treatment. A prerequisite is corresponding storage capacity of stock and water to cross-compensate variations caused by up and downs in production.

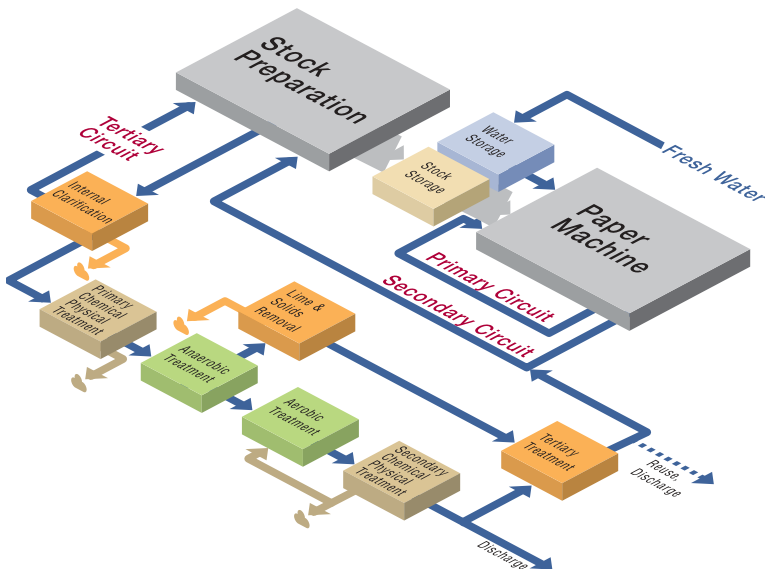


Figure 9.40 Closed water circuit.

At present, closed circuits make technical and economic sense only in paper mills producing board and packaging paper from recovered paper. For other paper grades, closed water loops are technically feasible using technologies such as membrane filtration and others. However, for economical and operational reasons, this cannot be seen as state of the art up to now.

9.8

Reject and Residual Disposal, Waste to Energy, Replacement Fuels for Incineration

*Lucas Menke and Udo Hamm**

There are many different disposal and recycling methods for rejects and residues. These are largely predetermined by statutory regulations or economic factors, as well as by the composition of rejects and waste.

Standard system designs cannot be generally applied here. An individual solution is usually developed for each paper mill or for each site on the basis of current and expected future conditions (permits, costs, logistics, etc.).

9.8.1

Solid Waste Composition and Characteristics

9.8.1.1 General View

The quantity and composition of rejects and residue depend mainly on the type of recovered paper on which production is based. In brown packaging paper production, larger quantities of plastic rejects accumulate, while sludges containing fillers and fines form the main proportion of residues that accumulate in the production of graphic and tissue papers.

Reject and residual waste quantities are calculated on the basis of the input of recovered paper that is fed into the material handling. The resulting specific reject and residue quantities depend on several factors, such as the recovered paper collection system and logistics and geographic region, and may differ considerably.

The composition of rejects and residues plays a major role in both recycling and landfill, for example, plastic rejects usually are a valuable RPFL because of its high calorific value. Sludges with high filler content have low thermal value, they are easier to deposit as landfill or can be recycled as an additive, for example, in the brick industry. In many cases, the degree of contamination of pulper rejects is critical. Coarse contamination and contaminants such as metal parts in particular must be removed, whereas plastic rejects (foil, plastic parts, etc.) must be shredded down to the required particle size.

9.8.1.2 Typical Quantities and Values of Rejects and Residues

From brown packaging paper production:

- 3–7% and higher high-calorific-value plastic rejects

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- 4–6% low-calorific-value fine rejects or fiber sludges
- 0.5–1.5% inert residues and scrap.

From graphic recycling paper production:

- 2–4% high-calorific-value plastic rejects
- 10–18% low-calorific-value deinking or fiber sludges
- 0.2–1% inert residues and scrap.

From tissue paper production:

- 1–3% high-calorific-value plastic rejects
- 15–30% low-calorific-value deinking, fine material sludges
- 0.2–0.8% inert residues and scrap.

9.8.1.3 Sludges from Wastewater Treatment

Residues and sludges can also accumulate from the final sewage plant. This depends on whether or not the sewage plant is operated by the paper mill itself. Depending on the chemical and physical nature of the wastewater treatment process – biologically aerobic, biologically anaerobic, or combinations thereof – the composition of sludges can be very different.

Sludge from wastewater treatment can be classified as follows:

- Primary sludges that are chemically and physically straightforward to be dewatered.
- Biological excess sludges, which accumulate in larger quantities in aerobic biological treatment processes, are difficult to dewater. It is advantageous to predewater the excess sludge, for instance, using a centrifuge, to ensure that the effectiveness of dewatering is not excessively impaired by the high proportion of biological sludge in combined dewatering with other residuals. Even very good dewatering processes usually only manage to produce dry content of approximately 22–25%. This means that the addition of biological sludge to the other residues is critical, particularly in the case of thermal sludge recycling.
- In anaerobic biological processes, either no biological sludge at all, or very little of it, accumulates for dewatering.

9.8.2

Regulations for Waste

Landfilling of rejects and waste residues is no longer permitted or has been allowed for a short time only in Western Europe. In contrast, very few legal requirements have so far come into force in other geographical regions. In the near future, it can be assumed that landfilling capacity will become severely restricted and recycling and/or energy recovery will become necessary, for economic or legal reasons, in all industrialized countries.

In Central Europe, regulations have been in force since 2005 under which the landfilling of rejects and waste from the paper industry is, in principle, no longer permitted. Although disposal prices rose sharply over the first few years after

these regulations came into force, disposal costs are currently easing or stabilizing, particularly because rejects are now being converted into valuable RPFLs to provide an important fuel source for newly built power plants. Over the next few years, these regulations will come into force accordingly in other European and overseas countries. In southern European countries in particular, the regulations are shifting from a “waste incineration ban” to mandatory energy recovery.

Therefore, before planning new production plants as well as for existing production plants, there is a need to clarify the new regulations that are expected to be introduced as regards disposal or energy recovery and any transitional arrangements with the relevant regional authorities.

Globally, many governments have committed themselves to waste prevention, or to recycling and energy recovery. Practical implementation is expected over the next decade, and the framework conditions for the landfilling of rejects and residues will consequently change considerably.

9.8.3

Economical Aspects and Conditions for Waste Handling

In addition to statutory provisions and regulations, economic considerations will play a major role in the handling of rejects and waste in the future. The intrinsic thermal recycling of rejects and residues will only be technically feasible and economical for large paper production plants.

Small and medium-sized production plants will therefore, still need disposal solutions in which the best economic approach to reject treatment, logistics, and collective thermal recycling will be developed jointly with partners.

The following alternatives have been established according to the reject quantities that accumulate (Figure 9.41):

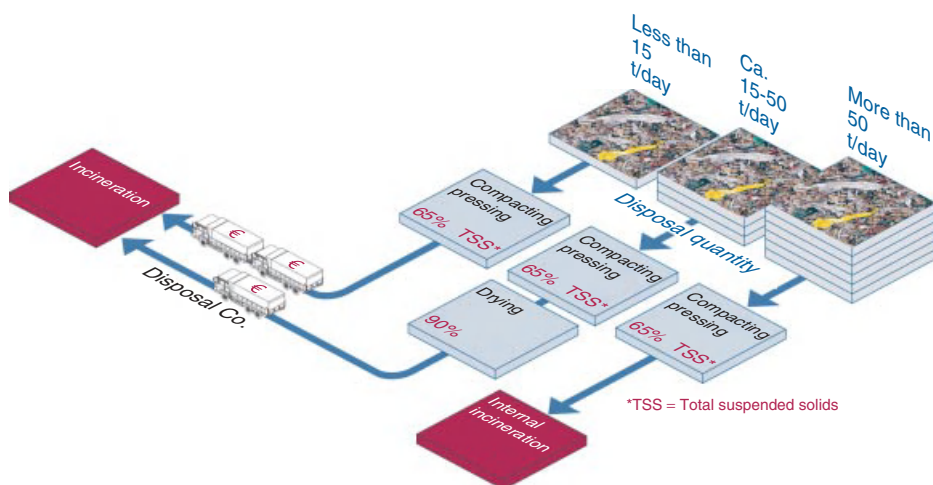


Figure 9.41 Alternative reject logistics to disposal or incineration depending on amount of rejects.

- Small reject quantities (up to approximately 15 t day⁻¹):
 - Best possible in-house dewatering subsequent collection and processing by waste management service providers, most of whom perform energy recovery
- Medium reject quantities (approximately 15–50 t day⁻¹):
 - In-house reject processing (crushing and metal separation) and best possible dewatering better than mostly external energy recovery, for instance, as part of framework agreements with cement or incineration plants
- Large reject quantities (more than approximately 50 t day⁻¹):
 - In-house reject processing (crushing and metal separation) and best possible dewatering, fuel storage, and fuel mixes
 - In-house energy recovery, for instance, in a separate residual material boiler at an existing power plant
 - In-house energy recovery with additional external fuel such as biomass or RDF.

9.8.4

Reject and Residual Drying – the Gateway to Economical Disposal

For smaller reject and residue quantities that must be disposed externally, disposal costs are calculated based on weight; it may be economical to dry these reject flows. Previously, mechanically treated rejects were dried in warm airstreams at a temperature of approximately 80 °C. Small particle sizes (below 30 × 30 mm²) and a uniform flow are prerequisites for the success of this process. The possibility of using residual heat from the paper machine to warm up the airstream is decisive in determining energy savings.

Properly designed plants provide a reject with a final dry content of about 90%. Savings are a given not only because of the lower disposal weight but also as a result of simplified logistics, as dried material is easy to handle in storage and transport. Figure 9.42 shows the schematic of a reject drying plant.

9.8.5

Waste to Energy, Incineration of Rejects and Residuals

The term *waste to energy* covers all methods in which energy can be recovered from waste, that is, rejects and residuals. Currently, combustion processes are established; other methods such as pyrolysis or composting have not been feasible on a large industrial scale up to now. In addition to conventional RDF combustion and rust firing systems, stationary or circulating fluid beds are also used in combination with biomass in the energy recovery process.

Energy recovery processes that use rejects and residues from paper production in whole or in part require careful preplanning and technical development to ensure the reliable and economic operation of the plant.

The following are the most important questions:

- What quantities of fuel are available “in-house” and how high is the external fuel demand?

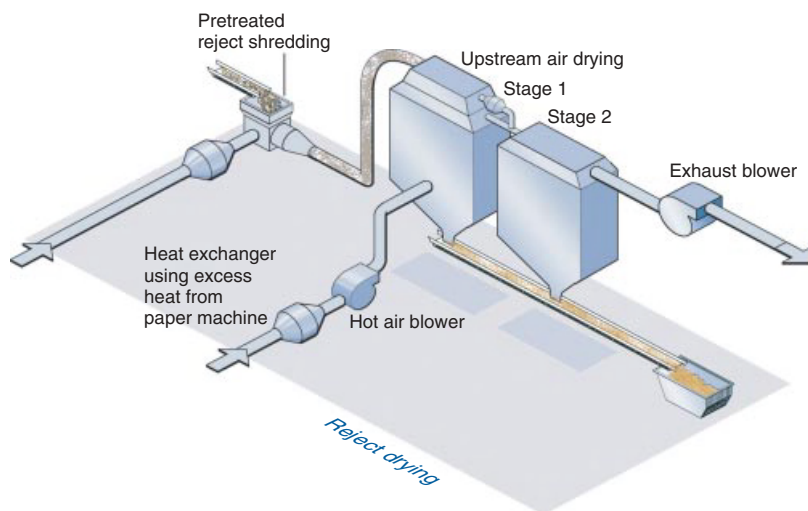


Figure 9.42 Schematic of a reject drying plant.

- Are fuel availability and fuel costs guaranteed in the long term?
- What in-house fuel logistics are required to operate the incinerator continuously, if production changes or shutdowns occur in paper production?
- How large must a fuel store be to compensate for variations in internal and external fuel availability and quality?
- What fluctuations is the fuel mix subjected to in terms of the calorific values of different raw materials or different production conditions?
- What are the disposal means for residual ash and how high are the costs?

With current technology, rejects and residues in the production of brown packaging paper based on 100% recycled paper can be used to generate 20–35% of the energy needs of a paper mill. In graphic paper production, this percentage is considerably lower because of the higher content of sludge that has a lower calorific value.

9.8.5.1 Characteristics of Replacement Fuels

The properties of the substitute fuels that are available are crucial when selecting a boiler type and boiler dimensions. Because reject and residue compositions and quantities change, specific belt-width dimensioning is usually required as a basis for fuel components and fuel mixtures. In addition to fuel composition, dry content also plays a major role. For rejects from pulping, which mainly consist of plastic (e.g., foils), the PVC proportion should also be determined to keep within the acceptable limits for incineration materials (dioxin prevention). If the PVC proportion is more than the prescribed limit of 1%, PVC components have to be separated. Near infrared (NIR) detection and blowing processes are used for this purpose, but they are technically complex and expensive.

9.8.5.2 Conditioning and Pretreatment of Waste and Replacement Fuel

The processing and handling of reject and residue flows from material processing is already widely used in reject handling systems in the WSR subsystem. For external RPFLs, rejects and residues that have been stored, additional pretreatment is usually necessary. This is to ensure that only materials that have been shredded sufficiently and are free from impurities are fed to incineration. Poor fuel quality can lead to major disruptions in the combustion supply system and in the boiler itself. The block diagram in Figure 9.43 shows a typical sequential circuit at various process stages, such as the usual stages for reject and residue handling in material processing and external or temporarily stored materials in the context of a fuel store.

9.8.5.3 Waste and Replacement Fuel Storage

The temporary storage of reject and fuel is also essential for ensuring that sufficient quantities of fuel for the boiler feed are available at all times. In general, high-calorific-value fuels such as plastic reject from pulping should be stored separately from materials such as fine rejects with a low calorific value and subsequently mixed in-line depending on the demand for calorific value, by the means of, for example, mixing screw conveyors.

For volume storage, bunkers are equipped with laser scanning claw gantry cranes for withdrawal, to secure feed logistics to incineration (Figure 9.44).

Continuous-feed conveyor elements then take the high- or low-calorific-value fuels to further handling stages (grinding, plating, etc.) before use. The high- and low-calorific-value fractions are continuously mixed according to the calorific-value requirements of the boiler in the supply system (Figure 9.45).

9.8.5.4 Waste-to-Energy Solutions Using External Waste and Multiple Recyclable Furnish (MRF)

As described earlier, a maximum of 20–35% of the required energy can be produced from rejects and residues from in-house production of brown packaging papers. As an alternative, external sources can be used to cover the demand for fuel. Besides using RPFLs (RDF) from external sources, biomass (wood and bark residues) or domestic and/or recycled refuse can be used as additional energy sources for incineration.

For small paper mills that are located close to urban centers in particular, in the future, it may make economical and logistical sense to combine garbage disposal and recovered paper processing on the one hand, and energy and paper production on the other.

9.8.5.5 Typical Incineration Technologies

9.8.5.5.1 Grate Incineration Grate combustion systems are especially suitable for lumpy fuels but not for moist, pastelike and finely grained fuels. With moist sludges, for example, the retention times on the grate can be insufficient for complete combustion. Nevertheless, grate combustion systems are used in the paper industry primarily for cofiring of sludges with reject, bark, or wood residues.

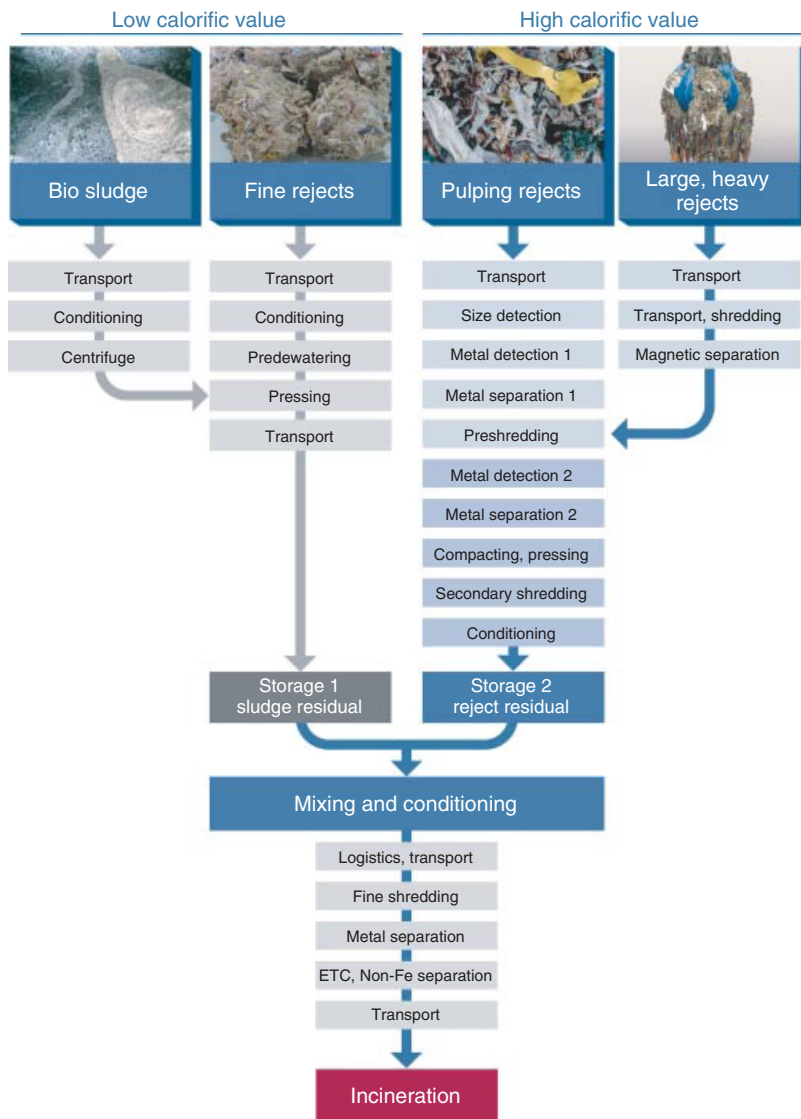


Figure 9.43 Block diagram of a typical system to convert rejects and residuals into replacement fuel including storage as subsequently used for incineration.

Grate combustion with a stationary grate is shown in Figure 9.46. Long reaction times and the difficult combustion control on the grate allow moisture and ash content of the fine rejects (sludge) fraction to vary only within narrow tolerances.

9.8.5.5.2 Fluidized Bed Incineration Fluidized bed incineration results in good heat transmission and intimate mixing of air and fuel. Combustion is better



Figure 9.44 Typical storage bunkers with intelligent laser scanning crane, live bottoms, shredding, and metal separation.

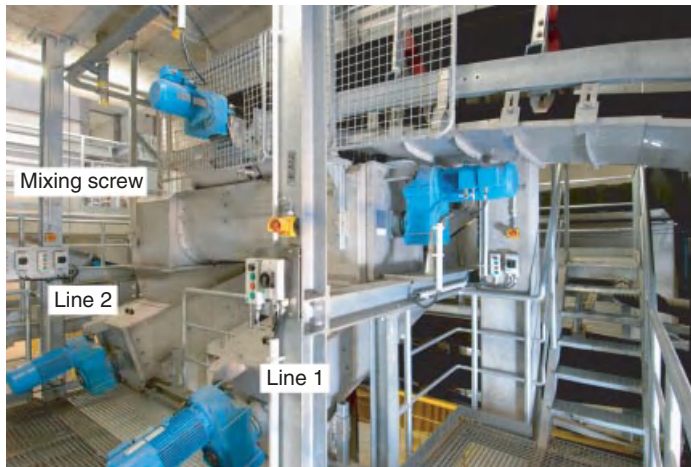
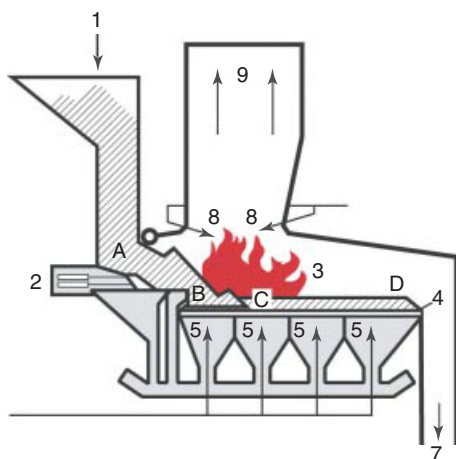


Figure 9.45 Equipment to mix high- and low-calorific-value fraction to be forwarded to incineration.

than in grate incinerators, and emissions are therefore lower. Figure 9.47 shows the scheme of a stationary fluidized bed furnace. In fluidized bed boilers, the combustion conditions can be controlled through regular temperature and pressure measurements, which is not the case with grates. Stationary fluidized bed furnaces as well as circulating fluidized bed furnaces offer very good operating conditions for low emissions of airborne pollutants. The emissions of nitrogen oxides are especially low, compared with grate combustion. Direct desulfurization is possible by the addition of basic sorbents such as limestone or dolomite into the body of the furnace.



- | | |
|----------------------------------|----------------------------|
| 1 Waste feed | A Waste |
| 2 Stoker | B Drying and ignition zone |
| 3 Combustion Chamber | C Burning zone |
| 4 Underair blower | D After-burning zone |
| 5 Underair blower | |
| 6 Primary air system | |
| 7 Slag removal | |
| 8 Secondary, tertiary air supply | |
| 9 Flue gas | |

Figure 9.46 Grate incinerator.

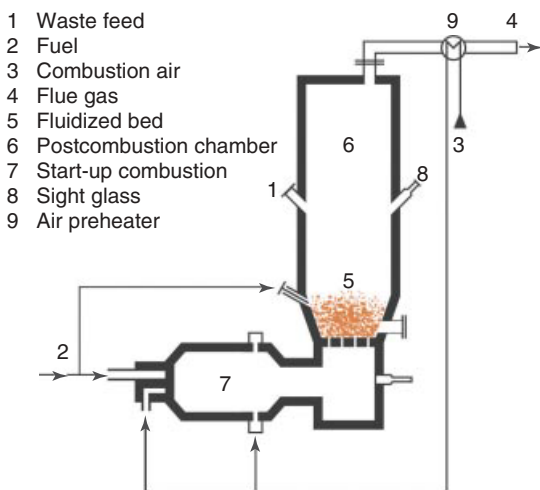


Figure 9.47 Fluidized bed incinerator.

9.8.5.5.3 Choice of Combustion Technology The choice of combustion technology depends on the operating conditions and the nature of the waste. According to recent knowledge, fluidized bed combustion is the most suitable for burning sludges and rejects. In fluidized bed combustion, neither fluctuations of heating value of the fuel nor changing proportions of noncombustible components such as sand, metals, or fillers have a negative influence on the combustion efficiency.

For fuels with a low heating value, such as deinking sludges, the stationary fluidizing is probably a more suitable option. Fuels with a higher heating value such as wood and bark are incinerated more effectively in a circulating fluidized bed. Owing to the mechanical flow requirements of the fuel, producing a consistent grain size distribution by mechanical processing such as extraction of metals, shredding, and grinding may be necessary. This requires consideration, especially when burning rejects along with sludges.

For sludge and reject incineration in paper mills, the conclusions concerning flue gas emissions are as follows:

- Emissions of solid particles, sulfur dioxide, hydrogen chloride, hydrogen fluoride, and carbon monoxide are low compared with legal standards. Owing to the high calcium carbonate content of deinking sludge, this sludge should not release all sulfur as sulfur dioxide. State-of-the-art flue gas purification guarantees that no significant environmental impact arises.
- The emission of heavy metals is very low compared with the legal standards, especially for emission of cadmium and mercury.
- The emission standard of nitrogen oxides can usually be met by improved combustion control (temperature and oxygen level). Sometimes, the application of specific measures to remove NO_x could be necessary.
- The stringent emission standard of polychlorinated dioxins and furans can be met without any additional measures in flue gas purification.

9.8.5.6 Use in Other Industries

Rejects, deinking sludges, and combustion ashes of paper mills are used in many branches of industry for material production purposes. The material use possibilities for deinking sludges and combustion ashes depend primarily on the composition of the inorganic components. The inorganic part of the deinking sludges consists mainly of calcium carbonate and clay. In the combustion ashes of deinking sludges, calcium oxide and sintered clay are primarily present. The aforementioned inorganic components also find use as raw materials in the construction industry. The possibilities for primary use are therefore the following:

- Cement production
- Brick manufacturing
- Concrete production
- Mortar and sand–lime brick production
- Road construction.

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10

Paper and Board Machines and Their Components

10.1

Overview

Herbert Holik and Johann Moser

10.1.1

General Remarks

The objective of the process on the paper machine is to produce a continuous paper web of the required quality, uniform in machine direction (MD), and cross-machine direction (CD). The process consists of the approach flow system, the headbox and the wire section, the press section, and the dryer section. Depending on paper grade a coating station, a size press and a calender may be installed before the reel. Reeling is an intermittent process. As soon as the mother roll has achieved a maximum or defined diameter, it is taken out of the reel. It is cut up at the winder into smaller rolls with defined widths and diameters for further in-house applications or according to the customers' requirements. The rolls are then wrapped, labeled, and made ready for shipment.

Figure 10.1 shows a schematic of a graphic paper machine and how the dryness (consistency) is typically increased along the way from the headbox to the reel. In Figure 10.2, a high-capacity paper machine for coating paper production is shown. The paper machine, with an in-line size press and film- and blade-coating stations, is about 430 m long. With the following steps of rewinding, calendering, and slitting, the total length adds up to close to 600 m. The wire width is 11.8 m, maximum operating speed 1700 m min^{-1} , and maximum gross production capacity 4500 t day^{-1} .

The various paper and board grades require special furnish makeups as well as paper machine layouts. For economic and quality reasons, these machines are now tailor-made for graphic paper, packaging paper, board, specialty paper, or tissue paper production. They differ, for instance, in wire, press, and dryer section design, in machine width, in operating speed, and finishing processes (coating, calendering). Machine widths are dependent on the grade produced, as the width is given by the requirements of further web (sheet)-processing equipment such as printing or corrugating board machinery. For instance, for corrugating board

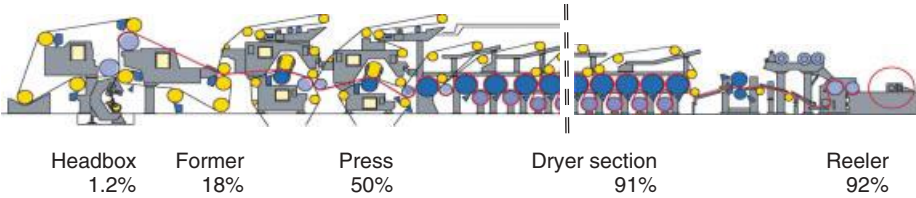


Figure 10.1 The sections of a paper machine for newsprint production and the dry content of the paper web after each section. (Source: Voith.)



Figure 10.2 Operators' view from the wet end toward the dry end of a high-capacity paper-making line nearly 600 m long. (Source: Voith.)

machines widths of 2.5 m are conventional whereas 3.3 m are standard for the new generation. So a trimmed width of slightly more than 10 m at the paper machine would fit both corrugating machine widths (4×2.5 and 3×3.3 m). Another example is rotary offset production, nowadays with new printing machines of 2.4 m maximum width that would need parent rolls at the reel of 9.65 m width. About 25–30 mm is cut off on each side of the web at the winder for save winder operation, which results in a final width of 9.6 m.

10.1.2

Progress

The immense technical progress over the last century can be recognized when comparing the two machines shown in Figures 10.2 and 10.3. Many major changes and improvements in their design and operation came up only in the last three to five decades:

- Increased use of recycled fibers putting higher demands, for instance, on fabric cleaning for high machine efficiency
- Changing the pH value of the suspension in the wet end from acid to neutral, allowing the application of calcium carbonate fillers and ensuring more durable papers

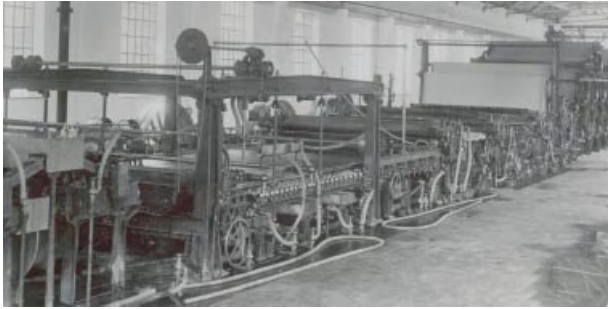


Figure 10.3 A paper machine commissioned in 1905 (speed 300 m min^{-1} , width 3 m).

- Hydraulic headboxes enabling higher machine speeds, higher throughputs, and easy application of twin-wire gap formers
- CD basis weight profiling in the headbox by dilution, resulting in improved paper uniformity and quality, thus enabling fiber savings by lower mean basis weights
- Twin-wire formers providing significantly higher dewatering capacity and symmetrical z-structure of the paper and high machine speeds
- Shoe presses (extended nip presses) with high dewatering capacity for high web dry content on entering the dryer section, thus saving drying energy and improving machine runnability because of increased web strength
- The single-nip shoe press reducing investment costs, space requirements, and operating costs to a minimum
- No-draw press enabling higher machine speed and better machine efficiency
- No-draw dryer section enabling higher machine speed and machine efficiency and changing the CD web shrinkage curve
- Advanced web stabilizer and fully automatic web threading systems
- Synthetic forming of press and dryer fabrics to best customize the fabrics to the requirements of application for uniform dewatering, smooth web surface structure, and long lifetime
- Process control with advanced measuring techniques and control strategies allowing the operators to continuously monitor the operation, see trends in paper quality and machine condition, and take appropriate action
- Film sizing with rod metering system, improving machine runnability significantly
- The film coating process with rod metering, reducing improving machine runnability, reducing investment costs, space requirements, and operating costs to a minimum
- Synthetic covers for coater and calender rolls
- Synthetic covers of calender rolls allowing integration of calenders into the paper machine at high machine speeds for high-quality paper grades
- Integration of coating (and calendering) into the paper machine even at high speeds of up to 1750 m min^{-1}

- Machine speed: Five decades ago the typical paper machine ran at a speed of about 300–350 m min⁻¹. At present, maximum machine speeds are about 2200 m min⁻¹ for tissue machines, more than 2000 m min⁻¹ in newsprint production, and above 1750 m min⁻¹ for woodfree grades (Table 10.1). Figure 10.4 shows the increase in maximum operating speeds within the last 100 years
- Machine width: The typical paper machine of five decades ago had a machine width of about 3–3.5 m. At present, most new machines have a wire width of about 10 m for packaging paper and more than 11 m for newsprint (Table 10.2). The increase in machine width over the years is also shown in Figure 10.4. The dotted line indicates that the width increase took place in several stages over the years.

At present, maximum wire width, as key machine design parameter, is 11 800 mm (11 045 mm maximum trim at the reel). A machine of that width with a design speed of 2000 m min⁻¹ was commissioned successfully in 2001. At present, maximum design speed is 2200 m min⁻¹ (tissue machines excluded), applied for newsprint machines. A further increase in width and/or speed for graphic and

Table 10.1 Recent approximate maximum operating speeds for different paper grades.

Paper/board grade	Approximate maximum operating speed (m min ⁻¹)
Tissue	2200
Newsprint	2200
SC paper	1900
LWC	1900
Coated woodfree	1800
Uncoated woodfree	1700
Corrugating medium	1600
Testliner	1400
Board	950

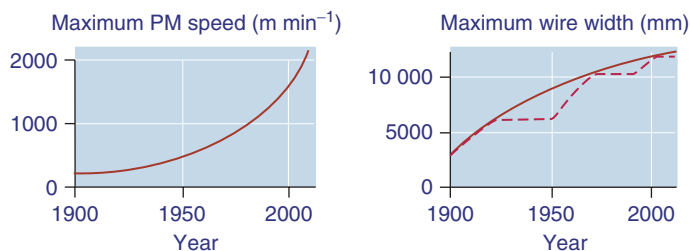


Figure 10.4 Increase in maximum operating machine speed and max. wire width over the years.

Table 10.2 The widest paper machines for different paper grades in use at present.

Paper/board grade	Approximate maximum wire width (mmm)
Tissue	8000
Newsprint	11 000
SC paper	10 500
LWC	10 100
Coated woodfree	11 800
Uncoated woodfree	11 100
Corrugating medium	10 000
Testliner	10 000
Board	8700

board and packaging machines does not seem to be economical for the time being. For tissue machines only, a further design speed increase can be expected.

When coating and (or) calendering units are integrated into the paper machine the investment costs drop considerably; however, the efficiency of the whole process decreases as there are two more sensitive process steps online, with interfaces to the preceding and succeeding process steps. Here, the weakest link in the chain limits the overall production efficiency. On the other hand, with off-line coating and calendering, the increase in investment costs and loss in material efficiency because of the batch process are considerable. Therefore, there is a clear trend toward online coating and calendering for most applications.

10.1.3

Operation

At present, paper making is a continuous, highly sophisticated process with high demands on precision and reliability of all components. For instance, the slice opening of headboxes should have an accuracy of about 1/100 mm (or 10 μm) over a width of 10 m in order to obtain the required CD basis weight uniformity and uniform main fiber orientation in CD. Precision in calender roll grinding should be about 3 μm , which is equivalent to 5% deviation when comparing it, for instance, with a paper thickness of 60 μm .

Paper machines are in operation 24 h per day throughout the year only interrupted by short planned or unplanned shutdowns. Both result in loss in production; this loss has to be minimized. The costs of a shutdown are calculated as about 10 000 up to 40 000 € per hour, depending on paper grade and capacity of the papermaking line.

Predicted machine maintenance or wire and felt changes are examples of planned shutdowns and should be synchronized. Unplanned shutdowns are caused, for instance, by rope carrier system going out of order (rope broke), hole in the forming wire, or failure of machine components (e.g., roller bearings). In earlier times, after

a web break, it took several minutes to thread the web toward the reel; a skilled operator was needed for tail feeding and lots of paper debris was created inside the machine. At present, threading is done automatically and all the disadvantages have disappeared.

In order to avoid web breaks, the web has to be guided safely through the paper machine taking into account its low strength when wet as well as its shrinkage and reduced stretch potential during drying. With recent high machine speeds free draws of the web have to be avoided and the drives finely adjusted. Local nonuniformities, such as poor profiles of basis weight or moisture in CD and MD, would further raise the web break risk.

After a web break (or at the machine start-up), the web has to be threaded through the machine as fast as possible to reduce production downtime. This is done by feeding either the web at full width or just a “tail,” a web strip of about 20 cm, at the machine tender side, which is then widened to the full machine width after completion of tail threading. The equipment for web or tail feeding includes air blowing nozzles, suction rolls, wires and felts, rope guides, and vacuum-supported conveyor belts.

During web breaks (nonproduction conditions), the paper web can be repulped at defined positions under the paper machine, in the couch pit after the wire section, after the press section, after the dryer section, and at the end under the reel that also services a calender stack. These broke pulpers beneath the paper machine extend across the whole machine width with several equally distributed rotors. They have to start work (including water addition) instantaneously and fully automatically when needed, and have to handle the design production capacity.

The web width changes during the run through the paper machine by

- edge trimming at the end of the forming section, which reduces the wet web width by about 150–200 mm; further trimming can be applied before the coater, the calender or before the reel;
- running the web under tension (draw);
- shrinkage in the dryer section, which reduces the web width by about 2–8%.

10.1.4

Paper Machine Components

A paper machine comprises one framework at the tending side and another at the drive side of the paper machine. These frames support most of the components of the paper machine such as the different kinds of rolls (Sections 10.2 and 10.3) as well as stationary elements such as dewatering components or beams for sensors. When worn fabrics are to be replaced, the front framework is opened (“cantilevered”) and an endless forming wire or press felt is installed. In the dryer section, a nonendless fabric is first threaded throughout the machine part and then closed inside the machine with a seam. The same can be done in press sections with a nonendless felt for certain applications. The fabric run is continuously controlled by guide (to avoid run out) and tension rolls (for adequate fabric tension) as well



Figure 10.5 Example of a roll doctor. (Source: Voith.)

as spreader rolls (to avoid “creasing” of fabrics). Fabric cleaning is done with the help of water spray nozzles.

Spray nozzles are also used for edge trim, web cutting, or cleaning of roll surfaces. Usually, the cleanliness of the roll surfaces is provided with doctors (Figure 10.5). Water supports cleaning and lubrication in most cases, so the abrasion caused by the doctor blade and the roll surface is low. Doctors are also used for taking the web off a roll surface at defined locations (i.e., center press roll) or when the web breaks inside the paper machine or for creping, for example, of tissue products. Best operation results require an optimum combination of the materials of the doctor blade and roll surface covers and coatings, as well as blade loading, and blade angle towards the roll face.

Dewatering in the wire section is done by dewatering elements such as forming rolls, foils, table rolls or vacuum foil boxes, flat boxes, and couch rolls (Chapter 14). For wide and fast machines, a large volume of filtrate called *white water*, has to be led out of the machine in a controlled way. This can be done e. g. by making use of the momentum energy of the filtrate by specially designed catch pans.

One important web quality parameter, formation, is mainly influenced by the dewatering elements of the wire section. Sometimes, for enhancing formation in lower speed machines, a dandy roll or wire shaking are applied. For the latter, the breast roll is shaken horizontally in CD to move the wire and suspension. Before 1920, the whole wire section was shaken. Frequency (e.g., 600 min^{-1}) and stroke (e.g., 25 mm) are adjustable. Breast rolls made of carbon fibers allow higher frequencies and strokes because of their lower deadweight.

In certain machines, nozzle moisturizers are installed. They shall remoisten the web to an appropriate dry content for calendering, as for higher quality demands the web is first overdried in order to obtain a uniform CD moisture profile. Moisturizers are also used to reduce curl problems. Sometimes the final CD moisture profile is controlled by local web moisturizing across width before the reel. Moistening is done by spraying fine water droplets onto the web. An adequate two-phase (air/water) generation of the droplets leads to their finest size and distribution (Figure 10.6). In earlier times remoistening of the paper was done by a wet cylinder surface moistened by a wet felt of controlled water content. Steam boxes are mainly

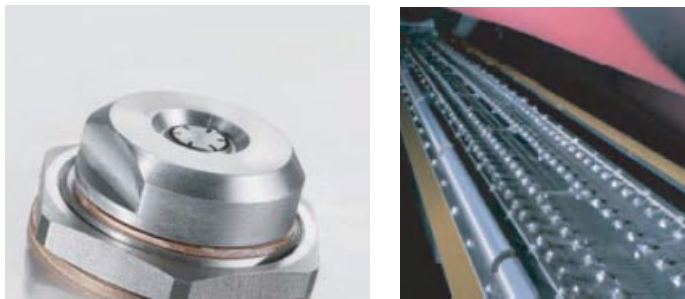


Figure 10.6 Example of a moisturizing nozzle and moisturizing system for curl control. (Source: Voith.)

applied before calender nips. They moisten just the web surface by steam condensation. Reducing the web temperature shall ease further process stages, e. g. coating which is mainly done with water-cooled cooling cylinders which do not “sweat”.

Air systems support web stabilizer systems, provide defined air conditions at the machine sections and the machine room, and exhaust the moist air, especially in the dryer section where the remaining water after the press section has to be evaporated. For doing this in a well-ordered way, the whole dryer section is covered by a hood. The schematic in Figure 10.7 shows the many ducts leading in and out of the dryer and press section, as well as the air supply with the heat recovery system.

In earlier times, all rotating elements in the paper machine were driven by a long drive shaft at constant speed. Speed adjustment for the different machine parts was done by driving belts and pulleys or cones (Figure 10.8). This could be done as the width of a machine at that time was small and the required driving energy low. At present, for example, driving a wide nip press requires a drive of more than 1MW. Later on, driving was decentralized, and in the 1960s and 1970s, the rectifier control motors with thyristors entered the market.

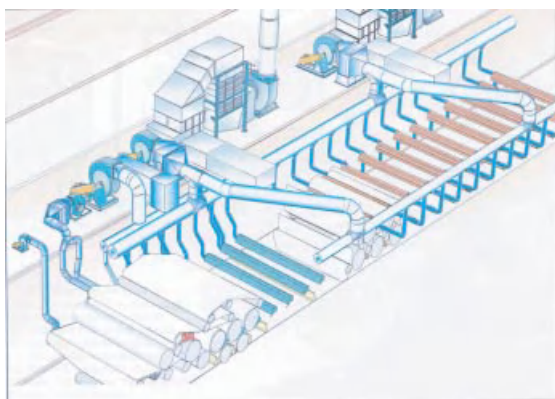


Figure 10.7 Schematic of an air duct system for supply and exhaust air for press and dryer sections. (Source: Voith Krieger.)



Figure 10.8 Central drive for a 183 cm wide paper machine in 1911.

Most of the driving applications operated with gears. Nowadays, direct coupling of the motors to the roll shafts is a common feature (Figure 10.9). Leaving out additional components such as gears or cardan shafts reduces energy consumption and noise, and increases accuracy and flexibility in operation and design. Synchronous motors as well as asynchronous are in use. In applications with successive acceleration and deceleration (brakes) cycles, regenerative drives can produce electricity.

Online measuring and control of the most important paper properties is a must. It started in 1952 when the first basis weight control had been installed, followed by the first moisture control system in the 1960s. Quality measurement and control should be done early in the process. This is a special challenge as the web is “hidden” most of the time by fabrics. In the machine of Figure 10.2, 10 frames with 54 sensors, as well as a monitoring system with 1400 measuring points, have been installed. In another paper machine, 50 cameras along the machine assist to analyze web breaks for measures to reduce them further.

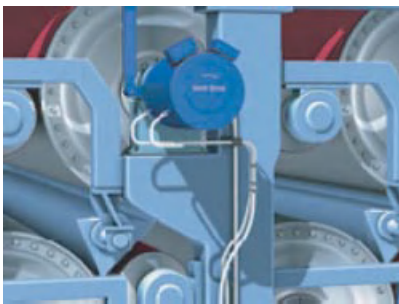


Figure 10.9 Directly coupled drive and the roll shaft. (Source: Voith.)

10.2

Rolls in Paper and Board Machines

Herbert Holik and Johann Moser

10.2.1

General Aspects

Different types of rolls are used throughout the paper or board machine as well as in off-line machines; these fulfill a variety of functions. Roll types are described in general in the following:

- Rolls guiding the fabrics – or the paper web – through the paper machine such as guide rolls and spreader rolls
- Rolls affecting the paper web such as press rolls, suction rolls, applicator rolls, and calender rolls.

All rolls have to be designed to meet the requirements as regards bending, strength, bearing lifetime, surface quality, and critical revolutions per minute. Usually, they have to be balanced. Increased machine speeds make good roll balancing even more important in order to avoid machine vibrations with their negative effect on paper quality and machinery. Owing to internal and external forces applied, the roll bends; this has to be limited. In press nips with high loads, deflection control rolls are frequently used to overcome these disadvantages.

Depending on their application, the rolls are made of steel, cast iron, bronze, or fiber-reinforced plastics, and at present, often of carbon fibers. The latter allow design of the shell according to its purpose as regards the elasticity in length or in circumferential direction by structuring the carbon fiber mat. Further advantages of carbon fibers are their low weight (about one-fifth of steel), resistance against temperature and hydrolysis, thermal expansion close to zero, and vibration dampening effect. The critical rpm (revolutions per minute) is distinctly higher. Depending on the purpose (e.g., wet pressing, calendering) and location (e.g., wet end, dry end) in the machine, various types of roll covers can be applied.

10.2.2

Rolls to Guide Fabrics and Paper or Board Webs

10.2.2.1 Guide Rolls

Each roll may be driven by its individual drive, and this may in turn drive the paper web, wire, felt, or belt. Alternatively, the rolls are driven through friction by a wire, felt, fabric, or belt. Depending on their application, the rolls are equipped with bearings at the tender side and drive side, covers, or coatings. Guide rolls give a stable run either to the paper web or to wires, felts, fabrics, or belts. They are about 400–1000 mm in diameter. They are also used in tension control devices to ensure that the fabrics operate at adequate tension in the MD, and in wire and felt guide systems for continuous control of the fabric position in the CD. Their specific deflection is limited to about 0.07 mm m^{-1} face length in the wire section,

which means that for a 10 m wide face length, there is a maximum deflection of 0.7 mm. Figure 10.10 shows a guide roll with a device in the center for balancing. For the dryer section guide rolls, the maximum deflection depends on the width (0.25 up to 0.50 mm m⁻¹ face length).

10.2.2.2 Spreader Rolls

An endless fabric running in a fabric loop may face wrinkles as a result of guide roll bending. That is why the bending must be limited. Spreader rolls are applied as a relief and they spread the paper web or fabrics in the CD in order to avoid wrinkling or flutes, especially before the paper web enters a nip. Owing to roll bending, the circumference of the fabric loop in the middle is less than at the edges (Figure 10.11).

The conventional spreader roll consists of several short cylindrical roll sections that are covered by one common flexible hose. The overall axis has a certain tailor-made bend or it can be adjusted for spreading. The bending curve is sectioned. Newer designs use carbon fiber shells of orthotropic bending characteristics, which results in a homogeneous bending curve (Figure 10.12). The deflection is strongly

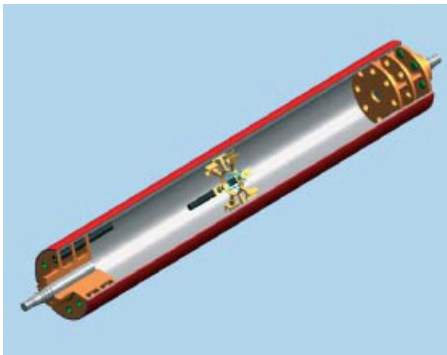


Figure 10.10 Example of a guide roll with a device in the center for balancing. (Source: Voith.)

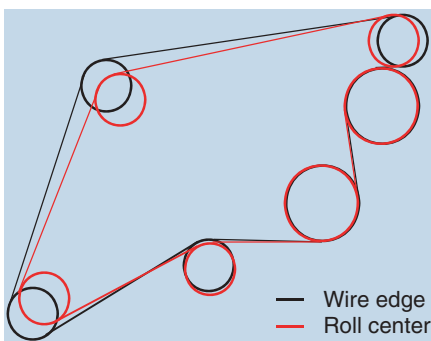


Figure 10.11 Conventional fabric run.



Figure 10.12 Spreader roll made from carbon fiber–reinforced material with a continuous bending curve. (Source: Voith.)

dependent on the location in the machine, as well as on width and wrapping angle (20° up to about 60°) of the roll.

Spreader rolls cannot have a doctor for roll shell cleaning, so there is always a risk of buildup of solids on the roll shell; this can damage a fabric, especially a forming wire.

10.2.2.3 Center-Supported Guide Rolls

The bearings are located at the quarter points of the roll, which is different from conventional guide rolls where the bearings are at the tender side and drive side. The result is a different deflection curve compared to that in conventional rolls (Figure 10.13). By combining conventional guide rolls and center-supported rolls in one common fabric loop, the difference between the circumference at the middle and at the tender and drive side is minimal (Figure 10.14). This results in a much better fabric run without a spreader roll. In a former, a center-supported roll can trim the wire run in such a way that a spreader roll is not needed at all.

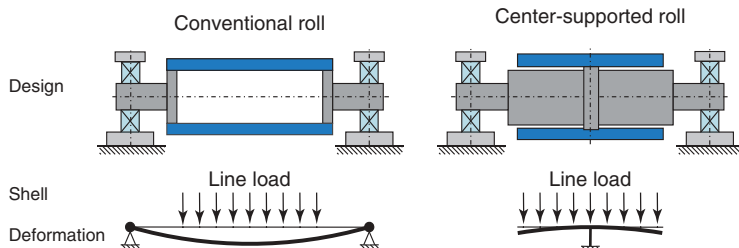


Figure 10.13 Conventional and center-supported guide rolls. (Source: Voith.)

10.2.3

Rolls to Affect the Paper and Board Web

10.2.3.1 Perforated (Open) Rolls

Perforated rolls are used in the wire section as well as in the press and dryer sections. Their open area (2–85%), which is the total area of the openings/holes on the roll surface related to the overall roll surface, and their design vary considerably. Their tasks can be

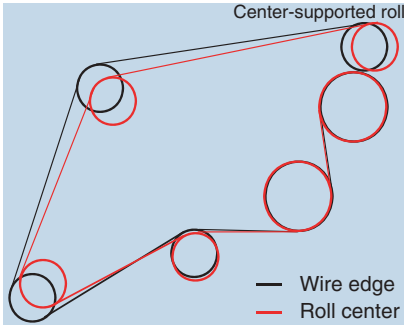


Figure 10.14 Fabric run with a center-supported roll.

- to dewater the paper web;
- to store the water and to release it in a controlled way;
- to remove the air between web and felt ahead of a press nip;
- to hold the web to the fabric (roll surface) for a certain circumference;
- to provide a defined web run.

Perforated rolls are used under various operating conditions:

- Without vacuum application, just storing water when it is pressed into the voids of the roll and releasing it afterwards. These rolls are used at lower machine speeds. A special open design of such a roll type with a wire cover is the dandy roll for formation improvement that is not drilled.
- With vacuum application in the wire section and dryer sections.
- With vacuum application and line load as suction press rolls in press nips.

Suction rolls apply controlled vacuum at a certain angle to the roll circumference to dewater the web, control web run, or for pickup and transfer. Most rolls with vacuum application emit a loud noise because of the siren effect when the holes under vacuum are suddenly refilled with ambient air. The noise level may be so high as to make ear protection measures necessary. The actual noise level depends on the roll drilling pattern, the vacuum level, machine speed, and the design of the sealing of the vacuum chamber inside the roll. Some typical perforated rolls are described in more detail in the following sections.

10.2.3.1.1 Forming Roll The forming roll (Figure 10.15a) is a suction roll positioned at the beginning of the wire section, for example, in high-speed, twin-wire formers. Here, a high amount of white water has to be stored, and low vacuum is applied (up to about 0.15 bar). The forming roll has a two-layered shell with an outer ring of high void volume (about 85%) and a perforated inner ring. New designs are 100% perforated with a second overriding drilling pattern (Figure 10.16). This kind of roll does not need a sleeve. A sealed vacuum chamber inside the shell defines the suction angle where the vacuum is applied. This is used for web formation control as regards, for instance, web symmetry in the z -direction. Older hybrid former designs are equipped with a forming roll in the top former unit.

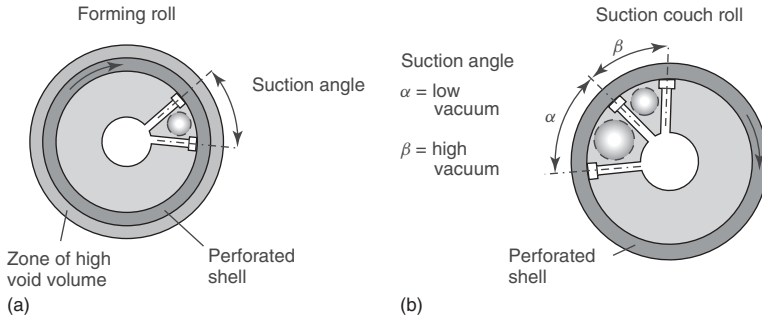


Figure 10.15 Schematic of a forming roll (a) and a suction couch roll (b).



Figure 10.16 Forming roll with an overriding second drilling pattern. (Source: Voith.)

10.2.3.1.2 Suction Couch Roll This roll (Figure 10.15b) is placed further downstream of the wire section, that is, at higher dry content where the web is already formed. It further increases the density of the web and increases its dry content. A small amount of white water is removed and the operating vacuum is about 0.3–0.7 bar. The vacuum chamber is divided into two zones with stepwise increase in vacuum. Shadow marking may occur on sensitive papers with too high vacuum application, operating the roll at a too low dry content, or inadequate drilling pattern. The open area is about 60%.

10.2.3.1.3 Suction Press Roll This type of roll is an open press roll with vacuum application at part of its circumference. The vacuum removes the air between the web and the felt ahead of the press nip and holds the web on the felt. It enables the water squeezed out in the press nip to flow from the web and felt to the roll void volume where it is stored and released after leaving the vacuum zone.

These rolls are very sensitive with regard to their stressing and material strength. Their main load is the linear force (usually up to about 120 N mm^{-1} and up to about 170 N mm^{-1} in special cases for shoe press application) in the press nip for dewatering. Additional loading occurs from the forces due to vacuum, felt tension, and dead weight. These forces result in a dynamic stressing of the shell. Stress concentration due to the drilling pattern and open area as well as the shell thickness have an impact on the actual maximum stress, which may be either more

“beam bending” (rolls with small diameter, high wall thickness) or more “shell deflection” (rolls with large roll diameter, low wall thickness). Figure 10.17 shows a schematic of a drilled roll with cover and vacuum chambers. The drilling pattern and the hole size define the amount of sucked air and dewatering capacity, the effect on the paper web (shadow marking), the noise generation, and the material stress in operation. A properly designed sealing strip can contribute to noise-level reduction (Figure 10.18).

Suction press rolls run in a corrosive ambience, so corrosion fatigue strength is an important material property. Corrosion fatigue strength decreases with the number of cycles and time. As a rule of thumb, it can be stated that 10% more stress (or less corrosion fatigue strength) leads to a factor of about 10 in lifetime reduction, which can be translated into a lifetime of either 10 years or 1 year. Suction press rolls are designed for a lifetime of at least 10^9 cycles. The material applied is bronze or special alloys exhibiting good corrosion fatigue characteristics. Figure 10.19 illustrates what happened in the 1970s and 1980s: a great number of rolls made from a newly developed and applied material A failed. It had a distinctly higher alternating bending strength at the beginning of life compared with a conventional material B. But in the corrosive atmosphere, the alternating bending strength of A decreased much faster than expected.

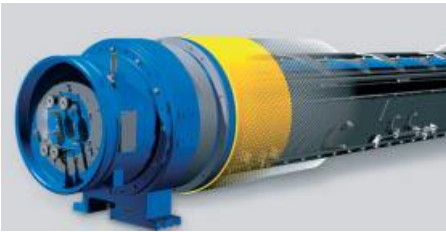


Figure 10.17 View of a drilled roll with cover and suction chambers. (Source: Voith.)

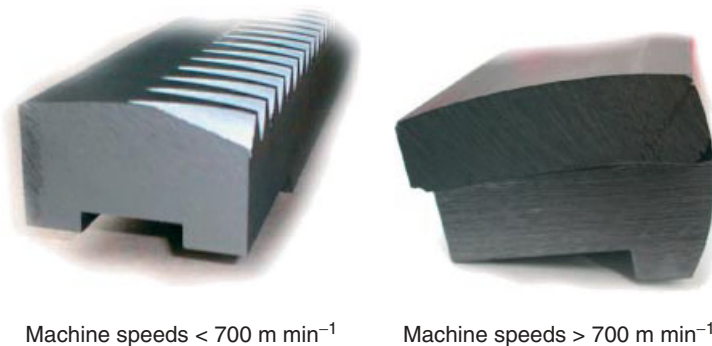


Figure 10.18 Sealing strips for noise abatement, applicable for different machine speeds. (Source: Voith.)

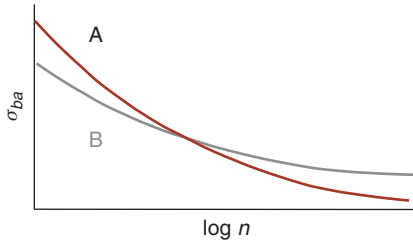


Figure 10.19 Reduction in alternating bending strength σ_{ba} over bending cycles n of two different suction roll materials in a corrosive atmosphere.

Shell thickness and open area define the amount of air to be removed constantly during vacuum buildup, which affects the amount of energy consumption. Hole diameters (about 4 mm, open area about 15–30%) in the metal shell are larger than those in the cover (about 2.5–4 mm, open area about 10–20%). The holes in the cover are drilled after the coating has been applied. The coating holes have to match the pattern in the shell, which is easier with smaller hole diameters in the coating.

10.2.3.1.4 Dandy Roll These rolls are driven and are used in Fourdrinier wire sections, the aim being to improve formation and surface smoothness or to generate watermarks. dandy rolls are wire-covered rolls with a very open structure behind the wire, either built up of rings and bars or of a honeycomb design (Figure 10.20). They are placed between two flat suction boxes a short distance upstream of the so-called “water line” (after which there is no more free water on top of the web surface). Here the structure of the freshly formed web is still weak enough to be partly rearranged without being completely destroyed. The dandy roll dips into the wet web, dewateres it for a short moment during the contact, generates gentle shear forces and “rewets” the web on leaving the nip. At higher speeds, more and more water is thrown out at the exit in the form of droplets and may harm the web.

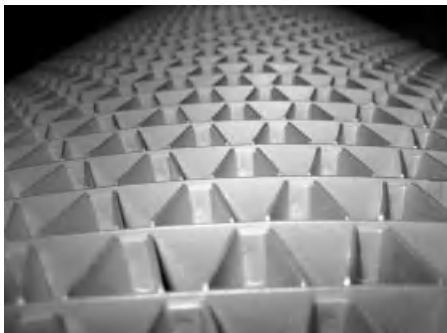


Figure 10.20 Close view of a welded honeycomb structure, for example, for dandy rolls. (Source: Voith.)

Hence the application of these rolls is limited to machine speeds of below about 1000 m min^{-1} .

10.2.3.1.5 Vacuum Rolls in the Dryer Section In a single-tier dryer section, vacuum-assisted, perforated, cast iron rolls are located between the drying cylinders to hold the web on the roll face (dryer fabric) by slight vacuum (about 800 Pa). Those rolls, with diameters up to 1500 mm, are essential at high speed machines. Vacuum inside the roll is created by a vacuum box riding on the roll. The box also provides proper web transfer from the dryer cylinder toward the vacuum roll. In older outdated designs, the roll is smaller in diameter and has a direct vacuum supply, which means the roll is more complicated and expensive. In modern machines, the rolls have a tailing zone for tail threading. During tailing, the vacuum is concentrated at the tail area so the tail is held tight against the dryer fabric. To ensure proper operation, cleaning devices are installed inside the roll to keep the perforation clean, so the vacuum can work on the web all the time (Figure 10.21).

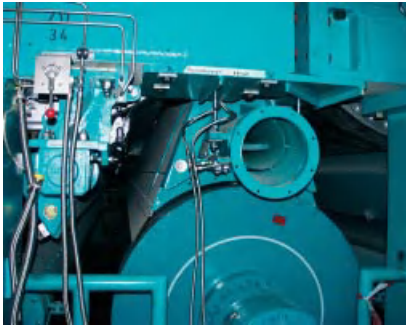


Figure 10.21 Perforated roll and vacuum box in the dryer section. (Source: Voith.)

10.2.3.2 Press Rolls

Press rolls are applied in the press sections of paper and board machines, and also when pressing the web to the Yankee dryer in tissue or MG paper production. Press rolls are used as well in sizing, calendering, at the reel, and at the winder (rider rolls). The roll design and the surface characteristics are determined by

- the line load to be applied (maximum and range);
- the requested length of the press nip in MD (dwell time) under operating conditions;
- the requested elasticity of the roll shell cover;
- operating conditions such as temperature, chemical environment, and machine speed.

Depending on the application, the shell surface can be the actual shell material, a tailor-made metal spiral, a metallic coating, or a synthetic or rubber cover of different elasticity behavior. The shell surface geometry is either plain, blind drilled, grooved, or drilled and grooved.

10.2.3.2.1 Press Section Typical for the press section are line loads from about 60 up to 150 N mm^{-1} . In the nip, water should be stored (in cooperation with the felt) and then released, all being different for the roll position within one press section. The rolls show all kinds of the surfaces mentioned earlier, also a grooved metal surface for a hard nip with good water storage and transport capability. Figure 10.22 depicts an example of a grooved roll surface and the cross section of the surface layer showing the “wire” material spirally wound onto the roll shell.

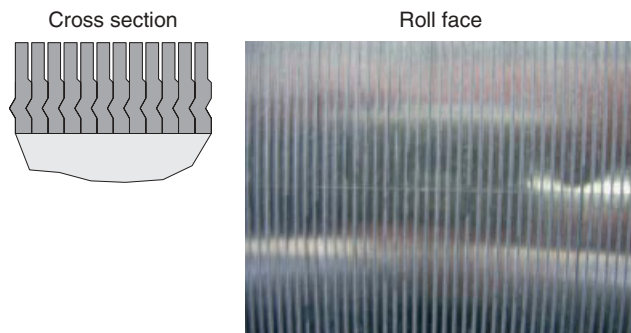


Figure 10.22 Example of a grooved surface of a steel roll. (Source: Voith.)

Extended nip press rolls are a special type of press rolls. An endless press sleeve replaces the metal roll shell and is pressed by a press shoe (with oil lubrication) against the mating roll. Here, line loads up to 1200 kN m^{-1} are applied.

10.2.3.2.2 Calender Rolls These rolls have to ensure, depending on location in the paper machine, either a uniform CD caliper profile, a defined porosity, or a defined web smoothness and gloss. Their loading varies in a wide range from 5 to 450 N mm^{-1} and CD deflection control is a must. They may have a metallic surface, or in other cases, be equipped with special covers and coatings. For example, the conventional supercalender, applied for specialty papers, has cotton-filled rolls. Rolls with metallic surface can be internally heated by hot water, saturated steam, or thermal oil, or externally heated by induction.

In heated rolls, the surface temperature has to be uniform across roll width as well as in the circumferential direction in order to ensure uniform paper technological results. Uniform circumferential temperature is also very important for calender operation. Even small surface temperature differences of, for example, 2°C in circumferential direction result in a run out of the roll of about $1 \mu\text{m}$. This may lead to vibrations during calender operation with negative effects (barring) on paper uniformity and machinery. Hence uniform heating is mandatory.

When the heating fluid passes through the “pipes” in the solid roll or roll shell, its temperature and consequently, the transferred heat, decrease along its path. There is a similar decrease in the shell surface temperature and, in consequence, in

that of the shell radius. In order to lower this effect, different kinds of flow guidance principles are applied. Various flow configurations are shown in Figure 10.23.

- Solid roll design (with cast-on or bolted-on journals)
 - In roll type R1, the heating medium simply passes through a center bore in one direction: remarkable temperature difference across machine width (CD), high uniformity in roll circumference (MD).
 - In roll type R2, every three peripheral bores form a set where the flow goes one after another through all bores, thus passing the roll three times; diagonal borings interconnect the single sets at the ends: good uniformity in CD, acceptable uniformity in MD.
- Thick shell wall design (bolted-on journals):
 - In roll type R3, feeding is through the center and return flow takes place through all the peripheral bores: acceptable CD temperature difference, high MD uniformity.
 - Roll type R4 is mostly built with two (or three) bore sets, one (or two) bore(s) for the supply and one for the return flow. Distribution, flow direction change, and collecting of the single flows are done in the journals: good CD uniformity, acceptable MD uniformity.

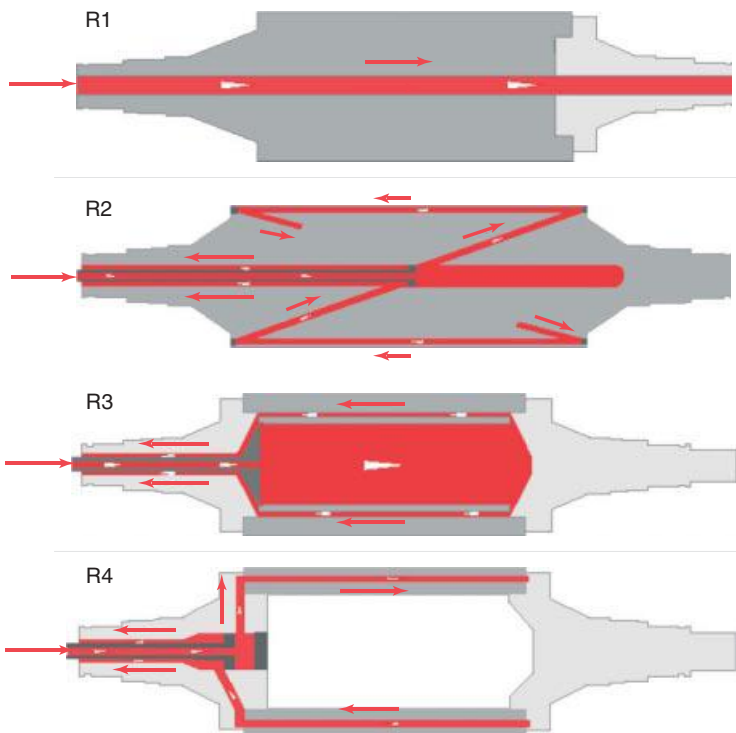


Figure 10.23 Flow-guiding principles for internally heated rolls. (Source: Walzen Irle.)

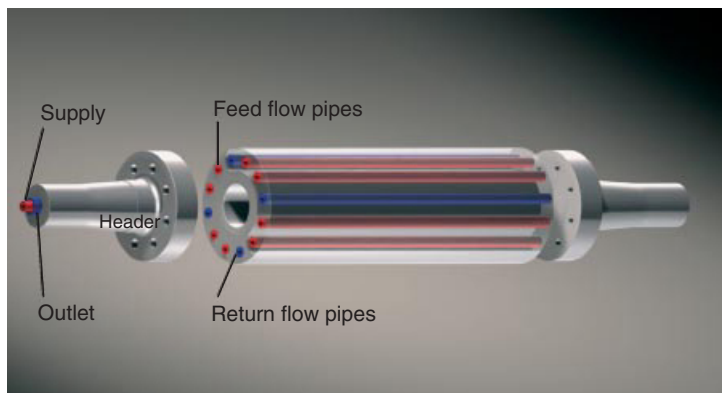


Figure 10.24 Schematic of an internally heated roll for application in calendering with a set of three bores, two for supply (red) and one for return flow (blue). (Source: SHW.)

Figure 10.24 shows a heated roll with the journals removed. In this special case, three peripheral bores in the thick shell build one set comprising two feed flow bores per one return flow bore, which are adequately connected at both ends.

The microstructure of the cast roll shells is not homogeneous across the wall, as a result of the solidification process. Mechanical and thermal properties, such as hardness and thermal expansion, differ for these material “layers.” A roll shell machined at ambient temperature may bend when heated up because of these differences. For demanding applications, the rolls are therefore often ground under heating conditions to further improve the situation as regards thermal bending and radius deviation in operation.

10.2.3.2.3 Rolls for Sizing and Coating In general, these rolls have rubber or plastic covers of about 15–25 mm thickness with a very wide cover hardness range (0–150 P&J) depending on application. To protect the covers from damage, the rolls can have a simple internal water-cooling system. A web knock-off device is installed ahead of the rolls as a must. A drive is mandatory, whereas CD deflection control is an option.

- **Pond size press:** The rolls of a pond size press have to generate a uniform CD line force and must force the starch into the paper. The loading is up to 60 N mm^{-1} . They have covers up to 15 P&J hardness. The press and mating rolls are equipped with different cover types, a hard and a soft cover. The web tends to follow the harder roll surface after the nip.
- **Film size press:** For medium- and high-speed applications, a film size press is the first choice. The rolls of these size presses have to generate a uniform CD line force and must transfer and force (high line load) starch into the paper. For coating purposes, the coat has to stay on the paper surface, so only a low line load should be applied. The loading for starch is up to 30 N mm^{-1} for graphic grades and up to 60 N mm^{-1} for packaging grades. For coating, the loading is up

to 20 N mm^{-1} . The rolls have covers, 30 P&J for sizing and 70 P&J for coating. Roll diameters up to 1600 mm are applied. Faster machines require larger rolls for getting a better coating, that is, for efficient coating color transfer.

- **Coater blade backing rolls:** Here covers of about 70 P&J hardness are the first choice. Roll diameters up to 1700 mm are applied for very wide machines.

10.2.3.2.4 Reel, Winder Drums The reel drums have diameters up to 1500 mm and a tailor-made surface pattern (Figure 10.25) depending on the paper grade. The objective of the pattern is to avoid web defects such as wrinkles. The reel drum can be perforated, grooved, or blind drilled. In special cases of demanding applications, a plastic roll face cover is needed. Covers are always a critical wear factor, so a cover should be avoided if possible. Doctors are provided at a reel drum against wrapping of the drum with paper. Figure 10.26 shows a perforated reel drum in combination with a device for safe tailing (a major relief for dry end operators) and a reel drum doctor.

Winder drums are similar to reel drums but more sophisticated in design. For demanding paper grades and high-speed applications, the drum must be perforated

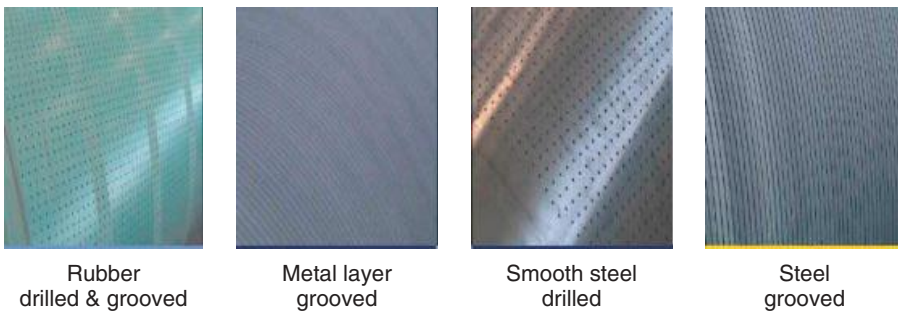


Figure 10.25 Different surface patterns on reel drums. (Source: Voith.)



Figure 10.26 Perforated reel drum and device for safe tail threading in a single-tier dryer section. (Source: Voith.)

and vacuum assisted, so no boundary air layer can be trapped during the winding process; this is important for preventing wrinkles.

10.2.4

Deflection Control Rolls

10.2.4.1 Controlled Nip Line Load Distribution

Rolls undergo a deflection under forces that may be due to roll dead weight, wire or felt tension, linear load in press or calender nips, or vacuum (low internal pressure) at a certain circumference angle of the shell. However, most often, a straight press nip or a uniform nip load in the CD is required with only small deviations being allowed. One simple means of achieving this is to crown the roll. This is done by grinding a curve onto the originally cylindrical shell with larger diameter at the roll center than at the edges, thus compensating for the deflection and resulting in a uniform nip load across the width. One disadvantage of roll crowning is that the local circumferential speed of the roll is different across the width because of the varying diameters. This may create problems in paper quality or in fabric operation.

The above nip conditions also have to be reached for different operating conditions, such as varying linear loads in press nips. A given crown really precisely fits, for instance, only one line load. So changes in operating conditions result in deviations from a constant line load in the nip over the width or from a straight press nip. With increasing width of the paper machines, the problem gets worse as deflection increases by the third power of the roll face length.

With the introduction of deflection control rolls, this general flaw can be overcome. The principle of all such rolls is that the bending deflection is taken by an axial beam that supports the shell by means of a kind of hydraulic “cushion,” be it just one or several “cushions” across the width of the roll. This “cushion” presses the shell to the counteracting roll. In Figure 10.27, the history of deflection control in press nips is illustrated.

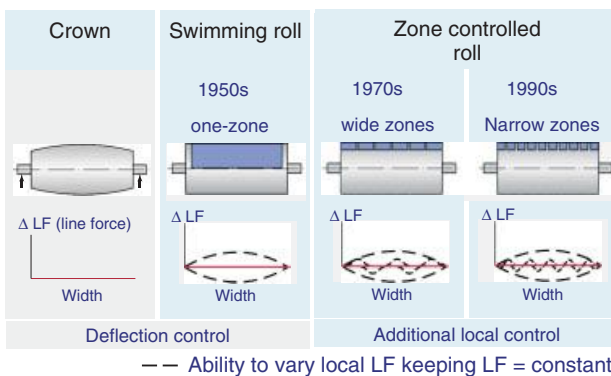


Figure 10.27 History of deflection control in press nips.

10.2.4.2 One-Zone Rolls

10.2.4.2.1 Swimming Roll The swimming roll (Figure 10.28) was introduced into the paper industry in 1960 by Küsters (Germany). In principle, the shell rotates around a fixed axial beam with bearings at each end. A pressurized oil chamber is placed between the shell and the beam, which is sealed along the axis against the rest of the inside shell volume and against the roll ends. The oil pressure can deform the shell toward the mating roll. The forces acting on the shell are carried by the axis supporting the oil chamber. High oil pressure tends to “blow up” the shell, resulting in more local load at the center of the press nip, whereas reduced oil pressure will reduce the local load at the center compared to that at the edges. Loading of the roll to generate the nip pressure is done by external loading devices. A further example of this type of roll is the Voith Econip roll.

10.2.4.2.2 CC Roll Introduced by Beloit in 1960, the shell of the crown control (CC) roll is supported by one shoe with hydrodynamic lubrication. The shoe can move in the nip direction in the fixed axial beam, which takes and deflects the line load forces, as with the swimming roll, loading is external.

10.2.4.2.3 Profile Roll Introduced by Voith in 1980, the shell support of this roll is similar to that of the CC roll. One main feature is that the distance between its end bearings equals the distance of the bearings of the counteracting roll, therefore, it is also called the equidistance roll. Loading is external.

10.2.4.3 Multizone Rolls

10.2.4.3.1 Nipco Roll The Nipco roll (Figure 10.29) was introduced in 1971 by Escher Wyss. It not only compensates for deflection but also allows local control of

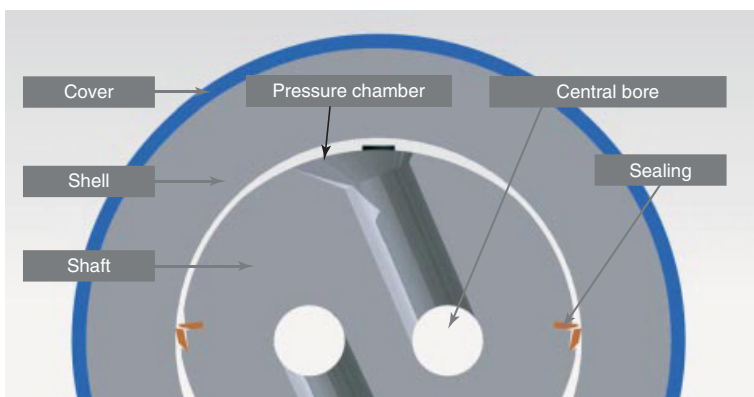
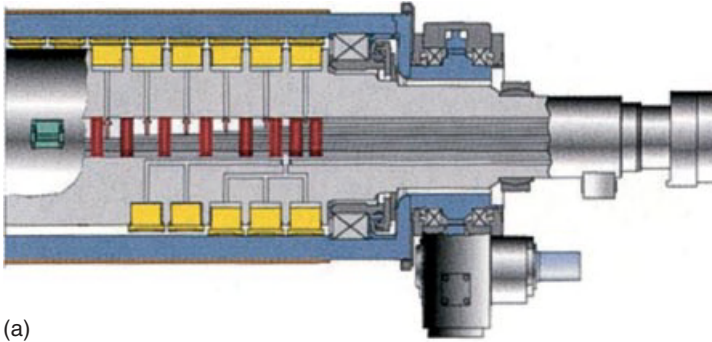


Figure 10.28 Swimming roll, an example of a one-zone deflection control roll. (Source: Voith.)



(a)



(b)

Figure 10.29 Example of a multizone nip control roll. (Source: Voith.)

the line load in the press nip. Here the shell is supported by a number of hydrostatic pistons that are grouped in at least six or eight zones with two counteracting zones at the edges. All zones are pressurized separately in order to “design” the CD line load curve. The pistons are supported by a fixed beam that takes and deflects the press force. One special feature of the Nipco roll is the self-loading characteristic of the F-type roll. Self-loading means that no external loading devices are required to load the press nip. The movement for loading, relief, or opening the nip is performed by the hydrostatic pistons mentioned earlier. This movement is made possible by special bearings that allow the shell to move in the nip direction only.

10.2.4.3.2 Hydrein Roll Introduced by Kleinewefers in 1979, the roll principle is similar to the Nipco roll with the special feature of having “double pistons” in a circumferential direction.

10.2.4.3.3 Hydro Vario Roll This roll was introduced by Küsters in 1980. It consists of a shell, a fixed axial beam, and between these, a pressurized oil chamber. For local line load control, hollow pistons placed inside the oil chamber are tightly pressed to the shell to eliminate the oil pressure and thus reduce the press force at that position. In addition, these pistons can be applied with a higher oil pressure than in the pressure chamber itself, which increases the line load locally.

10.2.4.3.4 Nipcorect Roll Voith introduced the Nipcorect® roll in 1994. These fine control rolls have been developed to control the line load profile in a much finer pattern, for example, with a roll having more than 30 and up to 60 zones. In order to make this fine control effective, the rigidity of the shell has to be reduced dramatically, for instance, by using very thin metal or nonmetal shells. Further examples of this kind of roll are the multi-HV roll of Küsters (now Andritz-Küsters) and the Sym CD roll of Metso.

10.2.4.3.5 Controls Complicated calculations are needed to define the optimum oil pressure in the different zones in order to give the best approximation to the desired CD line load profiles. These have to take into account all elastic bending characteristics not only of the deflection control roll itself but also the entire roll system involved. A control system based on these models assists the operator or closes the control loop in automatic operation.

10.3

Roll Covers and Coatings

*Yang Shieh, Johan Einarsson, Franz Grohmann, and Norbert Gamsjäger**

10.3.1

Objectives and Basic Design Criteria

Depending on their application, roll covers or coatings in the paper machine have to fulfill various functions. The main objectives of roll coverings or coatings may be

- to protect the roll body against corrosion in a corrosive environment;
- to protect the roll against wear from doctors, wires, or felts;
- to generate a soft (and thus wide) nip compared to a hard (and thus narrow) nip;
- to reduce the hydraulic pressure in a press nip;
- to increase dewatering function;
- to ensure good release of the paper web;
- to transfer coating or sizing to the paper;
- to provide elastic support for the paper in calendaring;
- to provide a very smooth and abrasion-resistant surface;

* Contributed to the First Edition.

- to avoid the agglomeration of deposits;
- to support the paper in winding operations.

The various applications in the paper industry require a considerable variety in the design and materials used for roll covers and coatings. The materials used range from very hard metallic coatings to very soft elastomeric covers, the surface geometry from plain polished to profiled with a highly open surface. In the following, the term *cover* is used for cover thicknesses of approximately 10–30 mm, the term *coating* is used for coating thicknesses of less than 1 mm. This is not a standardized nomenclature, but is established in the industry.

The design of a cover or coating is either defined by the application or by the design needs of the cover material used. Covers and coatings for the paper industry normally have a multilayer design (Figure 10.30) where the outermost layer provides the function of the cover for the papermaking process and the innermost layer ensures the bonding to the metal roll body. The use of additional intermediate layers is often required in order to withstand the shear stresses within the cover in loaded positions. A gradual adjustment of material properties such as hardness, Young's modulus, thermal expansion, and so on, in the radial direction is also desirable in order to avoid residual stresses in the cover. These residual stresses are caused by the differences in material properties of the metallic roll shell and the cover/coating.

Covers/coatings have to reach an extremely high number of load cycles during their operational lifetime. In double-nip installations, where the cover is loaded twice per revolution of the roll, the number of load cycles goes up to 10^9 . This dynamic load, in combination with temperature and the, eventually wet, chemical environment, requires high fatigue resistance of the cover/coating. Covers are usually ground several times before recovering is required. Depending on the application, operational lifetimes of between 18 months and several years are standard for covers.

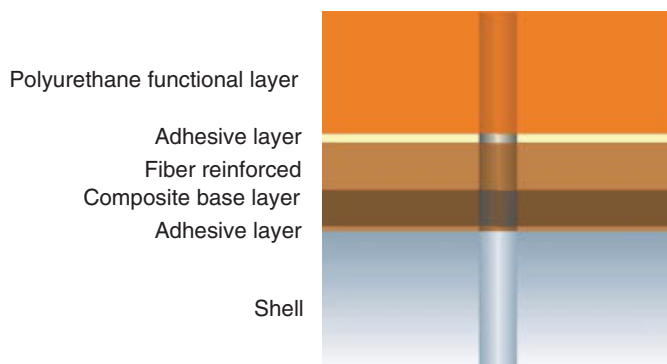


Figure 10.30 Cross section of multilayer design for suction press roll cover. (Source: Voith.)

10.3.2

Application and Function**10.3.2.1 Corrosion and Wear Protection**

Covers for paper, wire, or felt guide rolls have to protect the metallic roll body against corrosion or wear. In general, these covers are plain, and relatively hard materials are used. However, in drive roll applications where the cover has to transfer the torque to the driven wire or felt, softer elastomeric covers are also applied.

10.3.2.2 Nip Design in the Press Section

In the press section, the individual rolls are either hard or covered with a soft elastomer. The press nip (Figure 10.31) is created either by two profiled rolls or by a combination of one profiled and one plain roll. Covers with high open surface area, similar to tire technology, offer the necessary storage capacity for the water squeezed out in the press nip. The various surface designs include grooves, blind drilled holes, or suction holes, as well as combinations of these.

The press nip geometry is mainly defined by the diameters of the press rolls, the deformation characteristics of their covers, and the compressibility of the felts. The deformation characteristics depend on the dynamic Young's modulus and Poisson's ratio of the cover material, the thickness of the cover, and its surface design. The press nip geometry defines the nip pressure profile, which in turn affects dewatering in the press nip. For optimum press dewatering, the water storage capacity, the surface structure, and open surface of the cover have to be balanced, and the felt properties in terms of water storage capacity, compressibility, and water flow, optimized.

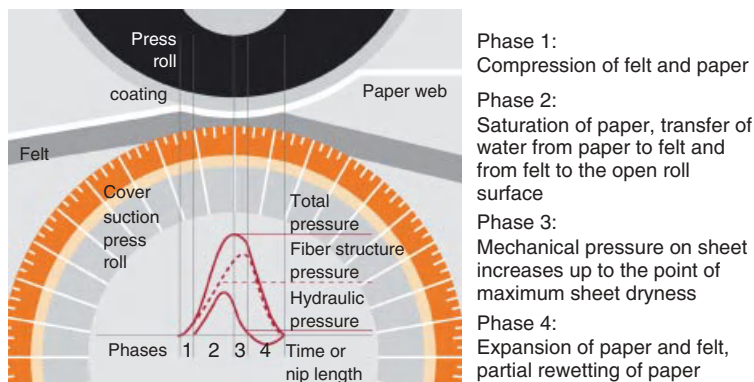


Figure 10.31 Schematic press nip (After B. Wahlström, (1960). A long term study of water removal and moisture distribution on a newsprint machine press section - Part I. *Pulp and Paper Magazine of Canada*, 61(8), T379-T401.)

10.3.2.3 Release Properties

In some press designs with hard, plain press rolls, the paper web comes into direct contact with a cover or coating. It needs to be pulled off the roll surface uniformly with preferably low force as it exhibits low strength because of its high water content. Web elongation in the MD also needs to be reduced to a minimum. Therefore, easy release of the paper web from the cover or coating is required for good paper quality and high machine runnability. This can be achieved by a special cover or coating material design, which has been optimized with regard to hydrophilic/hydrophobic areas and defined surface porosity.

Coating of drying cylinders in some positions aims to reduce the deposition of stickies or color on the roll surface. The release characteristics of the coating allow easier removal of the deposits by doctoring.

10.3.2.4 Nip Design in Coating and Sizing

For coating, sizing, or pigmenting in film transfer presses the primary purpose of the cover is both to provide a soft nip and to transfer the applied liquid film uniformly to the paper web. Abrasion resistance is important for keeping the nip geometry constant, as the film thickness of the applied coat/size is extremely thin and any nonconformity in the nip results in a nonuniform film application. Good wettability to give a uniform film, a stable surface roughness influencing film thickness and transfer rate, as well as good film splitting properties to reduce misting, are also required especially in applications in fast-running machines.

Figure 10.32 shows a film press cover.

In conventional puddle size presses, the hard and elastic covers must mainly ensure a uniform nip, in which the size is pressed into the paper web. Both temperature and chemical resistance of the covers are essential.

Coater backing rolls give elastic support and ensure transport of the paper web without slipping of the web, which is coated on the opposite side. Elasticity and optimized deformation behavior are the crucial parameters for roll cover design.



Figure 10.32 Example of film coating. (Source: Voith.)

10.3.2.5 Nip Design in Calenders

The functions of covers or coatings in soft nip calenders are twofold. The hard heated roll in the calender is either a chilled iron roll with a hard, wear-resistant surface, or it is coated for even more improved wear resistance. The surface of the hard roll needs to be extremely smooth, as the roll surface is imprinted onto the paper surface. The covers need certain surface characteristics for calendaring application; therefore, their surface quality is essential. As thermal energy must be transferred to the paper through the coating, its thermal conductivity and thickness are important.

The soft elastic roll presses the paper web against the heated roll. This cover must exhibit a certain local deformation ability in order to at least partly follow the “microscale” topography of the paper web in the calender nip. The compression modulus of the cover is of similar magnitude to that of the paper. The local deformation of the cover ensures that the paper is not just calibrated in the nip, but that the thinner areas of the web are calendered as well. Thus soft nip calendaring results in better printability compared to hard nips for most printing processes.

10.3.2.6 Other Applications

In winding, reeling, and cutting operations the covers mainly have to support the paper without affecting the paper surface negatively. Soft, sometimes compressible, covers are used, providing lower shear stresses in the nip compared to incompressible elastomeric covers.

10.3.2.7 Application Overview

The functions of roll covers and coatings are varied and significantly influence paper quality as well as the runnability of a paper machine. This explains the need for a variety of materials, which enables one to have custom-designed covers and coatings for all applications. Each of the major materials has its unique advantages; nevertheless, an overlap of the different cover materials exists for many applications. Table 10.3 gives an overview of the materials presently used as roll covers and coatings, their main properties, as well as their major applications in paper machines. In the following sections, these materials are described in more detail.

Future development of covers and coatings must take into account ever increasing production and demand for improved runnability. Here the main goals are

- reliability;
- predictable operation (grinding) intervals also when in contact with more abrasive fillers used in paper and coating;
- predictable lifetime and safety aspects in case of damage.

Furthermore, the expectations in energy efficiency, maximum dewatering, and improved paper quality, as also best bulk retention, will further increase, accompanied with a request for reduced consumption of water used for keeping the rolls clean.

Table 10.3 Roll cover applications.

	Wet section				Press section				Special press configurations							
	Wire guide roll covers (p)	Wire drive roll covers (p)	Wire suction roll covers (sd)	Lump breaker roll covers (p)	Paper guide roll covers	Wire and felt guide rolls (p)	Hard press roll covers (p)	Hard press roll covers (g)	Soft press roll covers (g, bd, gbd)	Suction press roll covers (s, sg, sbd, sbdgg)	Smoothing press, soft covers (p)	Shoe press counter roll covers (p, bd, g, bdg)	Long nip press (jumbo press) (bd)	Roll covers for tissue machines (bd, sbd, sg, sbdgg)	Press roll covers for marking press (p)	Press roll covers for glazing cylinders (p)
Rubber covers	x	x	x	x	—	x	x	(x)	x	x	x	x	x	x	—	x
Polyurethane covers	—	(x)	x	—	—	—	—	—	x	(x)	—	x	—	—	—	—
Composite covers (resin covers)	—	(x)	—	—	—	—	—	—	—	(x)	—	x	—	—	—	—
Composite covers fiber reinforced	(x)	—	—	—	—	x	—	—	—	—	—	—	—	—	—	—
Thermal coatings	(x)	—	(x)	—	(x)	(x)	x	—	—	(x)	—	x	—	—	—	—

Table 10.3 (continued)

	Dryer section				Sizing, coating, and pigmenting				Calendar			Reeling	
	Paper guide roll covers (p)	Wire and felt guide rolls (p)	Coatings for drying cylinders	Paper guide roll covers (p)	Hard roll covers for puddle size (p)	Soft roll covers for puddle size (p)	Film press roll covers (p)	Coater backing and applicator roll covers for coating machines (p)	Paper guide roll covers (p)	Elastic roll covers (p)	Hard roll covers (p)	Reel spool (p)	Reel drum (p)
Rubber covers	x	x	—	x	x	x	x	x	x	—	—	x	x
Polyurethane covers	—	—	—	—	—	(x)	x	(x)	—	—	—	x	—
Composite covers (Resin covers)	(x)	(x)	—	(x)	—	—	—	—	(x)	(x)	—	—	—
Composite covers fiber reinforced	(x)	(x)	—	—	—	—	—	—	(x)	x	—	—	—
Thermal coatings	(x)	(x)	x	(x)	(x)	—	—	—	(x)	—	x	—	x

Abbreviations: x = standard; — = special application; p = plain; s = suction drilled; bd = blind drilled; g = grooved.

10.3.3

Materials

10.3.3.1 Rubber Roll Covers

Rubber roll covers are the covers with the longest tradition. The hardness ranges from very soft elastomeric covers to hard rubber. Both natural rubber and synthetic rubber polymers are used. Typical rubber formulations consist of approximately 8–15 ingredients such as polymers, fillers, processing materials, tackifiers, antidegradant components, colorants, activators, and vulcanizing agents. The possibility of compounding standard formulations as well as high-performance formulations makes rubber an excellent material for roll covers.

Hard rubber covers are used for guide and hard press rolls. For guide rolls, the compounds are cost optimized because of the large number of guide rolls in a paper machine and the relatively low mechanical demands. Therefore, a large amount of conventional inexpensive fillers is used. Depending on the application, single-layer designs are usually used. Bonding of the covers to the metal shell is a combination of shrink-fit of the hard rubber and chemical bonding, resulting in good corrosion resistance, which is the main reason for applying the cover.

For hard press roll applications, the demand on surface quality and abrasion resistance is higher; therefore, more expensive fillers and combinations of fillers are used. Release properties of the cover can be adjusted by addition of polymer fillers such as PTFE. Two-layer designs are frequently used; they comprise a cost-optimized, hard-rubber bonding layer and a performance-optimized functional layer.

Soft press roll covers are formulated for good dynamic properties in combination with high wear resistance. Chemical resistance and swelling characteristics are adjusted by selection of the polymer. The higher loads of the nipped positions require two or three layer designs in order to withstand the shear forces in operation. Bonding is achieved through chemical bonding supported by the shrink-fit when a hard bonding layer is used.

Sizing/coating/pigmenting is the domain of the high-end formulations. Synthetic polymers such as CSM (Hypalon®) give outstanding aging and good chemical resistance; nitrile rubbers, for example, result in very good mechanical properties and abrasion resistance. Properties such as heat buildup, dampening, wettability, roughness, and low compression set for marking resistance must be considered for development of the compound in these applications.

Most roll cover manufacturers carry out their own rubber compounding because of the variety of the formulations, the demand for high quality, and the small batch sizes. Mixing of the compounds is frequently done in open mills (Figure 10.33) because of the small batch sizes, the high number of different compounds as well as hardness variations, and the good quality of this compounding procedure. The use of internal mixers is not always justified because of high equipment costs.

After mixing the rubber compound, it is strained to remove impurities and converted into either a feeding strip for an extruder or a calendered sheet for direct application.



Figure 10.33 Rubber compounding on an open mill. (Source: Voith.)

The surface of the roll is carefully prepared by cleaning and sandblasting before the application of chemical adhesives or rubber cements.

There are three basic methods for applying the rubber cover to the roll core:

- **Extrusion:** An extruded strip of rubber is spirally wound around the rotating roll body (Figure 10.34).
- **Knott method:** A narrow strip of calendered rubber is spirally wound around the rotating roll body.
- **Hand build:** Large calendered sheets of rubber are manually applied on the roll.

With each of these buildup methods, the desired layers of different materials are applied. The choice of application method depends mainly on the compound and the requirements for cover homogeneity. The hand-build method, as an example, is the most sophisticated and most expensive build method. For these reasons, it is only used for applications with extremely high demands on surface qualities such as sizing or coating.

Vulcanization of the covers is done in steam autoclaves, where the rubber polymer is cross-linked to the elastomeric network. The cover is finished by mechanical tooling, drilling, and grinding to the required geometrical dimensions.

10.3.3.2 Polyurethane Roll Covers

Polyurethane roll covers were introduced to the paper industry toward the end of the 1980s. The outstanding mechanical and dynamical properties make polyurethane



Figure 10.34 Extrusion of rubber cover. (Source: Voith.)

the most suitable material for elastomeric covers in press positions. Depending on paper quality and press design, high open surfaces up to 45% with grooves, blind drilled holes, or suction holes, as well as combinations thereof are used. An example of surface design is shown in Figure 10.35.

For these types of covers in modern machines, only polyurethane elastomers are able to provide enough wear resistance to reach acceptable grinding intervals. High-performance polyurethane formulations are used, giving the required mechanical strength and elasticity as well as outstanding hydrolytic stability.

Usually, the cover has a multilayer design in order to ensure excellent bonding of the polyurethane functional layer to the core as well as for safe running properties. The state of the art is composite base layers with fiber reinforcements that allow a gradual adjustment of the mechanical and thermal properties of the cover in a radial direction. This results in a gradual adjustment of the shear forces created by the nip load within the cover layers. Two-layer designs with a harder polyurethane underlayer are also used to provide bonding to the shell.

In fast-running machines, the dynamic heat buildup in the cover limits the application of elastomeric materials. Polyurethane polymers, based on special formulations with excellent dynamic properties, ensure good performance in these applications with minimal heat buildup. An example of such an application is the substitution of grooved steel rolls by elastomeric covers in shoe presses.

The functional layer of polyurethane covers is manufactured by casting processes, thus ensuring very homogeneous material properties.

Roll preparation is similar to that for rubber; chemical adhesives are used to bond the base layer. The base layer can be a fiber-reinforced composite, which is applied in a wet impregnation process of the reinforcement material. The glass fiber reinforcement (tapes or rovings) is impregnated in a resin bath and then spirally wound onto the roll shell. Curing of the base layer with infrared heating and/or ovens and tooling to a defined geometry are the next steps.

The polyurethane elastomer itself is a reaction polymer, created by the mixing of prepolymers and chain extenders or hardeners. This reactive mixture, which

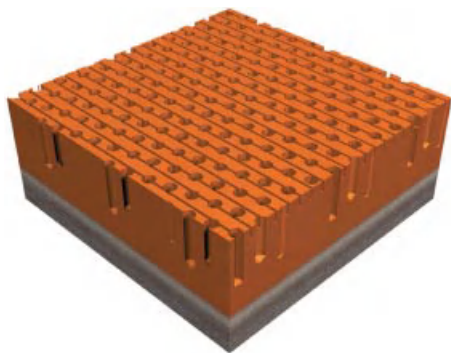


Figure 10.35 Example of surface design for polyurethane press cover (blind drilled and grooved). (Source: Voith.)

is created in the desired mixing ratio by special casting machines, is spread horizontally in a moldless rotational casting process (Figure 10.36). Here the reacting polyurethane mixture is cast as a spiral on the rotating roll; the fast reaction of the polyurethane mixture prevents the material dripping off the roll. Layers of different hardness can be applied easily with this method.

Most polyurethane formulations need to be post-cured at elevated temperatures for optimum material properties. The final mechanical manufacturing steps are similar to those of rubber covers.

10.3.3.3 Composite Roll Covers

Two basic composite designs for the functional layer of roll covers are used in the paper industry: composite covers with a fiber-reinforced functional layer and composite covers with a cast functional layer (resin covers).

10.3.3.3.1 Fiber-Reinforced Functional Layer Composite covers with fiber reinforcement in the functional layers are mainly used in calender applications. The use of fibers significantly improves the mechanical and thermal robustness of the cover. High-performance materials such as aramid fibers are used, where a high damage tolerance is required. Compared with structural composites, where the fiber characteristics dominate the mechanical properties, the fiber volume content of the functional layer of roll covers is relatively low. The major physical properties such as hardness, compressive modulus, or strength of the covers are mainly dominated by the particle-filled resin matrix.

The base layers of the multilayer designs are mostly glass fiber-reinforced; in these layers, the fiber content is higher, and therefore, the fiber properties dominate the properties of the composite.

For soft calendaring, different hardnesses – or more accurately different Young's moduli – of the covers are required in order to ensure the required paper properties. This can be achieved primarily by varying the amount and combination of different fillers in the fiber-reinforced composite.

The surface of the covers must be as smooth as possible, and with excellent wear resistance. These properties can be influenced, for instance, by the modulus of the



Figure 10.36 Moldless rotational casting of polyurethane cover. (Source: Voith.)

fibers, particle size distribution, and hardness combinations of the fillers and, to a minor extent, by the properties of the resin. Temperature resistance and low heat buildup of the cover under dynamic load is mainly a function of the resin matrix system. Operating conditions of calenders, such as 25 Hz load frequency, 90 °C surface temperature, and 50 MPa nip pressure as well as expected load cycles of $>10^9$, make the elastic calender covers the most demanding applications of roll covers. Figure 10.37 shows an elastic composite cover in a multi-nip calender.

For lower demand applications, composite covers with conventional fiber reinforcements (glass or polyester) are used. These covers are for applications such as guide rolls or special press positions.

10.3.3.2 Cast Functional Layer (Resin Covers) Composite covers with cast functional layers are applied in the press section or in calenders. Typically, mineral-filled resin systems are applied onto a fiber-reinforced base layer. The advantages of the cast resin systems are extreme homogeneity of the functional layer and good abrasion resistance. These properties are important for applications such as soft calender covers or center press roll positions. Special formulations of the resin/filler composite allow the adjustment of sheet release properties as well as wear resistance. Limitations for this type of cover are the sensitivity to mechanical damage and thermal shocks because of the relatively brittle functional layer.

For the manufacture of composite covers, wet impregnation processes are primarily used. The reinforcement fibers (tapes, rovings, or nonwovens) are impregnated in formulated resin mixtures and wound onto the roll body. Multilayering with different fiber reinforcements and different fiber orientations is applied. The winding angle of the reinforcement material mainly governs the reinforcement direction of the fibers, creating anisotropic (direction-dependent) material properties. These special material properties are used for design purposes, for example, to influence the strength, thermal expansion behavior, or modulus of the composite structure.

Particle-filled functional layers are applied by casting processes similar to that for polyurethane covers.

The curing of the resin systems, which are primarily epoxy based, is done by infrared heating and/or by heated curing ovens. The mechanical processes are

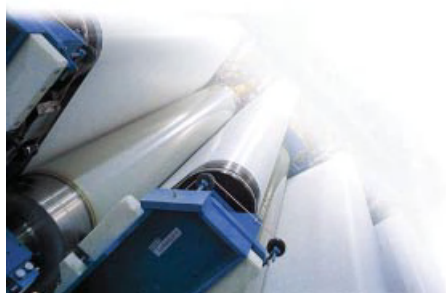


Figure 10.37 Elastic composite cover in multi-nip calender. (Source: Voith.)

similar to those used for the other cover types. The final surface grinding requires special techniques to reach the desired smooth surface properties.

10.3.3.4 Thermal Coatings

Thermally sprayed coatings are gaining wider use in modern paper machines because of their outstanding wear resistance. Even thin coatings of 0.2–0.7 mm provide both excellent resistance and long lifetime. Different thermal spraying processes (e.g., plasma, HVOF, flame/arc spraying) allow the use of a large variety of materials.

10.3.3.4.1 Ceramic Coatings Oxide ceramic coatings based on Al, Ti, Cr oxides, or combinations, are used in hard press roll positions. The outstanding wear resistance of the ceramic surface, as well as excellent sheet release, makes these coatings suitable for high-speed paper machines. Owing to the well-defined porosity structure of the ceramic, a hydrophilic coating surface is created. This results in excellent sheet release and a low tendency for deposition of hydrophobic stickies on the roll surface. The surface topography of the coating, an important factor for sheet release, is kept constant over its lifetime, even under doctored conditions.

The coating itself is usually a two- or three-layer design. The functional layer made of ceramics is, by its nature, porous. To ensure a corrosion-resistant coating, either chemical sealing of the pores is carried out or corrosion-resistant nonporous underlayers are applied.

The main applications are for hard press rolls/center press rolls in fast-running paper machines.

10.3.3.4.2 Hard Metal Coatings Hard metal coatings are carbides, nitrides, and borides of transition metals. Carbides of the Cr-group are mainly used for thermal coatings. These wear-resistant layers are used for grooved or drilled press rolls, providing increased grinding intervals. Optimized formulations of these multiphase coatings are used to coat heated calender rolls. These coatings can be polished to extremely fine surface smoothness and they provide very efficient heat transfer to the sheet. The durability of these systems allows continuous doctoring of the coatings.

10.3.3.4.3 Metals and Alloys Metals and/or alloys are sprayed mainly as base or underlayers in combination with oxide ceramics and hard metal coatings. The difference in thermal expansion of the oxide layer and the metallic roll is partly compensated by these layers. The major features of these materials are ductility and toughness, improving the overall coating performance.

Thermal spraying is the buildup of a coating on a substrate from particles sprayed at defined temperature and kinetic energy onto the roll surface. The thermal energy is required to melt the powder particles or the wire, while the gas flow is necessary for the particle acceleration. Energy sources can be either electrical (arc, plasma) or chemical: H₂, propane, or kerosene (flame spraying). The

melted and accelerated particles hit the surface, resolidify, and build up the coating layer by layer (approximately 10–20 $\mu\text{m}/\text{pass}$).

Arc and plasma spraying can be performed either in vacuum (VPS) or under atmospheric (APS) conditions, but only the latter is applicable for roll coatings. Differences in flame spraying mainly concern the particle velocity. High-velocity spraying can be continuous (HVOF) or discontinuous (D-Gun). The plasma coating of a press roll is shown in Figure 10.38.

10.3.3.5 Chromium Coatings

Galvanic chromium coatings are used in special applications for coating the hard calender rolls. But their supreme surface finish and dense homogeneous coating is sensitive to damage and have limited doctorability. This is why thermal coatings compete in these applications.

10.3.3.6 Thermoplastic Covers, Sleeves, and Coatings

Pure thermoplastic materials are applied only in niche applications.

Cast or extruded polyamide tubes are used as counter rolls in marking presses, for example, for cigarette papers, thin PTFE sleeves are applied as hoses on bow rolls. High-performance thermoplastic covers are applied in niche calendering applications.

Limitations of thermoplastic materials are their moderate wear resistance and the dimensional instability of thermoplastics under load.

Combinations of thermoplastic coatings with an extremely open layer of a hard metal coating combine the properties of both material classes. Release coatings of PTFE sintered on thermally sprayed hard metal coatings for good release properties are examples of these hybrid coatings. The hard metal underlayer ensures wear resistance, and the thermoplastic PTFE layer fills the pores and creates the good release. This type of coating is applied, for example, in the dryer section for the first drying cylinders after the press or size press, as well as for critical guide roll applications.



Figure 10.38 Plasma coating of press roll. (Source: Voith.)

10.3.3.7 Granite Rolls and Calender Paper Shafts

Granite rolls and paper- or cotton-filled paper shafts are not roll covers or coatings in the usual sense. Here, the material that provides the function is also part of the load-bearing structure of the roll itself.

Certain properties of granite rolls or of cotton-filled paper bowls were of great advantage to the papermaker and these were also targets for the steadily improved coatings and covers, which in turn could provide additional advantages. Granite rolls, for instance, have become history, regardless of their excellent release characteristics, because of the operational risks at high machine speeds or the technical and economic problems encountered when building this equipment for modern paper machines of 10 m width or more. The release properties in the meantime were matched by ceramic coatings or synthetic, composite, or rubber covers.

Cotton-filled paper rolls remain in some applications with insufficient heating capacity of the supercalender and very high demands in terms of paper gloss; but in existing supercalenders, the competition from composite covers is increasing because of the limited marking resistance of the filled rolls.

11

Fabrics for Paper and Board Production

Matthias W. Schmitt

Only 2% of the overall cost of paper production constitutes expenditures toward paper machine clothing such as forming fabrics, press felts, and dryer fabrics. The remaining 98% are fiber, labor, energy, and chemicals costs. In fact, fabrics are a minor part of the costs but have a major impact on runnability, product quality, as well as performance and energy consumption of a paper machine.

Almost throughout the whole papermaking process the paper web is in contact with fabrics on one or both sides. Hence the surface characteristics of the fabrics are of high importance because they are visible in the paper web as wire or felt marks. Perfect dewatering and high quality of the produced paper through the whole fabric lifetime, quick startup, secure web guidance through the paper machine, and good resistance against abrasion and contamination are main features of a modern paper machine clothing and requires a balanced set of fabric properties. The main tasks of paper machine clothing are given below:

- In the forming section, one or more forming fabrics remove 98% of the water from the fiber suspension via filtration.
- In the press section, the formed web is mechanically dewatered under pressure up to 12 MPa. Press felts sponge half of the water from the incoming the paper web and guide the paper web through the press nips.
- In the dryer section, the dryer fabric transfers the paper web through the section, enhances drying by good and uniform contact heat transfer from the cylinder surface to the web, enables free escape of the vapor, and reduces web shrinkage in the cross-machine direction (CD).

To fulfill all these different tasks, paper machine (PM) clothing in a modern paper machine are highly developed and specialized parts of the papermaking process, tailor-made for the individual position and well concerted with all other parts of the paper production process.

* Contributed to the First Edition.

11.1

Forming Fabrics

*Matthias Höhsl and Arved Westerkamp**

11.1.1

Requirements

Forming fabrics, also called *wires*, are used in the forming section of the paper machine to dewater the fiber suspension and thereby build up a continuous paper web. As web formation is the most critical phase in paper manufacturing, specialized fabrics have to be used to achieve the required paper sheet properties such as smoothness, filler distribution, or printability. The fabrics used for forming are woven on looms, where the machine-direction (MD) yarns (warps) and cross-direction yarns (weft) are interlaced with each other. Depending on the kind of paper machine, forming fabrics have a length between ~25 and 105 m. Typically in a gap former, the length of the wires is between 25 and 30 m. As the paper machine width has been increasing significantly in the past 15 years, the widest fabrics nowadays would be close to 12 m. Forming fabrics are endless and their installation in a modern paper machine usually takes about 1 h. The configuration of the rolls and blades determines the fabric's course and its lifetime which is typically between 30 and 120 days.

The main requirements forming fabrics have to meet are as follows:

- uniform and controlled dewatering of the suspension exiting the headbox and uniform buildup of the paper web;
- gentle and uniform web support during intensified web dewatering at blades, foils, and vacuum suction boxes;
- safe web transport to the couch position;
- easy web release.

This means that the forming fabrics have in part to meet contradictory requirements, such as the following:

- the fabric surface should be very smooth for uniform paper web support while having a large open area for uniform dewatering with low flow resistance;
- the durability of a fabric should be large, resulting from thick weft diameters, but this leads to more void volume in the fabric and can cause undesirable water absorption.

All these properties should be constant over the width and length of the individual fabric and over the whole lifetime.

11.1.2

Designs and History

Historically, various alloys of bronze, copper, nickel, brass, and stainless steel were used to weave forming fabrics or wires as this term fits better to the used

* Contributed to the First Edition.

materials. Increasing paper machine speeds as well as the demand for improved paper properties led to a change in the raw materials employed, which started in the 1960s with the use of synthetic materials, primarily polyester and polyamide.

By using plastics, product lifetimes increased significantly, while at the same time problems arose such as stretching of the fabric in the machine direction (MD) and narrowing in the cross direction (CD). So it became necessary to introduce new manufacturing processes such as heat-setting to fix the dimensions of the woven structure. Because of the change to the plastic materials, welding technology could no longer be used, so an entirely new seaming technology also had to be developed.

Since this time, the fundamental manufacturing process chain has remained the same. It consists of the following:

- **Warping:** winding up MD yarns on sectional warp beams
- **Weaving:** interlacing MD and CD yarns
- **Heat-setting:** locking the knuckles in the weave
- **Seaming:** forming an endless loop
- **Finishing/packing:** surface treatments, width determination, edge treatments, identification by number, and running instructions.

Increasing demands on the paper quality and machine speeds, diversity on paper machine layouts and paper grades, or economic reasons have led to a plurality of new forming fabric designs since the 1970s. The main focus of ongoing design developments is still today the permanent reduction of fabric caliper and void volume and improvements in the fiber support as well as the fabric stability. The development process has gone through several major and minor steps (Figure 11.1). The different designs and their main properties are as follows:

- **Double layer:** Improved lifetime by a weft layer on the wear side with long floats and a weft layer on the sheet side with shorter floats.
- **2½ layers:** An additional thin weft layer alternating with the top wefts, giving more fiber support for better sheet formation.
- **Triple weft layer:** A middle weft layer with perfect stacking to the top weft layer as well as to the bottom weft layer, increasing the CD bending stiffness, designed for PM positions with high requirements on dimensional stability and paper CD profiles.
- **Triple layer:** First design with two warp layers and two weft layers while the top warp and weft yarns are thinner than those on the bottom side of the fabric. The layers are bound together with an additional thin yarn called *binder yarn*. Because of the high bending loads of forming fabrics in the MD, these thin binder yarns are subjected to wear. This often ends in delaminated fabrics and results in streak formation of the paper. A typical version of a triple-layer fabric is a 2 : 1 weft ratio having double weft counts on the paper side than on the wear side. Improved fiber retention and better sheet formation result.
- **Sheet support binder (SSB):** These SSB designs integrate the binding yarn of a triple layer in the structure of the top layer. The binding yarns could be warp yarns and these designs are called *warp bound SSBs* but the more popular version of

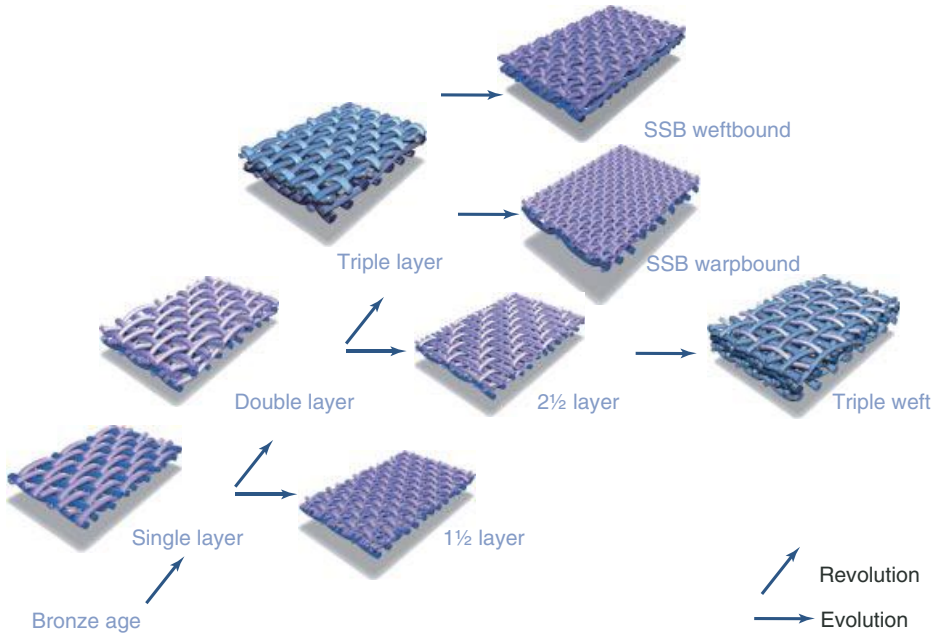


Figure 11.1 Evolution and revolution in the design development of forming fabrics. (Source: Voith.)

SSBs have wefts for binding (see yellow and red yarns in CD cut in Figure 11.2). This improves the delamination issue of the triple-layer fabrics because of better binder yarn fixation and reduces the chafe of binding yarn. Typical weft ratios are 1 : 1 to prove thin caliper, 2 : 1 to prove high fiber support, and 3 : 2 to balance good fiber support and lifetime. Like the triple layer, the SSB has two warp layers usually, each with the same mesh count resulting in a warp ratio of 1 : 1.

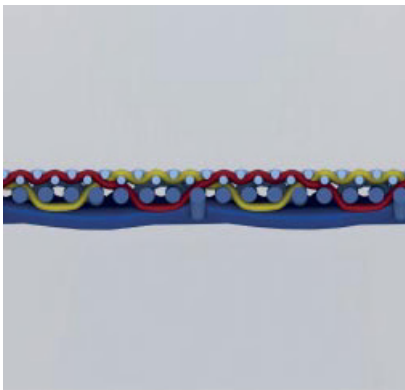


Figure 11.2 Weft path of a modern SSB design. (Source: Voith.)

Further design developments have taken place recently on SSBs with different warp ratios than 1 : 1 or different weft ratios to further improve fiber support and sheet formation.

Individual weave designs may differ not only by the warp or weft ratio but also by the material properties or density and, of course, by different combinations of all of them. The common variations are the following:

- yarn diameters between 0.50 and 0.09 mm to influence the fabric caliper, wear volume (durability), or fabric stability;
- yarn density to influence the drainage speed or drainage volume;
- materials such as polyethylene terephthalate (PET) or polyamide (PA) to influence the abrasion resistance, energy consumption, or mechanical fabric loads.

Although all design improvements provide advantages in papermaking such as process efficiency or improved paper quality, the old single- and double-layer designs still exist. However, their share in the sales statistic has permanently declined. The share of SSB designs in forming fabrics is more than two-thirds and is still growing.

11.1.3

Fabric Design Parameters

Comparing forming fabrics by design, the yarn diameter or yarn density is not enough to predict the effect on papermaking reality. Important is the suitable translation from the papermaking process requirement into a forming fabric property. Especially, since the introduction of SSB fabrics in the 1990s when hundreds of variations were generated, their comparison by technical data has become necessary. Besides warp and weft count and yarn diameters, the most important parameters of forming fabric are the following:

- **Support points:**

These are the crossing points of weft and warp yarns on the paper side of the fabric and the support of fibers and the paper web on the fabric. They influence the mechanical fiber retention and the paper smoothness. The weave design has a large influence on this parameter, so a plain weave surface gives the highest number of support points. The usual unit is the number of support points per square centimeter or per square inch.

- **Permeability:**

This determines the air flow through the fabric due to the pressure drop between the top side and the bottom side of the fabric. Common units are

- (cfm) ($\text{ft}^3/\text{ft}^2/\text{min}$) measured at 127 Pa,
- ($\text{m}^3/\text{m}^2/\text{h}$) at 100 Pa sometimes reduced to (m/s), or
- ($\text{l}/\text{m}^2/\text{s}$) at 100 Pa.

- **Fiber support index (FSI):**

This parameter reflects better the drainage conditions than just the air permeability [1]. Besides the air permeability, the meshes of the forming fabric are

considered:

$$FSI = 2/3(A \times N_m + 2 \times B \times N_c)$$

A and B represent fiber support section fraction, which are both 1 for plain weave structures such as the paper side of SSB designs. N_m represents the number of yarns in the MD and N_c the number of yarns in the CD. All yarn counts are per inch.

- **Drainage index (DI):**

The DI usually used in the forest industry has been modified for forming fabrics [2].

$$DI = 10^{-3} \times AP \times B \times N_c$$

AP is the air permeability in cubic feet per minute (cfm), N_c is the number of cross-machine yarns, and B a fiber support section fraction which is 1 for plain weave structures such as the paper side of SSB designs.

The formula seems to work well on single or double layers, but since the triple-layer age the DI does not represent the drainage capacity any more. Nevertheless, this index still exists on most of the data sheets.

- **Surface open area (SOA):**

This factor is an additional indicator for the drainage potential of a forming fabric. Contrary to the DI, the weave design and the yarn diameters are considered. The unit of SOA is (%) of the projected area.

- **Void volume:**

This is the open volume inside the fabric with the potential of water retention or water splashing. This is an important parameter, especially for the top fabrics on twin-wire machines.

11.1.4

Manufacturing Technology

Forming fabrics are manufactured on weaving looms with a width of up to 16 m, where CD yarns (wefts) and MD yarns (warps) are interlaced with each other. The weft insertion is typically made by using shuttles, projectiles, or band rapier systems.

The weft insertion speed on the looms is up to 1500 m min^{-1} . A modern loom and the principle of weaving are shown in Figures 11.3 and 11.4, respectively.

After the fabrics are woven, they are heat-set. Here, their final properties are determined by applying heat to the fabric while simultaneously stretching it in the MD and allowing a controlled CD shrinkage (Figures 11.5 and 11.6). The temperatures depend on the materials used, which are usually between 180 and 210°C . During heat-setting, the temperature is increased following a time sequence. The stretch achieved in the MD is normally between 8% and 12%, and the narrowing is up to 9%. As the fabric is only partially heated in the heating zone, the total dwell time depends on the speed ($2\text{--}4 \text{ m min}^{-1}$) and the number of revolutions.



Figure 11.3 TransCent TCR rapier loom. (Source: TEXO AB.)

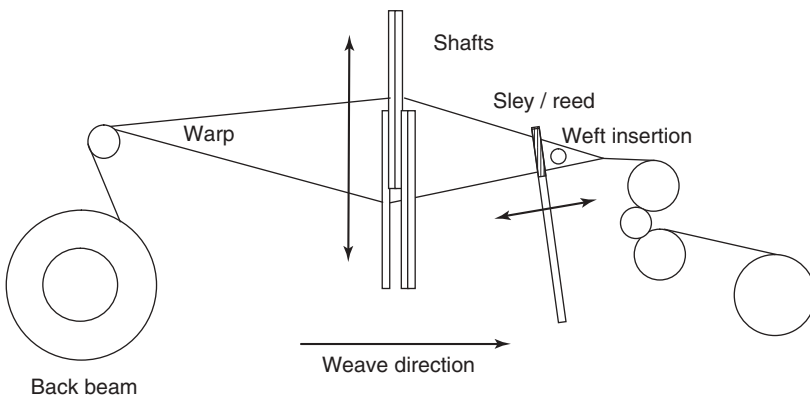


Figure 11.4 Weaving principle.

After being cut for seaming, the fabric is made endless by using a single thread selection weaving technology called the *Jacquard system*, where the weave is rebuilt in the seam area by turning it through 90° .

In the final finishing, moderate temperature is applied to the fabric in order to stretch out creases. After any protruding yarn ends in the seam area are cut off, the fabric will usually be sealed at the edges (and sometimes ground to enhance smoothness) before it is packed for dispatch as defined by the customers (usually wound on poles in wooden boxes).

Forming fabrics are continuously checked for quality during manufacture, following the manufacturing process. Qualifying criteria are defined for each manufacturing step. Typical tests would be hysteresis/stress-strain tests and profile testing (i.e., mass distribution, cfm, caliper).



Figure 11.5 Forming fabric heat-setting machine. (Source: Voith.)

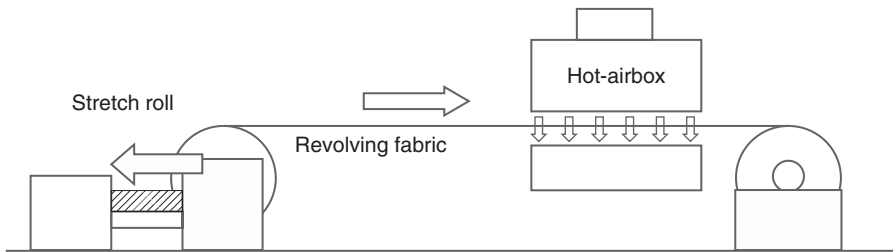


Figure 11.6 Heat-setting principle.

During development, other criteria such as bending stiffness, sheer, warp burial, and abrasion resistance are tested.

Comparability of data from all suppliers is achieved by using similar test and calculation methods as defined in the standard test procedures laid out by the Paper Machine Clothing Association (PCA).

11.2

Press Felts

Matthias W. Schmitt

11.2.1

Requirements

Press felts are used in the press section of the paper machine and are tailor-made for every particular position in the different press nips. Press felts are in direct

contact with the paper surface and strongly influence both the quality of the paper and the economy of the papermaking process. Press felts are porous laminates, composed of a base woven layer with nonwoven layers on either side, which are assembled by a needling process. The thickness of a press felt is in the range of 3–4 mm, the length between 15 and 75 m, the weight per area between 800 and 1500 g m⁻², and the air permeability between 15 and 450 l dm⁻² min⁻¹ (5 and 150 cfm). The total production of press felts in Western Europe is about 4500 tons per year (2010). The average value of press felts is in the range of €60–65 kg⁻¹ (2010), depending on the design. The lifetime of a press felt, for example, in a graphical paper machine is between three and four weeks.

The functions of press felts are the following:

- to pick up the formed paper web from the wire in the forming section and guide it through the press section of the machine;
- to support the wet paper web in the press nip and to store the water squeezed out of the web.

The resulting requirements the press felts have to meet are as follows:

- smooth paper-side surface for good printability of the produced paper and low rewetting (i.e., water flowing back from the press felt into the paper web after the press nip);
- low abrasion at the roll-side surface;
- high storage volume to store the water removed from the paper web;
- “constant” dewatering behavior over the lifetime including quick start-up behavior (full operating capability within a short time after installation);
- very uniform distribution of nonwoven layers (base weave) in MD and CD for uniform dewatering conditions and in MD to prevent vibrations;
- good dimensional stability (no width change, no permanent elongation) over the lifetime (12 m-wide press felts running at a speed of about 2000 m min⁻¹ and with a press load up to 12 MPa).

The actual requirements put on each individual felt depend on the particular position of its application in the press section, and thus the focus and felt design may vary. All press nips in modern paper machines are single- or double-felted. Shoe presses are mainly double-felted. The pickup felt is in the first press felt position: it has to transfer the wet paper web from the forming wire to the press section. While the loads of the press nips increase from one press position to another of the press section, the diameter of the felt fibers on the paper-side surface decreases. Changing from a coarser press felt surface to a finer one enables the transfer of the paper web, because of the increased adhesion by capillary forces and the larger contact area.

During its lifetime, the press felt runs several million times through the press nip. Reduction in felt thickness, abrasion, and contamination are the main reasons why a press felt has to be replaced. Fillers such as calcium carbonate, clay/kaolin, other papermaking additives, and adhesives, for example, from recovered paper,

deposit in the press felt structure, impeding or even locally preventing water flow. In some cases, not even alkalis and acids can reopen the press felt structure.

11.2.2

Press Felt Design and History

At the beginning of industrial papermaking, simple cloths made out of wool were used. In the early 1960s, these felts were replaced by improved designs based on high-tech textiles. This replacement was necessitated because of the increasing demands (lifetime of more than six days, use of abrasive fillers, higher machine speed).

Figure 11.7 illustrates the principle of a typical press felt structure. The base weave is found in the middle layer of the structure. The base weave is circularly woven; this means that the weft yarn during weaving is the yarn in the length direction of the finished press felt. The warp yarn is the yarn in the cross direction. The weaving loom produces a seamless hose, which can be up to 12 m in width and 70 m in length. Weaving looms can be up to 33 m in width. These endless felts are also called *seamless felts* and can be used in all applications.

Seamed felts, in contrast, are used mainly in the production of board and packaging and are not endless. They are closed in the paper machine with a seam, which is produced in a special variation of the weaving process. They are very common in North America (NA) (about 80% of all press felts in NA are seamed felts) and are easier and safer to install in the paper machine. A disadvantage is the marking of the seam, namely, a small stripe in the CD which may negatively affect the printability of the produced packaging paper or board.

The nonwoven layers on the top and bottom of the base weave consist of staple fibers with different yarn counts (3.3–100 dtex, which means a diameter of

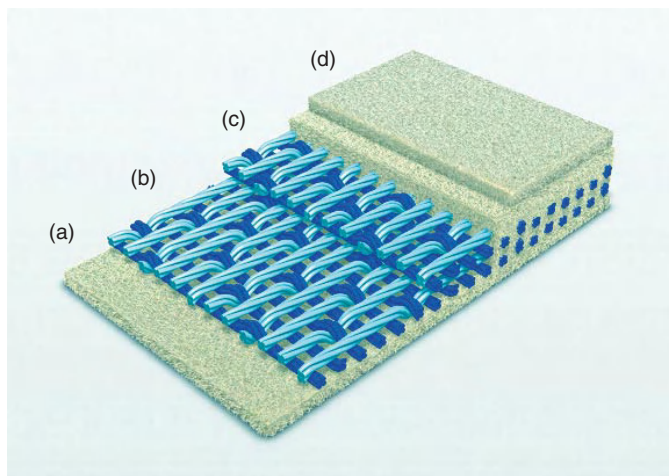


Figure 11.7 Principal structure of a double-layer press felt. (a) Roll side fiber layer, (b) first base weave, (c) second base weave, and (d) paper side fiber layer.

20–100 μm). The nonwoven layer at the bottom is in contact with the roll covers and protects the press felt against abrasion. The nonwoven layer on top is in contact with the paper surface and ensures a low and uniform water flow resistance during the dewatering of the paper web. A coarser, nonwoven layer is used in the first press nips with a higher amount of water removed from the paper web, whereas finer nonwoven layers have use in the further press nips with a lower amount of water extraction.

Polyamide 6 and polyamide 66 are the raw materials used for both the base weave and nonwoven layers. In some cases, polyamide 6.10 is used to increase the cross-machine stability during the felt lifetime, due to its reduced water absorption.

11.2.3

Manufacturing

The fiber batt for the nonwoven layers on both sides of the base weave is produced from compressed staple fibers by carding lines. The fiber batt is stabilized in a preneedling machine which makes it manageable for further production steps. On the finishing needling machine (Figure 11.8), the top and the bottom fiber batts are connected to the stretched base weave. After 5–15 revolutions in the needling stage, the press felt is washed to remove the spin finishing and decontaminated. The following hot air drying causes both the base weave and fibers to shrink, which results in a dense and stable press felt.

Some press felts have additional special layers, such as membranes, punched plastic films, and elastomeric fiber batts as one of the middle layers. These are introduced to control the water flow and to prevent rewetting or to act as an elastic damper against vibrations (Figure 11.9).

Elastomeric particles embedded and molten into the surface are able to improve surface smoothness of the felts and hence of the produced paper. These particles



Figure 11.8 Finishing needle machine for press felt production.

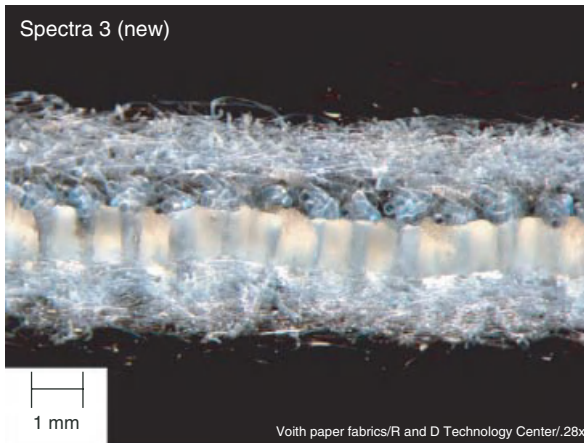


Figure 11.9 Light microscope image of a press felt cross section – top fiber layer, base weave, punched plastic film, bottom fiber layer.

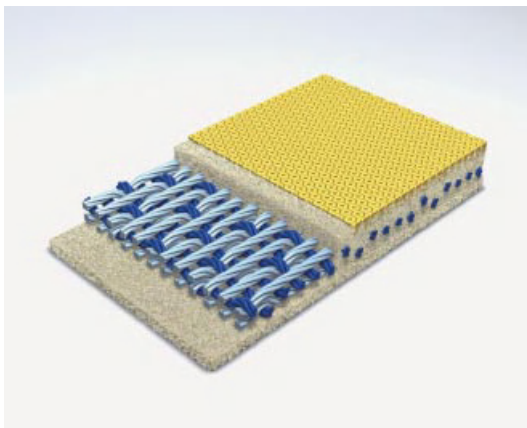


Figure 11.10 Schematic of a press felt with a particle coating (“pressure plates”) on the paper side.

act like “pressure plates,” transferring the applied press load more equally into the wet paper web (Figure 11.10).

Quality control during production includes monitoring the thickness, weight per area, and air permeability. As the allowed tolerances are small, high production accuracy and uniformity are required.

11.2.4

Transfer Belts

Transfer belts are specialty belts used in the second bottom position of a double-shoe press replacing a press felt. These transfer belts guide the paper web from the press

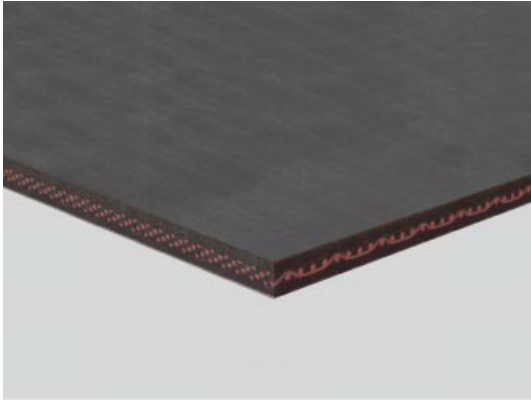


Figure 11.11 Cross section and the paper-side surface of a transfer belt; the thickness is about 4.3 mm.

section to the dryer section. The requirements transfer belts have to meet are as follows:

- smooth paper-side surface for good printability of the produced paper;
- impermeability to water to prevent rewetting;
- easy pickup and release behavior of the paper web;
- long lifetime.

Transfer belts are made from a reinforcing structure such as a dryer fabric or a base fabric for press felts and polyurethane cast on both sides. These belts are very stable and last up to nine months in a paper machine.

A different belt design uses an endless press felt which is covered with a polyurethane or rubber layer on the paper side. These belts are lighter and last up to four months.

Figure 11.11 shows the cross section of a transfer belt with a smooth paper side.

11.3

Dryer Fabrics

*Juergen Abraham and Antony Morton**

11.3.1

Requirements

Dryer fabrics guide the wet web through the dryer section. The tension on the fabric is used to press the wet web to the hot cylinder surface to facilitate heat transfer from the cylinder to the web and thus to increase the drying rate.

The resulting requirements put on a dryer fabric are as follows:

* Contributed to the First Edition.

- Paper contacting surface to have a high contact density for optimization of heat transfer from the cylinder to the paper web;
- Smooth paper contacting surface and inline seam for nonmarking of the paper;
- Sufficient vapor permeability to allow evaporative drying to occur freely. The permeability profile must be uniform across the full fabric width to ensure that it does not influence the moisture profile of the paper web. Permeability must not be too high, else this will adversely affect web runnability. For example, on high speed, single-tier type dryer sections, web transport and control is critical. For heavier weight packaging grades running at slower speeds, heat transfer may be of primary importance;
- Contamination resistance to allow a clean run, keeping the permeability up and thereby allowing the water to evaporate also through the fabric;
- Aerodynamic surfaces and low void volume for reduced air carriage to maintain good web runnability and tail feeding;
- Assistance in the safe transfer of the web between one group in the dryer section and another and within a conventional dryer section;
- Low internal void volume to ensure cleanliness during application and accessibility of dirt by the cleaning devices to allow effective cleaning;
- High performance and quality running lifetime in hot, humid conditions;
- Dimensional stability during running lifetime (typically 12–18 months) in hot, humid conditions;
- Safe and fast installation. All dryer fabrics are joined on the paper machine.

The importance of the various requirements for fabrics is dependent on their application.

Different paper machine designs, paper grades, and positions of the fabric in the machine require a tailored set of fabric properties to allow optimized performance of the fabric in this position.

11.3.2

Fabric Design and History

Before the invention of “man-made” fibers, dryer fabrics were made from natural materials such as cotton.

Advances in chemistry have seen the invention of polyesters and polyamides. These materials could be spun and formed into monofilaments. Polyester, more precisely PET, quickly became the preferred choice for dryer fabrics because of its abrasion resistance and dimensional stability.

However, all polyester materials are prone to hydrolytic degradation of the polymer under the hot, humid conditions in the dryer section. Therefore new polymer systems such as poly(cyclohexylenedimethylene terephthalate) (PCTA) were introduced to dryer fabrics. PCTA shows an improved hydrolytic stability compared to PET and polyphenylene sulfide (PPS), and is not prone to hydrolytic degradation, which further improves the fabric performance and resistance to the environment.

In state-of-the-art dryer fabrics, all three different materials, PET, PCTA, and PPS, are found, with PET being the dominant one. PET used for dryer fabrics has been steadily improved over the years via the addition of stabilizers to close the gap to PCTA and PPS.

PPS is inert to the environmental conditions encountered in a paper machine. This material is used for the construction of fabrics running on the hotter, more humid machines, for example, packaging machines.

Dryer fabrics comprise MD (warp) and CD (weft) yarns. These yarns may comprise monofilament, multifilament, spun, plied (twisted), and so on. Figure 11.12 shows a dryer fabric suitable for high speed, state-of-the-art paper machines.

Dryer fabrics may also be produced by linking a series of alternating left- and right-handed spiral monofilaments. The spirals are linked together by a connecting monofilament. Figure 11.13 shows a spiral fabric design.

11.3.3

Dryer Fabric Manufacture

Dryer fabrics are woven as a continuous, flat fabric. The MD warp yarns are held on canister spools at the back of the loom and passed through a series of “reeds” and “sheds” (spacers and pattern makers). During the weaving process, the sheds are raised and lowered according to the desired final weave pattern. At each shed

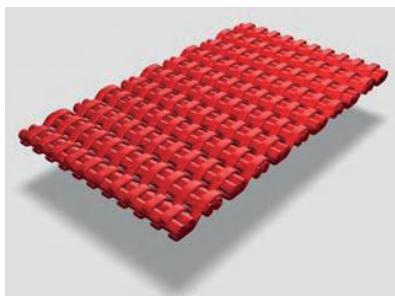


Figure 11.12 Dryer fabric for high speed paper machines.

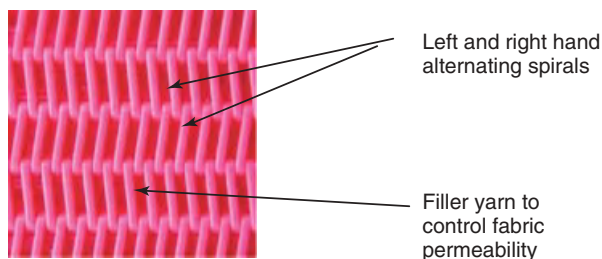


Figure 11.13 Top view on a spiral fabric design.

motion, a weft system is fired through the so-formed “warp tunnel.” The reed then pushes the newly formed section tightly into line with the rest of the fabric body.

The fabric is removed from the loom and relaxed and stabilized through the use of heat and tension. A typical heat-setting temperature is 180–200 °C for dryer fabrics. The tension is set according to the running tension on the paper machine section to which the fabric will be applied.

A seam is then created either from the MD yarns looped around themselves or by insertion of a spiral yarn around looped warp yarns.

In the case of a spiral link fabric, there is no weaving to be done. The left- and right-handed spirals are formed around a hot “mandrel.” These are then meshed together, and joining wires are used to link adjacent spirals. Spiral fabrics may or may not be “stuffed” with filler material in order to control their permeability.

Dryer fabrics typically range between 1.2 and 2.5 mm in thickness, depending on the fabric design required for the application. Their weight is typically 800–1500 g m⁻². Dryer fabrics are typically supplied in the permeability range of 80–950 cfm depending on the application.

11.4

Fabrics in Operation

Matthias W. Schmitt

During operation of a paper or board machine, the fabrics and belts need a certain degree of care and attention. The stretching and guiding of fabrics and belts are decisive for optimum running conditions, whereas cleaning and conditioning are important for good performance and lifetime. Cleaning is also very important for the quality of the produced paper or board.

11.4.1

Stretching and Guiding of Fabrics and Belts

All fabrics and belts have to run under tension in the MD. If the tension is too low, the clothing will run in wrinkles, perhaps leading to creasing, and the torque of the rolls will not drive the fabrics. This may lead to fabric slippage, causing abrasion and damage. Furthermore, the paper web will undergo a shear stress and will be damaged when, for example, the felts in a double-felted nip run at different speeds. If the tension is too high, seams can open, fabrics can burst, and, because of a “tie-effect,” the fabric will narrow. To apply the right tension, paper machines are equipped with stretch rolls (Figure 11.14). The stretch rolls are mounted on slide rails and are moved with spindles. Load cells monitor and control the applied load, that is, fabric tension. The wrapping angle for forming fabrics around the stretch roll is about 90°, for press felts about 180°, and for dryer fabrics about 120°. Typical numbers of stretching tension and wrapping angles of paper web clothing are given in Table 11.1.



Figure 11.14 Press felt stretcher with stretch roll, spindle, and slide rails. (Source: Voith.)

Table 11.1 Typical stretching tension and wrapping angle of paper machine clothing.

Type	Tension (kN m^{-1})	Wrapping angle ($^{\circ}$)
Forming fabric	7–9	90
Press felts	3–4	180
Dryer fabrics	2.5–4	120
Transfer belts	4–6	180

Running a fabric or a belt around a multitude of rolls leads to a certain movement in the CD. This is due to nonhomogeneous tension distribution in the fabric or when the roll axes are not exactly perpendicular to the MD. If this movement is not compensated by a guiding system, the fabric or belt may move off the machine. A guiding system needs three rolls and a sensor (palm). The two outer rolls are fixed, whereas the middle roll is fixed only on one side and movable on the other (Figure 11.15). The fabric or belt will always leave a roll perpendicular to its rotational axis. If the fabric or belt tends to move to the left, the roll will turn to the right and vice versa.

11.4.1.1 Functional Principle of the Guiding Unit

The guide palm of the palm unit (5) touches the fabric edge (6). On fabric run-out, the guide palm actuates the nozzles via a cradle, which controls the pressure in the spring-centered servo cylinder (7) (Figure 11.16). The servo cylinder moves the bearing arm (1). The bearing arm adjusts the guide roll (2). Base adjustment is done with the hand wheel (3). The base (4) can be shifted until the pointer on the bearing arm settles around the zero point on the dial at the actuator.

11.4.1.2 Functional Principle of the Palm Unit

A guide palm (4) is installed on the palm lever (3) of the palm unit (Figure 11.17). The palm lever with the guide palm is pressed onto the edge of the clothing (5) by a preloaded spring unit. The palm lever with the guide palm actuates two nozzles (2) via a cradle (1). In the vertical center position of the palm lever, both nozzles of

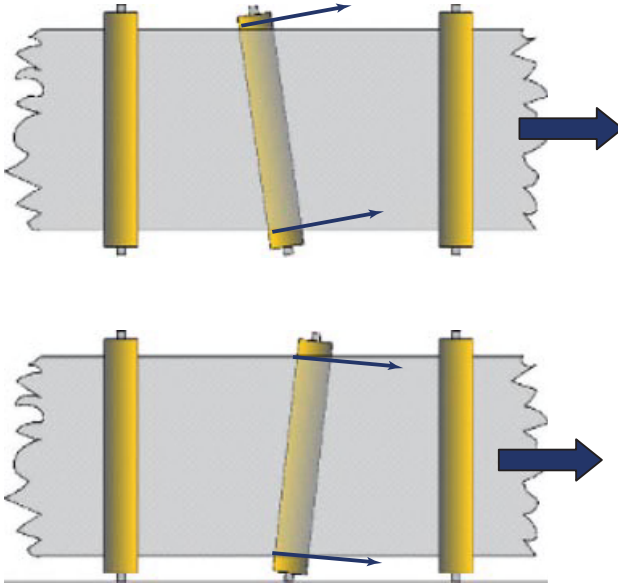


Figure 11.15 Guiding of paper machine clothing with a guide roll.

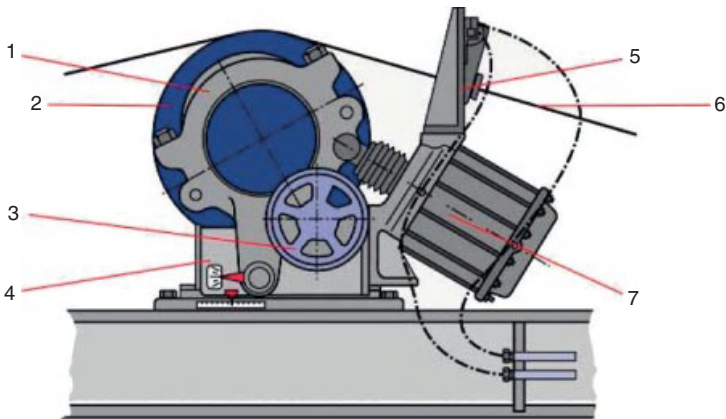


Figure 11.16 Guiding system at the moveable part of the guide roll. (Source: Voith.) Bearing arm (1), guide roll (2), hand wheel (3), base (4), palm unit (5), fabric (forming fabric/press felt/dryer fabric) (6), and servo cylinder (7).

the palm unit are closed. On fabric run-out, one of the two nozzles opens. In this way, the air pressure on the corresponding side of the servo cylinder is reduced.

The correct distance of the guiding system rolls is of great importance. The system will not work if the dimensions are too large or too small. As a rule of thumb, the distance between the two fixed rolls should be the width of the fabric or belt, and the guide roll should be in the middle. The wrap angle of the fabric

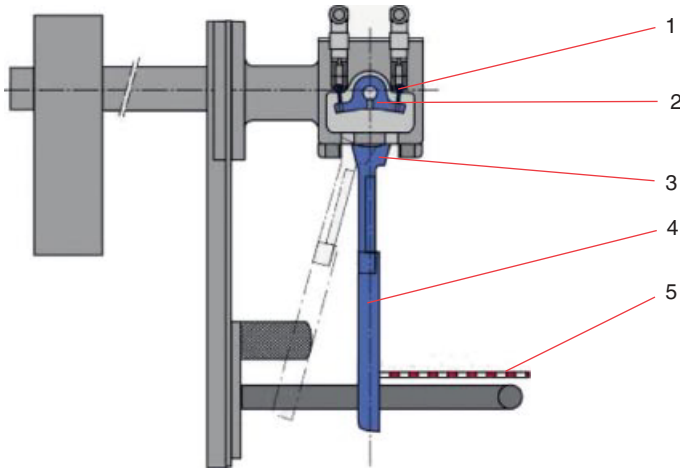


Figure 11.17 Palm unit of a guiding system. (Source: Voith.) Nozzle (1), cradle (2), palm lever (3), palm plate (4), and fabric (5).

or belt around the guide roll should be a minimum of 25° , but preferably $30\text{--}45^\circ$. The wrap angle around the fixed roll should be greater than 25° .

If the guiding system is shifting the guide roll continuously from one maximum point to the other, it is an indication of major problems with the fabric, belt, or roll axes alignment.

11.4.2

Cleaning and Conditioning of Fabrics

When using chemicals for fabric cleaning, safety rules have to be followed conscientiously. Paper machine clothing materials such as polyamide (forming fabrics and press felts) and polyester (forming fabrics and dryer fabrics) are sensitive to acid- and alkali-based chemicals. It is strongly recommended to follow the instructions of the cleaning chemical suppliers to avoid damage to the fabrics and the paper machine. Cleaning chemicals can also be hazardous, so personal protective equipment must be used in order to avoid any health risk. All chemicals should be applied in accordance with the manufacturer's recommendations and environmental and safety regulations.

Contamination is a major problem of fabrics in operation. Stickies, fillers, cellulose fibers, and residuals of process chemicals are collected on and in the paper machine clothing. Cleaning of the fabrics is necessary to provide good dewatering and to avoid paper quality problems, such as holes, dirt spots, and marks, as well as nonuniform profiles due to uneven dewatering.

Conditioning of fabrics, especially press felts, is necessary to provide a defined water content of the press felts. If the water content is too low, the press felts cannot absorb the right amount of water. If the press felt is too wet, rewetting takes place

and the dry content of the paper sheet after pressing will be lower. Water content across the width has to be uniform too.

To clean and condition the fabrics during operation, different showers are installed in the paper machine. High pressure showers with needle nozzles (0.7–1.0 mm diameter) create water jets with a pressure of up to 30 bar. The water consumption of one high pressure needle shower is between 1 and 3 l min⁻¹, and the recommended distance from the surface is 100–150 mm. Low pressure showers with fan nozzles (1.0–2.5 mm diameter, fan angle 60° or 75°) create a water fan with a pressure between 2 and 4 bar. The water consumption of a low pressure shower is between 3 and 4 l min⁻¹. In Figure 11.18, examples of needle and fan nozzles are shown. To prevent erosion, the nozzles are made of stainless steel or sometimes ruby. The nozzles need cleaning, the common technology being brushes inside the pipe, turned automatically or manually.

The water used for the showers is fresh water or filtered paper machine water. To prevent the nozzles from clogging, a filter system should be installed to filter fibers and suspended solids. For example, for a 1.0 mm needle nozzle, a filter pore size of 80–100 μm is recommended.

The showers are installed on an oscillating spray bar (Figure 11.19). A constant distance between the nozzles provides a uniform cleaning effect. The oscillation velocity has to take into account the machine speed, the fabric length, the spacing of the nozzles, and the nozzle diameter in order to clean the whole fabric area



Figure 11.18 Examples of needle and fan nozzles. (Source: Spraying Systems Deutschland.)

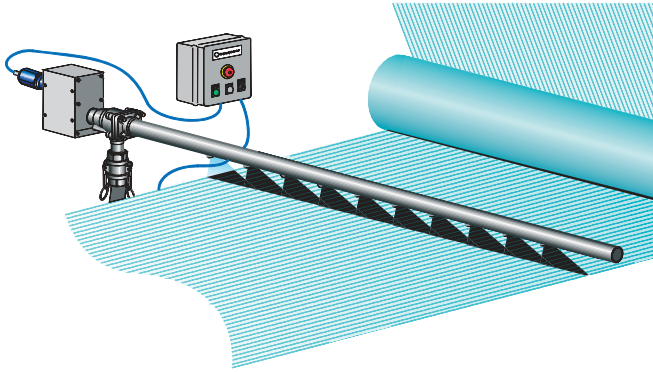


Figure 11.19 Spray bar for forming fabric cleaning. (Source: Spraying Systems Deutschland.)

uniformly. It can be calculated as the fabric speed times the jet diameter, divided by fabric length. The water jets generate mist, which has to be exhausted to keep the machine and machine room clean. The water loaded with fines and stickies has to be cleaned thoroughly.

11.4.2.1 Cleaning of Forming Fabrics

High pressure showers are the main cleaning devices of forming sections. The water jet is directed onto the paper side of the fabric if a multilayer design is used. Only single-layer designs are sprayed from the inside. To prevent the sensitive surface of modern forming fabrics with its small diameter yarns from damage, the water jet of the cleaning devices is rotated. Figure 11.20 shows a rotating cleaning head for forming fabrics in action.

The cleaning is discontinuous; only 10–15% of the time the water jet is on. Depending on the quality of the stock, stickies may need to be cleaned with organic solvents and detergents. Stickies would clog the dewatering channels of a forming fabric and create a mark in the paper sheet. If the sticky is tacky, the paper web can bond and create a hole after its separation from the wire.

Modern continuous cleaning devices use a powerful stream of air (up to $2400 \text{ m}^3 \text{ h m}^{-1}$ wire width) blown between two machine-wide blades



Figure 11.20 Rotating cleaning head for forming fabrics. (DuoCleaner™, Source: Voith.)

(Figure 11.21a,b). The pressure impulse on the first strip (similar to the blade impulse of a dewatering element) and the impulse of the blowing air ensure uniform cleaning and drying of the fabric over the entire width. The lubrication water fed in before the first strip is crucial for the efficiency of cleaning. An oscillating high pressure spray pipe pointed at the first strip is used to eliminate highly adhesive contaminants. Stock residues and accumulates are thus lifted from the fabric and removed by the blast of air. Air, water, and dissolved solid matter are removed by two-phase, high power suctioning. Inside the air duct, there is a machine-wide, intermittently driven flood spray pipe. The air duct and blasting gap are thus kept free of contaminants, without affecting production.

11.4.2.2 Cleaning of Press Felts and Transfer Belts

Press felts act like a filter and collect all kinds of materials used in the papermaking process. Paper stock and fines, fillers such as calcium carbonate and clay, sizing and wet strength agents, stickies and white pitch, oil and grease, and all possible reaction products can be found in press felts. If the contaminants are not removed continuously, the felt will be clogged and will lose its capability to transport and remove water.

To clean press felts physically, high pressure and low pressure showers are used in combination with suction boxes. The showers spray water on the paper side of a felt. The following vacuum box (Uhle box) is also located on the paper side and sucks water from the face of the felt together with stock, fillers, and other contaminants. This arrangement provides a cleaning “against” the direction of the clogging.

To clean press felt chemically, three different options are available:

- continuous cleaning using detergents applied via the showers;
- intermittent washing using stronger chemicals applied via the showers during a paper web break;
- shutdown felt washing using alkali and acid wash with longer dwell time.

Shutdown felt cleaning is the most efficient. The first step is the alkali cleaning. A 3–5% solution of sodium hydroxide is applied on the felt for 15–20 min. The polyamide fibers start to swell, enabling the adhered resins and other organic contaminants to be removed. Thorough rinsing to remove all contaminants with fresh water for 10–15 min is most important, using showers and the vacuum box. The second step is acid cleaning, using 2–4% hydrochloric acid (which is corrosive), or better 3–5% sulfamic acid or an organic acid, and a detergent. Calcium carbonate will be dissolved and the swollen polyamide fiber neutralized. Thorough rinsing is also most important. The use of sulfuric acid is not recommended if calcium carbonate is used. The reaction product, calcium sulfate, is insoluble and will clog the felt irreversibly. Several suppliers offer consultation and tailor-made packages for special cleaning problems.

Besides the cleaning, the conditioning of press felts is a major topic. Conditioning involves adjusting the water content of the press felt to the right amount so that the dewatering process is optimized and the transfer of the wet paper sheet from

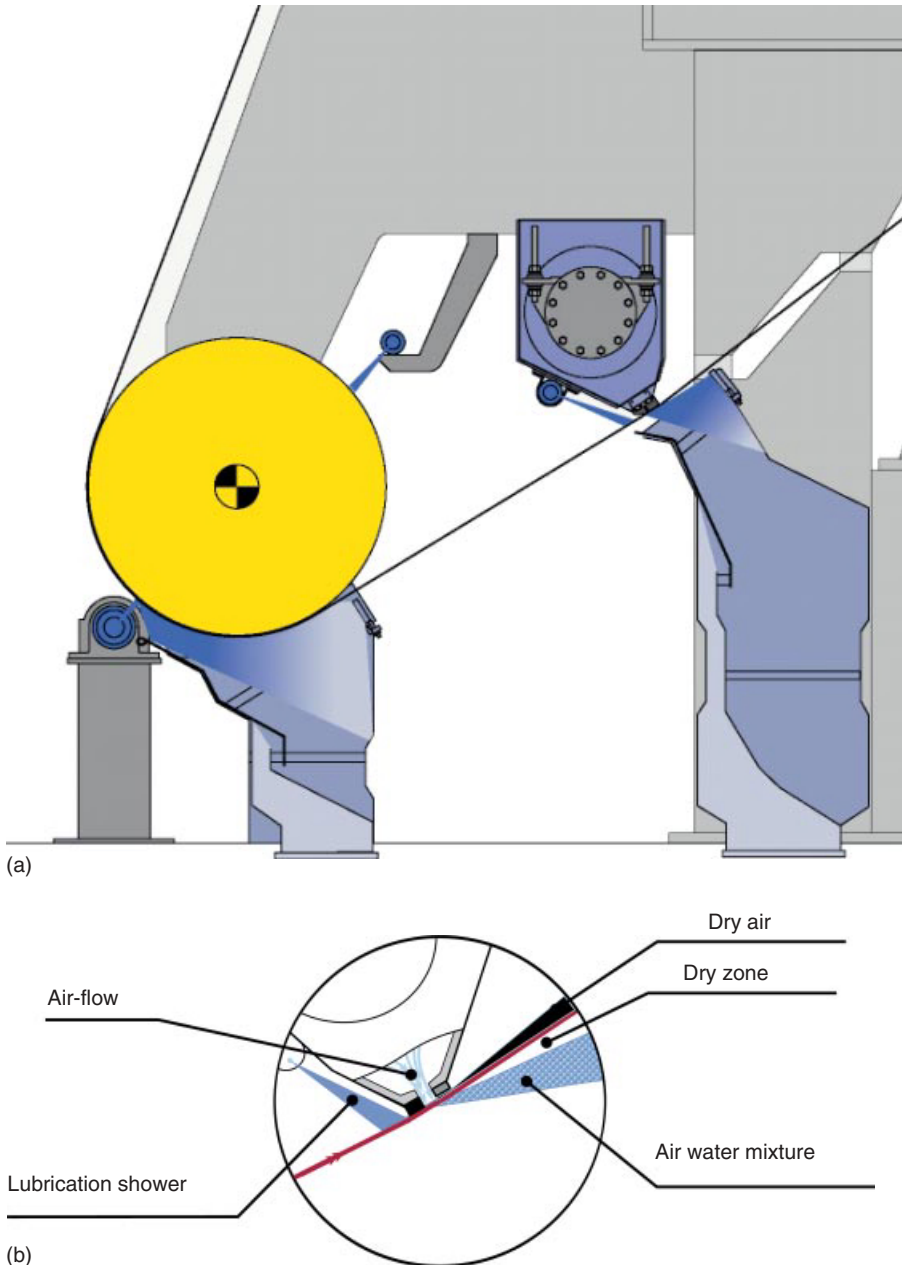


Figure 11.21 (a) High efficiency cleaning device for forming fabrics. (JetCleaner™, Source: Voith.) (b) Cleaning head of a JetCleaner™ for the forming section. (Source: Voith.)

one felt to the next is not disturbed. The vacuum boxes play a major part in the conditioning process. The change of the ratio of added water and vacuum to remove water can be used to adjust the moisture content in the felt.

11.4.2.2.1 Cleaning of Transfer Belts Because of the impermeable nature of transfer belts, all spray-through devices such as showers are ineffective. Transfer belts are cleaned in a similar manner as polyurethane roll covers using polyethylene blades to avoid damage and scratches of the belt surface. Lubrication showers are necessary.

11.4.2.3 Cleaning of Dryer Fabrics

The typical contamination of the dryer section is a dark layer of tar-like material. The most efficient way to remove this layer is a traversing cleaning head using high water pressure, which cleans the fabric during operation. To avoid wet streaks, the cleaning water must be removed instantaneously. Figure 11.22 shows an example of a state-of-the-art cleaning device. Up to six needle nozzles ($\varnothing = 0.25$ mm, water pressure: 20–30 MPa) create a high pressure water jet against the running direction. The water jet cleans the surface and the structure simultaneously. The removed contaminants and the residual surface water are discharged with a water injector. The residual water in the fabric structure is removed with an air knife. The cleaning result is shown in Figure 11.23. Alternative cleaning devices use brushes, showers, or steam, but these devices are less effective and more aggressive to the fabrics than cleaning heads using high water pressure.

A very effective shutdown cleaning method for dryer fabrics is to spray solid carbon dioxide snow (dry ice) onto the surface. Because of the low temperature

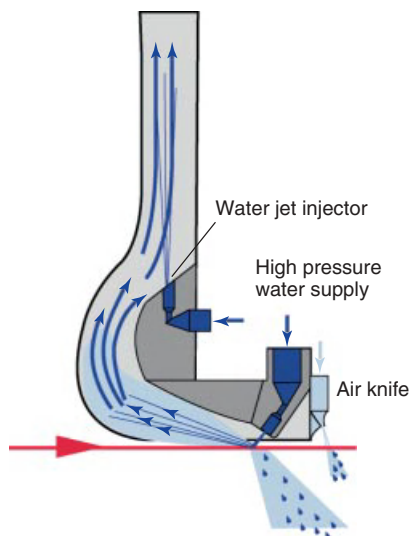


Figure 11.22 Cleaning device for dryer fabrics. (DuoCleaner™ Express, Source: Voith.)



Figure 11.23 Cleaning result of a high water pressure cleaner for dryers. (Source: Voith.)
(a) Contaminated and (b) clean fabric with blue color.

of dry ice, the contaminants become brittle and can be removed very easily. Disadvantages of this cleaning method are the relatively high cost of dry ice and the need for the dryer section to be stopped.

11.5 Changing of Fabrics

Herbert Holik and Johann Moser

All fabrics in the paper machine undergo wear, which finally results in quality problems and reduction in machine efficiency. They may also be contaminated with fines, fillers, binders, or stickies, or an unexpected failure of a fabric can happen. The normal lifetime of the fabrics may be similar to that of the wire in the forming section (about 4–12 weeks) and the press felts (about four to eight weeks), but greatly differs from the lifetime of the dryer fabrics (about one year).

The fabrics have to be changed early enough after a certain operating time, based on experience or measurements such as the felt permeability and caliper, and by monitoring the operating conditions. As fabrics can contribute remarkably to the operating costs, their lifetime should be as long as possible. The costs for the downtime of a larger paper machine can range from 10 000 to 40 000 € h⁻¹. So the downtime should be kept as short as possible, and unplanned downtime must be avoided.

For these reasons, the downtime of the paper machine is planned and all necessary fabric changes are done as fast as possible. Mostly, the wire(s) and press felt(s) are changed at the same time. Also, maintenance work is performed during this time. The planned shutdown of the paper machine has the advantage that everything can be prepared for having the fabrics changed in the shortest possible time. Nevertheless, unplanned shutdown of the machine may occur, for example, when a fabric is damaged or heavily contaminated.

In earlier times, the forming fabrics and press fabrics were not endless. The fabric loop was seamed inside of the paper machine using special seaming procedures for wires (welding or weaving) and felts. Forming fabrics with seams do not exist

anymore, whereas for certain applications such as newsprint seamed felts are still in use even for high machine speeds.

Today's state-of-the-art technology comprises endless wires and felts (except dryer fabrics). For their installation, the framing must be opened at suitable positions, then the draped wire has to be inserted through these gaps with great care, and afterwards the openings have to be closed and secured for gaining full stability of the framing.

Today, a well-prepared fabric change in the wire and/or press section is carried out within less than 1 h. The new wire or felt is arranged in full size and draped outside the machine (for a wire width of 11 m it needs more than 11 m space in front of the machine to arrange it) hanging now on tailor-made beams. The worn out wire or felt is cut out and taken off the site.

The framing is opened at the defined positions on stands at the tender side of the machine. For that, intermediate removable blocks (spacers) are integrated into the stands or framing. To remove these blocks out of a stand, the top part of the stand is lifted by some 5 mm to remove the spacers. This is supported by the so-called cantilever beams rigid enough to carry the weight of the top frame structure plus other items such as rolls. One or more rolls or dewatering elements have to be moved (swinging or linear) to allow the fabric to be easily slipped in. This is shown in Figures 11.24 and 11.25 for fabric change in the wire section; the principle is the same in the press section. After having the fabric properly arranged in the machine, the framing is closed by placing back the blocks and lowering the

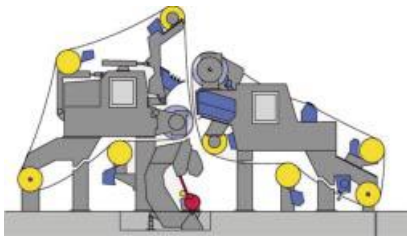


Figure 11.24 Cantilevering a gap former – positions of spacers and cantilever beams to open the framing for wire change.

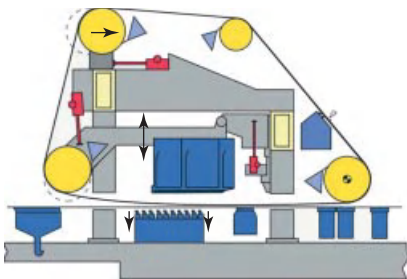


Figure 11.25 Cantilevering a hybrid former – moving rolls and dewatering elements.

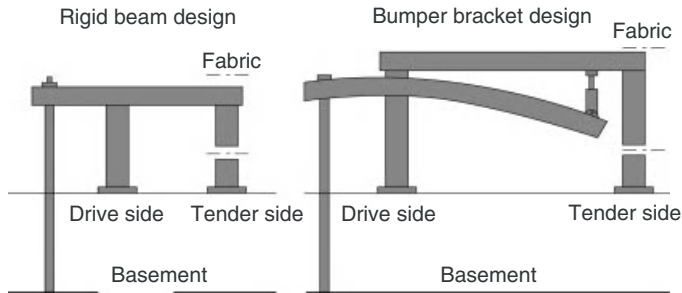


Figure 11.26 Principle of cantilevering for narrow and wide machines.

cantilever beams. The rolls and other machine parts are repositioned and the fabric is stretched according to the operating requirements.

The force to lift part of the framing can be induced at the drive side or tender side. Today, the tender side solution is no longer the first choice because in this case the fabric change needs more expenditure in terms of time and manpower. For narrow machines (width < 6000 mm), a very rigid cantilever beam is applied; for wide machines (width > 6000 mm), a cantilever beam bumper bracket design is used which is a more economical solution (Figure 11.26). With the rigid beam design, the cantilever beam is part of the framing and projects to the drive side. Here, the force is induced by a tie rod to lift the beam at the tender side for removing the spacers. With the bumper bracket design, an additional cantilever beam is integrated into the framing. This beam acts as the support to apply the force for lifting the framing.

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Further Reading for Section 11.4

12

Approach Flow System

*Christian Bangert, Herbert Holik, and Andrea Stetter**

12.1

Definition and Tasks of the Approach Flow System

The approach flow is part of a wider system, the so-called wet end process (WEP), which itself mainly comprises

- approach flow system
- broke handling and broke preparation
- fiber recovery.

This chapter covers the approach flow system, which extends from the point where the various stock components enter the system to the inlet flange of the headbox. It comprises the dosing and mixing units, the white water system, the fan or headbox pump, and in most cases some equipment for stock cleaning.

The tasks of the approach flow system are to

- meter and dose the required components (different kinds of fibers, mineral and chemical additives);
- mix the stock components to a uniform suspension;
- remove contaminants that were not removed in the stock preparation or were generated in the wet end process, for example, impurities in the broke fed back to the approach flow, or any agglomerations in the system;
- dilute the stock to headbox consistency;
- control the air content in the suspension fed to the headbox at a level that does not impair paper quality or paper machine operation;
- provide a highly uniform flow to the headbox in terms of consistency, composition, and pressure.

Furthermore, the approach flow system should

- avoid any deposits, and not promote any stringing of fibers;
- be easy to clean;
- have minimum fiber loss;
- allow fast grade changes.

* Contributed to the First Edition.

12.2

Metering and Mixing of the Stock Components and Feed to the Headbox

12.2.1

Metering and Mixing of the Stock Components

Variations in the headbox feed as regards pressure and consistency lead to poor paper profiles. While pressure fluctuations mainly influence the basis weight profile in the machine direction (MD), variations in consistency affect the basis weight profile mainly in the cross-machine direction (CD) (Chapter 23).

12.2.1.1 Dosing

The fiber components, fillers, and chemical additives have to be dosed in the required ratio. Dosing of the fiber components is done at 3–4% consistency. These components usually come from machine chests, fiber recovery, and broke systems. The individual streams have to be constant as regards their amount, consistency, and component ratio.

12.2.1.2 Mixing of Stock Components

The best results are obtained when mixing the stock components (e.g., virgin fibers, DIP, broke, recovered fibers) in a mixing pipe before feeding them to the mixing chest (Figure 12.1). Here the different furnish components are fed tangentially into the mixing pipe in the order of dewatering behavior and filler content: the component with the best dewatering characteristics is fed first, so it can be also used as sweetener stock for the save-all unit in the case of a disc filter installation. The remaining small consistency variations may be further reduced in

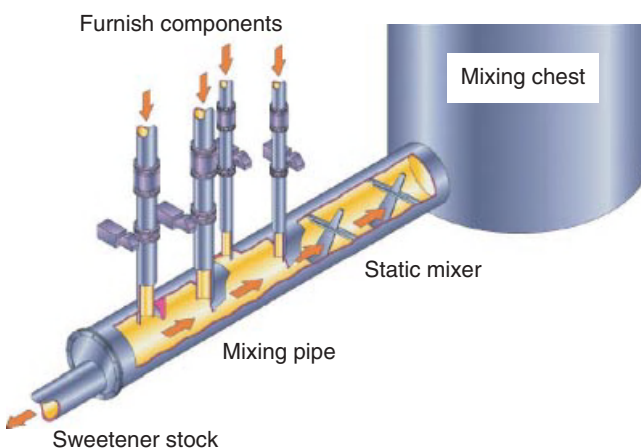


Figure 12.1 Mixing pipe with static mixer ahead of the mixing chest. (Source: Voith.)

the following mixing chest [1–4]. This concentrates the mixing energy to a smaller volume, and thus is more efficient. A static mixer in the mixing pipe further enhances uniformity. A good premixing allows smaller mixing and machine chests, which in turn saves energy and gives a shorter response time to grade changes.

The classical approach is a mixing chest ahead of the machine chest. The latter has a constant slight overflow back to the mixing chest, thus providing constant pressure for the stock pump. With improved controls and automation equipment, it is possible to run with only one combined chest.

12.2.2

Metering and Mixing of Thick Stock and White Water

Huge volumes of the white water silos can lead to microbiological pollution and also result in long process dead times. The silos therefore have been re-engineered and replaced by stock–water mixers, as shown in Figure 12.2. One task of these mixers is to recombine backflows, for example, from deaeration, cleaning, and screening, by adding them to the white water I before the thick stock injection in the vertical collector. The kinetic energy of the backflows is used to premix the streams. The thick stock is injected in the center at the lower part of the mixer. Good mixing of the thick stock is provided by optimum velocity difference between thick stock and white water at injection [1–5]. At constant thick stock supply, the consistency of the suspension fed to the headbox depends on the pump throughput, which in turn is controlled by the revolutions per minute of the fan pump.

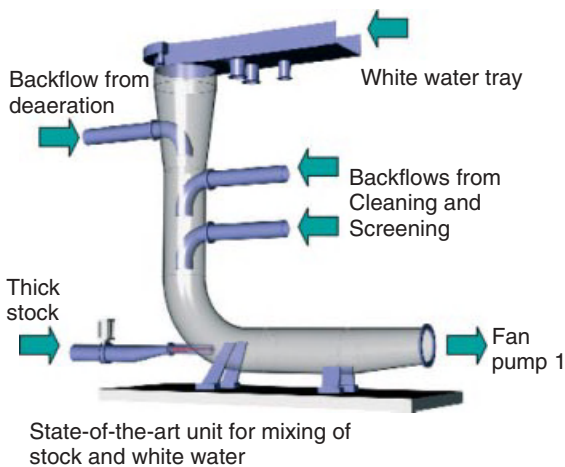


Figure 12.2 Example of a state-of-the-art unit for mixing of stock and white water.

12.3

Final Cleaning and Screening

Depending on the process design of the preceding fiber preparation plant, the final cleaning and screening in the approach flow system may only have a “police function.” In this case, the stock preparation system includes sufficient cleaning and screening capacity. On the other hand, especially in packaging paper mills, for cost reasons, screening and cleaning are often partly or even completely done in the approach flow system.

12.3.1

Final Cleaning

Cleaning is done after thick stock dilution with hydrocyclones in a multistage cascade system in order to remove small dense debris. The debris can be sand, grit, shives, pitch, or other dense particles. There are two options for the setup of the cleaning plant, either a full cascade or a broken cascade. A full cascade has the highest cleaning efficiency, while a broken cascade is more compact and lower in investment and operating costs (Chapter 7).

In the case of coated paper production, the final stage of the cleaner cascade is very rich in pigments or filler. Owing to the separation principle of the cleaners, especially coarse filler particles and agglomerated pigments from coated broke are rejected. The amount of final rejects can be reduced by recovering these minerals [6].

12.3.2

Final Screening

Even if all the stock components including broke were previously fine screened, bundles and lumps can be created thereafter by deposition. Secondary stickies and pitch particles may also form in the paper machine water system. Final screening is therefore done directly before the headbox with pressure screens (Chapter 7). Owing to their position in the process, the screens before the headbox have to exhibit special characteristics, that is, very low pulsation generation by using special rotary elements, polished surfaces to avoid deposits, high availability by simple design and special design to prevent air pockets [6].

In most cases, the screen baskets are slotted. Hole screens have a higher specific throughput per screen area and are more easy in operation, but the screening efficiency is lower. This means that impurities are much more likely to pass through, resulting in more dirt in the sheet; an increased number of sheet breaks may even occur. If slotted screens cannot be used directly ahead of the headbox, for example, owing to space restrictions in the building, a slotted screen should be installed before the machine chest. These screens will require significantly less space because of their higher operational consistency.

12.4

Air in the Papermaking Process and Its Removal

12.4.1

General Overview

Air in the system may cause problems during paper production. It can lead to reduced machine runnability by reducing the dewatering capacity, to sheet breaks, to decreased pumping and screening efficiencies, to foam problems and subsequently accumulation of hydrophobic and sticky material, and to increased microbiological activity. Paper quality can also be negatively affected by poor formation, by pinholes, and by dirt inclusions. As air may lead to cavitation and variations in pressure and flow velocity, poor basis weight profiles can result. Air intake in water and stock happens through splashing in the forming unit of the paper machine, in the white water tray, and in the chests.

To avoid depositions and pressure pulsations in the piping, the pipes should have a positive slope in flow direction, an air extraction valve should be positioned at the highest point of a piping, and suspension velocity should always be high enough ($>1 \text{ m s}^{-1}$).

12.4.2

Avoiding Air Intake

Air may be entrained in the forming section during dewatering, in the white water channel, and in the chests. To minimize air intake, some rules should be followed, such as

- pipes, which feed chests, end below the suspension level in the chests;
- suspension flows from open channels enter the chest with low velocity;
- eddies (“bathtub eddies”) at the outlet of the chests are avoided by a grid or a cover plate at the top of the chest exit pipe;
- the “hydraulic jump” of high-velocity suspension flows in open channels are avoided by energy dissipation.

In Figure 12.3, some examples for the prevention of air intake are given.

- The dynamic energy of the air/suspension two-phase flow is broken in a tank equipped with a drilled cylinder separating air and suspension and dividing the high-energy suspension flow into a large number of low-energy jets (Figure 12.3a). Optionally, it is connected with a low-vacuum pump.
- A grid over the outlet of a chest prevents eddies (Figure 12.3b).
- An outlet system with pipes at different levels prevents air entrainment when throughput varies widely (Figure 12.3c).

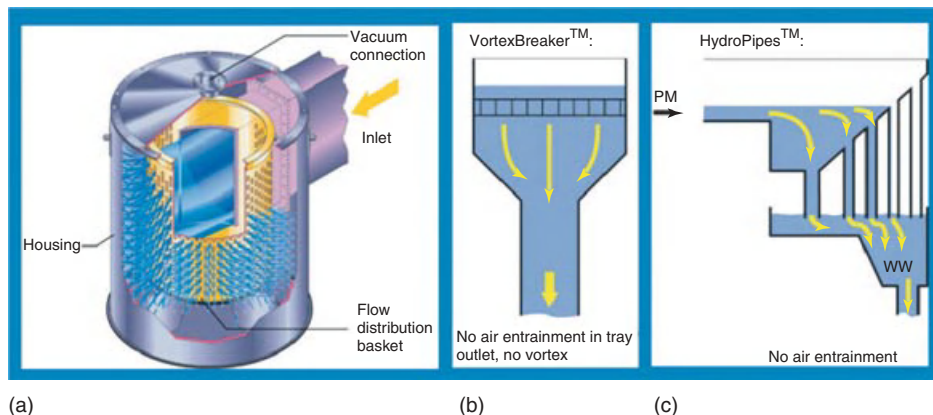


Figure 12.3 Examples of equipment to prevent air intake.

12.4.3

Deaeration

For most paper grades, low gas content is very important. The “gas” is mostly air but can also comprise carbon dioxide and other substances. The more common term *air* in the industry is used here. Air can be present in the stock in free and dissolved form. The adverse effects of air, especially on dewatering, reaction of chemicals, system cleanliness, and so on, have been extensively reported [7].

Free air is found in small bubbles in the liquid. These hydrophobic bubbles may hinder dewatering, decrease retention, cause pinholes, and so on. Dissolved air has very little or no influence on the paper machine or the paper unless it does not transform into free air, for example, when the pressure is lowered or the temperature is increased. Therefore, most of the dissolved air from the system is removed, as well.

Vacuum deaeration of the complete stock was introduced to the industry in the late 1950s. Since that, it has been widely accepted as the standard process. Most paper machines in use now are much faster than those at that time and the length of the dewatering zone in a gap former is much shorter than on the Fourdrinier wire. Recent investigations [8] doubt the necessity for the extreme extent of gas removal practiced at present. Both the very short dewatering zone and the high pressure in the headbox may hinder the development of free air during formation. First, the stock is subjected by the fan pump to a pressure in excess of 500 kPa in the headbox, and dewatering in the gap former is so fast (order of magnitude 0.01 s) that the dissolved air may not transform into free air, that is, to larger bubbles, during sheet formation.

Typically, fast gap formers ($>1500 \text{ m min}^{-1}$) have fewer problems with air than the Fourdrinier machines because of the longer dewatering time of the latter. Wood-containing or recycled grade suspensions absorb more air in the process because of the larger amount of surface-active substances, and their more hydrophobic material interacts with the free air. Therefore, deaeration still remains

one of the important tasks of the approach flow to avoid any negative impact on the process [9].

There are three methods for deaeration of the stock:

- by gravity, mostly supported by chemical additives;
- by vacuum;
- by centrifugal forces.

12.4.3.1 Deaeration by Gravity

Deaeration by gravity is achieved in the white water system by giving the air bubbles time to reach the surface. This process is often promoted by chemical additives that lead to the coalescence of smaller gas bubbles into bigger ones. These can ascend much faster to the surface.

Large white water trays are not only space consuming and expensive but also reduce the reaction time for grade change. It also enhances the buildup of deposits because of the low flow speeds. Here, a good compromise is a comparatively shallow, long, and narrow white water tray. This way the volume of the tray and the distance the air bubbles have to travel vertically are kept small, while higher flow velocities in the long channel prevent deposits and also insure sufficient time for the air to escape.

To a certain extent, deaeration can be achieved in the white water silo, provided the descent velocity of the white water in the silo does not exceed about 0.1 m s^{-1} . On the other hand, white water silos should always be slender to prevent deposits and dead corners. Therefore white water silos can no longer be considered as state-of-the-art.

12.4.3.2 Deaeration by Vacuum

Since its introduction, deaeration by vacuum has been, and still is, the dominating deaeration method in the paper industry. This method relies on the fact that liquids contain less and less air as the temperature or pressure approach boiling conditions at which all air escapes. The air content and thus its partial pressure in the suspension are relatively low, therefore the suspension will boil at pressure/temperature conditions close to those of water. In the approach flow system, it is the pressure that is lowered, so that the stock or white water is close to the boiling point at system temperature. A rough indication of the pressure required in a deaeration vessel for complete deaeration is given in Figure 12.4.

The vacuum is created in water ring pumps (single- or dual-stage). Before the vacuum pumps, a condenser is installed in which the overall temperature is lowered and vapor is condensed. This significantly reduces the actual gas/vapor volume that has to be processed.

Deaeration is further enhanced by impingement of the stock onto the roof of the deaeration vessel. Thus fiber bundles that may have trapped air bubbles are broken up so that the air can escape (Figure 12.5). After impingement, the stock drops to the liquid surface. As this may generate turbulences, which can impair the hydraulic stability of the following process, the distance between the spraying zone and the accept zone must be sufficiently large. This allows turbulences to dissipate.

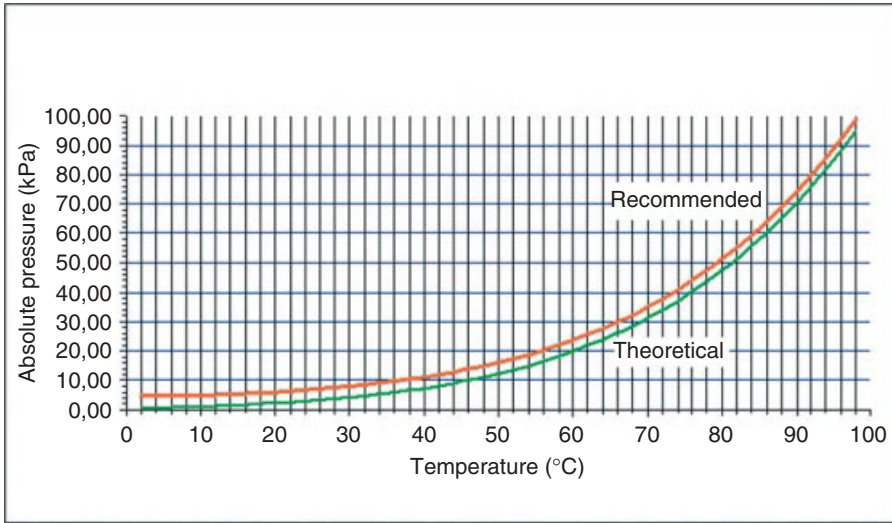


Figure 12.4 Theoretical and recommended absolute pressure for deaeration depending on suspension temperature. (Source: Voith.)

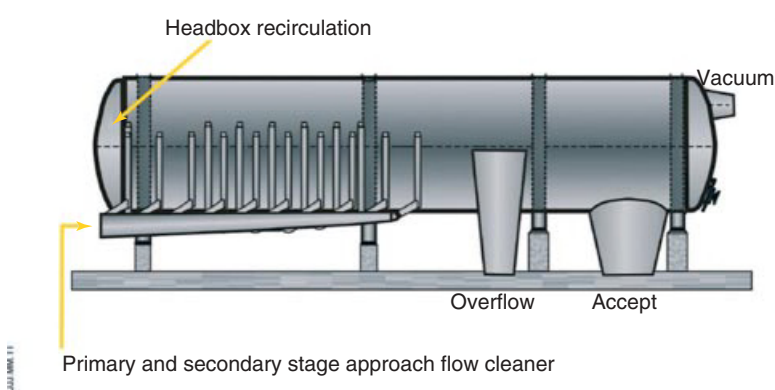


Figure 12.5 Typical deaeration tank. (Source: Voith.)

There is further improvement on placing a circular overflow outlet between the spraying and accept zones; this “absorbs” bigger waves (i.e., turbulences) as they fall over the overflow weir.

12.4.3.3 Deaeration by Centrifugal Forces

Deaeration by centrifugal forces, also called *mechanical deaeration*, can be done either in hydrocyclones, in this case as by-product of the cleaning process, or in purpose-built deaerating centrifuges.

Deaeration in hydrocyclones (also called *Combi cleaners*) is a “by-product” of the cleaning process [10]. Since the cleaners are optimized for high cleaning efficiency

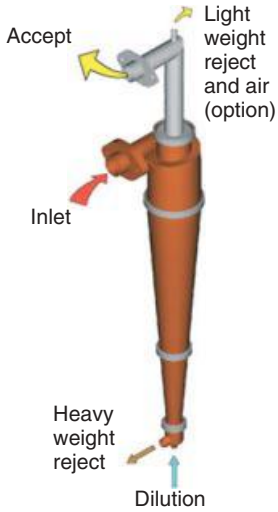


Figure 12.6 Deaeration cleaner. (Source: Voith.)

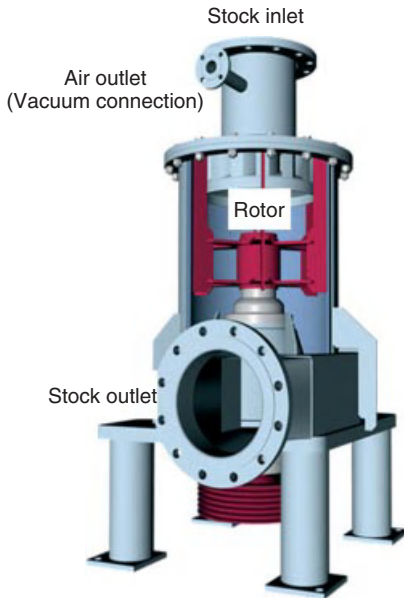


Figure 12.7 Centrifuge as a mechanical deaerator. (Source: Voith.)

and not gas removal, only part of the gas is removed; in addition to that, Combi cleaners require a higher counter-pressure to get the gas out, thus increasing energy consumption of the system if the elevated pressure must be dissipated. On the other hand, using the Combi cleaner is the easiest way to achieve partial deaeration of the system; it is a good solution for machines with less stringent requirements on gas content (Figure 12.6).

Deaeration can also take place in purpose-built centrifuges, which create a centrifugal force field that helps to separate the gaseous and liquid phases (Figure 12.7).

The liquid, in most cases white water, enters the centrifuge on the rotation axis of the rotor. The rotor forces the white water to the wall, creating a relatively thin layer of liquid on the wall. The thickness of this layer is relevant for deaeration efficiency, as the gas has only a fraction of a second to separate from the liquid and migrate to the gas-filled core of the machine. The thickness of the layer depends on the throughput of the centrifuge used, so a lower throughput results in thinner water layer, which more readily deaerates than a thicker layer. These centrifuges have much higher efficiency than Combi cleaners but not as good as that in vacuum deaeration.

Mechanical deaeration is widely used for specialty paper machines with many grade changes because they require only a small volume and can be easily installed as an upgrade. On the other hand, the specific energy demand of mechanical deaeration is the highest of all deaeration methods and therefore less suitable for big new machines, where space is less restricted and throughput is high. In these cases, vacuum deaeration, fully or partly, is still the method of choice.

12.5 Further Aspects

12.5.1 Energy Recovery from Backflows

The high speeds of today's paper machines require high pressure. Taking into account the pressure losses for screens, piping, or cleaners, pressure levels above 800 kPa in the feed to the headbox are found.

Both screening and operation of the headbox require the recirculation of a certain portion of the total flow, for trouble-free operation of the screen and often for leveling the headbox pressure in the CD.

Usually, these backflows are 5–10% of the total flow. The pressure of these flows needs to be reduced to the much lower pressure required for the other process steps. Normally, this is done with one valve, or often two valves in series. This pressure reduction puts, apart from being very noisy, high mechanical stress on the valves and the pipings, which often leads to excessive wear.

A new approach is the application of turbines or reverse-running pumps at these positions (Figure 12.8). Apart from recovering energy that can be fed back to the mill grid, these turbines show less wear than valves and ensure better hydraulic stability. If hydraulic stability is not really important, the relatively expensive turbine may be replaced by a reverted pump.

The turbine is equipped with an asynchrony generator. Once connected to the grid, this keeps the revolutions of the turbine constant, regardless of throughput. Thus the pressure loss inside the turbine is less volatile to fluctuations in flow than in a static valve.

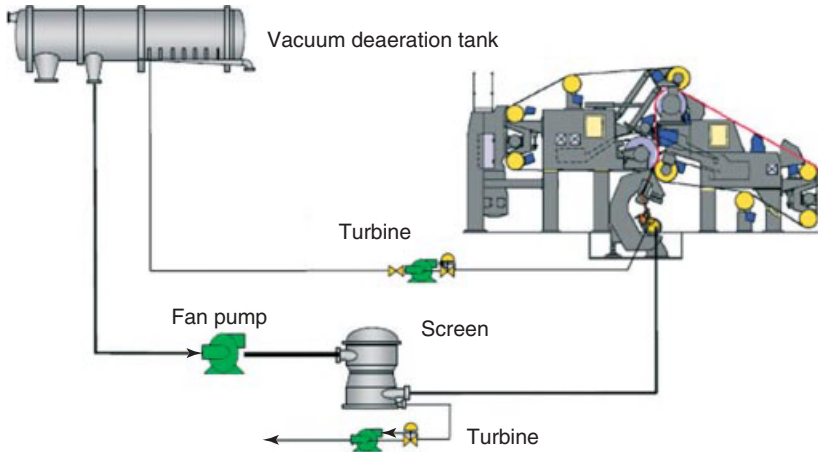


Figure 12.8 Potential positions for implementation of an energy recovery turbine. (Source: Voith.)

With the new developments in headboxes and screens, the necessity for the turbine in new systems is diminishing as headbox designs with no recirculation or screens with reduced reject flow are available.

12.5.2

Engineering

A good performance of the approach flow system is not only due to its components but also to a large extent due to the system design as a whole. For instance, the layout of piping and chests has great influence on the stability of the system. This means, for instance, that all pipes should have a positive gradient in the flow direction, all flows should have a defined flow direction, and suspension velocities in pipes should be high enough to prevent demixing and buildup of bacterial slime or fiber stringing. In many cases, polished surfaces are chosen in order to prevent deposits. Dosage positions (e.g., when shear-sensitive and/or different chemicals are used) and dosing techniques (for instance, multiple injectors) for chemicals have to ensure good and fast mixing and high efficiency of the chemicals [2, 3].

12.5.3

Automation

Automation by fast, stable, and accurate control loops for consistency, flow, pressure, and level is elementary for providing the necessary constancy in the approach flow system for stability of good CD and MD basis weight profiles. In addition, the retention on the paper machine and the chemical conditions of the water systems must be kept constant. Here, a retention control loop is standard in many applications; it keeps the white water consistency constant by adapting the

quantity of retention agent added. Controls for filler, color, air content, cationic demand, or zeta potential are also available at present. Combining the different controls into a total control system will lead from purely functional controls to control systems, which also address quality and production issues.

12.6 Approach Flow Design

There are several designs dealing with the supply of stock from the machine chest to the headbox at the required quantity and quality. The basic design of the approach flow system depends on

- the paper grades, which have very different demands on air content or pulp cleanliness;
- the stock preparation process ahead of the approach flow system.

At present, there are four basic modern system designs for the four main paper grade groups, which are graphical, packaging, specialty, and hygiene.

12.6.1

Approach Flow System for Graphic Paper Machines

Cleanliness of the sheet is highly important for graphic paper grades (Figure 12.9). Therefore, cleaning and fine-slot screening, in addition to cleaning and screening in stock preparation, are integral parts of the approach flow. Especially, in coated paper production, no impurities in the stock can be tolerated, as these may have disastrous effects on the runnability of the coating equipment.

The improvements in cleaning technology allow increased consistency in the cleaners of 2% or even higher. The cleaner plant can thus be reduced in size, saving

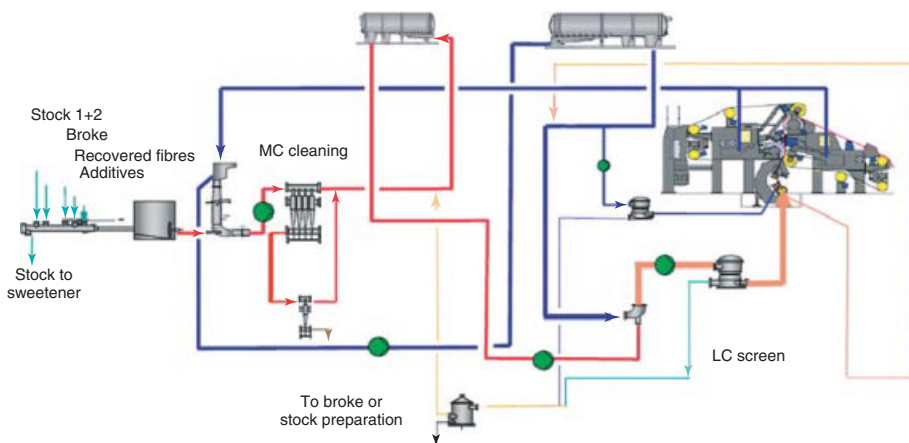


Figure 12.9 Modern approach flow system for graphic paper machines. (Source: Voith.)

energy, investment costs, and space, but this requires a second dilution step in the approach flow. Depending on the allowed air content, the thick stock or the white water or both are deaerated.

Screening is done with slotted screens directly ahead of the headbox. For all paper grades, the use of a common tailing screen for approach flow screening and broke screening is recommended. So there is only one point of fiber loss. Alternatively, the reject can be fed back to the stock preparation for further treatment. Rejects of a modern cleaner plant are practically fiber free, so that they may be sent directly to the mill sewer system.

12.6.2

Approach Flow System for Packaging Paper and Board Machines

In recent years, with increase in production speed and decrease in basis weight, the layout of paper machines for packaging grades, especially liner and corrugating medium, has become more and more similar to that for graphical paper machines. (Figure 12.10).

Therefore, the approach flow of a modern high-speed liner paper machine also bears a lot of similarities to that of a graphical machine. Both use slotted screens and deaeration equipment for improved runnability, although the latter may be a mechanical deaeration, which is not yet so common in graphical processes.

In packaging grade production, overall yield is more important than sheet cleanliness. So the cleaning plant in the approach flow system can be considered in some cases as only an option for these grades. But this calls for a stock preparation with good cleaning. Some mills have gone the other way and run a sophisticated approach flow after a simple stock preparation. In this case, the fiber quality may be comparable, but there is no water separation between the stock preparation and

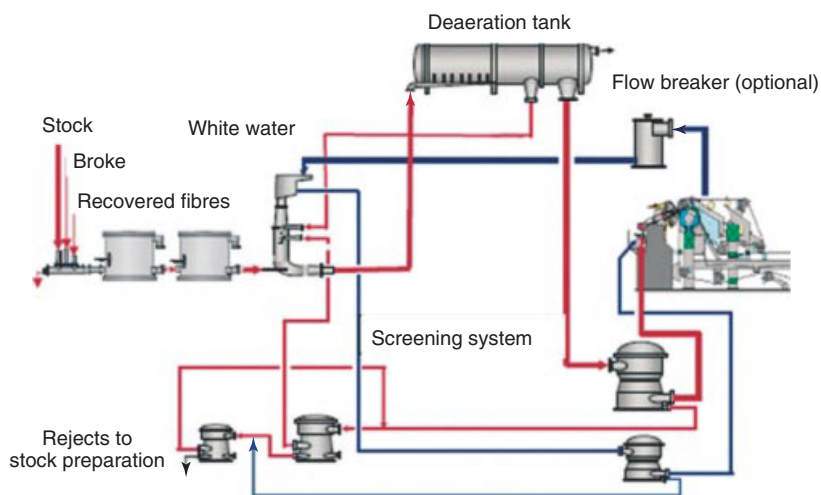


Figure 12.10 Approach flow system for packaging grades. (Source: Voith.)

the paper machine. Thus a lot of detrimental substances enter the water system of the paper machine and influence its runnability negatively.

Deaeration in most cases takes place only partly, for example, there is no deaeration in the low-consistency line to the headbox, as the products are less sensitive to air in the stock. However, owing to the closed loops associated with packaging paper manufacture, the white water is more likely to absorb air. That is why fast-running liner machines often use a flow breaker directly after the former (Figure 12.3a). Instead of the flow breaker, a large cyclone can also be used.

Very often, paper machines for packaging grades feature multilayer headboxes or, for higher basis weights, multiple forming with up to four individual headboxes and formers. Depending on the required quality of the layer or ply, the individual approach flows can be interconnected. For instance, the screening for the top ply uses finer slots than in the filler ply, thus the reject of the top ply screening can be used as material in the filler layer, which is the only layer with a tailing screen.

12.6.3

Approach Flow System for Tissue Grade Machines

The most important features of this system are simplicity and the ability to produce the highest headbox pressures without wasting energy and fibers.

As the tissue-making process is less sensitive to small contaminants in the approach flow than, for instance, the process for graphical papers, the white water can remain unscreened. As the headbox consistency is very low (typically between 0.2 and 0.4%), screening directly ahead of the headbox would become very costly because of the big volumes that are handled and the high pressure that is required.

For these reasons, the approach flow systems for tissue machines are now more often equipped only with a screen in the predilution stage, where consistency is around 1%. This results in a significantly smaller screen, which in turn reduces investment and operating costs considerably. The working pressure of this screen in predilution is around 2 bar, whereas a screen installed directly ahead of the headbox on a fast tissue machine has to bear a pressure of up to 10 bar, necessitating a complex screen design.

Figure 12.11 shows the basic system of an approach flow for a single-layer tissue machine without dilution control for the CD profile of basis weight. Tissue machines for high-quality tissue are, in general, equipped with multilayer headboxes, in most cases two layers, sometimes three, and also have dilution control of the CD basis weight profile. So in total, there can be up to four (three HC and one LC) headbox pumps.

12.6.4

Approach Flow System for Specialty Paper Machines

The wide variety of specialty papers leads to a similar variety of machines and approach flow systems. In general, the approach flow systems for specialty paper machines are specified for low volumes and double-dilution systems. This allows

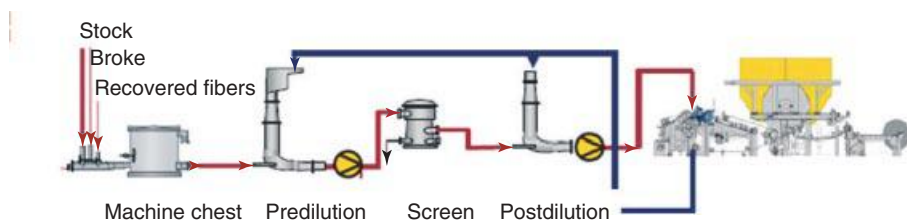


Figure 12.11 Approach flow system for a single-layer tissue machine. (Source: Voith.)

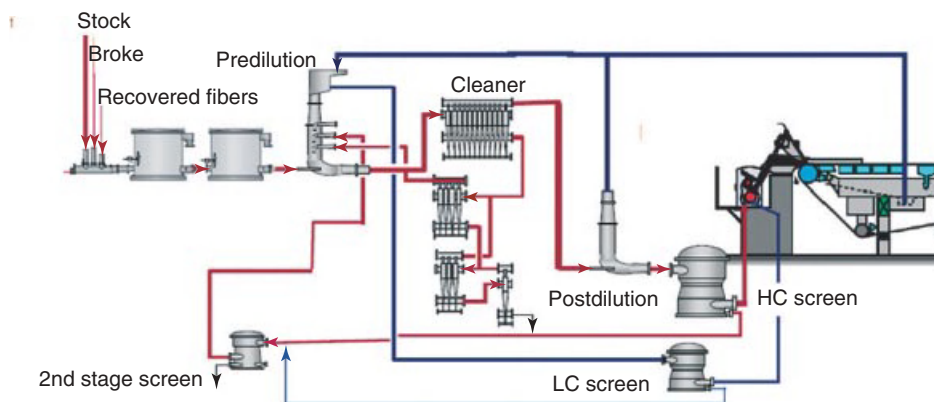


Figure 12.12 Approach flow system for a specialty paper machine with predilution and postdilution. (Source: Voith.)

shorter grade change times and more flexibility in headbox flow as well as lower investment costs, since smaller chests are required (Figure 12.12). However, this also makes them less “foolproof” to operate compared with larger volume systems. It depends on the desired response time whether the thick stock system comprises two chests (mixing chest and machine chest as shown here) or just a single chest. The position where the recovered fibers are fed back into the system may also vary. Easier operation is obtained by dosing it to the mixing chest; however, faster system response is achieved when the recovered stock is dosed directly in the postdilution, after the cleaner system.

In specialty paper manufacture, deaeration, except the white water tray, is often not necessary. In case deaeration is needed, a mechanical deaeration is used in most cases as this adds no process volume to the system.

Some specialty grades, such as laminating paper, contain high amounts of filler. This filler is prone to build up deposits if not constantly in motion. That is, apart from the shorter grade change times, another reason for a small process volume. Also, the flow velocity in the piping has to be higher, and the pipes sized smaller. This keeps the pipework clean, but has the disadvantage of increased friction losses and higher pumping energy.

The approach flow design for wet laid machines with inclined wire (e.g., filter paper) is not discussed in this chapter. They mostly are an integral part of the forming section and often feature uncommon equipment, such as a white water tower under vacuum.

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13

Headbox

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13.1

Overview and Principle Aspects

13.1.1

Objectives

The goal of the headbox is to distribute the suspension in the cross-direction of the paper machine and supply a suspension jet of high uniformity, and about machine speed fully controlled to the wire section. The required high uniformity of the suspension jet relates to uniform fiber and filler dispersion, to equal velocity and thickness, as well as its orientation (exactly into machine direction and in one plain) over the whole machine width (CD, cross machine direction) and time. For good sheet formation, fiber flocs that have already formed have to be broken up, and flocculation has to be prevented, at least for a short time until the suspension is transferred to the wire. Thus, the headbox is a key element in the paper machine defining many important quality parameters of the finished paper.

13.1.2

Tasks and Principle Solutions

The suspension is delivered from the approach flow system through piping that has a circular cross-section and finally leaves the headbox through a thin slice. Thus, the following tasks have to be fulfilled

- The flow has to be turned into machine direction and distributed uniformly with great accuracy across the full width of the headbox. This is usually done by a distributor pipe or header feeding the suspension through an arrangement of holes to the headbox chamber.
- During its flow through the headbox, turbulent shear forces must be generated in the suspension to break up fiber flocs. This is done by turbulence generators. On the other hand, any coarse turbulences have to be avoided or reduced along the path through the headbox.

- A uniform velocity profile at the nozzle entrance has to be ensured by adequate design of the whole headbox construction.
- In the nozzle, the suspension is accelerated up to the required velocity at the exit. The exit is a narrow slit normally called a *slice* (6–25 mm in height, and more in certain applications and up to more than 10 m wide).
- The fibers in the exiting suspension should be randomly orientated or (at least) a symmetrical orientation profile in z -direction (thickness of the jet). This has to be assured, for example, by symmetrical nozzle design and flow.
- The surface of the exiting jet has to be smooth over a longer distance as, for example, required for twin-wire headboxes by adequate turbulence intensity and wavelengths.
- The jet should impinge the wire at a defined position as a straight line, so jet direction has to be adjustable.

13.1.3

Some Basics

13.1.3.1 Uniform Distribution across Machine Width

Uniform distribution across machine width is achieved by passing the suspension through a distributor on the backside of the headbox to at least one perforated plate. The relation of the velocity in the distributor to that into the perforated plate is about 1–3. The pressure in front of the plate as well as the approach angle has to be constant. Thus, the geometry of the distributor has to take into account the steadily decreasing throughput as well as the friction losses of the suspension along the distributor. Friction losses are compensated by slightly reducing the suspension velocity (Bernoulli equation) due to corresponding increase in the pipe's cross-section. Many individual streams produced by the perforated plate are reunited to form a single uniform stream in the headbox and the nozzle, which then provides a constant jet of suspension.

Suspension velocity in the distributor is between 2 and 5 m s⁻¹. A change in throughput means a change in distributor velocity, which in turn results in a change in the friction factor. Same is true for variations in consistency or stock type. So, the design of a distributor is exact only for a narrow range of operating parameters. The influence of pressure deviations on the header decreases with increasing machine speeds according to the decreasing pressure ratio $\Delta p/p$. A generally accepted calculation method is given in [1].

To prevent air problems and for fine-adjusting the pressure distribution in the header pipe, a certain amount of return flow from the end of the distributor is usual for lower machine speeds.

13.1.3.2 Turbulence

Turbulence means differences from a mean velocity, varying over time, place, and direction, that is, superimposing a flow. The intensity of turbulence [2] can be described as a percentage turbulence T that is

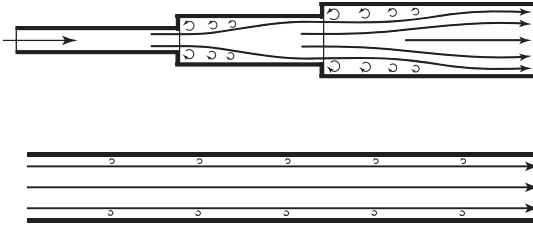


Figure 13.1 Principle of turbulent flow after sudden geometry changes and in tubes.

$$T = 100 \times \frac{\sqrt{u^2}}{U}$$

with u being the turbulent fluctuating velocity and U the average velocity. The intensity can also be considered as a measure of the kinetic energy in the flow to break up fiber flocs.

Turbulence can be generated by friction in small-diameter tubes or channels (such as given between lamellas), as well as by sudden geometry changes (as carried out in rectifier rolls or step diffusers). Figure 13.1 shows a schematic of turbulent flow conditions in pipes, channels, and after a sudden increase in cross-section as given in step diffusers. The turbulence intensity should be adjusted to the stock type, and the wavelength should be short. Too high turbulence and large wavelengths destroy the desired smooth surface of the exiting suspension jet, especially at larger jet lengths.

13.1.3.3 Jet Velocity

In the headbox nozzle, the suspension is accelerated to approximately machine speed.

The exit velocity can be calculated roughly with the reduced Bernoulli equation as

$$v = \sqrt{\frac{2 \times p}{\rho}}$$

where p is the pressure inside the nozzle measured at the position of lowest velocity and ρ is the density of the suspension ($\sim 1000 \text{ kg m}^{-3}$).

The more precise calculation, which is used in production machines, takes into account additional influences

- wall friction in the nozzle;
- pressure loss of slice blade;
- geodetic height difference between pressure measuring point and jet impingement.

In the case of a gap former, the suspension has to enter into an area under pressure due to the wire tension and the curved geometry. Therefore, wire tension and forming roll diameter are also considered in the formula.

13.1.3.4 Volumetric and Stock Mass Flow

Both the slice opening and the jet velocity define the volumetric flow Q of suspension supplied to the wire section

$$Q = v \times w \times s \times k$$

where v is the jet speed; w , the width of the headbox nozzle; s , the slice opening; and k , the contraction factor due to the contraction induced by the slice blade at the nozzle exit.

The amount of stock mass flow M supplied to the wire section is

$$M = Q \times c$$

where c is the consistency of the stock flow.

13.1.3.5 Jet Direction

The direction of the jet in the z -plane depends on the geometry of the nozzle end area. With a fixed position of the headbox, the jet direction defines the impingement line on the wire in Fourdrinier and twin-wire forming. Jet direction depends on the angle of top and bottom lips, their relative lengths, and the angle and projection of the slice bar. The jet direction at the exit defines the impingement line on the wire. Figure 13.2 gives an example of the interdependencies of these parameters [3].

13.1.3.6 Pulsation Damping

In case if too high pulsations arrive from the approach flow, they have to be damped. In principle, this can be done by interference, absorption, or reflection

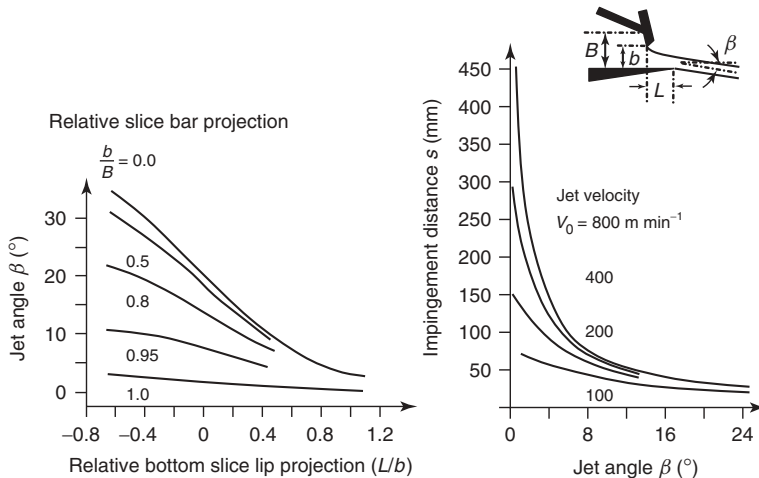


Figure 13.2 Influence on jet angle at the exit of the headbox and impingement distance depending on the geometry at the nozzle tip [3].

[4]. With interference dampening, one pulsation is superimposed on another one of the same frequency and amplitude but displaced by half a wavelength. This kind of dampening shows high reduction in amplitude, but it is difficult to obtain a good effect over a wider frequency range.

Dampening by absorption means that pulsation or sound energy is transferred into heat, that is, by turbulence or absorption in a hydropneumatic system. Here, the dampening effect covers a wide frequency range, whereas amplitude reduction is limited.

Pulsations can also be reflected, for example, by reduction in cross-sectional area of the hydraulic path such as presented by a perforated plate, by a sudden change in sound velocity or at the free surface of a liquid. Reflection dampening is effective over a wide frequency range and shows a high reduction in amplitude.

Sound propagation in structures (vibrations) has to be avoided, as they may excite pulsations in the hydraulic path to the headbox.

13.2 Historical Review

The headbox looks back on a very interesting history with many impressive improvements, what underlines its important role in papermaking with the ever-increasing operating and quality demands [5]. In the following sections, the focus is on the progress as regards the main headbox functions.

13.2.1 Distribution

For distribution of the suspension across width, an accuracy in the order of magnitude of 1% is required. This demanding requirement could not be met by the earlier distribution principles when machine width and speed increased some of them, as shown in Figure 13.3

- **Plain diffuser:** Its length should be proportional to the machine width, which resulted in a very high length. When using more than the admissible diffuser angle (which is only about 4° per side), flow instabilities may occur. This would happen in spite of the fact that a certain acceleration of the flow can be used to stabilize the flow.
- **Folded diffuser:** The length could be decreased compared to the plain diffuser, as the pressure loss due to the folded design helps to distribute the suspension in CD, but flow instabilities cannot be avoided.
- **Cross-countercurrent distributor:** The suspension flow is not clearly defined, and flow instabilities occur.
- **Branched piping:** Again the flow is not clearly defined, so flow instabilities occur as well.

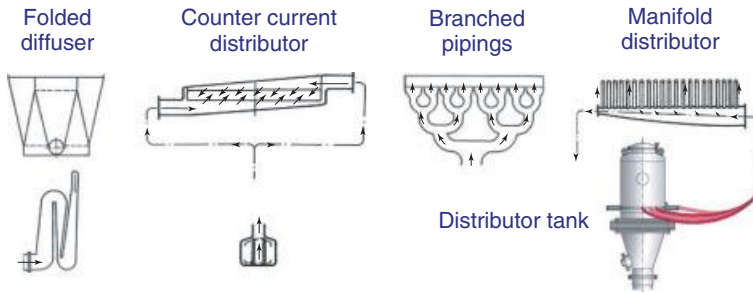


Figure 13.3 History of means for suspension distribution across machine width.

- **Manifold distributor:** This modern concept follows most important fluid dynamic rules. The suspension is passed through a “conical” distributor pipe on the backside of the headbox at about constant velocity and approaches a block with a large number of small pipes under a (nearly) constant angle in MD, thus producing a large number of identical streams.
- **Distributor tank:** This type of distributor is a tank with a large number of long, large-diameter pipes feeding the suspension to the headbox. It can be regarded as a special version of the manifold distributor.

13.2.2

Suspension Acceleration, Deflocculation, and Delivery

In Figure 13.4, some steps in the development of the headbox design is shown.

- In earlier times, the suspension was supplied to the (at that time very narrow) forming wire through the pond slice headbox having a (diffuser) distributor and, for example, three bars in sequence equalizing the suspension flow across width.

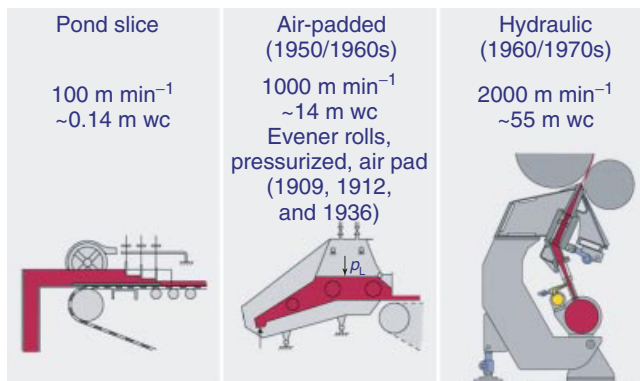


Figure 13.4 History of developments in headbox design.

For a jet speed of 100 m min^{-1} , a pressure of 0.14 m water column (WC) ahead of the slice would have been needed. The knowledge about the influence of jet wire speed ratio on paper properties was limited at that time.

- Since 1911, the so-called high-pressure headbox was available, still working under atmospheric pressure but with increased suspension level in the open headbox. This level was about 1250 mm for a jet velocity of 300 m min^{-1} , which meant high speed at that time. As a disadvantage, both the free suspension level and a high throughput provoke eddies at the nozzle (as found at the bath tube outlet).
- The air-padded headbox with evener rolls started to make its way in the 1950s and allowed further increase in machine speed. It was based on earlier patents of useful principles such as evener rolls (1909), closed headbox pressurized by a pump (1912), and a special kind of air-padded headbox (1936). The dimensions of such a headbox were sometimes enormous: for a throughput of $450 \text{ m}^3 \text{ min}^{-1}$, the headbox was 10 m long (1960).
- To match the ever-increasing machine speeds, the high-turbulence or hydraulic headbox has been developed. First attempts were made in the 1960s; the breakthrough was in the 1970s. Flexible or rigid foils (1960s), small-diameter pipes as well as step diffusers (1970s) were introduced as turbulence generators. Since that time, a certain convergence as regards the headbox design concepts of the different machine suppliers could be observed.
- Since the 1980s, multilayer headboxes, based on the hydraulic headbox principle, were developed. This type of headbox, mainly in a two-layer design is typically installed in machines for tissue and packaging grade production.

13.2.3

Pulsation Elimination (for MD Basis Weight Control)

- In the former days, the suspension was fed from an open chest, which was placed at elevated position above the headbox. So no pump pulsations could get through the headbox. Furthermore, nonpressurized headboxes have a free suspension level and a relatively large suspension volume. So, any incoming pulsations are eliminated.
- When pressurizing the headbox to increase jet velocity, the air-padded headbox was still able to successfully dampen pressure deviations coming from the approach flow. The inbuilt attenuation principle was absorption by hydropneumathical dampening.
- The modern hydraulic headboxes usually have no air pad. In certain cases, it needs a pulsation damper, which is installed ahead of the headbox. This kind of equipment is a passive damper using the dampening principles of reflection and absorption (1970s). The above-mentioned distributor tank works following a similar principle.
- Pulsation dampers can be left out today – at least for high-speed twin-wire machines – when low-pulsation pumps and low-pulsation pressure screens as available today are used.

13.2.4

Cross Machine (CD) Control of Basis Weight and Fiber Orientation

The progress in control of CD basis weight profile is shown in Figure 13.5.

- In the pond slice headbox, the control of CD basis weight profile could be done by just placing a flow resistance piece (i.e., a brick) into the headbox flow or a strip in the exit slice opening at the position needed.
- In the following generations of headboxes, the slice bar was introduced. It can be finely positioned and locally adjusted.
- CD basis weight control by dilution with white water has been introduced in the 1980s and 1990s. The white water is locally added in a way that the total amount of suspension at that position is kept constant. This allows an independent control of basis weight and fiber orientation profiles.

13.3

State-of-the-Art Headboxes

A wide variety of headbox designs is found in the paper industry today. This is due to the many different operating conditions, paper machine designs, and forming sections, all resulting from individual production requirements of the various grades. Earlier headbox designs such as pond slice headbox or the open headbox are not covered here. Both types by far do not meet any longer the modern demands on throughput and speed, they are of minor importance. Nevertheless, they are still found in the paper industry for some special applications. Here, the focus is on the headbox types, which are mainly found in the industry, the rectifier roll and the hydraulic headboxes. Their application and special design principles as regards suspension distribution, deflocculation, acceleration, and jet formation as well as pulsation dampening is described.

As today's machine speeds exceed 2000 m min^{-1} , the pressure in the nozzle chamber is about 5 bar and above. This results in high bending forces in CD acting on the construction. For operational reasons, especially for improved dewatering characteristics in the wire and press sections, the suspension is fed to the headbox at elevated temperatures, for instance, at $40\text{--}55^\circ\text{C}$, and in special applications

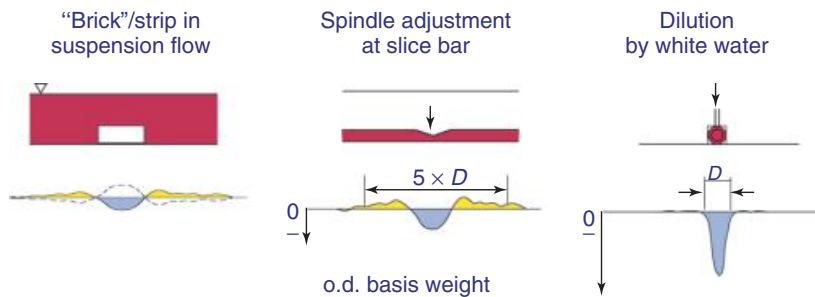


Figure 13.5 History of basis weight control in cross machine direction.

(e.g., fully integrated mills) up to 65 °C. This induces temperature differences between individual construction elements, which may result in shape deviations of the headbox parts. Higher temperature would further promote dewatering, but for safety reasons and operational reasons (mist and performance of process chemicals), it is not common. Nevertheless, some machines for specialty paper production (parchment paper) run at suspension temperatures of up to 90 °C for operational and technological reasons. Furthermore, a headbox for a paper machine with more, for example, 10 m width has a high dead weight.

All these parameters induce a strong deflection of the originally straight structure of the headbox, and on the most sensitive parts, which are the nozzle chamber and the slice blade. They can negatively affect the uniformity of the suspension jet exiting the headbox.

13.3.1

Rectifier Roll Headboxes

This type of headbox is also called *evener roll headbox*.

13.3.1.1 General Design Features

Figure 13.6 shows a rectifier roll headbox, which is still found in the industry in many mills. Typical are the use of two or three rectifier rolls as well as the integrated air cushion.

13.3.1.2 Application

This headbox principle is in application only for Fourdrinier machines. The design has been applied to all kinds of paper grades, at machine speeds and widths of up to 800 m min⁻¹ and 6 m, respectively.

The rectifier roll headbox is still used for a few applications, which may not be best covered by hydraulic headboxes. These include lower throughputs and machine speeds as well as special stock mixtures, especially when containing long fibers. So, it is mainly used in the production of cigarette paper grades.

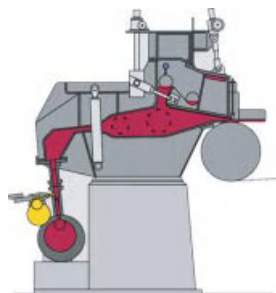


Figure 13.6 Example of a rectifier roll headbox with an air cushion. (Source: Voith.)

13.3.1.3 Distribution

The predistribution of the suspension in CD is done by a conical header. A recirculation valve allows to adjust the overflow for tuning the pressure distribution across width in a certain range. The fine-distribution is done by the perforated rectifier rolls (holy rolls and evener rolls), which slowly rotate in the suspension, and by the long path through the headbox.

13.3.1.4 Deflocculation

In the conventional design, the suspension passes through the holes of the rotating rectifier rolls, whereby shear forces are generated.

13.3.1.5 Suspension Flow, Acceleration, and Jet Formation

The headbox has an inclined front wall and a slice bar with spindles (or rods) for CD slice control. The spindles can be actuated by step motors (the rods by inductive heating). Too low front wall inclination may result in eddies in the vicinity of the wall, which will be found as stripes in the paper. The slice opening is changed by sliding or swinging part of the front wall. For jet angle adjustment, the top lip or the bottom lip can be positioned by sliding or by a double nuckle design. The air cushion above the suspension is pressurized, and for very low machine speeds (in some cases), it operates under slight vacuum. This design principle needs adequate control of suspension level and air pressure at the same time.

13.3.1.6 Pulsation Dampening

This headbox principle incorporates a dampening system mainly based on the air cushion (absorption and reflection) and to a small degree by reflection at the distributor and the evener rolls. In the older design, the cushion extends nearly over the whole headbox length, whereas in the newer design, the air cushion is reduced to a short dome.

13.3.2

Hydraulic Headboxes

13.3.2.1 Hydraulic Headbox for Fourdrinier Wire Section

13.3.2.1.1 General Design Features Hydraulic headboxes are also called *high-turbulence headboxes*. A conventional hydraulic headbox and an example of a latest design are shown in Figures 13.7 and 13.8, respectively. Many of the design features of hydraulic headboxes for Fourdriniers are also found in twin-wire gap former headboxes (and vice versa). Most of them are explained in this chapter [6].

Modern headbox designs use the C-clamp principle, which means that the top and bottom sides of the nozzle have a C-clamp structure with a closed power flow. No force is passed through the side shields. In that consequence, the expansion of the headbox nozzle owing to the operation pressure is parallel over the width; thus



Figure 13.7 Example of a conventional hydraulic headbox for Fourdrinier wires. (Source: Voith.)

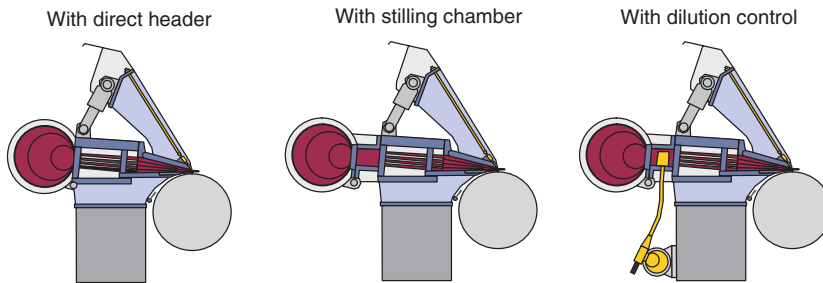


Figure 13.8 Examples of state-of-the-art hydraulic headboxes for Fourdrinier wire section and hybrid former. (Source: Voith.)

no additional bending compensation is needed. For the temperature compensation of the nonstock touching parts, typically heating chambers with a water circulation system are placed within the top lip beam as well as the bottom support of the headbox. Some recent designs with a very symmetrical structure of the top and bottom sides of the nozzle do not even need such a heating system any more. On the basis of a special rip design, the parts can expand while maintaining an absolute parallel nozzle geometry.

13.3.2.1.2 Application These headboxes are used for machine speeds of up to 1200 m min^{-1} and 1500 m min^{-1} , which are the speed limits for Fourdriniers and hybrid formers, respectively. Machine widths are up to 10 m. They are used for production of most paper grades such as woodfree writing and printing or container board.

13.3.2.1.3 Distribution Rectangular or circular-conical header designs are used here. With a recirculation valve, the pressure distribution ahead of the distributor plate can be adjusted. Some recent headbox types are designed without recirculation. Flow variations are compensated by a special hydraulic concept using adapted pressure drops and the stilling chamber principle.

13.3.2.1.4 Deflocculation In the turbulence generator, typically one- or multiple-step diffusers are used to generate turbulence to break up the fiber flocs. To adapt the intensity of turbulence to the particular application, plastic inserts or bushes are used in some headbox types. Recent designs of turbulence generators have round inlet and a rectangular or square outlet geometry.

13.3.2.1.5 Acceleration and Jet Formation In the nozzle, the suspension is accelerated. The suspension friction at the nozzle walls reduces the suspension velocity and gives some further turbulence. To create additional turbulence and adapt intensity and size of the turbulence eddies, lamellas of different lengths are used. These are typically placed between every row of the turbulence generator outlet geometry. To smooth out the jet surface, a few millimeters of a slice bar stick down is used.

13.3.2.1.6 CD Basis Weight and Fiber Orientation Control With the most common slice bar design, the nozzle outlet and thus the suspension height can be adjusted locally across the width to an accuracy of 1/100 mm by means of spindles (Figure 13.9). This kind of CD control has been used or is still used to compensate for deviations in the cross machine basis weight profile of the web. The blade is equipped with a lot of spindles across the width with a standard spacing between these spindles of 75–200 mm. In combination with a dilution control system, the slice adjustment is used for an independent control of fiber orientation.

In contrast to the suspension height adjustment by slice bar control, the dilution control principle (Figure 13.10) locally adjusts the consistency of the suspension. For that dilution of water, usually white water is added to the suspension flow by a great number of valves over the machine width. The valves are individually controlled by actuators. For the spacing of these control modules, a range of 35–150 mm can be found in the industry. The control answer of this spacing in the paper depends on the point of addition as well as on the hydraulic design of the headbox.

A more modern way of fiber orientation adjustment is given with an edge flow control system (Figure 13.11). At the very edges on tender and drive side, the suspension is fed and controlled through separate channels. With more or less addition, a cross-flow can be created and, for instance, a reduced suspension pressure due to friction at the edges can be counteracted.

13.3.2.1.7 Pulsation Dampening Process machines installed upstream of the headbox (e.g., the fan pump or the screen) may generate pulsations, which can be higher than allowed (for instance, less than 1% deviation allowance). In such

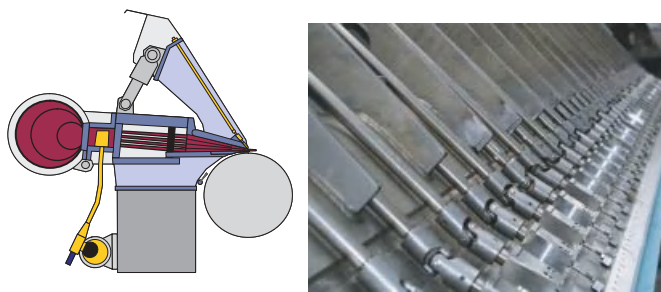


Figure 13.9 Schematic of a slice bar spindle arrangement. (Source: Voith.)

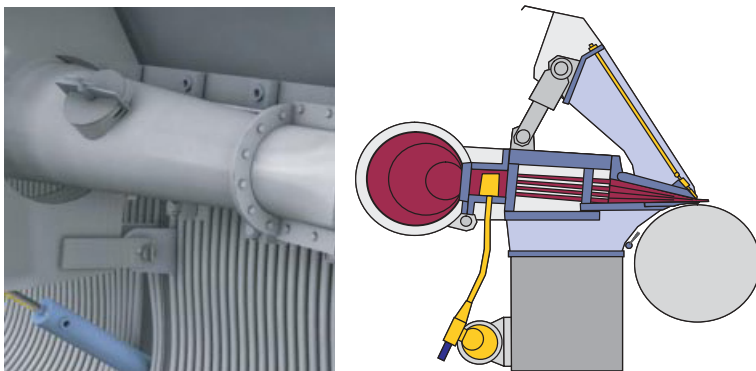


Figure 13.10 Schematic of a dilution control arrangement. (Source: Voith.)

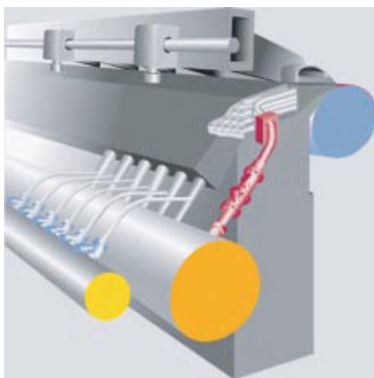


Figure 13.11 Schematic of an edge flow control arrangement. (Source: Voith.)

a case, pulsation damper-reducing pulsations over a wide frequency range should be installed ahead of the distributor of the headbox or integrated into the headbox. Figure 13.12 shows an example of such a damper with a perforated plate to reflect incoming pulsations; the upper part of the tank being partly filled with air, thus acting as a hydropneumatic damping system. This is to absorb and dissipate most of the remaining pulsation energy passing the perforated plate.

13.3.2.2 Hydraulic Headbox for Twin-Wire Gap Formers

13.3.2.2.1 General Design Features In general, all details described for the Fourdrinier headbox are also valid for the gap former headbox. A special demand of a gap former headbox is a smaller angle of the nozzle structure in order to fit into the wire gap in order to realize an acceptable jet length (Figure 13.13). A gap former application has normally a smaller basis weight range compared to a Fourdrinier. In addition, especially for the roll gap former design, the jet

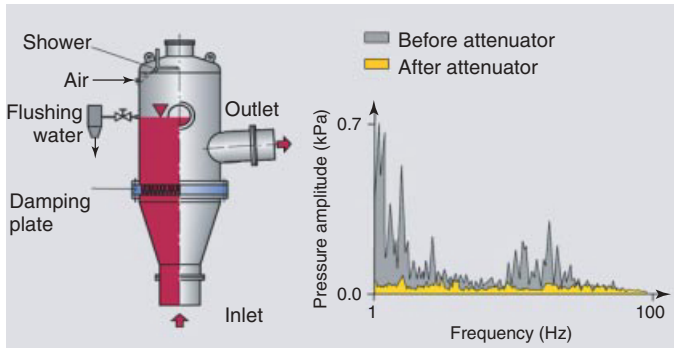


Figure 13.12 Example of a passive pulsation damper working after reflection and absorption principle and typical damping characteristics. (Source: Voith.)

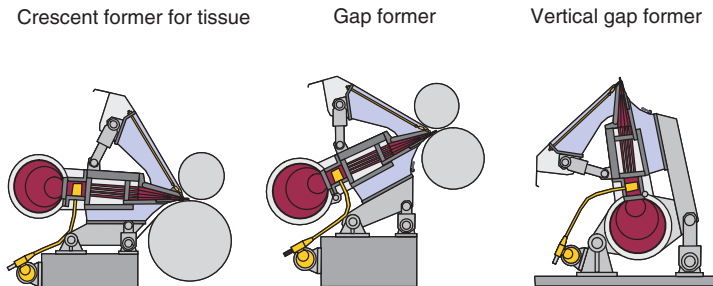


Figure 13.13 Example of a state-of-the-art headbox for twin-wire gap former application. (Source: Voith.)

impingement geometry is rather insensitive to small variations. For that reason, a movement of the top or bottom lip is not realized for many gap former headboxes. Instead, typically the entire headbox can be rotated by a few degrees.

13.3.2.2.2 Application These headboxes are used for machine speeds of up to 2000 m min^{-1} for graphic applications and even beyond for tissue machines. Machine widths for modern graphic paper production lines are up to 11 m. Gap formers are also used for packaging grades. For tissue and packaging grades, in many cases, the headbox is designed as a two-layer application.

13.3.2.2.3 Pulsation Dampening The much higher jet-to-wire velocity ratio as well as the immediate drainage to both sides makes the gap-forming process less sensitive to pulsations in contrast to a Fourdrinier. In that consequence, pulsation dampening is not needed for a gap former headbox.

13.3.2.3 Two-Layer Headbox

13.3.2.3.1 General Design Features Figure 13.14 shows an example of a two-layer headbox for twin-wire formers. Here, two separate suspension lines with mostly

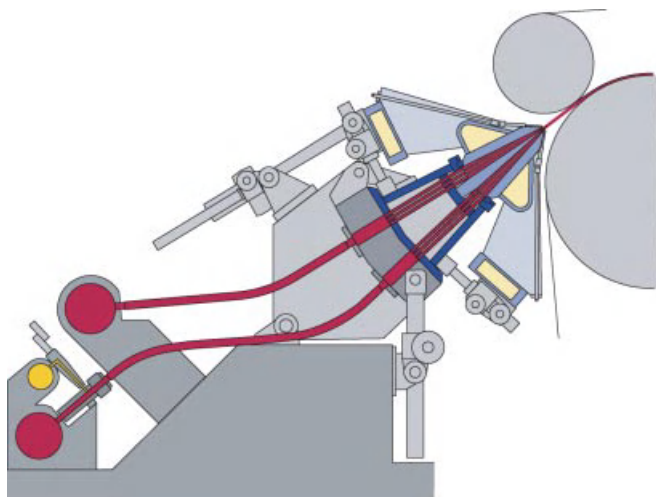


Figure 13.14 Example of a two-layer headbox for twin-wire gap formers. (Source: Voith.)

different furnishes are fed to the headbox, which in principle consists of two headboxes in one housing. Only in the last short free jet length itself and during dewatering can mixing of the two suspensions occur. So, the two jets are kept separated as long as possible by a separating element. This separating element can be either a kind of flexible lamella or a fixed wedge. For the latter, a small difference in jet velocity (z -direction) between layers can be applied, which can be advantageous in some cases. The tip of the separating element is decisive for low mixing along the free jet length. Distribution, deflocculation, acceleration, and jet formation are done as described for the other twin-wire headboxes.

13.3.2.3.2 Application In recent years, multilayer headboxes have been installed in tissue, board, and packaging grades. For graphic paper production, some applications exist but the benefits in full scale are minor. Operational speeds are beyond 2000 m min^{-1} (tissue) and widths up to 9 m (packaging). A multilayer headbox is advantageous for multi-ply production by saving one of the forming sections and in single-ply production by hiding the inferior furnish under the more expensive cover furnish. However, compared to two separate plies, some restrictions regarding minimal layer weight and covering quality have to be considered. Two-layer headboxes are mainly used for gap former applications, where the sheet can be immediately drained to both sides and fixed. Good results can be achieved with hybrid formers as well. For Fourdrinier wire sections, also a few applications exist but with limited success because of the single-sided drainage.

13.3.2.4 Secondary Headbox

This hydraulic single-layer headbox has a special shape and nozzle geometry to be placed above an existing Fourdrinier (Figure 13.15). The jet is delivered after

Secondary headbox

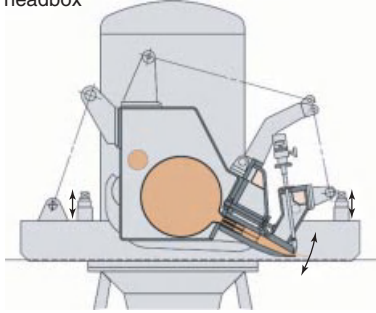


Figure 13.15 Example of a secondary headbox. (Source: Voith.)

the wet line of an already existing bottom layer. From the process point of view as well as the reachable covering quality, this principle is placed between the separate plies and the two-layer headbox. However, owing to the boundary layer air and the jet landing on an existing sheet, the machine speed as well as the maximum basis weight is limited. A secondary headbox is typically followed by a top wire unit to drain the secondary layer to the top.

13.3.3

Headbox with a Central Distributor Tank

This headbox design makes use of a centrally positioned tank distributing the suspension to a plurality of flexible pipes of equal pressure loss, which end – equally distributed across the width – at the backside of the headbox, which shows the same design characteristics as described earlier (Figure 13.16). Here, a recirculation valve is not needed. A further function of the central distributor tank is to attenuate pulsations. This kind of headbox is in use for Fourdrinier machines as well as for twin-wire formers and is suited for lower throughput.

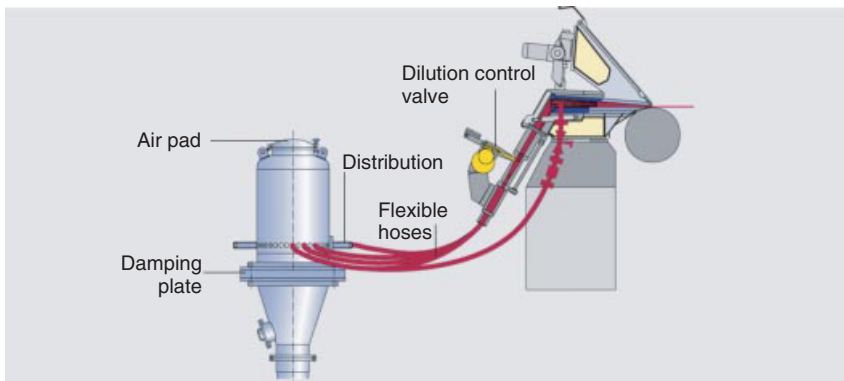


Figure 13.16 Example of a headbox with central distributor tank. (Source: Voith.)

13.4

Influence of Operational and Design Parameters on Technological Results

13.4.1

Changing Operational Parameters

13.4.1.1 Change of Consistency at Constant Basis Weight

Change of consistency at constant basis weight means to increase or reduce the volumetric flow through the headbox nozzle at the same amount of thick stock feed. This is reached by opening (closing) the nozzle. The headbox control device keeps the pre-set pressure (jet velocity) constant by adjusting the headbox pump motor speed.

13.4.1.2 Change of Basis Weight

The mean basis weight (grams per square meter) to be produced is related to the mean volumetric flow through the nozzle and the consistency of the suspension. For changing the basis weight, the amount of thick stock feed has to be adjusted. Usually, when basis weight is changed, the consistency will also be adjusted on a new level for optimum technological results. In this case, for lower (higher) consistency, a higher (lower) volumetric flow respectively is required.

13.4.1.3 Change of Jet Velocity and Jet Angle

Jet velocity is changed by varying the pressure in the headbox. This is done by increasing the supply pressure of the headbox pump, which is done by revolutions per minute control. The jet angle is changed by rotating the headbox or changing the end nozzle geometry and thus the jet deflection. The latter is used for Fourdrinier application, where a wide range of jet angle and jet length adjustment is required. The deflection is influenced by a horizontal movement either of the apron or the top lip beam. The relation of the extension of the apron to the slice opening defines the extent of jet deflection. For applications, where only a small range of jet angle is required, for example, roll gap formers, the complete headbox is moved. For demanding cases with sensitive jet impingement conditions, a combination of both can also be used.

13.4.2

Technological Dependencies

13.4.2.1 MD/CD Ratio of Paper Properties

The velocity ratio of suspension on the wire and the wire itself affects web structure by the degree of fiber orientation. Assume that the fibers in the suspension jet are randomly orientated in the three dimensions, the suspension flow on the wire is parallel to the machine direction and no velocity difference is given to the wire itself. The fibers then remain randomly oriented on the wire. When there is a certain velocity difference between the suspension and the wire, the amount of fibers laid down in the machine direction during web formation is greater than in the CD. The fibers tend to align mainly in the direction of the velocity

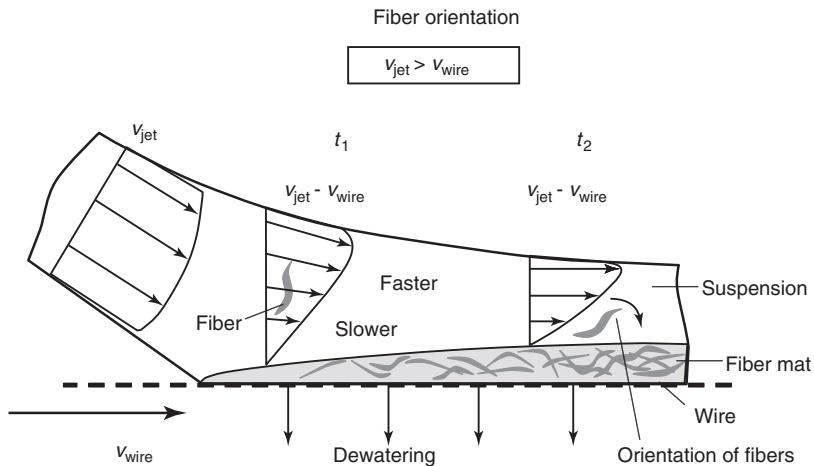


Figure 13.17 Principle of fiber orientation due to velocity difference between jet and wire.

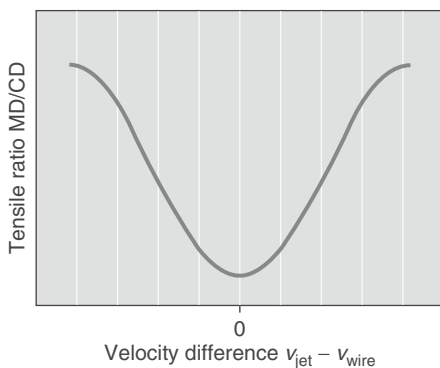


Figure 13.18 Principle relationship between MD/CD tensile ratio and velocity difference between the suspension on the wire and the wire itself.

difference between the suspension and the wire, be it drag or rush (Figure 13.17). This results, for instance, in differences in the web characteristics, such as tensile strength or stiffness, in MD versus CD. It also influences shrinking behavior during web drying and expansion behavior when the finished paper sheet is exposed to heat or moisture. This might be of interest, for instance, in a copy machine or during printing in the press room. Figure 13.18 gives an example of how higher (rush) or lower (drag) suspension velocity on the wire in relation to the wire speed itself affects the MD/CD tensile strength ratio. In case of preorientation of the fibers in the jet in MD, the minimum MD/CD ratio is limited.

13.4.2.2 Formation Quality

Formation defines the way the fibers are distributed, aligned, and mixed when a sheet has been formed. A more practical description is the uniformity of the sheet



Figure 13.19 Influence of jet quality on formation.

determined by basis weight variations up to a wavelength of about 50 mm. Visually, the “look-through” gives a subjective idea on “formation quality.”

With the delivery of the jet out of the headbox, a certain formation quality is already fixed. Depending on the kind of forming section and its influence on the formation level during the forming process, the headbox influence is more or less dominant. Figure 13.19 shows how streaks in the jet can be found as streaky formation in the paper, whereas a finer jet quality results in a more uniform look-through. Other predominant factors are stock consistency and fiber properties.

The main influencing factors on formation from the headbox are the jet impingement geometry, the jet wire speed difference, and the type and level of turbulence generation. The jet wire speed difference and, to some smaller extent, also the jet impingement geometry are responsible for the level of shear forces that are applied to the suspension to break down fiber flocs or maintain low flocculation level, respectively. The turbulence generation in the headbox determines the overall level of fluidization as well as the size of the floc structure. Larger flocs already delivered with the jet can be quite difficult or even impossible to be broken down again afterward. Finally, the consistency of the suspension influences the fluidization level and the reflocculation tendency.

Figure 13.20 shows how the difference in velocity of suspension and wire affects formation quality. Usually, formation quality is poorest at zero velocity difference. In Figure 13.21, some examples of the influence of consistency on formation are given. It also shows the different kinds of formation from “milky” to “cloudy.”

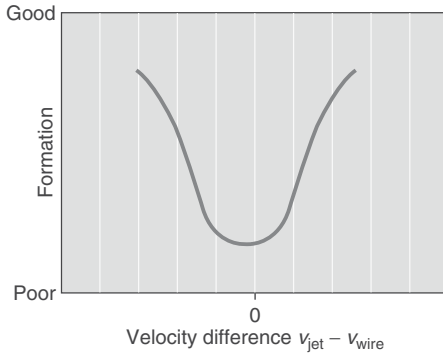


Figure 13.20 Principle relationship between formation quality and velocity difference between the suspension on the wire and the wire itself.

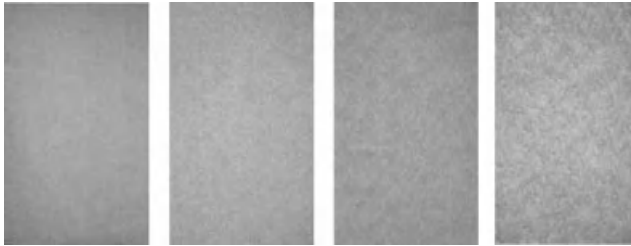


Figure 13.21 Examples of the effect of consistency on formation quality. (Source: Voith.)

13.4.2.3 Nonsymmetry in z-Direction

A certain preorientation of fibers in MD is generated by friction at the wall by viscosity forces within the suspension or acceleration. In case of nonsymmetry in z-direction by

- nonuniform acceleration (nonsymmetrical nozzle);
- nonsymmetrical friction (different lengths of top and bottom plates of the nozzle); or
- speed difference between top and bottom wires.

The fiber orientation in the jet will differ between the top and bottom sides of the jet, which may lead to quality problems such as curl (Figure 13.22) in graphic paper converting or copy machines [7].

13.4.2.4 CD Basis Weight Profile

The deviation from the desired CD basis weight has to be a minimum, for instance, 0.5%. Furthermore, for operational reasons, the ideal CD basis weight profile should often have somewhat lower values at the edges. As a standard for a long time in the past – and still today – the CD basis weight profile has been and is controlled by a slice blade. The effect on the basis weight profile is shown in Figure 13.23. It demonstrates that at the position of the lowered spindle, the basis

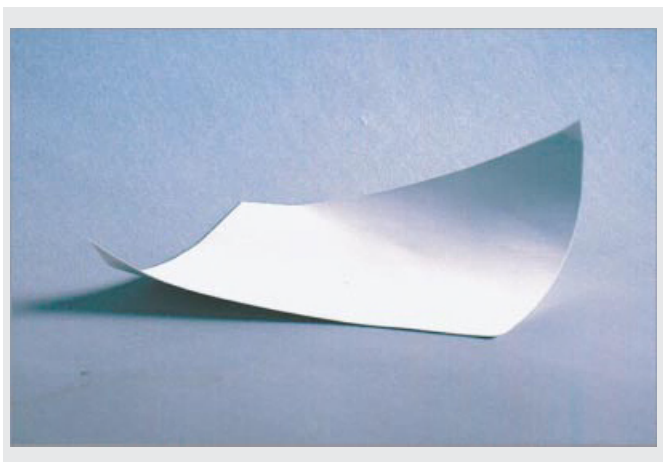


Figure 13.22 Example of curl due to nonsymmetry in fiber orientation of top and bottom sides of a paper sheet. (Source: Voith.)

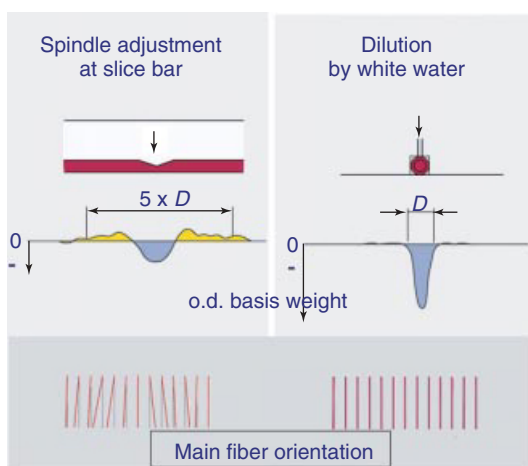


Figure 13.23 Principle effect of CD control of basis weight by slice bar adjustment and dilution and the effect on main fiber orientation.

weight is reduced to a certain degree, whereas in the neighborhood at both sides of the adjusted spindle, the local basis weight is increased. As the impact on the CD profile is about five times wider than the local change in slice opening, the potential for CD basis weight profile control is limited and complicated. This kind of response is induced by local cross-flow of the suspension in the nozzle when adjusting the local slice opening. This means that the jet exiting from the headbox at the controlled area is not exactly oriented in machine direction. This deviation is strongly magnified on the wire. The result is a main fiber orientation in the web under a certain angle against MD, which is explained in the following paragraph.

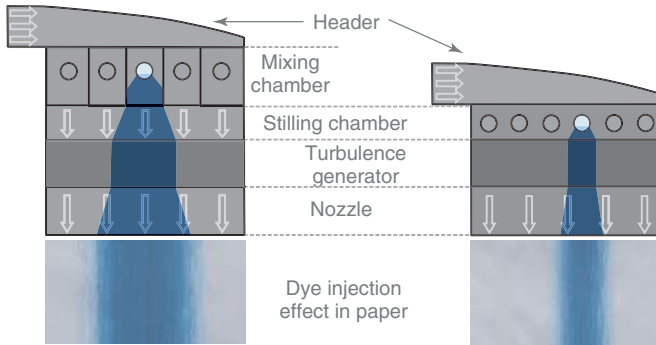


Figure 13.24 Visualization of the effective width of dilution control by adding ink into one single stream.

The dilution principle avoids cross-flows. Here, a constant “high-consistency” volumetric flow is fed to the headbox where it is mixed with a “low-consistency” stream. At positions across the width where a lower basis weight is required, the “low-consistency” stream is increased at a constant local overall flow rate. If the local basis weight should be increased, the local “low-consistency” stream is reduced at a constant local overall flow rate. The influence on the width of a local adjustment is limited to about twice the width of the control (Figure 13.23). Effective width of dilution control is visualized by adding some ink into one of the single streams that the point of addition along the flow path in the headbox is important for a limited side effect (Figure 13.24).

13.4.2.5 CD Main Fiber Orientation Profile

The main fiber orientation angle describes the direction of the plurality of the fibers in the paper and can be measured by laser or ultrasonic devices. It has an impact on other important paper properties. As mentioned earlier, local slice bar adjustment causes cross-flow in the nozzle chamber and the exiting jet. Even a small angle of the jet velocity vector against the machine direction results in a large main fiber orientation angle (Figure 13.25). With a change from drag to

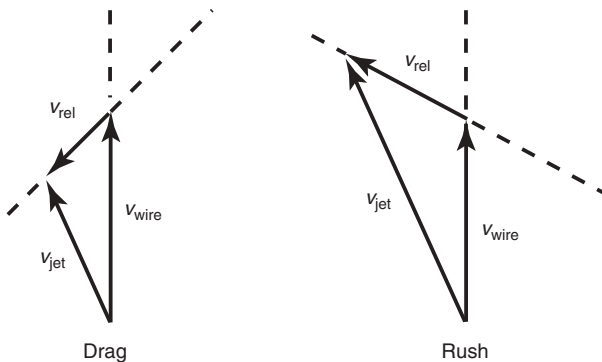


Figure 13.25 Influence of jet velocity, jet angle, and wire speed on main fiber orientation.

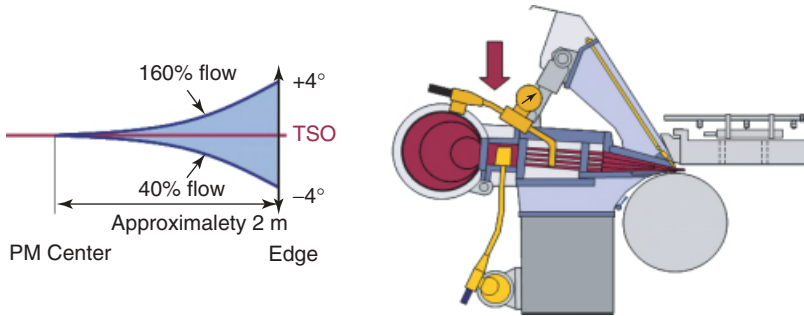


Figure 13.26 Influence of a change in volumetric edge flow on main fiber orientation. (Source: Voith.)

rush or vice versa, the direction of fiber orientation changes as well. Under rush conditions, the deviations of jet direction and fiber orientation go into the same direction for drag into different directions.

An example may show this: a deviation of 1° in the jet at 1000 m min^{-1} means a CD velocity component of 10 m min^{-1} . Together with an MD velocity difference between the suspension on the wire and the wire itself of, for instance, 40 m min^{-1} , an angle of 14° in the resulting velocity vector on the wire occurs. This angle of the velocity factor defines the orientation of the plurality of the fibers, which are laid down during dewatering of the suspension in the forming process. At a jet velocity of 2000 m min^{-1} and again 1° deviation in the jet, the CD component is 20 m min^{-1} . With the same MD velocity difference between the suspension and the wire, it adds up to an angle of about 27° of the main fiber orientation.

A major advantage of CD basis weight control by the dilution principle is that CD profiles of main fiber orientation are not affected (Figure 13.23). In Figure 13.26, the influence of a change in volumetric edge flow on main fiber orientation is shown.

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14

Wire Section

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14.1

Overview and Theoretical Aspects

14.1.1

Objectives

In the wire section, a fiber web is formed out of the suspension supplied by the headbox. The kind and quality of suspension delivered from the headbox to the wire has a strong impact on the quality of the paper web formed. Therefore, the headbox and wire section – together with the approach flow system – have always to be regarded as one interdependent unit. The main objectives of the wire section and their principal solutions are as follows:

- extensive separation of fibers, fillers, and fines from water, done by drainage perpendicular to the wire;
- well-ordered and defined deposition of the fibers on the wire, obtained by oriented shear due to the velocity difference between the wire and suspension jet exiting the headbox;
- prevention of too much fiber flocculation; excess flocculation can be counteracted by oriented shear, turbulence, and acceleration elongation generated by dewatering elements and their pressure pulses.

The different mechanisms prevailing in sheet formation interact with each other [1–3].

14.1.2

Drainage and Retention

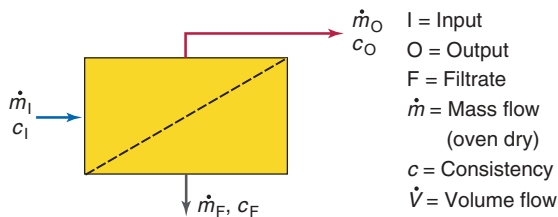
The separation of the fibers from water (drainage) is a combined filtration and thickening process. During pure filtration, a filter cake (paper web) is built up above the auxiliary filter layer (wire), whereas the consistency of the suspension above the filter cake remains the same as before. Pure thickening means that the consistency of the suspension as a whole is increased. In paper web forming, filtration prevails.

In a simplified chronological sequence, first some fibers are retained by the forming wire. Then more fibers are collected and a first fiber matt is created. Owing to the drainage force, the fiber matt is subjected to compaction. The thicker and densified fiber matt with higher binding forces can now retain the much smaller fines and fillers. In areas of lower basis weight (thinner retained fiber matt), drainage resistance is less, causing a higher drainage flow supplying more fines, fillers, and (short) fibers in that area. In this sense, the dewatering process has a self-healing effect.

Drainage force is opposed by the resistance to filtration of the auxiliary filter (wire) and the web already formed. The latter depends on the thickness of the filter cake; on the degree of beating, chemical treatment, and type of the stock; as well as on the amount of fines and fillers present. The water removed in the filtration process carries away fibers, fines, and fillers and is called *white water* in the paper industry. The percentage of solids of the suspension retained on the wire is called *retention*, and can be increased by the addition of retention aids. In Figure 14.1, the definition of retention is explained by mass flows and consistencies. Figure 14.2 shows schematically the consistencies of the filter cake and the filtrate as well as retention, over time. At the beginning, the filtration resistance is low, but it increases with filtration time when the filter cake (the web) is built up. Both the amount of filtrate and the consistency of the filtrate decrease with time. For high retention, low dewatering forces have to be applied at the beginning. Later on, these have to be increased for minimizing the overall dewatering time.

The driving forces for dewatering the fiber suspension can be hydrostatic, vacuum, or mechanical, and include the following:

- The height of the suspension above the wire, including any additional pressure applied;



Retention: Percentage of mass retained on the wire

$$\text{Ret}_1 = \frac{\dot{m}_O}{\dot{m}_i} = \frac{\dot{m}_i - \dot{m}_F}{\dot{m}_i} = \frac{\dot{V}_i c_i - \dot{V}_F c_F}{\dot{V}_i c_i}$$

$$\text{with } \dot{V}_i \approx \dot{V}_F$$

$$\text{Ret}_1 = \frac{c_i - c_F}{c_i} = 1 - \frac{c_F}{c_i}$$

Figure 14.1 Definition of retention.

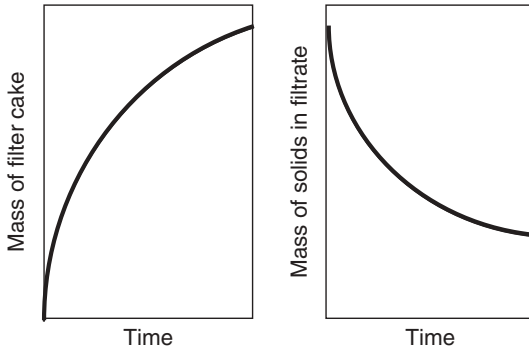


Figure 14.2 Principles of filtration as regards filter cake, filtrate, and retention.

- A vacuum behind the wire, produced by direct vacuum application (in suction boxes or suction rolls), or by suction boxes or suction rolls, or by the hydrodynamic effect of the dewatering elements (table rolls and foils);
- For a twin-wire forming section, the pressure generated by the tension of the outer wire covering the suspension when running in a sandwich over a curved surface which may be a roll or a curved shoe. The pressure p exerted on the suspension is $p = S/R$, with S representing the wire tension [N cm^{-1}] and R the radius [cm]. The drainage pressure generated by the wire tension is effective on both sides of the wire sandwich. In addition to that, the pressure caused by the centrifugal force is effective only toward the outer wire. Owing to the centrifugal acceleration $c = v^2/R$, the suspension thickness of t would represent a suspension height of $c \times t/g$ in the gravity field. As a consequence, the total drainage pressure against the inner wire or roll is reduced, and that to the outer wire is increased. Depending on the suspension height, the drainage pressure by the centrifugal force may dominate, especially at the beginning of the dewatering and at high machine speeds.

The filtration process in general can be described by Darcy's law. This equation describes the flow of a fluid through a porous medium, and is given by

$$q = v \times A = (-1/\mu \times k) \times i \times A$$

where q is the flow rate, μ the viscosity, k the permeability, i the pressure gradient, and A the flow area.

The time t [s] for dewatering a suspension height of h [mm] is

$$t = h^\beta$$

where β is a parameter to be determined for a given situation depending on the stock properties and dewatering forces. t decides the dewatering time for a given machine speed.

14.1.3

Jet Quality as a Precondition for Good Formation Results

The ideal jet impinging the wire for being dewatered should show a uniform profile in cross machine direction as regards jet velocity, thickness, smoothness, fiber distribution (flocculation), and consistency. The higher the consistency of the delivered suspension, the higher the binding forces between the individual fibers and the tendency of rapid reflocculation. A high turbulence level ensures a more homogeneous suspension with a high fluidization level with only small flocs. Too high a degree and/or too large wavelengths of turbulence, however, result in a rough or even destroyed jet surface, causing disturbances at the jet landing on the wire, and later in web formation.

A lower turbulence level will create a smoother jet surface, but can only maintain a lower fluidization level. So larger scale flocs will exist and be transported to the wire. The larger the flocs, the more difficult it is to break them down again in the wire section.

The end geometry of the headbox nozzle is typically not symmetrical in order to ensure good guiding and controllable deflection of the jet. As a consequence, the jet does not show a perfectly symmetrical velocity and fiber orientation profile in the *z*-direction. Depending on the type of forming section and the symmetry level of its forming process, the jet properties can contribute to the orientation anisotropy of the sheet, which can be relevant for the dimensional stability of the final sheet. A typical defect is curl, which may occur in the machine in the cross or diagonal direction and is especially crucial for format papers (Chapter 23).

14.1.4

Fiber Deposition and Orientation

The fiber orientation anisotropy is mainly determined by the difference between the wire speed and the speed of the jet landing on the wire surface. The magnitude of shear is a function of the speed difference. In addition, some minor impact is given by the velocity profile of the jet from its bottom to top surface, as well as by the jet consistency and the impingement angle.

For a gap former, where the jet is directly delivered to a gap between two wires (running over curved dewatering elements), a higher jet speed is needed in comparison to a fourdrinier (flat wire) to reach the same orientation level. The reason is that, in a gap former, additional jet energy is needed to overcome the drainage pressure that is gradually created when entering the curved wire gap (Chapter 13). As shear forces are applied to the suspension from the first contact of the jet with the wire, the minimum reachable orientation level of a gap former will be always higher than for a fourdrinier.

14.1.5

Control of Flocculation Level and Dispersing in Web Formation

Web formation in the wire section can be divided into two steps or parts: a first part where the actual sheet forming happens, and a second part where the dryness increases and further sheet compaction takes place. In the first part, the main properties such as sheet symmetry, fines, and filler distribution as well as web formation are determined to a large extent. The end of this first part is defined by the immobility point which lies at a consistency of about 5%, depending on the stock properties.

After this point, the internal binding forces of the fiber network reach a level at which the single fibers or single flocs can no longer be moved or displaced easily. Any further extensive force application would destroy the sheet structure on a larger scale, leading to a defective paper. In the second part, the web structure is fixed, with the exception of the outermost surface layers. Here, some fines and fillers can be still sucked in or washed out by increasing the pressure levels here. This further increase in web dryness should reach a sufficient level for safe web pickup.

14.2**Historical Review**

The first continuously operating forming section was built in 1798 by Nicolas-Louis Robert. For many centuries up to that time, each paper sheet individually had been made manually by using deckle frames and a dipping vat (chapter 1.5). The first types of industrial forming sections were the fourdrinier wire and the mold former. Both principles are still in use today. Over time, the machines have been continuously improved in terms of machine speed, width, and production capacity.

Sometimes, pure improvements of a particular technique have led to impasses. So new technical and technological approaches were necessary to overcome the physical limitations. Some of these steps and changes were the use of foil blades instead of the table roll, the invention of the twin-wire formers, or the substitution of bronze wires by synthetic forming fabrics. A wide range of sheet-forming techniques have been developed and used for many different purposes [4]. As an overview, the main developments in the wire section are shown in Figure 14.3. Table 14.1 gives today's maximum speeds and widths of the different web-forming techniques and their main applications for the various paper and board grades.

14.2.1

Fourdrinier Wire Section

The fourdrinier wire section is a horizontal forming wire supported by different types of dewatering elements. Starting with its commercial use in the nineteenth

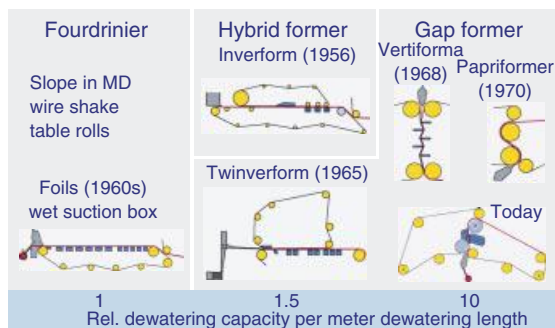


Figure 14.3 Main developments in the wire section.

Table 14.1 Maximum operating speeds, maximum widths and produced grades for Fourdriniers, hybrid formers, gap formers, and suction formers.

Type	Speed (m min^{-1})	Wire width (mm)	(Preferred) grades
Fourdrinier	1300	10 000	All
Hybrid former	1500	10 000	All
Gap former	2000	12 000	Graphic papers
	2200	6000	Tissue
Suction former	500	8000	Board
	1500	6000	Tissue

century, it was the most common forming principle in the past. In earlier times, in some machines, the fourdrinier wire section was provided with an adjustable slope in the machine direction. This was to accelerate the free suspension on the wire, thereby influencing the formation and fiber orientation. In the 1920s, wire shaking with only the breast roll (instead of shaking the whole wire section) was introduced, which allowed the increase in shaking frequency and stroke. Dandy rolls are being used since 1827 for formation improvement and watermarks. Suction rolls were introduced to the industry in 1908, and suction couch rolls for vacuum pickup of the web in 1937.

Table rolls were introduced in the 1830s. Their use ensured good drainage and turbulence generation by building up pressure and vacuum pulses. But their use is limited to machine speeds of about 500 m min^{-1} because too high a pulse would destroy the web.

In the 1960s, foils were introduced to the market. With different angles, the intensity of the pulses could be adjusted. Also, a higher drainage capacity was gained by the use of wet suction boxes. As a consequence, the machine speeds could be increased. Ceramic materials for the foil surface and the new forming wires made from synthetic material further improved the situation (since the 1960s).

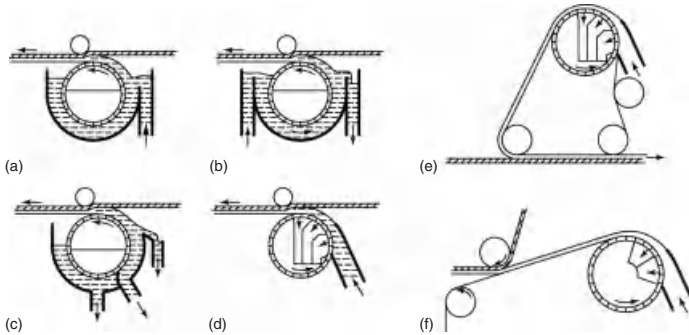


Figure 14.4 The way from the mold former to the suction former and the suction breast roll former (a) contra-flow former, (b) uni-flow former, (c) nonimmersed mold former, (d) suction former, (e) suction former with rotating wire on a Fourdrinier, (f) suction breast roll former for tissue production.

14.2.2

Cylinder Formers

A few years after the introduction of the fourdrinier machine, the single-mold former was invented in the early nineteenth century (1809). From 1903 onward, these machines were extended to multimold former machines. An internal vacuum was introduced since 1952 on for increased production potential. The mold former of different designs was replaced by a nonimmersed cylinder former since 1964, finally leading to the suction former (Figure 14.4). Suction formers and suction breast roll formers were common in the 1970s for board, packaging paper, and tissue production. They are still employed in new machines for certain special paper grades such as banknote paper.

14.2.3

Twin-Wire Formers

- **Twin-wire hybrid former:** The first hybrid former was installed in 1956 (Inverform at St. Ann's Board Mill). A hybrid former is built up by a fourdrinier wire combined with a second rotating forming wire loop placed on top. After a certain drainage length on the fourdrinier, this second wire loop comes into contact with the suspension and thus enables drainage to both sides. With the use of the twin-wire principle, the drainage efficiency could be further increased and the sheet symmetry properties were significantly improved.
- **Twin-wire gap formers:** The first gap formers introduced to the market were the Twinverform (Beloit, 1965), the Vertiforma (Black Clawson, 1968), and the Papriformer (Pulp and Paper Research Institute Montreal, 1970). The following "families" of Belbaie-, Duo-, Sym-, and Twinformers showed a lot of variants as regards the wire run (horizontal, inclined, and vertical) and dewatering elements depending on the machine speed or product. Delivering the suspension jet directly into the twin-wire gap, the gap former principle was superior to a hybrid

former in terms of machine speed potential. Over the years, this machine concept has enabled a continuous increase in production speeds.

14.2.4

Wires, Retention Aids, and Chemical Additives

For a long time, bronze wires were the standard. In 1958, the first plastic wires came into the market. They started to replace the (single-layer) bronze wires over the next 10–20 years and were optimized during the 1970s and 1980s. This resulted in wires with two and three layers with different yarn dimensions at the paper and the running side (Section 11.1). Also the use of chemical additives and their continuous improvements contributed a lot to increased drainage capacity and process stability (Chapter 6). Only on that basis could machine speeds and production capacity be increased to such a large extent.

14.3

State-of-the-Art Web Forming Designs

During web forming, the suspension is guided between the wire and air (fourdrinier), between the wire and a solid wall (former), or between two wires (twin-wire formers). Drainage can occur on one or both sides of the web. The different principles are realized in different forming section designs, which are explained below in more detail.

14.3.1

The Fourdrinier Wire Section

The fourdrinier wire (Figure 14.5) is the classical method of web forming. Usually, the fourdrinier is equipped with a forming board, foils and/or table rolls, wet suction boxes, suction boxes, and suction rolls. Drainage proceeds in the direction of gravity. A dandy roll may be used as well (at lower machine speeds), installed just in front of the water line to improve formation and sometimes to apply watermarks.

Wire shaking improves formation, too. A shaker vibrates the breast roll and thus the wire horizontally in the cross-machine direction with a frequency of up to $f = 10$ Hz and an amplitude (stroke) of up to $s = 25$ mm. The shaking intensity $SI = f^2 s/v$ defines the mechanical impact on the suspension. It is used at low machine speeds for fourdrinier wires and hybrid formers.

Speeds up to about 1300 m min^{-1} are achieved with the fourdrinier wire. This is a reasonable limit because of excessive turbulence on the free suspension surface and dewatering capacity. The application of table rolls is limited to machine speeds below about 500 m min^{-1} . With increasing machine speeds, the pressure and vacuum pulses increase over-proportionally, resulting in stock jumping and reinforced dewatering. fourdriniers are still widely used for many different paper grades. For grades with special requirements on its two-sidedness or orientation properties, fourdriniers can be the first choice even today. Typical grades are, for

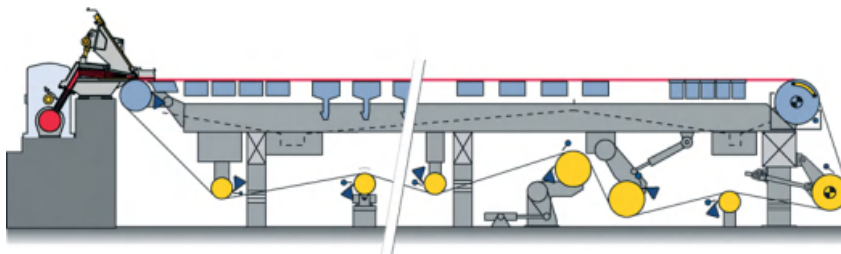


Figure 14.5 Schematic of a Fourdrinier wire section. (Source: Voith.)

example, cigarette paper, sack kraft paper, machine glazed paper, and also the lighter layers for multilayer grades. The highest machine speeds are reached for light basis weights or for very coarse furnishes.

14.3.2

Inclined Wire

Sheet formation on an inclined wire section is carried out in the area where the wire is covered by a box filled with the suspension and is usually under pressure (Figure 14.6). Here, the wire is supported by some type of forming board. The pressure under the forming board can be controlled. This type of forming unit is for low machine speeds and operates with low consistencies of down to about 0.01%. It is used for the production of special papers and nonwovens.

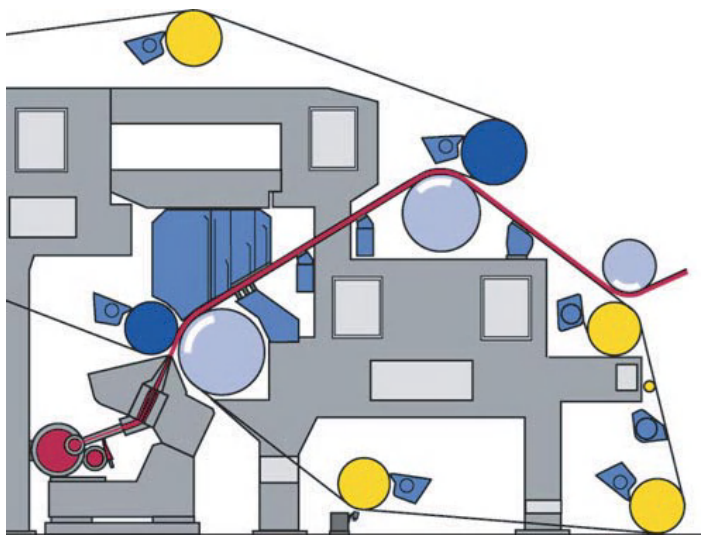


Figure 14.6 Schematic of an inclined wire section. (Source: Voith.)

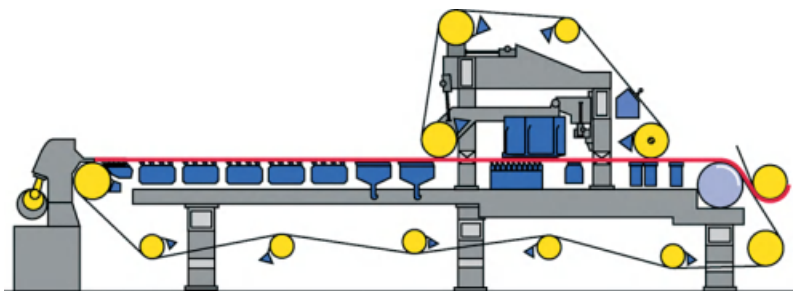


Figure 14.7 Schematic of a hybrid twin-wire section. (Source: Voith.)

14.3.3

Hybrid Former

The first section of the hybrid former consists of a fourdrinier, which is followed by a twin-wire section in which dewatering also occurs through the top wire (Figure 14.7). For that, the top wire is equipped with suction boxes. The top wire increases the drainage capacity of the base-forming unit and improves symmetry in the z -direction of the paper web. The amount of suspension that can be dewatered to the top is 30 to about 50% of the headbox flow. Thus, the symmetry in the z -direction of the web is better than with the fourdrinier. For good formation results, the suspension properties entering the top wire/fourdrinier wedge have to be optimized by adjusting the dewatering conditions ahead, such as the dewatering capacity, turbulence level, or dwell time on the free fourdrinier part. As the suspension enters the twin-wire part with a consistency much below the wet line consistency, a good and adjustable portion of sheet forming is done here.

In the past, a large variety of configurations of hybrid formers have been developed by applying rolls, foils, blades, loadable blades, curved shoes, and suction boxes in different sequences. Modern hybrid formers with state-of-the-art headboxes achieve machine speeds up to 1500 m min^{-1} at graphic grades. For board and packaging grades the higher production capacity of a hybrid former is more desired than the speed level. In a multilayer forming section for board and packaging grades, a hybrid unit is typically used for heavy basis weights in a middle or back layer. In general, a hybrid forming section provides a very flexible drainage capacity in the fourdrinier part. This is favorable especially if a wide range of basis weights and grades are to be produced.

14.3.4

Gap Former

In the gap former, the jet is injected directly into the gap between the two wires that run at the same speed. Drainage is usually through both wires, but sometimes, for example, tissue production, it is only through one side. At the beginning of the

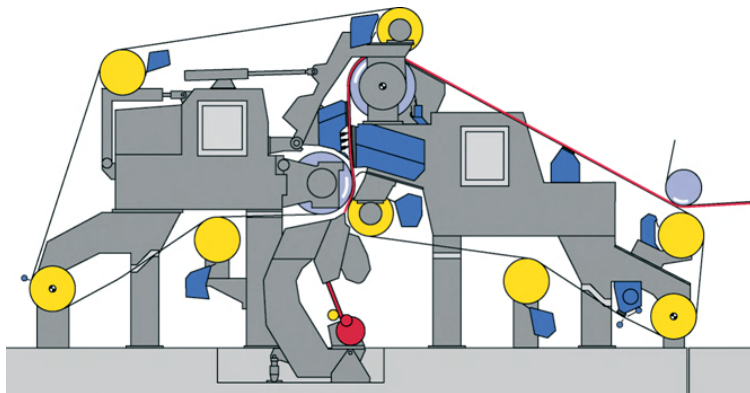


Figure 14.8 Schematic of a twin-wire gap former. (Source: Voith.)

gap former drainage, where the wires are guided over a forming roll or a curved shoe, one of the driving drainage forces is due to the wire tension. In addition, vacuum can be applied. In the further wire run, open rolls, suction rolls, forming blades, and vacuum shoes are used to increase the drainage capacity and improve formation.

Also, in gap former development, a large variety of configurations have been and still are on the market. Today's standard of a high-speed gap former is a roll–blade–roll configuration (Figure 14.8). This means that the forming roll is followed by a curved forming shoe for graphic grades, usually with counteracting forming blades (counter blades). The first forming zone is S-shaped or C-shaped. So the forming roll is positioned either at the opposite side (S-shape) or at the same side (C-shape) of the forming shoe. In the further wire run, the drainage increase is done over flat suction elements and a suction couch roll. The wires are separated on a transfer suction box or on a suction roll. The main direction of the wires in the first forming zone is vertical or inclined, which eases white water handling as well as maintenance and changing of the rolls and wires. The headbox is typically placed at the bottom for graphic grades, whereas in applications for tissue and packaging grades with a very large forming roll wrapping, it is at the top. The dewatering ratio between the two sides is adjustable by vacuum. So the symmetry of the sheet in the z-direction is ensured.

With machines of this kind or of similar configuration, speeds of more than 2200 m min^{-1} are achieved for tissue machines, 2000 m min^{-1} for newsprint, 1900 m min^{-1} with SC and LWC papers, 1800 m min^{-1} for woodfree writing and printing grades, and 1600 m min^{-1} for packaging grades production.

14.3.5

Cylinder Former

In the cylinder former family (Figure 14.4), web formation occurs on a wire-covered, water-permeable cylinder. The uniflow and contraflow former with an immersed

mold represents the oldest design. These were later replaced by the nonimmersed mold former and finally by the suction former. In suction formers, drainage is further increased by vacuum in the interior of the forming cylinder. The suspension is led between the wire cylinder and a solid wall called the *lip*. Suction formers are employed in the manufacture of single layers of board at speeds of more than 400 m min^{-1} . Higher speeds (up to 1500 m min^{-1}) are achieved with the suction breast roll former only in the production of tissue. A similar forming unit can also be placed, for example, on a fourdrinier wire in multiply packaging paper production.

14.4 Machine Elements

The elements used for dewatering, formation improvement, and wire support in the different types of wire sections are as follows:

- The forming board is positioned at the beginning of the fourdrinier wire where the stock jet impinges. It consists of several blades or bars arranged closely together. Thus, it performs a gentle initial drainage of water from the suspension. Too intense a drainage at this position would increase drainage resistance in the following drainage elements because of excessive compaction of the formed fiber mat.
- Forming rolls can have closed or open shells of different designs. Vacuum is applied through the interior to accelerate and control drainage. They are used in web formation as suction breast rolls, suction formers, and suction forming rolls.
- Table rolls (Figure 14.9) are used in the fourdrinier section for drainage and to generate turbulence. Pressure is developed in the upstream nip between the wire and the roll, and a vacuum is induced in the downstream wedge.
- Dewatering foils (Figure 14.10) are used on both the fourdrinier wire and twin-wire formers. They have an acute-angled leading edge to doctor off the water hanging under the wire and a slope on the downstream side (foil angle of $0\text{--}3^\circ$) which induces a vacuum for drainage. Apart from wedge-shaped foils, step foils are also in use.
- Foil boxes combine several foils in one unit. In a vacuum foil box, controlled vacuum is applied in addition. In a step foil box, every second foil is lowered as a step to allow the wire a certain deflection and for the creation of a pressure pulse.
- Blades are “foils” at a fix position with zero foil angle, whereas counter blades are blades which are movable perpendicularly to the wire and can be pressed with adjustable forces. Their main aim is to induce shear forces and doctor off the water and to improve the formation quality.
- Wet suction boxes are dewatering elements that are located in front of the water line. They operate under vacuum and, in contrast to suction boxes, mainly remove white water from the suspension. The water line is a line beyond which no free

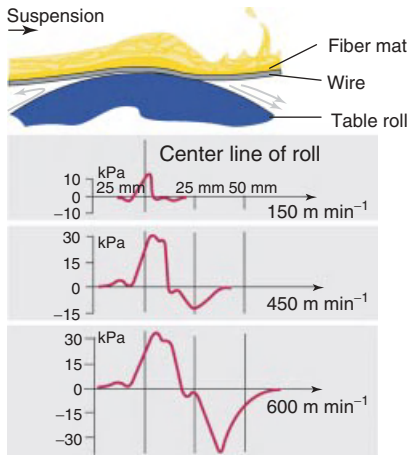


Figure 14.9 Schematic and operating mode of table rolls. (Source: Voith.)

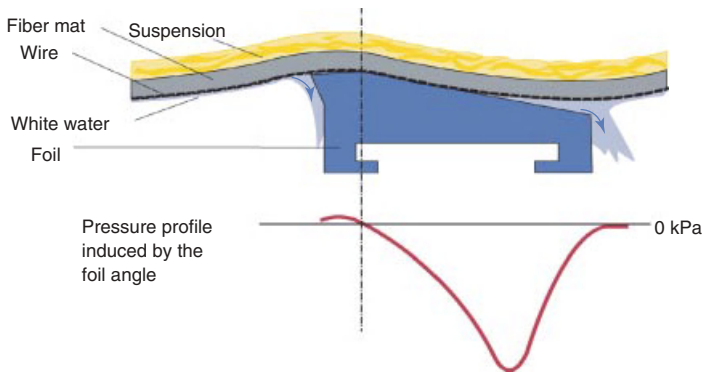


Figure 14.10 Schematic and operating mode of foils. (Source: Voith.)

water is present on the surface of the freshly formed web. That is discernible on the fourdrinier wire by a change in light reflection.

- Suction boxes are dewatering elements that are generally located behind the water line. They operate under a higher vacuum and, in contrast to wet suction boxes, also suck air through the paper web.
- Suction rolls have an open shell of different designs. Vacuum is applied through the interior. They are used at initial web forming as forming rolls, or as suction couch rolls at the end of the wire section. Suction rolls accelerate drainage and increase the dry content in the web.
- Dandy rolls are wire-covered open rolls with a honeycomb structure, which dip into the suspension. They are used in special cases on fourdrinier machines ahead of the water line. They improve formation quality by distributing the fibers more uniformly and are also used for watermark application through

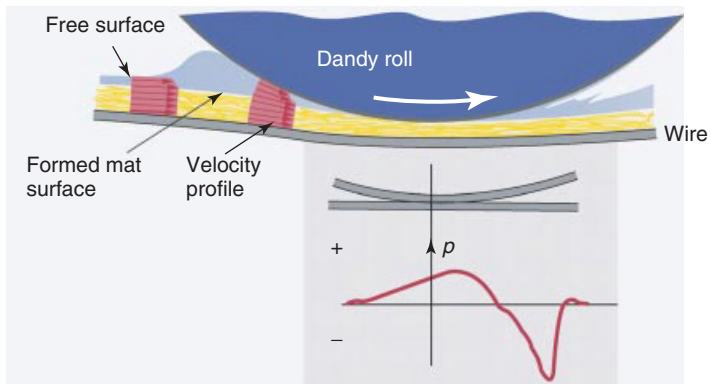


Figure 14.11 Schematic and operating mode of a dandy roll. (Source: Voith.)

displacement and compression of fibers (Figure 14.11). These marks are visible in the finished paper in transmitted light. They are generated by a raised pattern soldered onto the roll. The dewatering effect is low and usually can be neglected.

14.5

Wires

At present, mainly multilayer wires are used. The material now employed is plastic but in some cases bronze or steel is still in use. The properties of the wire, which acts as a filtering auxiliary layer, influence the surface properties of the web (wire mark), fiber orientation, retention, dewatering capacity, and machine operation.

An example of the dimensions will give an idea of the process during initial dewatering. The wire, as the auxiliary filter layer, may have, for example, a weft yarn diameter of about $120\ \mu\text{m}$ and the distance between neighboring weft yarn centers may be about $150\ \mu\text{m}$; the “hole” in between the yarns is then $60\ \mu\text{m}$ deep, converging to about $30 \times 30\ \mu\text{m}$. In comparison, a fiber may have a length of $50\text{--}2000\ \mu\text{m}$ and $30\ \mu\text{m}$ thickness, and a filler particle size of about $2\ \mu\text{m}$.

Thorough cleaning of the wire is of high importance to ensure uniform dewatering and to prevent or reduce formation interference and sheet breaks as well as fines deposits in the machine (Chapter 11).

14.6

Operational and Technological Aspects

14.6.1

General Remarks

The operational and technological objectives of the web-forming process can be summarized as follows: first, to obtain the desired properties of the web such as the

level of uniformity (formation), the level and symmetry of compaction, porosity, and surface characteristics, as well as the symmetry of fines, filler distribution, and the level of surface imprints; second, to reach a sufficient dryness level for a safe pickup of the web from the wire and transfer to the press section.

Furthermore, a stable run of wires, including wire guiding and wire cleaning, has to be ensured (Section 11.1) as well as the proper processing of the white water. Up to 90% of the water exiting the headbox has to be handled in the wire section. A part of it (about 15%) ends up in the suction boxes, but the greater part is thrown out from the wire at the machine speed and has to be collected inside the machine and channeled out properly into the white water tank. The white water is reused to dilute the thick stock entering the approach flow. In order to avoid misting in the machine room and to ensure good cleanliness of the paper machine, the mist is sucked off to the drive side.

A minimal air content of the suspension exiting the headbox can be allowed. If the air content exceeds a certain level, more pinholes and poor machine runnability (web breaks) result. The requirements as regards the air content differ for the various grades and machine speeds (Chapter 12).

14.6.2

Web-Forming and Dryness Increase Functions

The main structure of the web is fixed when reaching the immobilization consistency, which lies at a level of about 5%. The remaining task is now to further increase dryness. As the drainage resistance increases with the dryness level, a continuous increase of the drainage force is needed. This is done by adjusting the vacuum force. Pulsating suction elements, such as flat suction boxes with ceramic bars, as well as nonpulsating suction rolls are used with vacuum levels of up to -70 kPa at the end of the wire section. For a twin-wire machine, the wires are typically separated after reaching a dryness level of about 8–12%, which provides a stable web condition and avoids extensive water spray or streaks. After that point, the web is less sensitive to being transported only on one wire. Also, rewetting from the second wire is avoided when running over the following suction elements to reach the final dryness level.

High dry content after the wire section is desired in order to ensure sufficient web strength for the pickup and transfer to the press section. Also, stable conditions at the trim squirts as well as for the trim separation are crucial for good machine runnability. Depending on the furnish, basis weight, and filler content, usually dryness levels between 16 and 24% are reached.

The time for web forming and dryness increase depends on the type of wire section and on the machine speed. Two-sided drainage reduces the drainage time and the length of the dewatering zone. Typical forming length of a fourdrinier wire section is about 20 m. At 800 m min⁻¹, this means a drainage time of about 1.5 s. A hybrid former with 20 m in total length and operating at 1200 m min⁻¹ has a drainage time of about 1 s, whereas for a twin-wire gap former of 5 m drainage length at 2000 m min⁻¹ operating speed the drainage time is about 0.15 s. So the

relative dewatering capacity per length unit of the forming section increases from 1 for the fourdrinier as reference, to about 1.5 for the hybrid former, and to about 10 for the gap former. In Figure 14.12, examples are given for dryness increase in the forming zone of a twin-wire former and on a fourdrinier. The dewatering effect of the different dewatering elements of a twin-wire former is shown in Figure 14.13.

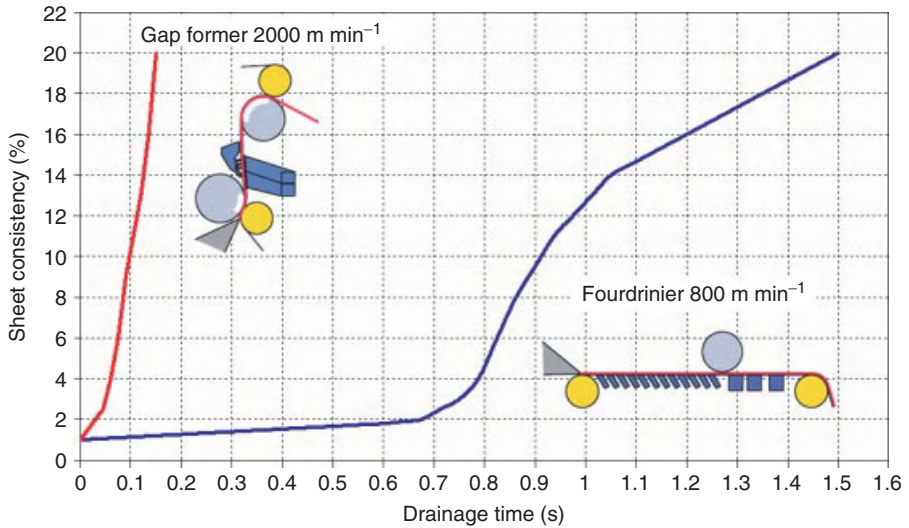


Figure 14.12 Examples for dryness increase in the forming zone of a twin-wire former and on a Fourdrinier. (Source: Voith.)

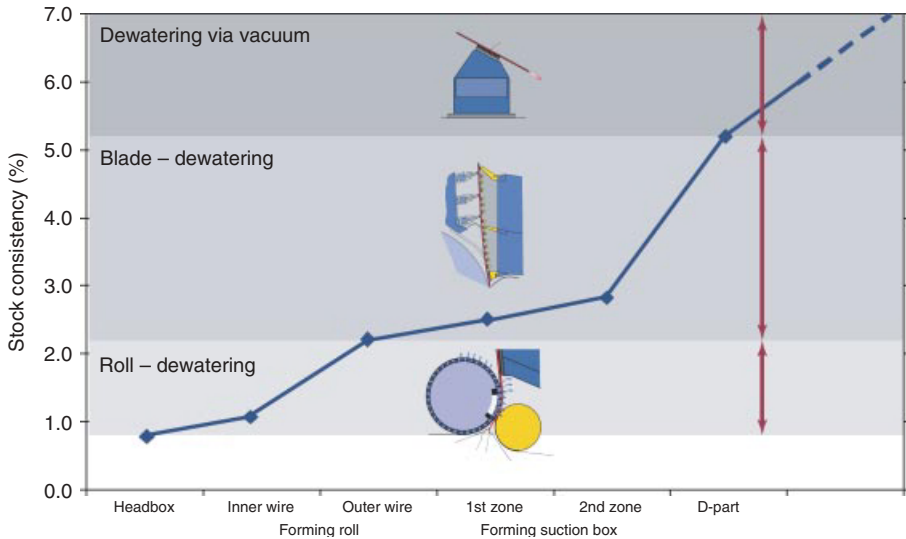


Figure 14.13 Example for dryness increase in a twin-wire former. (Source: Voith.)

14.6.3

Web Formation

The short-wave turbulence (microturbulence) generated in the suspension in the headbox to maintain fiber deflocculation dissipates rapidly. For this reason, a good formation requires the fiber web to be fixed very quickly, and/or additional turbulence has to be generated in the suspension to be dewatered. This can be achieved by means of pressure and vacuum impulses from table rolls, foils, and blades. However, impulses that are too strong are harmful, for example, by table rolls at machine speeds above approximately 500 m min^{-1} . This may also occur by foils with too high a foil angle at elevated machine speeds. In special cases, on fourdrinier wires, formation is improved by agitating the wire.

In a twin-wire sheet-forming zone, where the web is fixed between two wires, no free suspension surface exists and higher pulses can be applied. A prerequisite for a positive effect on sheet formation is that, between the already fixed outer layers of the web, there should be a core with low consistency still below the immobilization point. Here, pressure pulses can break down fiber flocs. For the best possible formation levels, flexible, loaded ceramic blades are used to control the intensity of the pulses. Figure 14.14 shows examples of good and poor formation quality.

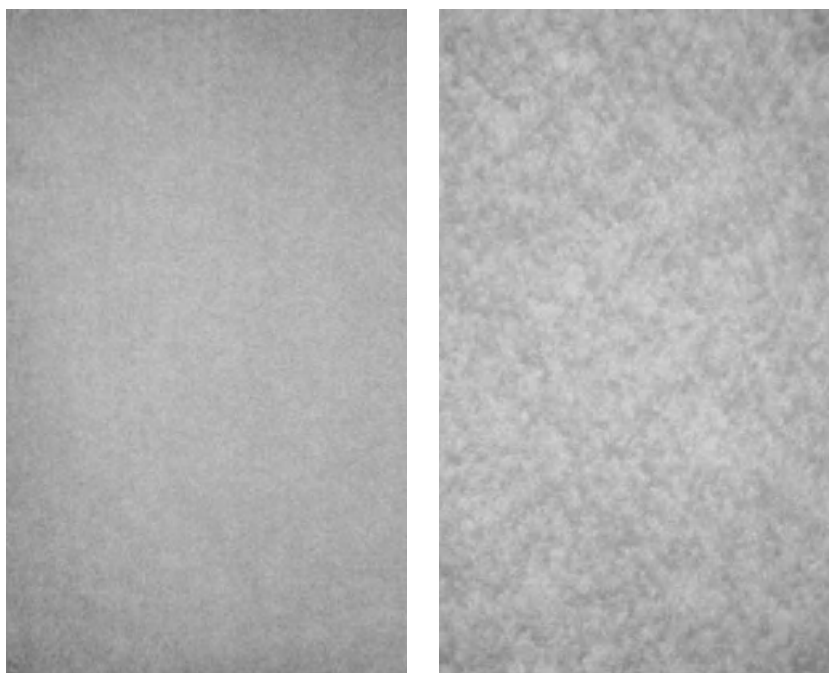


Figure 14.14 Examples for good and poor formation quality. (Source: Voith.)

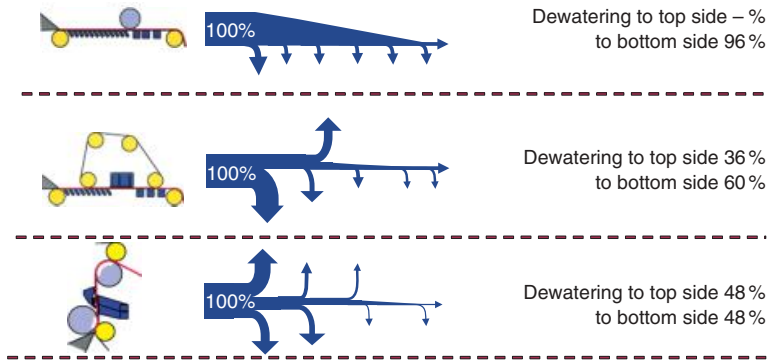


Figure 14.15 Dewatering distribution in different forming principles. (Source: Voith.)

14.6.4

Web Symmetry in Fines and Filler Distribution

For single-sided drainage on a fourdrinier wire, the symmetry control of the web is limited. All drainage flow goes to one side of the sheet. Only the local intensity of drainage can be influenced; however, again this is limited at least until the water line is reached and the free suspension on the surface is gone. As a result, a fourdrinier wire always produces a pronounced two-sided sheet with a higher sheet compaction at the bottom and an enrichment of fines and filler at the top.

In contrast, two-sided drainage produces a more symmetrical paper. The symmetry can be improved to a certain extent by hybrid formers, as they partly dewater to the top side. The best symmetry potential is given by a twin-wire gap forming section with a two-sided drainage right from the beginning (Figure 14.15). The large drainage flows at the beginning of the wire section contribute to a rather symmetrical drainage and compaction of the first built-up web layers at the top and bottom sides. With the following suction elements, the drainage flow and, consequently, the compaction of both sides of the web can be controlled. The level of pressure pulses applied in this stage also determines to what extent fines and fillers are washed out from the middle of the sheet and, consequently, can reach the top and bottom layers and be retained there.

Figure 14.16 shows the filler distribution in the z -direction (across web thickness) for dewatering the stock to only one side and symmetrically to both sides.

14.6.5

Fiber Orientation Anisotropy in the Web

The velocity difference between the jet and the wire is decisive for the controlled deposition of the fibers on the wire [5–7]. If the jet and the wire have the same speed the fibers are deposited with random orientation. This may not be true when

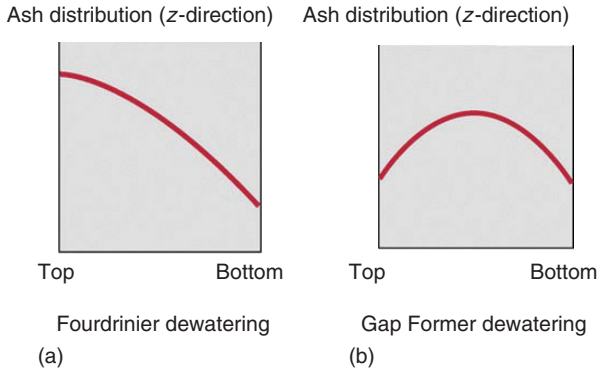


Figure 14.16 Filler distribution in the z-direction for (a) one- and (b) two-sided dewatering. (Source: Voith.)

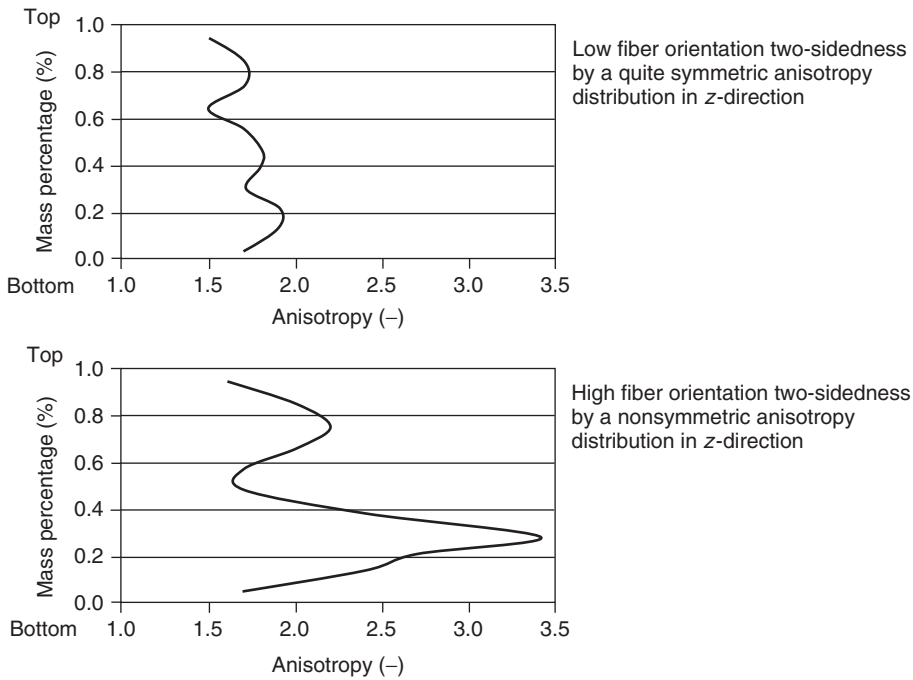


Figure 14.17 Example of decent and poor symmetry in main fiber orientation of top and bottom layers. (Source: Voith.)

the fibers are already pre-oriented in the nozzle. If the jet is slower or faster than the wire, more fibers are aligned in the machine direction. The highest value for the tensile strength of paper is observed in the direction of the main fiber orientation. The relationship between the properties in the longitudinal and cross directions is often important in the processing and use of paper. So, depending on the paper

grade, the magnitude of orientation (anisotropy) is adjusted by setting the jet to wire velocity difference, which is typically in the range between 0 and 80 m min⁻¹.

If the jet from the headbox is not directed exactly in the machine direction, this angular deflection is magnified on the wire many times over (Chapter 13). The main fiber orientation is then no longer in the machine direction, which can lead to diagonal sheet stress and problems with the final paper quality when used.

Variations in the magnitude of fiber orientation also exist in the z-direction of the sheet. Part of that is delivered with the jet, which has already some extent of orientation and a certain velocity and fiber orientation profile in the z-direction. In interaction with the wire surfaces, variations of the anisotropy in the z-direction are created. Furthermore, in twin-wire forming, small speed differences between the wires may occur, contributing to variations of fiber orientation in the z-direction as well. For copy papers, the layered orientation is of high importance. If there is a strong difference in the layer orientation between the top side and bottom side of the sheet (z-direction), a CD curl after the photocopy process can be expected. Thanks to advanced headbox designs and gap former operations, such defects can be avoided. Figure 14.17 shows a decent and a poor example of layered orientation of a copy paper.

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15

Press Section

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15.1

Introduction

15.1.1

Overview

The purpose of the press section is to increase the dry content of the paper web by compression. This kind of mechanical dewatering reduces steam consumption in the dryer section and increases the strength of the web in order to avoid web breaks during the transfer of the paper web to the dryer section and during the drying process. Mechanical compression in the press section significantly affects the paper structure and surface properties. Sheet densification influences porosity, caliper, bulk, and internal bonding strength. The water penetrating the outer layers and the densified web surface carries fines and fillers, which affects oil and water absorption of the product. The impression of the felt(s) results in a certain surface topography that is measured in terms of roughness.

Figure 15.1 compares the water removal parameters, such as dryness after the different sections or their proportion of the total dewatering amount, in the wire, press, and dryer sections. The total energy consumption in the press section is approximately three times higher than that in the forming section, whereas in the drying section, this is approximately 20 times higher. The proportion of energy consumption (electrical-to-heat/steam energy) indicates the large differences between the sections in this respect.

15.1.2

Operating Principles Governing the Press Section

The wet paper web is picked up from the wire section and transported by felts or press belts through the press section, which contains one or more press nips to be passed. The so-called press nip is formed between two opposing rolls pressed together or between a press roll and a counteraction roll with shoe and a sleeve,




	Forming (%)	Pressing (%)	Drying (%)
Dryness after press (%)	16–22	40–55	90–96
Proportion of the total dewatering amount (%)	94	5	1
Normalized energy input	1	3	20
Proportion electrical energy Proportion steam energy			

Figure 15.1 Comparison of the press section with the forming and drying sections concerning final dryness, water removal, and energy consumption. (Source: Voith.)

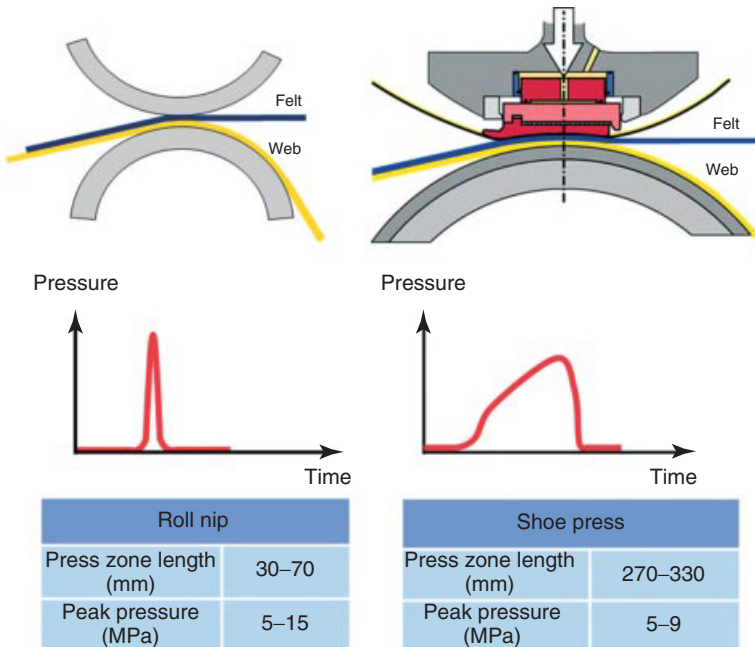


Figure 15.2 Nips formed by two opposing press rolls (short nip with a high peak pressure) or a press roll and a roll with a shoe and a sleeve (long nip with a low peak pressure). (Source: Voith.)

allowing a long nip (Figure 15.2). Hence, the pressure curve and the dwell time are quite different.

At present, the paper web is usually transported – and supported at the same time – either on one press fabric in the top or bottom position or between two press fabrics as a sandwich. This so-called “closed draw” transfers the web with the support of at least one fabric. In some cases, when the paper web is strong enough

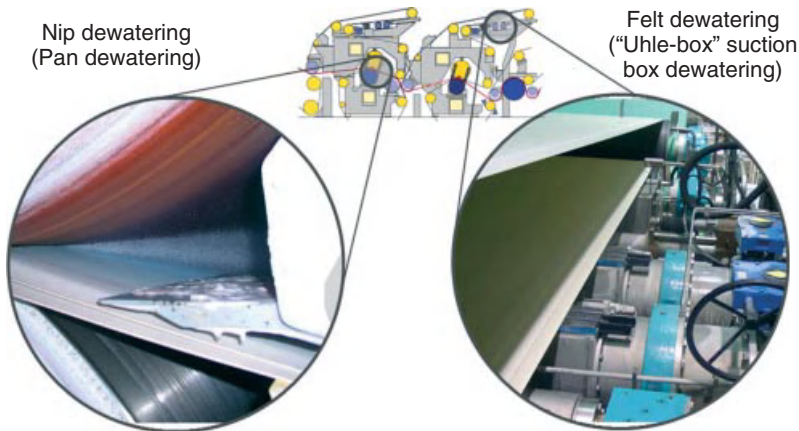


Figure 15.3 Nip dewatering with water spray into the catch pan and felt dewatering into the suction boxes. (Source: Voith.)

compared with the applied stress in operation, the web can be transported toward the next press nip or to the dryer section without any felt support (“open draw”).

The water removed from the web can be stored and carried away in the felt and removed by suction boxes (“Uhle boxes”), a process known as *felt dewatering* or *suction box dewatering*. In the case of fast paper machines or high water extraction, the felts carry an almost constant water freight (saturated) throughout its loop run, and web dewatering takes place through the felt. The water is stored in the void volume in the press rolls behind the felt. At the nip exit, the water sprays off and is caught in pans (save-all pans). This dewatering is known as *nip dewatering* or *pan dewatering*. The proportion of pan dewatering increases with increase in machine speed, when the felts have low void volume, and when the press-roll cover or the press sleeve has a grooved surface. In some press designs, suction press rolls are also used for the storage and transportation of water. In Figure 15.3, both dewatering principles are shown.

15.2

Theoretical Aspects of Press Dewatering

15.2.1

Hydraulic Pressure and Fiber Structure Resistance

Generally, the applied nip pressure must first overcome the fiber structure resistance of the web before it can generate the hydraulic pressure required for web dewatering. Fiber structure resistance at the beginning is low and increases with higher dry content; this is shown in Figure 15.4 for static conditions.

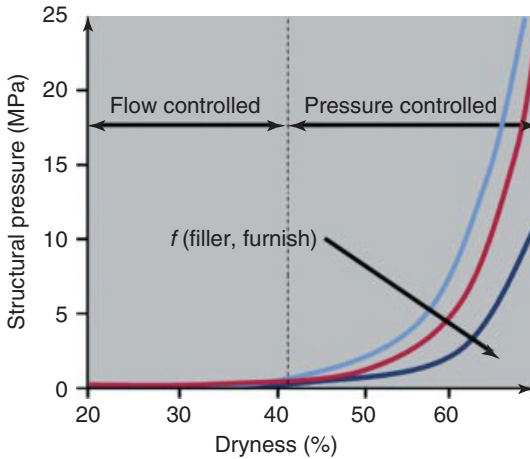


Figure 15.4 Fiber structure resistance as a function of web dryness under static loading conditions for different furnishes. (Modified after Ref. [1].)

In the “flow-controlled” range, dewatering is limited by the flow resistance of the fiber structure. A longer dwell time and gentle pressure gradients yield improved dewatering. This behavior is more pronounced with strongly beaten fibers, woodfree and recycled fibers, or high filler content (direction of arrow in Figure 15.4).

In the “pressure-controlled” range, the fiber structure itself counteracts further densification. When open pore volume in the sheet cannot be further compressed, no hydraulic pressure gradient can be built up for water extraction. A nip in the “pressure-controlled” range should feature high peak pressure and a high line load for best dewatering performance. Wood-containing furnishes, for example, thermomechanical pulp (TMP), exhibit typical “pressure-controlled” behavior [1–3].

At higher basis weights, the water flow from the noncompressed inner layers of the web is restricted by the already densified outer (interface) layers of the web. In the literature, this is described as a third type of dewatering behavior called *interface controlled* dewatering [4].

In press sections with several nips, the nip pressure has to be increased from nip to nip, corresponding to the decreasing water content and increasing web structure resistance. However, when the hydraulic pressure is too high, the paper web may be damaged (crushing), especially at higher moisture content. This is most relevant for press sections with several roll press nips with their typical high peak pressure and short dwell time. In shoe press applications, the nip is long enough to gently build up the nip pressure with enough dwell time.

The higher the hydraulic pressure and the longer the time of action, the better is the dewatering performance. Both the factors result in the “press impulse” (Figure 15.5). *Press impulse* is defined as the area under the time–pressure curve, respectively, the applied line load related to the speed. It is a good means to evaluate

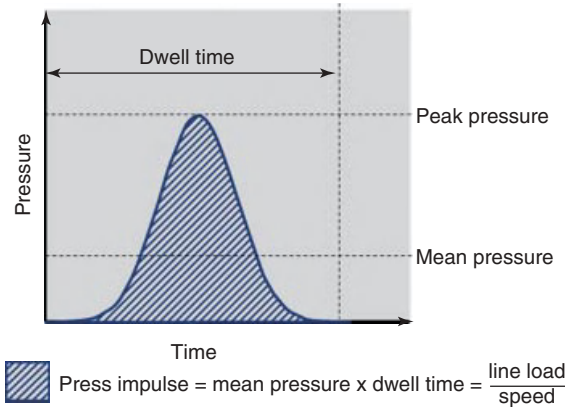


Figure 15.5 Time–pressure curve for a press nip-defining press impulse. (Source: Voith.)

the dewatering potential of different press nip designs and operating conditions. Of course, the validity of the press impulse is limited to operating conditions usually found in practice. For example, at very high press impulses, a further increase of press impulse shows only little increase in dryness after press.

The water flow resistance in the web is determined by the type of stock, the fiber treatment, and the amount of fines and fillers. Increasing the web temperature by steam boxes (or heated press rolls or infrared (IR) heating) increases the dewatering effect by lowering the water viscosity and the structural strength of the web. As a rule of thumb, an increase in temperature of 10 °C results in approximately 1% higher dryness of the web.

15.2.2

The Four Phases during Dewatering in the Nip

In Figure 15.6, the principle of dewatering in a press nip is shown by defining four phases [2, 5].

- 1) **Densification:** Felt and web enter the press nip. Before a hydraulic pressure for dewatering can be established, the structural resistance of web and felt must first be overcome. The contact between the web and the felt is intensified and air is squeezed out of the felt and the web. In the first phase, the hydraulic pressure is marginal.
- 2) **Saturation and dewatering:** With further compression, the saturation of the web is reached and a hydraulic pressure starts to build up. The pressure gradient triggers the dewatering flow from the web into the felt. In the case of nip dewatering, the felt is also saturated, building up a hydraulic pressure, and thus creating a water flow through the felt toward the void volume of the roll or sleeve surface. The flow velocity depends on the pressure gradient, the permeability of the web and the felt, and the water viscosity, following Darcy's law, which is explained in Figure 15.7. After having reached its peak,

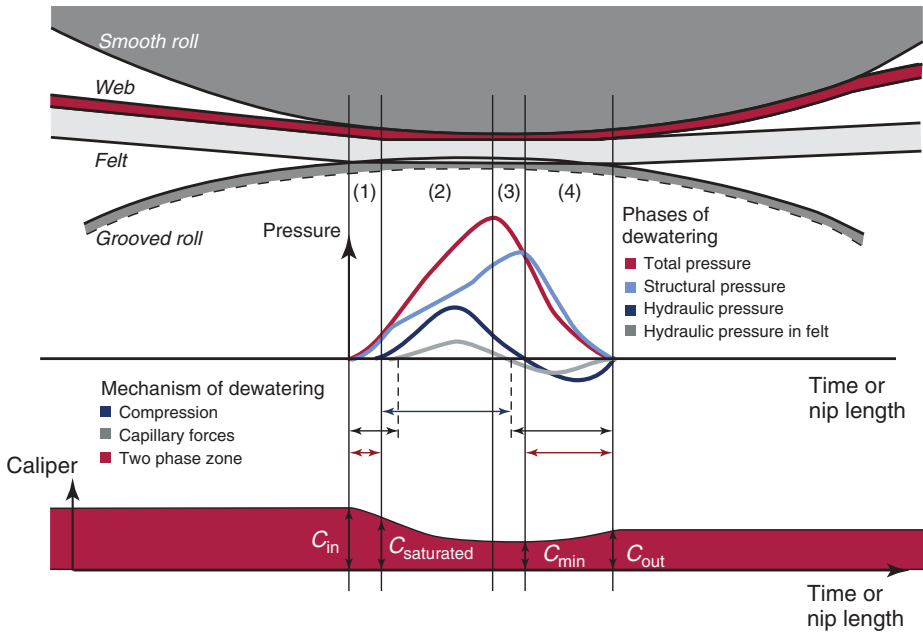
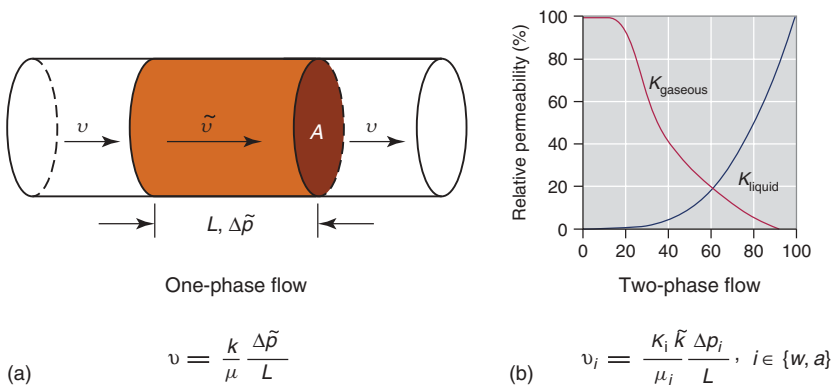


Figure 15.6 Phases during dewatering in a press nip. (Modified after Refs. [2, 5].)



(a)
$$v = \frac{k}{\mu} \frac{\Delta\tilde{p}}{L}$$

(b)
$$v_i = \frac{K_i \tilde{k} \Delta p_i}{\mu_i L}, \quad i \in \{w, a\}$$

With flow velocity v , permeability k , relative permeability K , viscosity of the liquid μ , and pressure gradient $\Delta\tilde{p}/\Delta L$.

Figure 15.7 Darcy's law for (a) one phase (water) and two phases (air and water) [modified, after 7].

the hydraulic pressure decreases and the structural pressure increases while dewatering goes on.

- 3) **Maximum total pressure:** After reaching the maximum total pressure in the middle of the roll press nip or at the peak pressure zone in a shoe nip, the hydraulic pressure further decreases rapidly until the end of this phase. Owing to the equilibrium with the total pressure, the structural pressure further increases until the hydraulic pressure is zero. The structural pressure now equals the total pressure and reaches its maximum. Here, the theoretical maximum dryness of the web is reached. With decreasing total pressure, the felt starts to expand, creating an underpressure in this phase.
- 4) **Expansion:** Once the maximum structural pressure is reached, the web starts to expand and an underpressure in the web is built up. Owing to the still existing intense contact between the web and the felt, the web reabsorbs water through capillary pores (“internal rewetting”) [6].

15.2.3

Influence of Furnish Type on Dewatering

Besides the press design, the available linear loads, machine speed (press impulse), and basis weight, the dry content after the press section is also significantly ruled by the furnish and its treatment in the stock preparation. A furnish characteristic used to describe the efficiency of water removal in the press section is the water retention value (WRV). The WRV gives the moisture ratio of a furnish sample after centrifuging it under defined centrifugal force and time. The two most frequently used methods are the TAPPI Useful Method UM 256 and the Zellcheming Merkblatt IV/33/57 [8]. The dry content after centrifuging is called “*limiting dry content*.” It allows a rough estimation of the maximum dry content (%) for modern press sections. As a rule of thumb, the same maximum dry content as obtained by the Zellcheming test can be achieved with roll presses. For shoe presses, a factor of 1.1 up to 1.2 can be applied to the measured limiting dry content.

Typically, never-dried pulps are significantly harder to dewater than market pulps or recovered furnishes. Figure 15.8 shows both WRV and dry content after centrifugation at different beating degrees for never-dried bleached eucalypt kraft pulp and the same pulp once dried. For the same beating degree, the never-dried pulp has 18–25% higher WRV and 2.5–4.5% lower limiting dry content.

Modern measuring and evaluation techniques allow to record the development of the dry content over time in a press nip and thus characterize a furnish [9, 10]. Pressing parameters such as pressure profile, temperature, dwell time, or basis weight can be varied within a wide range. For better comparability, the dry content is plotted against the press impulse (Figure 15.9). During the early phase of press dewatering, most furnishes show a flow-controlled behavior, and for a given press impulse, better dryness is achieved with low pressure and long dwell time. Chemical pulps typically afford long dwell time at moderate pressure, whereas wood-containing furnishes such as pressurized groundwood (PGW) require high

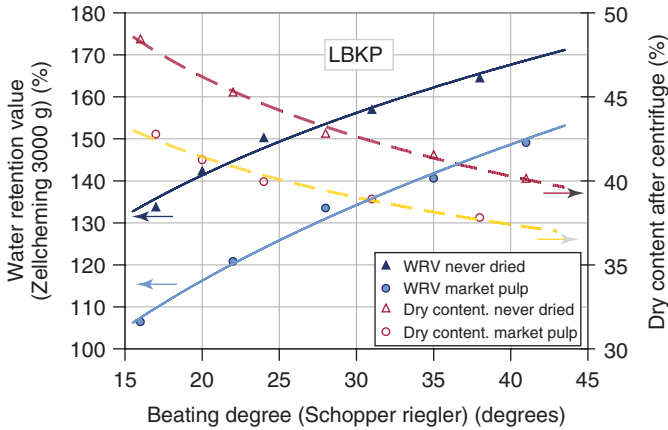


Figure 15.8 Influence of the water retention value (WRV) on dry content after press section of dried and never-dried leaf-bleached kraft pulp (LBKP).¹

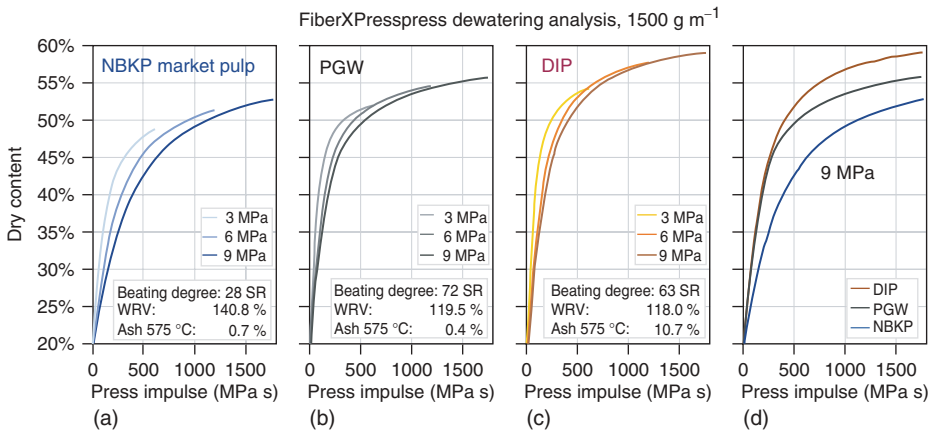


Figure 15.9 Behavior of press dewatering for (a) northern bleached kraft pulp (NBKP), (b) pressurized groundwood (PGW), (c) deinked pulp (DIP), (d) comparison at 9 MPa; results obtained by FiberXPress [9, 10].

pressure. Under the same conditions, deinked pulp (DIP) has a higher dryness potential than a pressure-limited PGW or a softwood kraft pulp.

15.2.4

Rewetting

Besides the “internal rewetting” (Section 15.2.2), external rewetting (“contact rewetting” and “separation rewetting”) can also be defined [11], as shown in Figure 15.10.

“Separation rewetting” takes place when the water film between web and felt is split and part of the water stays at the web surface. The water film is expelled

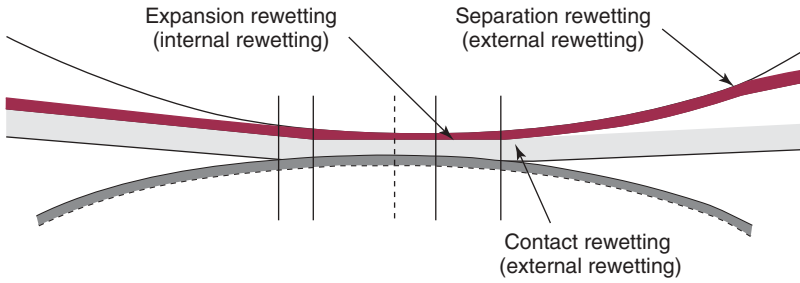


Figure 15.10 Rewetting in the press section. (Source: Voith.)

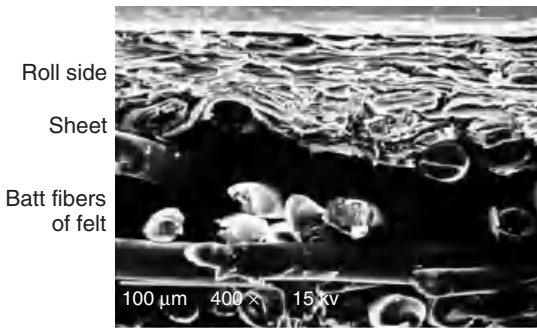


Figure 15.11 Scanning electron microscope (SEM) image of the contact of the web with a press felt in a single-felted nip.¹

water that stayed in the cavities created because of the nonuniform contact between the surface batt fibers of the felt and the web [6, 12, 13]. A closer look at this situation is shown in Figures 15.11 and 15.12. Sometimes “separation rewetting” is not regarded as real rewetting because the pressed-out water is still associated with the web [14]. “Separation rewetting” is sometimes distinguished from “film splitting” too. The latter includes a gaseous phase, when, during separation, an underpressure at the level of vapor pressure is created [6, 15].

During “contact rewetting,” water is absorbed by the web because of capillary suction, as paper is more hydrophilic and has smaller pores than felts, resulting in a higher affinity to water [16]. Additional external rewetting takes place because of web-guiding elements, where the vacuum intensifies again the contact between felts and the web (Figure 15.13) or by water sprays.

Rewetting influences the contact time of the web with the wet press felt and the web basis weight. Higher basis weights are less sensitive to overall rewetting because the ratio of surface to mass is smaller and the elastic expansion is smaller compared to light basis weights. Also, the various furnishes show different behaviors of rewetting because expansion is different depending on whether a more plastic (woodfree furnish) or a more elastic deformation (wood-containing furnish) occurs

1) Beloit, SEM picture.

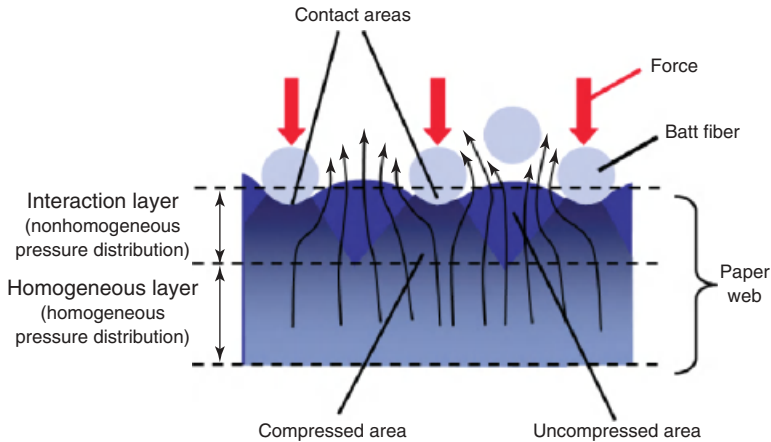


Figure 15.12 Layers with nonhomogeneous and homogeneous pressure distributions in the web due to nonuniformity of the contact of the felt surface batt fibers with the web. (Source: Modified after Refs. [12, 13].)

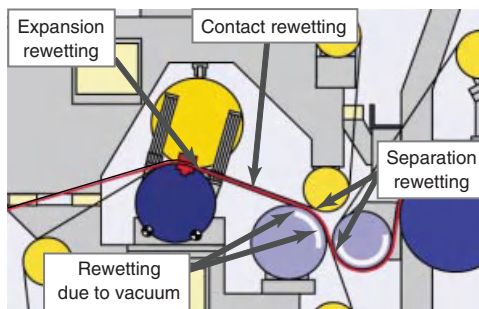


Figure 15.13 Rewetting of the web in a double-felted press at web-guiding elements. (Source: Voith.)

(Figure 15.14). The additional parameters are temperature, dryness, and permeability of the web, as well as fiber coarseness and moisture content of the felts [13, 16].

15.2.5

Crushing

To intensify dewatering in the press nip, the press load cannot be increased in any order. Especially, in the first nip, the water content of the web is high, and this could lead to crushing. Crushing is described as visible cracks on the surface due to slippage of inner layers of the web. As the hydraulic pressure also causes water flow in the direction of the paper, shear forces are created between the inner layers of the web (where the hydraulic pressure is high) and the outer layers of the web (where the hydraulic pressure is zero). If the hydraulic pressure is too high, it can create shear forces exceeding the paper shear strength. The inner layers start to slip,

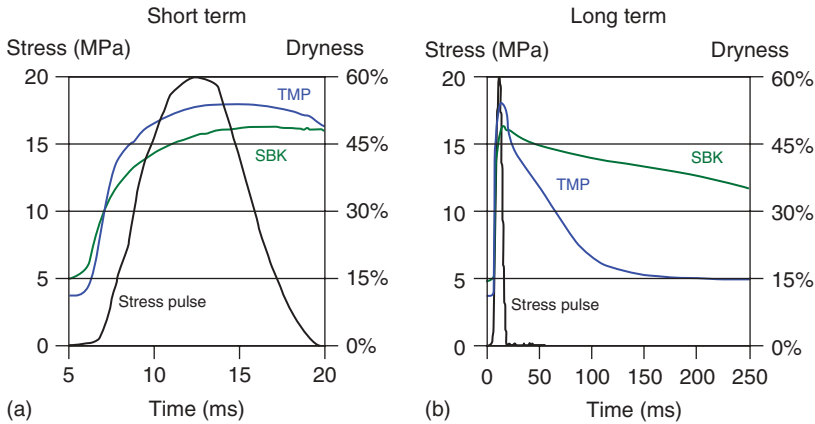


Figure 15.14 Compression, expansion, and rewetting (short- and long-term behaviors) of saturated fiber webs of thermomechanical pulp (TMP) and softwood bleached kraft (SBK) pulp after a press pulse in a lab press [13].

and cracks between the layers arise and propagate to the surface. The important parameters are dryness and furnish type, which are related to the shear strength of the web, the pressure maximum, and the pressure gradient in the nip, as well as the dynamic permeability of web and felt [17].

15.3

State-of-the-Art Press Sections

15.3.1

Press Designs with Roll Press Nips

A conventional press section usually consists of three or four successive press nips (Figure 15.15). The rolls are pressed against each other with linear forces of $20\text{--}150\text{ kN m}^{-1}$ and up to more than 300 kN m^{-1} in some special designs. For conventional press rolls, the magnitudes of the resulting pressure and nip length mainly depend on the diameter of the roll, the elastic characteristics of the material, and the geometry of the shell and of the cover (steel or bronze, rubber or polymer, and ceramic coating; plain, grooved, or drilled), as well as the felts. For high basis weights, the viscoelastic properties of the paper web are also important.

To avoid crushing in the first nip, for example, in board machines, suction press rolls are used (Figure 15.16). Their further benefits are a reduction of rewetting at the nip exit (e.g., in tri-nip presses with double-suction press rolls) and their use as web-guiding element for good runnability when applied in the first nip in straight-through presses and in center roll press designs. Suction press rolls are expensive concerning both investment and operating costs. Their loading has

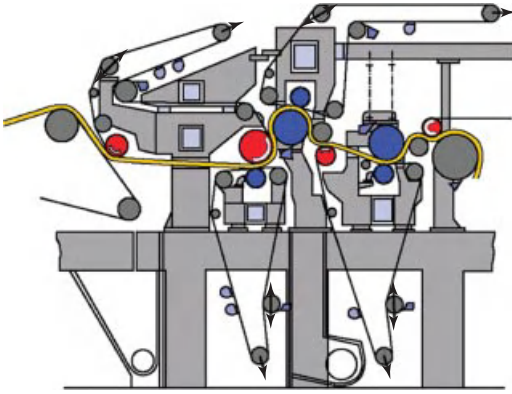


Figure 15.15 Conventional four-nip press section with roll press nips. (Source: Voith.)

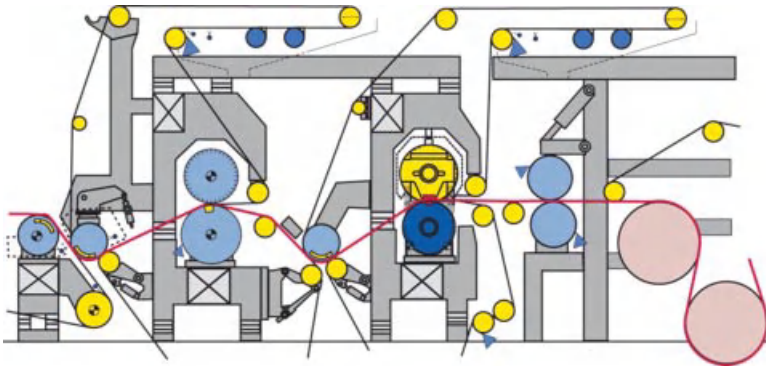


Figure 15.16 Press section for board grades with a double-felted suction press roll in the first nip. (Source: Voith.)

to be limited as the shell is weakened by the drilling pattern and the corrosive atmosphere during operation [18].

15.3.2

Press Designs with Shoe Presses

15.3.2.1 The Shoe Press

The time during which the pressure acts on the web can be prolonged about 10-fold compared to conventional presses by using shoe presses. In this press type, a concave shoe presses a flexible revolving plastic sleeve or belt against the counteracting press roll (Figure 15.17).

The shoe works on the hydrostatic/hydrodynamic lubrication principle. The increase in pressure along the press nip is by far not as steep as in conventional press nips; the maximum nip pressure is lower than in comparable roll press positions (Figure 15.2). Furthermore, the shape of the pressure curve along the

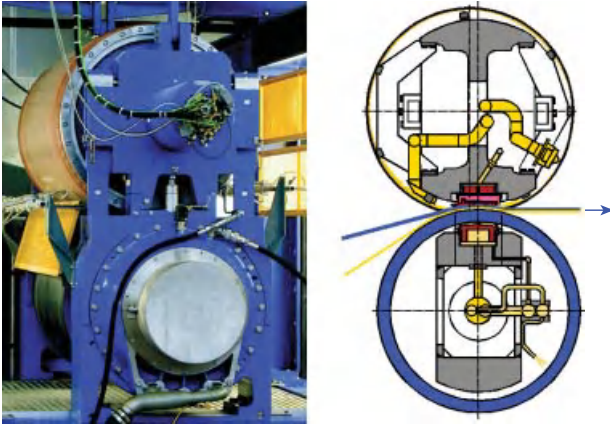


Figure 15.17 Example of a shoe press consisting of a top roll with a sleeve and concave shoe and a bottom roll with an iron shell supported by hydrostatic bearings. (Source: Voith.)

press nip can be adjusted in a certain range to adapt to the dewatering behavior of different furnishes. For roll nips, the press zone length is about 30–70 mm and for shoe presses about 250–330 mm. The peak pressure is 5–15 MPa for the roll nip and 5–9 MPa for the shoe press nip.

15.3.2.2 Press Designs with Shoe Nips

Shoe presses have been standard in press sections for containerboards since the 1980s. Later, they also became state of the art in carton board and graphic paper machines. At present, modern straight-through press sections of high-speed paper machines consist of two shoe nips. They have, for instance, two double-felted nips or one double-felted nip followed by a second nip with a felt and a transfer belt (Figure 15.18). Classic tri- or four-nip center roll press designs often have the shoe press in the third nip (Figure 15.19).

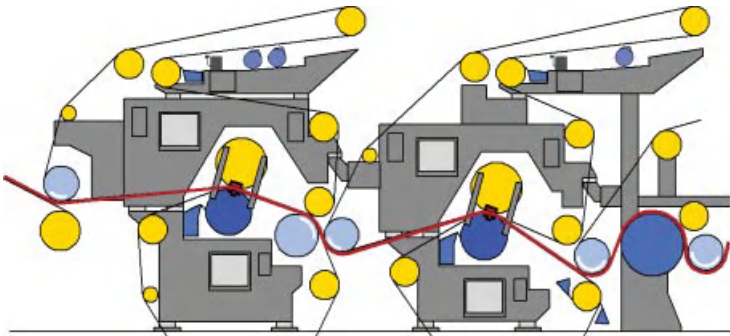


Figure 15.18 State-of-the-art press section with a double-felted first press nip and a second nip with felt and transfer belt. (Source: Voith.)

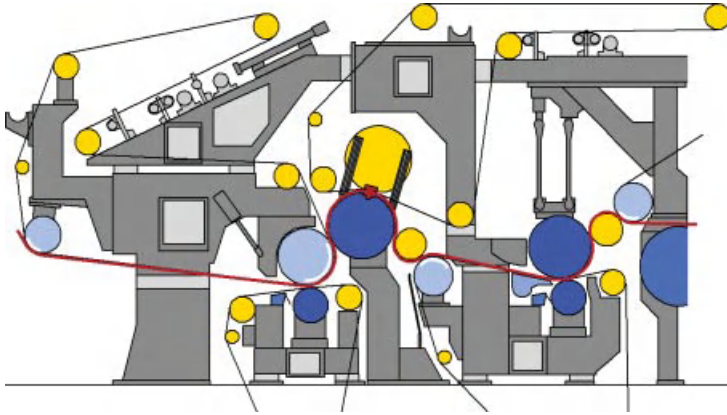


Figure 15.19 Four-nip press section with a shoe press in the third nip. (Source: Voith.)

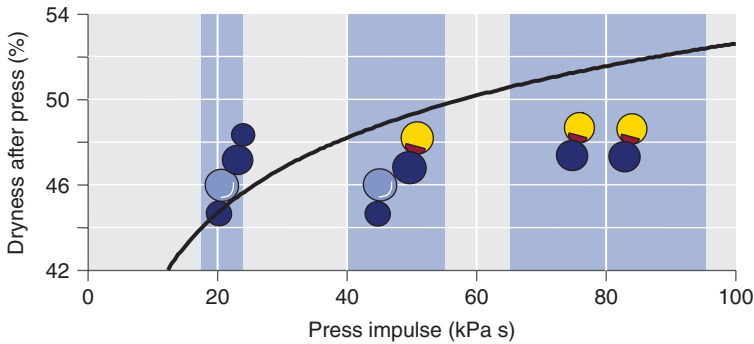


Figure 15.20 Increasing press impulse and dryness after press in different press designs. (Source: Voith.)

The double shoe press configuration operates at line loads of up to 1300 kN m^{-1} . There have been some cases of shoe press installations with line loads up to 2000 kN m^{-1} . A steam box ahead of the second press nip for enhanced dewatering effect and cross-machine direction (CD) moisture control is optional. The sandwich felt–paper–felt in the press nip assists symmetrical dewatering, providing good z-direction symmetry of the sheet. A press design with two single-felted nips is mainly applied for specialty paper production. With the introduction of the shoe presses, various press designs were developed so that press impulse and resulting final dryness could be significantly increased compared to the roll press designs, as is demonstrated in Figure 15.20.

15.3.2.3 Single-Nip Shoe Press

A prominent press design for graphical paper is a single-nip press section, where the web is dewatered in just one nip (Figure 15.21). With a shoe of length more than 300 mm, a dryness of about 54% is reached in woodfree paper production at

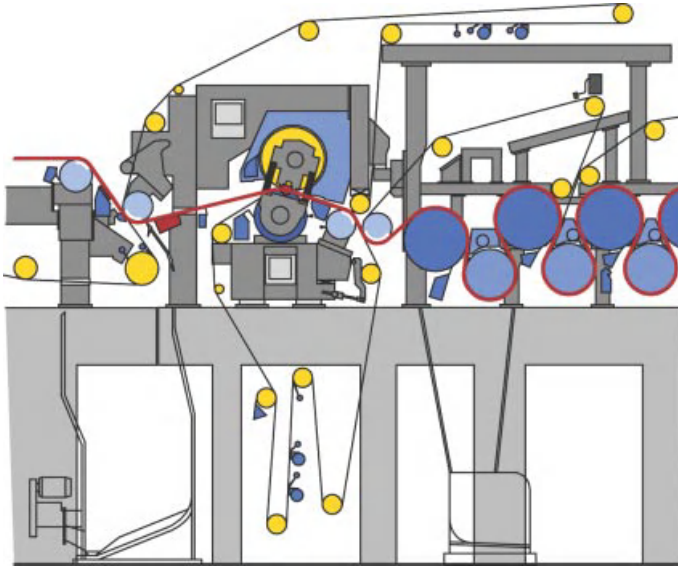


Figure 15.21 Single-nip shoe press section with a double-felted nip. (Source: Voith.)

more than 1500 m min^{-1} . This results from the high dewatering capacity of the only nip and low rewetting.

In this design, the number of components is reduced to a minimum; thus the maintenance is quick, resulting in minimal downtime. Investment and operating costs are lower. With low space requirements, the single-nip shoe press is especially suitable for rebuilds.

But using just one nip means also a balancing act in a narrow operation window given by a lower densification potential, intense imprints of two felts with issues concerning paper surface quality, and the demanded dryness. It is also more sensitive to fluctuations in the wet end or forming section. The single-nip design features a higher exposure of the fabrics and the web run is more critical because the web adhesion varies from 20% to more than 50% dryness, covered by just one nip with its fabrics. Hence, fabric design, roll cover, and press design have to be finely adjusted.

The single press with just one felt is a suitable press design for very light basis weights. For lightweight packaging grades, the single felt in top position is able to handle the complete water removal. In the bottom position, an impermeable transfer belt is installed, minimizing rewetting and offering a safe web run. The basis weight ranges from 30 to 90 g m^{-2} at 600 m min^{-1} , after the shoe nip reaches a dryness of 45%. After it has passed through the press section, the web is transferred to an MG cylinder (Figure 15.22).

Shoe presses are also used in tissue production. Here, the advantages are higher bulk and sheet dryness after the press. In this application, the shoe press replaces the suction press roll of the conventional machine acting against the Yankee dryer.

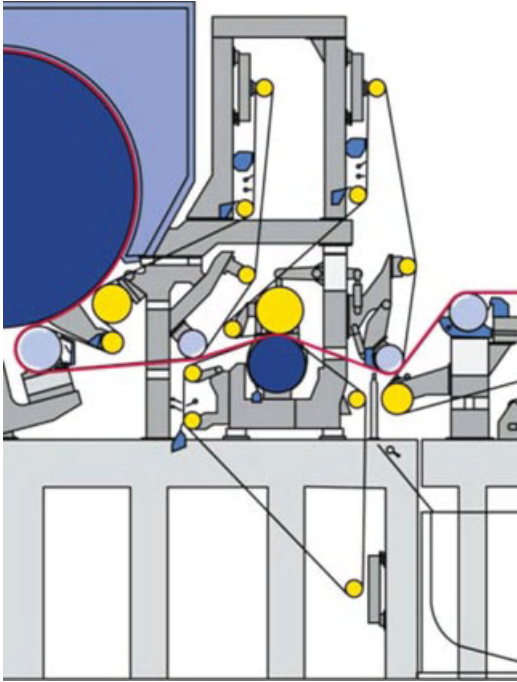


Figure 15.22 Single-nip shoe press section with a single-felted nip for packaging paper. (Source: Voith.)

With its flexible shoe, the CD moisture profile can also be controlled within a certain range (Section 20.4).

15.4 Historical Review

The long journey from the straight-through press with woven wool felts and open draws to the one-nip press was completed in a number of steps [18]. Some of these are described in the following.

Safe web transfer from the wire to the press section was supported by the introduction of the couch roll (Millspaugh patent, 1908) and vacuum pickup (1937). The nip control roll principle (since the 1960s) enables uncrowned press rolls and is especially important for wide machines. It also allows a smaller roll diameter at large machine widths. This results in a higher maximum pressure in the press nip if required. The self-loading press roll (Nipco Roll F) allows simplified press configurations as it does not need any outside loading devices (1975). The shoe press with a long press nip provides further increased dryness after the press section (1983). The two-nip shoe press with safe web transfer for high machine speeds was

introduced toward the end of the 1990s, and the one-nip press with high dewatering capacity in the 2000s. In 2002, three-nip straight-through presses with closed draw transfer and high paper quality (similar to center roll designs but with higher speeds) came to the market. Since 2005, machines with wire widths exceeding 10 000 mm with double shoe press configuration have been in operation, and since 2007, several newsprint machines with double shoe press configuration report production speed records above 2000 m min^{-1} . By 2012, the first board machine may exceed a production of 4.000 t day^{-1} with a triple-shoe press section at 1400 m min^{-1} .

By 1909, the synthetic caoutchouc had been invented, replacing the pure rubber application. In the 1980s, polyurethane covers were introduced. The improved materials allowed high nip load and drilling and grooving of the cover at the same time. In the early 1990s, ceramic-covered steel rolls replaced the granite rolls, which are sensitive to temperature differences and centrifugal forces (due to higher speeds), and are also limited in size. Since 2003, press rolls with wound profile metal wire on cast shells were introduced, allowing higher void volume with more delicate design (deeper and smaller groove width) and higher lifetime. Owing to the progress in material development, shoe press belts achieved running times of one year even in fast paper machines.

The change from woven wool felts to synthetic needled felts began in the 1960s. With the new technique, the felts could be designed much better to suit special purposes, for example, as regards their position in the press. The development of nonwoven press fabrics was introduced for fast-running paper machines, providing faster start-up time and higher nip dewatering, and yielding higher dryness. Transfer belts were developed toward the end of the last century to safely transfer the web from the last press nip to the dryer section. Semipermeable belts were developed for special application cases, where a good runnability and the low rewetting of a transfer belt as well as a certain densification of the web are demanded. Surface-treated press fabrics (since 2000), the first sublayers being covered with polymers, provide a more even and an increased contact with the web, resulting in better base paper smoothness, higher web dryness, and reduced rewetting.

The dryness of the web after the press section increased from about 33% (2 kg water/kg fibers) in the straight-through press to about 40% (1.5 kg water/kg fiber) in the compact press designs, and finally to about 50% and more with the shoe press (less than 1 kg water/kg fibers). This higher dry content was achieved in spite of a tremendous machine speed increase in the last 100 years, for example, for newsprint from about 300 m min^{-1} to more than 2000 m min^{-1} .

15.5 Further Approaches in Pressing

In the recent past, further approaches in wet pressing have been developed such as high-intensity pressing (“hot pressing” and “impulse pressing”) or displacement dewatering by gas flow due to pressure or vacuum.

15.5.1

High-Intensity Pressing

With this press technology, dewatering in the press section is intensified by the use of additional intense heat transfer during mechanical pressing. The idea behind “hot pressing” and “superhot pressing” is to improve the dewatering effect by decreasing the viscosity due to the elevated temperature and thus reducing the flow resistance of water. A further benefit is the higher compressibility of the heated fiber network (Figure 15.23). The web temperature stays below 100°C and the system has two phases (without air) consisting of solid fibers and liquid water [19].

The “impulse pressing” technique uses higher temperatures; so, a three-phase system (without air) fiber–water–vapor is given. In addition to the use of the above-mentioned effects of the heat, steam-assisted water displacement is also used. The major problem of the impulse press technology is delamination of the web or, at the least, reduction of z -strength because of the spontaneous phase change of the hot water into vapor due to sudden pressure reduction at the press nip exit [19].

15.5.2

Displacement Dewatering

In conventional wet pressing, water is removed from the moist paper web only by mechanical compression. The sheet compression goes hand in hand with a consolidation of the fiber structure, which is to some extent undesirable. For a lot of tissue, paper, and board grades, the bulk is a critical property limiting the dewatering in the press section.

With displacement pressing, the development of dryness and bulk in mechanical dewatering can be decoupled to some extent. Displacement pressing applies an additional hydraulic pressure gradient between the two sides of the fiber web while mechanically pressing it. This differential pressure can be vacuum or pressurized gas or both [20, 21].

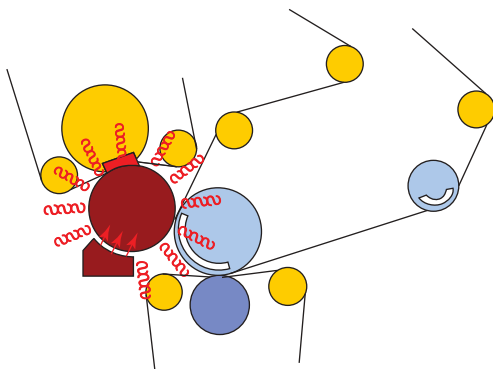


Figure 15.23 Schematic diagram of high-intensity pressing with a heated center roll. (Source: Voith.)

15.5.2.1 Displacement Dewatering by Pressure

In one configuration, four press rolls pressed together form a pressurized chamber. The bottom roll is vented to allow airflow; the smaller “cap rolls” and the top roll seal the chamber. The chamber is closed with the bigger roll on top and with a special set of press seals on both ends (Figure 15.24). The paper web passes the pressurized chamber sandwiched between a membrane on top and an “anti-rewet” layer beneath. The airflow through the only slightly permeable membrane causes a pressure difference and as a result, the membrane mechanically presses the paper web. The airflow displaces water out of the porous sheet structure and drives it into and through the anti-rewet fabric [22]. In spite of reduced rewetting and good bulk preservation, this design concept had to be abandoned because of sealing and energy disadvantages.

15.5.2.2 Displacement Dewatering by Vacuum

A process for displacement dewatering by vacuum was introduced in the market in 2006 for producing tissue paper with extra high volume while maintaining the high rate of mechanical dewatering [23, 24]. A permeable belt forms a long press nip, slightly compressing the sandwich of fabrics when it passes the vacuum zone and intensifying the dewatering by vacuum-induced airflow. Water removal is further enhanced by hot humid air, for example, exhausted from the impingement

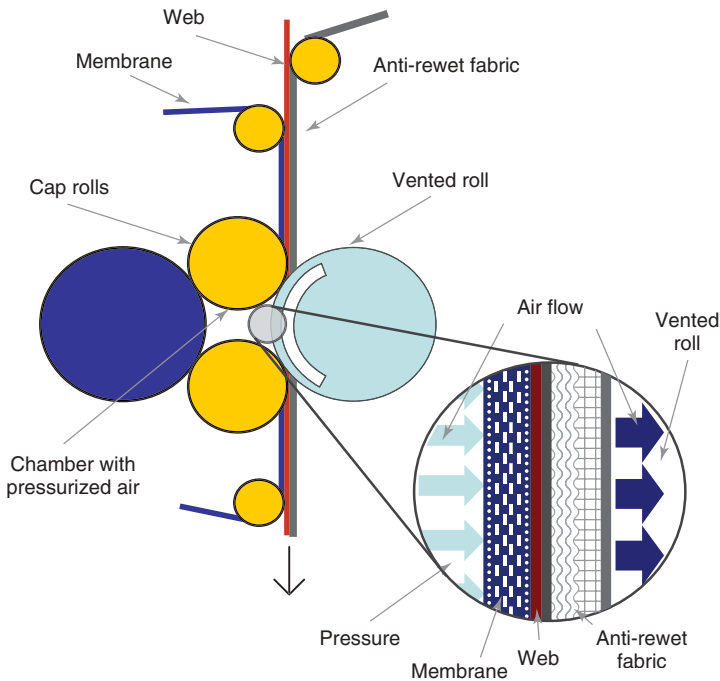


Figure 15.24 Schematic drawing of displacement dewatering with pressure application. (Source: Modified after Ref. [22].)

hood, reducing the water viscosity. Reported dry content achieved with this process is 35–42%, which is about equal to that achieved in conventional tissue machines (Section 20.4).

15.6

Operational and Technological Aspects

15.6.1

Dryness

Costs for removal of 1 kg of water in the dryer section are about 10 times higher than those in the press section. Furthermore, the strength of the paper web is increased, which helps avoid web breaks during production. When higher dryness is achieved with increased temperature, wet strength may remain about the same, as web strength is lower at higher temperature and same dry content. Higher dryness resulting from higher filler content does not increase the wet strength. With a 4% higher filler content, approximately 1% higher dryness is yielded. Also, applied chemical additives such as retention aids or starch have a significant effect on web dewatering behavior in the press section.

Typical dryness ranges obtained after press section for different paper and board grades for the different press designs are listed in Tables 15.1–15.3.

15.6.2

CD Moisture Profiles

A uniform moisture profile in the CD on the reel is very important for reasons of quality and economy. This requires a uniform nip pressure as well as a uniform dewatering effect of the felts in the CD. The preconditions for this are uniform felt design, structure, and conditioning. Correction press rolls are used to obtain uniform CD moisture profiles, and these can vary the line force selectively across the width; sectionalized steam boxes, and sometimes IR heaters, are also used, which heat the web to varying extents across the width (Chapters 16 and 23).

Table 15.1 Typical dryness after press section for different graphic paper grades.

Press design	Newsprint (100% DIP) (%)	LWC paper (60% DIP) (%)	Woodfree paper (%)	SC paper (%)
Single shoe nip	–	–	50 (53–55)	–
Double shoe nip (three felts/four felts)	50–52	50–52	50–53	55–58
Center roll press with roll presses	45–49	45–49	45–49	48–51
Center roll press with one-shoe nip	48–51	48–51	47–51	50–53

Source: Voith.

Table 15.2 Typical dryness after press section for containerboard and sack paper (usual figures are italicized).

Press concept	Testliner/ corrugating medium (%)	White top testliner (%)	Kraftliner (%)	Sack paper (%)
Double shoe nip with three felts	51–52–53	–	44–45, 100% Kraft (with 40% OCC: 48%)	–
Double shoe nip with four felts	52–53–54	–	100% Kraft: 44–45 (with 40% OCC: 48%)	–
Center roll press with three nips (one-shoe nip)	50–52	51–52	42–44 100% Kraft	40–41
Roll nip presses	44–46 with Jumbo – 48%	44–46 with Jumbo – 48%	38–40 100% Kraft	35–36

Source: Voith.

Table 15.3 Typical dryness after press section for carton board grades (usual figures are italicized).

Press concept	White line chipboard) (%)	Plaster board (100% AP) (%)	Folding box board (w' containing primary fibers) (%)	Carrier board (pulp primary fibers) (%)	Solid bleached sulfate (%)
Double shoe nip with three felts + offset press	–	49–51	45–46	42–43	45–46
Double shoe nip with four felts + offset press	50–53	50–53	46–48	43–45	46–48
Center roll press with three nips (one-shoe nip)	–	49–51	–	–	–
Roll nip presses	46–48	46–48	44–46	39–41–43%	39–44–46
Roll nip press + shoe press	48–52	48–52	45–47	42–44	45–47

Source: Voith.

15.6.3

Felts

Felts have to cover several functions in the press section. Besides dewatering, they must ensure a safe web transport from the forming section to the dryer section, and with their intense contact with the web, they contribute decisively to the surface quality. Depending on the position in the press, the felt design has to fulfill all these

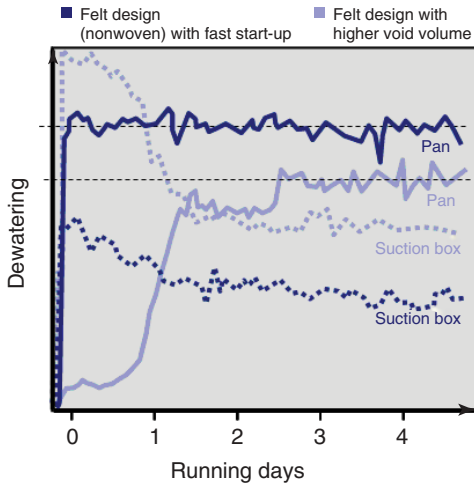


Figure 15.25 Start-up behavior of dewatering of different felt designs. (Source: Voith.)

requirements adequately, which are to some extent contradictory. For example, for a fast-running paper machine, a felt has to start with full pan dewatering right from the beginning; the machine should have a strong compact structure with low void volume to avoid the costly run-in phase of the felt that would result in lower productivity. Figure 15.25 illustrates the start-up phase of two different felt designs (felt with fast run-in and felt with higher void volume), each with its pan and Uhle box for dewatering. The demand for a fast run-in is contrary to the required maximized lifetime, a long constant running phase, and a not too dense felt at the end of its lifetime. Typical felt lifetime is four to six weeks, mainly depending on the press design, position of the felt, felt design, machine speed, furnish, and contaminants in the furnish.

To ensure the handling of high dewatering amounts, especially in the initial positions in the press, the felt design should feature an open structure with a high permeability. At the same time, for a high paper web surface smoothness and a high web densification, the felt batt layer (the top layer with contact with the web) should be fine and homogeneous to ensure maximum number of contact points. In a modern press felt, for example, the staple fiber diameter at the web-contacting felt surface goes down to $20\ \mu\text{m}$, which is even lower than the paper fiber thickness (about $30\text{--}40\ \mu\text{m}$). So, risk of felt marking is lower. Different types of felts are selected for the top or bottom positions in the individual nip as well as the different press nips, taking into account the press water flow, surface quality requirements, and the target of sheet transfer. Newly developed felts allow an operation without Uhle boxes (e.g., fast-running paper machines) even in the run-in phase. The advantages are lower felt wear and drive and vacuum energy consumption. Machines with lower production speeds usually use felts with high void volume. Here, the dewatering of the felts is performed with

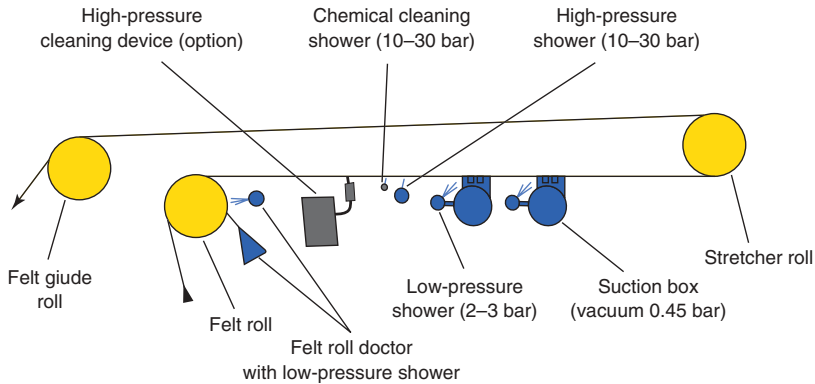


Figure 15.26 Felt conditioning in a felt loop. (Source: Voith.)

suction boxes after the nip, followed by conditioning (Figure 15.26). Continuous or intermittent treatment with a fine, high-pressure water jet and/or wetting facilities (felt conditioning) keeps the felt clean and maximizes its working life (Section 11.4).

15.6.4

Web Transfer and Guiding

A reliable web guidance system is important to prevent web breaks, especially at high machine speeds, low basis weights, and low dry contents of the web, as found after the first press nip. In modern paper machines, especially in the press section, the web is not conveyed freely, but is nearly always supported by a felt, belt, or wire or by the surface of a roll.

15.6.4.1 Web Transfer

15.6.4.1.1 Web Transfer in a Closed Draw Preferably at lower dryness, the web is fully supported in a closed draw at least with one press fabric. When the web is transferred in a closed draw to the next driven group, it is separated from the supporting fabric and directly picked up from the accepting fabric at the same time. Depending on the machine speed, the transfer is assisted by web-guiding elements such as suction rolls or suction boxes (Figure 15.27). Among the advantages of the closed web transfer are (automatic) threading with full web width and a more stable run, largely independent of external influences.

15.6.4.1.2 Web Transfer in an Open Draw Web transfer in an open draw often takes place where the web has to be released from direct contact with a smooth roll. In this case, the web is pulled off the roll and transferred without a support in an open draw to the next web-guiding element or fabric. The runnability is more sensitive to airflows and pressure differences between the sides of the web.

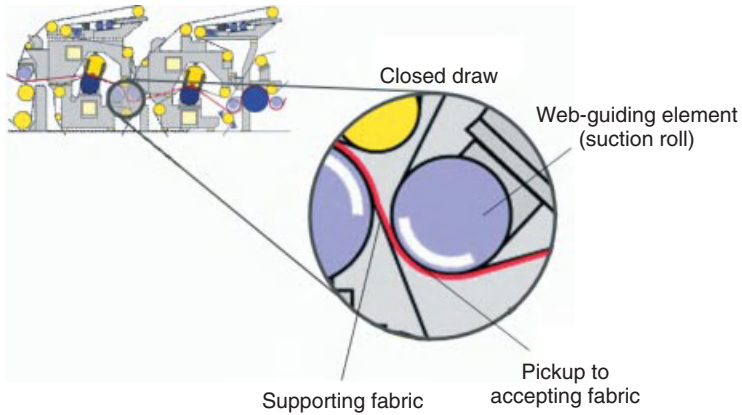


Figure 15.27 Details of a web transfer in closed draw of a modern double-nip shoe press. (Source: Voith.)

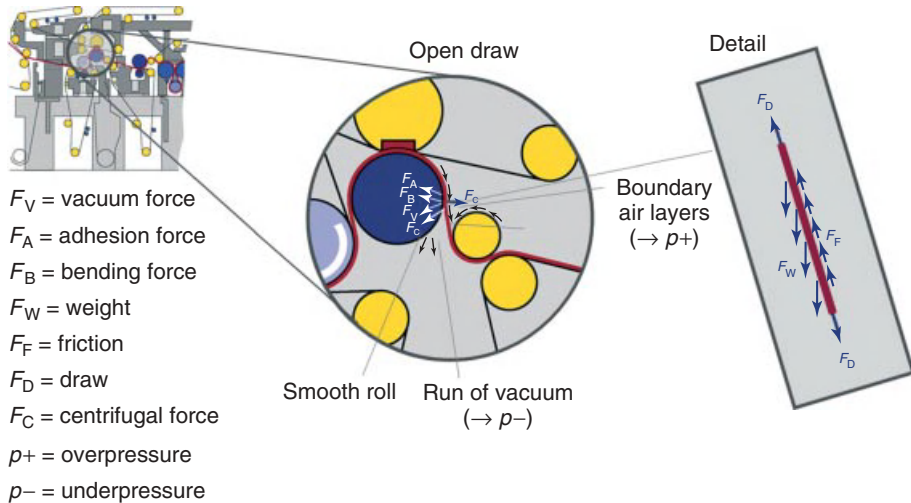


Figure 15.28 Forces on the web during transfer in an open draw of a modern center roll press nip. (Source: modified after Ref. [25].)

The complex situation of potential forces [25] is shown in Figure 15.28. In longer free draws, a so-called paper roll is introduced. This roll shortens the free draw and stabilizes the web run. A paper roll is operated at a differential speed to avoid deposit buildup on the surface.

15.6.4.1.3 Closed Web Transfer Sometimes, there is reference to a “draw-free” web transfer, which actually means a “closed transfer.” In either case (closed or open draw), a draw due to the speed difference between driven groups (also within different groups in the press section) is generated. It has to build up and maintain

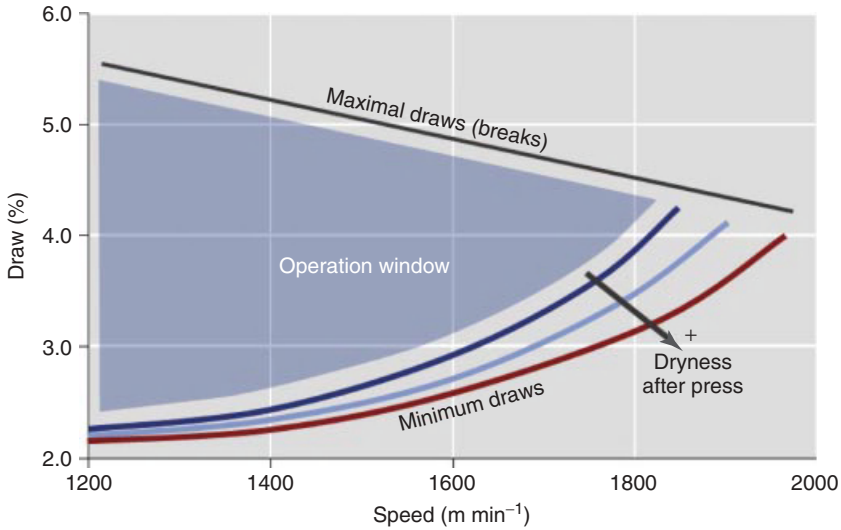


Figure 15.29 Relation between machine speed, web draw, and web dryness. (Source: Voith.)

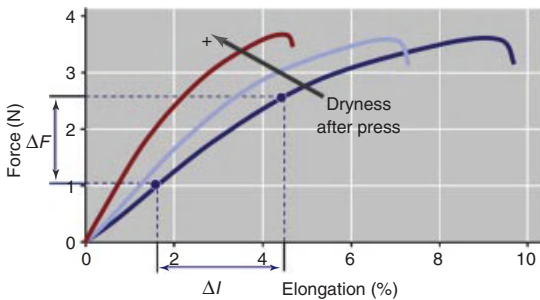


Figure 15.30 Stress–strain curve for paper samples at different dryness contents. (Source: Voith.)

the required web tension, allowing web transfer without wrinkles through the press and the dryer sections. The draw for the required web tension mainly depends on the speed, the adhesion of the materials in contact, the type of furnish, and the dryness of the web. With higher machine speeds, higher draws are needed to create sufficient web tension (Figure 15.29). The amount of draw strain is limited by the wet web strength properties (initial wet web strength and elongation at rupture), which are furnish properties at a given dry content. So, a required high draw can limit the speed of the machine. As such, a draw close to the wet web strength limit will dramatically increase the number of breaks at this speed level. For further speed increase, the dryness (wet web strength) at the position of the draw must be increased. Figure 15.30 shows examples of stress–strain curves of paper samples

of various dryness contents. For the same force (required web tension), the web with a higher dryness exhibits lower elongation (the gradient $\Delta F/\Delta l$ is steeper).

15.6.4.2 Web Guiding

When the web is transferred, it is guided by one or two felts to the following press nip. The air transported with the felt and paper web into the press is squeezed in the closing nip. The removed air flows against machine direction and tends to create air bubbles between the felt and paper web ahead of the press. To avoid air bubbles, the guiding felt usually forms a prewrap, pressing the paper web against the opposing press roll; this squeezes air out of the sandwich ahead of the nip and thus stabilizes the web.

In cases where sufficient long prewrap is not possible, or where the prewrap alone is insufficient, a blow box can be utilized. The blow box provides gentle vacuum on the roll side of felt and keeps the web in contact with the felt.

Blow boxes are also applied in top felts before and after a press to support the web and avoid web drop-off.

The fast-moving elements in the machine drag air and build a complex system of airstreams. Closing and opening gaps between felts go hand in hand with the airstream in the CD, stimulating web flutter. Flutter itself causes irreversible elongation of the fiber web and is often accompanied by initial tearing and edge cracks and wrinkles, which may initiate web breaks. In this case also, the use of blow boxes may be an appropriate measure to stabilize web run and eliminate sheet flutter.

15.6.4.2.1 Double-Felted Nip After a double-felted nip, the web must be separated and guided by the use of vacuum elements. At machines with low speeds or high basis weights, the web can also be separated from the top and bottom felts with an open draw (Figure 15.31).

In cases where the wet web is not strong enough to bear an open draw, the web needs to be separated from one felt first. On machines operating only at low speed, a postwrap of the felt–web–felt sandwich on the press roll of the felt keeping the web may be sufficient. The postwrap allows breaking of the vacuum in the releasing

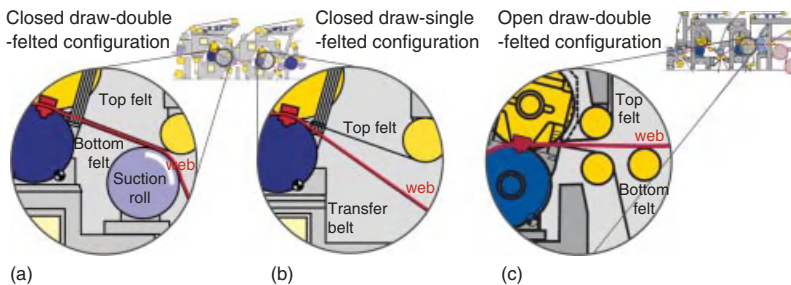


Figure 15.31 Details of web guiding after (a) a double-felted press nip (closed draw), (b) single-felted press nip (closed draw), and (c) a double-felted press nip (open draw) in a modern double shoe nip press. (Source: Voith.)

felt first, while keeping the vacuum in the other felt. Depending also on the roll diameter, a typical measure for this postwrap angle is about 5°.

It is not easy to control the web run in every case just by adjusting the postwrap. The web can also follow the wrong felt after separation. This effect is called *sheet stealing* and may be caused by high felt saturation due to high dewatering rate, inadequate felt conditioning, or too low a permeability of the press felt – either by design or compaction and/or contamination. Increasing the machine speed also contributes to the phenomenon of sheet stealing. Therefore, an adapted press section design incorporates an additional vacuum element, giving safe and reliable sandwich separation. In a conventional press nip, a suction roll can be used to separate the web directly after the press nip. Examples are first presses in carton board machines (Figure 15.16) and tri-nip presses (Figures 15.15 and 15.19) often used in machines for graphical paper and containerboard. In a highly loaded shoe press, the sandwich is separated by means of a separating vacuum element – either a suction felt roll (Figure 15.31) or a transfer suction box – following the press nip. This arrangement is also used when nip dewatering on the top as well as the bottom side of the press nip exit is desired.

15.6.4.2.2 Single-Felted Nip Because of the high differences in surface adhesion after a single-felted nip, the web follows the smooth roll or the transfer belt at the nip exit and no additional web-guiding element is needed. In this case, the permeable fabric that has to be separated must wrap the opposite roll. This ensures that air can stream back to the expanding fabric and break the vacuum that otherwise could steal the web (Figure 15.31).

15.7

Impact of Wet Pressing on Paper Surface Properties

The press felts have to be designed to meet high demands as regards large storage capacity under pressure, good water retention behavior on leaving the nip (which reduces rewetting of the web), and the smoothest possible felt surface for uniform pressure on the web and to avoid felt marking. Besides the structural properties of the paper, owing to the intense direct mechanical contact, wet pressing has a major influence on surface quality of the paper as regards surface roughness and surface densification.

15.7.1

Surface Roughness

Surface roughness, often differentiated into micro- and macroroughness, is related to the fiber type, the fiber network structure with fines and fillers, the microstriations due to shrinkage, and the contact with fabrics in the paper machine. Contrary to wet markings in the forming section, the press felt imprints have no regular pattern.

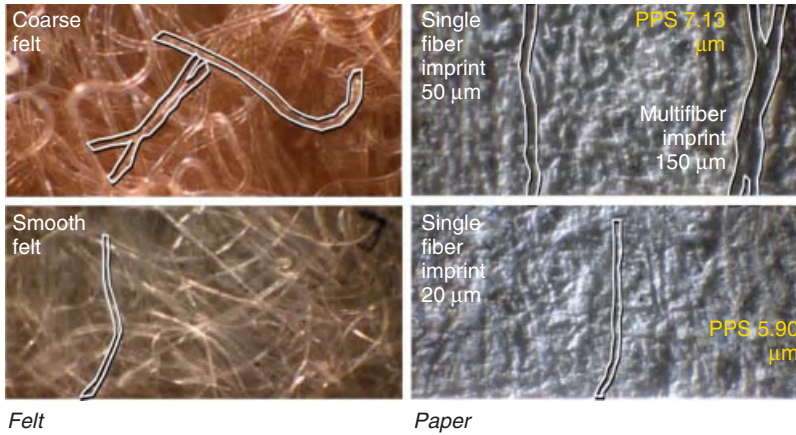


Figure 15.32 Light microscope photograph of a base paper and corresponding press felt surfaces [26].

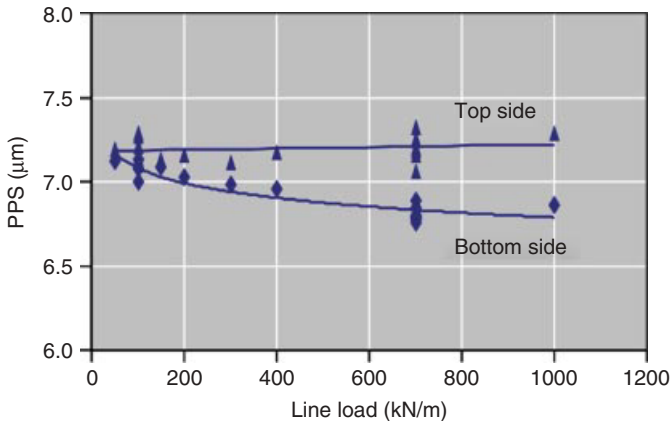


Figure 15.33 Smoothing of the paper surface with a single-felted last shoe press nip. (Source: Voith.)

Created by batt fibers of the felts, the imprints are predominantly orientated in the machine direction because of the alignment of the batt fibers (combing) during the machine run. Their shape and dimensions can be visually related to the felt surface (Figure 15.32). The finer felt design of the last nips in the press section can interfere and thus reduce the imprints of the coarser felt fibers of the first press. In addition, wire marks from the forming section can be reduced to some extent. The direct contact with a smooth roll in the press section can almost completely eliminate the imprints and lower the roughness level significantly, as shown for the bottom side in Figure 15.33. However, very deep fabric imprints or imprints on very sensitive paper grades (high beating degree and high filler and fines content) often cannot be evened out by smoothing in the press section or calendering. This

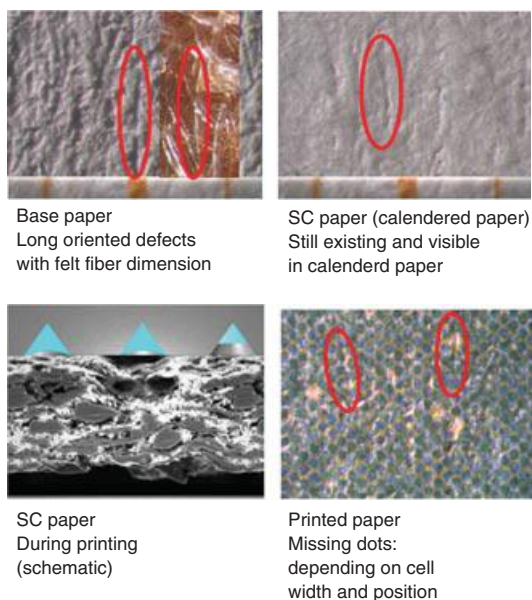


Figure 15.34 Origin of paper surface structures due to felt imprints leading to a printing defect in SC paper. (Source: Voith.)

may cause printing defects such as missing dots in rotogravure printing, as shown in Figure 15.34 (Chapter 24).

15.7.2

Surface Densification

15.7.2.1 Dewatering and Densification

Symmetrical dewatering has to be aimed for in order to obtain symmetry in densification as well as fines and ash content in the z-direction, especially of the top and bottom web surfaces.

Surface densification is related to the dewatering of the web toward the felt as the dewatering direction. The water flows from the pore volume of the fiber network to the felt. With increasing removal of water, the structural pressure gets higher and the layers close to the surface become densified (Figure 15.35). Here, the flow resistance increases. At the impermeable roll side, dewatering is blocked, which prevents the densification of the inner layers. After drying and thermal removal of the water from the pore volume, the roll side of the web exhibits a significantly lower densification. In Figure 15.36, a crosscut shows the stratification of a single-sided, dewatered, high basis weight web [27].

15.7.2.2 Absorption

Densification of the surface strongly contributes to the ability of the surface to absorb liquids. In Figure 15.37, the comparison of the paper surface absorption

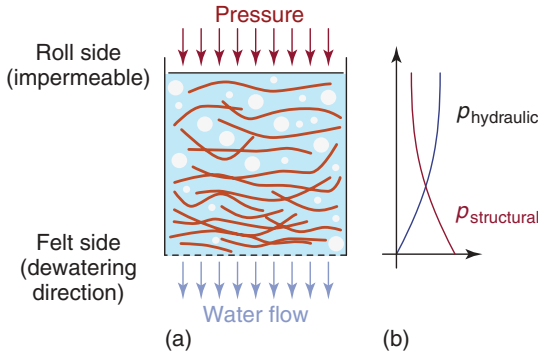


Figure 15.35 (a) Principles of densification as well as (b) hydraulic and structural pressure curves at single-sided dewatering. (Modified after Ref. [28].)

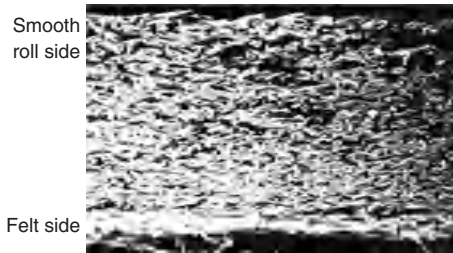


Figure 15.36 An SEM picture of a crosscut of a single-sided dewatered pulp web with a basis weight of 750 g m^{-2} [27].

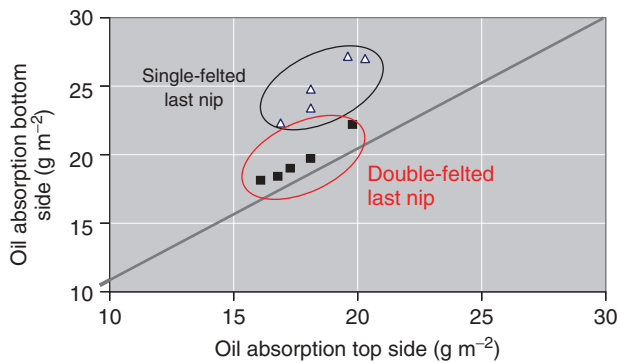


Figure 15.37 Comparison of oil absorption of the top and bottom sides of a last single-sided (felt in top direction) and a last double-felted press nip of a double shoe press [26].

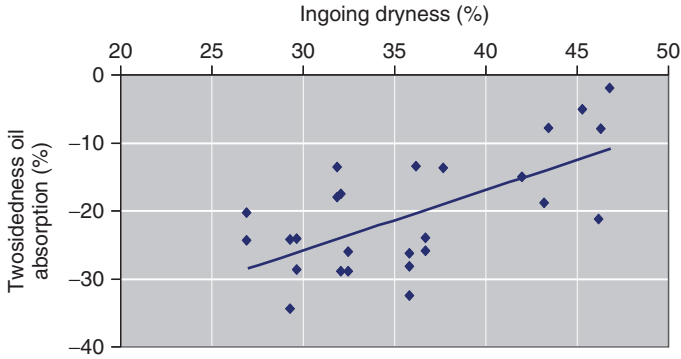


Figure 15.38 Oil absorption two-sidedness related to the web dryness before a last single-felted nip [26].

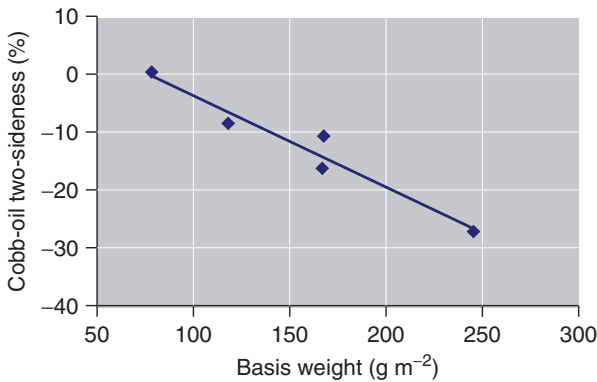


Figure 15.39 Oil absorption two-sidedness with increasing basis weight. (Source: Voith.)

(measured using the Cobb–Unger oil test) of a last single-sided (felt in top position) and a last double-felted press nip of a double shoe press configuration is shown. The non-felted side of the single-felted nip (bottom side) shows a higher absorption compared to the felted side.

The intensity of the two-sided absorption also depends on the intensity of dewatering. If the major drainage was performed by a double-felted nip before (and the ingoing dryness level to the single-felted nip is already high), the impact of the single-sided dewatering concerning the two-sidedness decreases, as shown in Figure 15.38 [26].

With increasing basis weight, the two-sidedness increases significantly (Figure 15.39). It is assumed that at low basis weight, the flow resistance of the fiber network allows a certain dewatering through all layers of the web, even from layers closer to the roll side. With increasing basis weights, the flow resistance of the thicker web becomes higher, further limiting the dewatering and thus the densification of the layers closer to the roll side.

On the one hand, the absorption of the surface determines the behavior of the paper in the further papermaking process, for example, the penetration of starch at surface sizing or the consumption of liquid color during pigment coating. On the other hand, concerning printing quality, the absorption of the paper has an influence on mottling, print holdout, print show-through, and dusting, among others [26].

Besides the absolute level of absorption of the web, two-sidedness – which describes the different absorption abilities of the top and bottom sides – is of highest importance. So, one-sided dewatering means, for instance, nonsymmetrical surface characteristics such as printability of top and bottom sides.

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16

Dryer Section

Herbert Holik and Roland Mayer

16.1

Overview

The main purpose of the dryer section is to increase the dry content of the paper web by evaporation, usually to a dryness between 90 and 98%. During drying, the fibers develop hydrogen bonds that provide the natural strength of the paper web. Drying is a coupled heat and mass transfer process. The energy for evaporation has to be supplied by a heat source and transferred to the paper. The evaporated water has to be carried off by air (except in press drying). Heat sources can be heated surfaces such as cylinders for contact drying, hot air in impingement or through air drying, and a radiator as in infrared drying. In Figure 16.1, examples of the main drying principles in paper drying are shown.

Depending on the type of paper machine, different drying principles as well as their combinations are applied. The most common type of dryer section is the multicylinder dryer section, whereas drying with only one large diameter cylinder, air impingement drying, or infrared radiators are used in more special cases.

In multicylinder dryer sections, reliable web run and easy tail threading has to be ensured. The paper web picked up after press section has a dry content between 45 and 55% and thus only low strength. So it has to be reliably guided throughout the dryer section.

A paper machine for coated or sized paper grades has a predryer section for drying the raw paper and one or more after-dryer sections for drying the sized or coated web.

16.2

Drying Principles and Basics

16.2.1

Drying Rate and Energy Balance

The *drying rate* is defined as mass flow of water removed from the paper web by evaporation. The drying rate describes how fast the paper web is dried. For a high

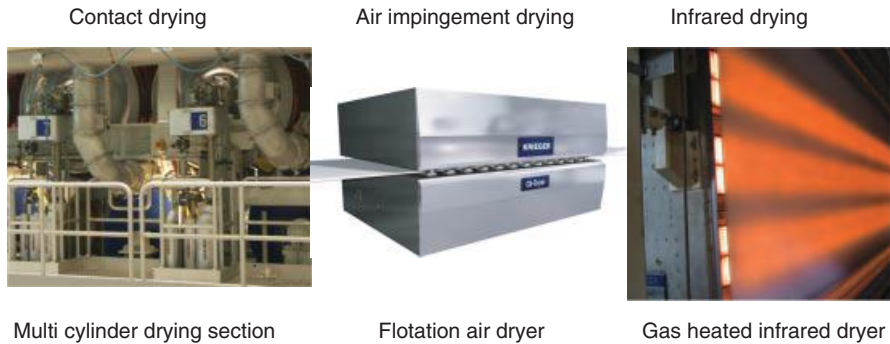


Figure 16.1 Examples of the main drying principles in paper drying.

Table 16.1 Overview and comparison of drying techniques, their typical effect, energy efficiency, and applications.

	Drying principle		
	Contact	Air impingement	Infrared (IR)
Energy source	Steam	Gas/steam	Gas/electric power
$\alpha_{\text{to paper surface}}$	500–3000 W (m ² K) ⁻¹	50–350 W (m ² K) ⁻¹	50–110 W (m ² K) ⁻¹
$\Delta T_{\text{to paper surface}}$	10–40 °C	200–400 °C (600)/ 50–100 °C	800–1000 °C/ 500–650 °C
Heat flux	10–40 kW m ⁻²	20–120 kW m ⁻²	50–110 kW m ⁻²
Efficiency (used energy for drying/ transferred heat)	85%	50–70%	35–60% (25–30% radiation + 10–30% hot air)
Application	Cylinder dryer section/Yankee cylinder	Yankee hoods for tissue drying Flotation dryer in coating machines	Coating machines (binder immobilization)

drying rate, both the heat transfer and the mass transfer have to be sufficient. In the case of good heat transfer but low mass transfer, for example, if air ventilation is insufficient, the paper web would mainly be heated up which subsequently reduces heat transfer rate and leads to less drying.

The heat flux is a function of the transfer coefficient, of the temperature difference between heat source and paper, and of the heated area. The mass transfer depends on the mass transfer coefficient, on the partial pressure difference of the vapor between paper and air and on the free area for mass transfer. The coupling between heat and mass transfer is the evaporation enthalpy. Table 16.1 gives an overview and comparison of drying techniques, typical properties, and applications as well as indicative figures for the energy efficiency for the main drying principles.

The energy balance describes how much energy is used for drying. It is given by the amount of water m_v evaporated in the dryer section

$$Q = m_v \times \Delta h_e$$

where Δh_e is the latent heat of evaporation. The overall amount of thermal energy consumed by the dryer section depends on the energy losses. The energy efficiency of the dryer section is the ratio of the energy used for drying and the overall thermal energy supplied to the dryer section. The higher the temperature of the heat source, the higher is normally the loss of energy in the heating system and the lower is the energy efficiency.

16.2.2

Contact Drying with Steam Heated Cylinders

Contact drying is the most common principle in paper drying because of its high energy efficiency and its advantageous heat source which is low pressure steam. The almost saturated steam condenses at the inner surface of the cylinder shell, the heat is conducted through the wall and transferred to the paper web, the web is heated up and water is evaporated. Air flow takes up the evaporated water. The heat transfer rate Q from steam to paper is calculated as

$$Q = k \times A \times (t_s - t_p)$$

$$\text{with } (k)^{-1} = ((\alpha_c)^{-1} + (s/\lambda)^{-1} + (\alpha_p)^{-1})^{-1}$$

where A is the area, t_s the saturated steam temperature at the given steam pressure, t_p the paper temperature, α_c the heat transfer coefficient from steam to the cylinder shell, s the wall thickness, and λ the thermal conductivity of the wall material (mainly gray cast iron, sometimes also steel). For special gray cast iron λ is about 45–48 W(m K)⁻¹, for steel about 50–52 W(m K)⁻¹, α_p the heat transfer coefficient from the cylinder surface to the core of the paper. For the heat transfer coefficients α_p , common values are about 800–3000 W(m² K)⁻¹ for paper at a dry content of around 40% and 400–800 W(m² K)⁻¹ at lower moisture contents. α_p is not only a function of the water content of the sheet but it also depends on the contact of the sheet with the cylinder surface, which is mainly defined by the tension of the dryer fabrics. A negative influence is given when steam is generated between the surface and the sheet. This may occur because of too high heating or too low fabric tension.

Higher steam pressure increases the temperature difference and thus the heat transfer rates. Maximum steam pressure applied in paper drying is about 6–12 bar. For high drying rates, not only a good heat transfer but also a good mass transfer is necessary. Therefore, the evaporated water needs to be carried off by good ventilation.

In combined contact and impingement drying (e.g., tissue drying), the paper surface is “cooled” by the intensified mass transfer of the impinging air. Here, paper surface temperature is a function of heat transferred from the cylinder and the properties (temperature, humidity, heat, and mass transfer coefficient) of the impinging air.

Accumulation of air inside of the cylinder has to be avoided as it would reduce the condensing temperature according to the partial pressure of the steam. A vacuum pump is installed within the steam and condensate system to get rid of any air in the steam.

The heat transfer rate from the steam to the cylinder shell is reduced by the condensate layer and depends on the flow pattern of the condensate motion. This flow pattern is mainly dependent on the machine speed and to a lower degree on the amount of condensate volume in the cylinder and on the cylinder diameter.

At low speeds of up to about 300–500 m min^{-1} , a pond of condensate is found in the cylinder. At higher speeds, that is, above the “rimming speed,” the condensate builds up a ring.

Figure 16.2 shows the approximate speed with fully developed rimming in a 1.8 m diameter cylinder for different condensate volumes expressed as mean condensate film thickness [1]. Other sources report lower rimming speeds of about 10–20% less. With larger diameters, the rimming speed is slightly higher, and in cylinders with spoiler bars lower. During pond operation drive energy demand rises considerably with speed. During the transition to rimming speed, the drive is unstable and gets distinctly lower when starting rimming. After that the drive energy slightly increases with speed. Collapsing of the ring occurs at lower speeds than rimming between about 280 and 350 m min^{-1} [2, 3].

Acceleration during “ascending” of the condensate ring is against the rotating direction and in the rotation direction when descending. This results in a swinging condensate motion relative to the cylinder with the effect that the condensate ring

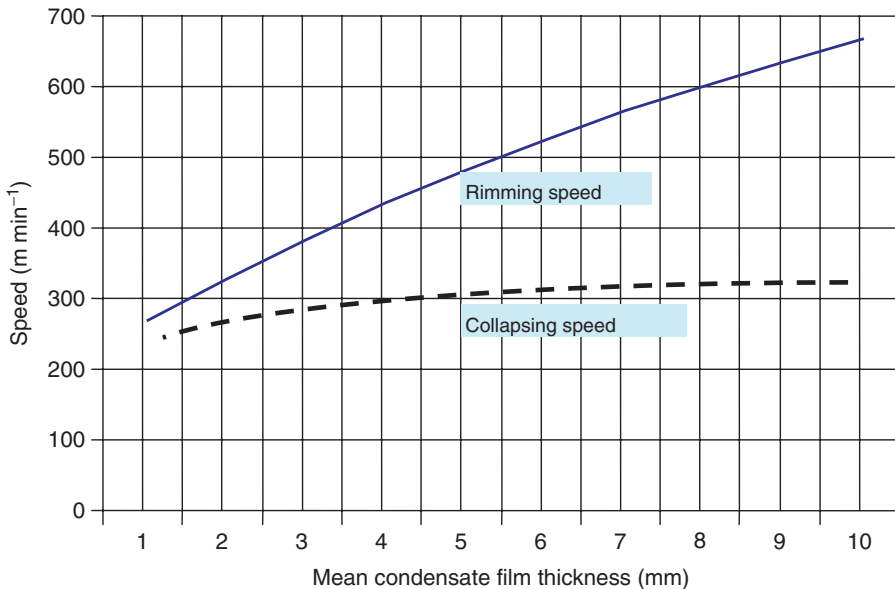


Figure 16.2 Approximate rimming and collapsing speed for a drying cylinder of 1.5–2.0 m diameter depending on the average condensate film thickness [1–3].

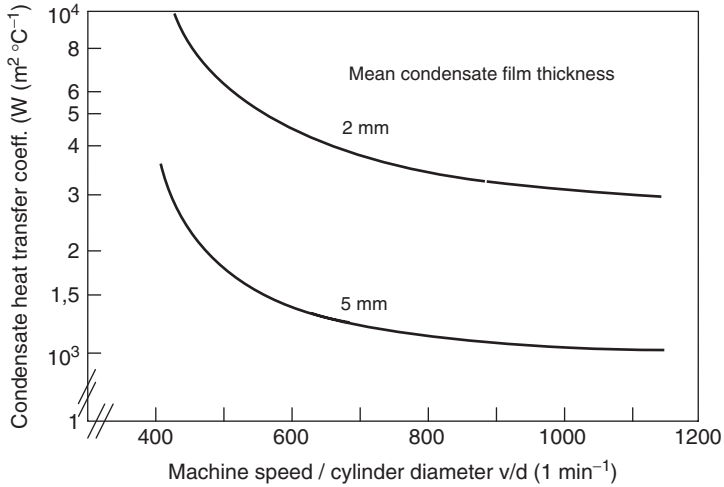


Figure 16.3 Heat transfer coefficient as a function of the ratio of machine speed and cylinder diameter for several condensate thicknesses [4].

velocity is lowest and thus its thickness is highest at the culmination point and not in the bottom position. For high machine speeds, the condensate motion and thus heat transfer decrease. In Figure 16.3, the heat transfer coefficient in a drying cylinder is given as a function of the ratio of machine speed and cylinder diameter depending on the condensate film thickness. The condensate behavior in a 2 and 5 m diameter dryer is characterized for the two diameters in Figure 16.4 as regards maximum relative velocity between wall and condensate ring, maximum variation in condensate ring thickness, and the half amplitude of the condensate ring oscillation as a function of machine speed [4].

For heat transfer enhancement and uniform drying, spoiler bars inducing turbulence to the condensate layers are installed. These are used in multicylinder dryer sections as well as in Yankee dryers for tissue production. Usual values for α_c with spoiler bars are $2000\text{--}4000 \text{ W (m}^2 \text{ K)}^{-1}$. In Figure 16.5, an installation of a set of spoiler bars in a drying cylinder is shown. The amount of increase in heat transfer by spoiler bars depends on their spacing, condensate thickness, and machine speed.

The condensate is removed from the inner surface of the cylinder to its axis by siphons (Figure 16.6) in the form of a two-phase flow of steam and condensate. This enables to remove the condensate at a reasonably low pressure difference. In a cylinder of 1.8 m diameter running at 2000 m min^{-1} , a centrifugal force that is about 125 times the gravitation is effective, whereas for a 6 m cylinder it is still a factor of 37. The siphons either rotate (for machine speeds up to 800 m min^{-1}) or are stationary (for higher speeds). To generate the two-phase flow, a pressure difference of about $0.2\text{--}0.3 \text{ bar}$ is required for stationary siphons. For rotating siphons, at least $0.4\text{--}0.5 \text{ bar}$ is necessary to overcome the centrifugal forces. Depending on machine width, one or two (front and back side) siphons

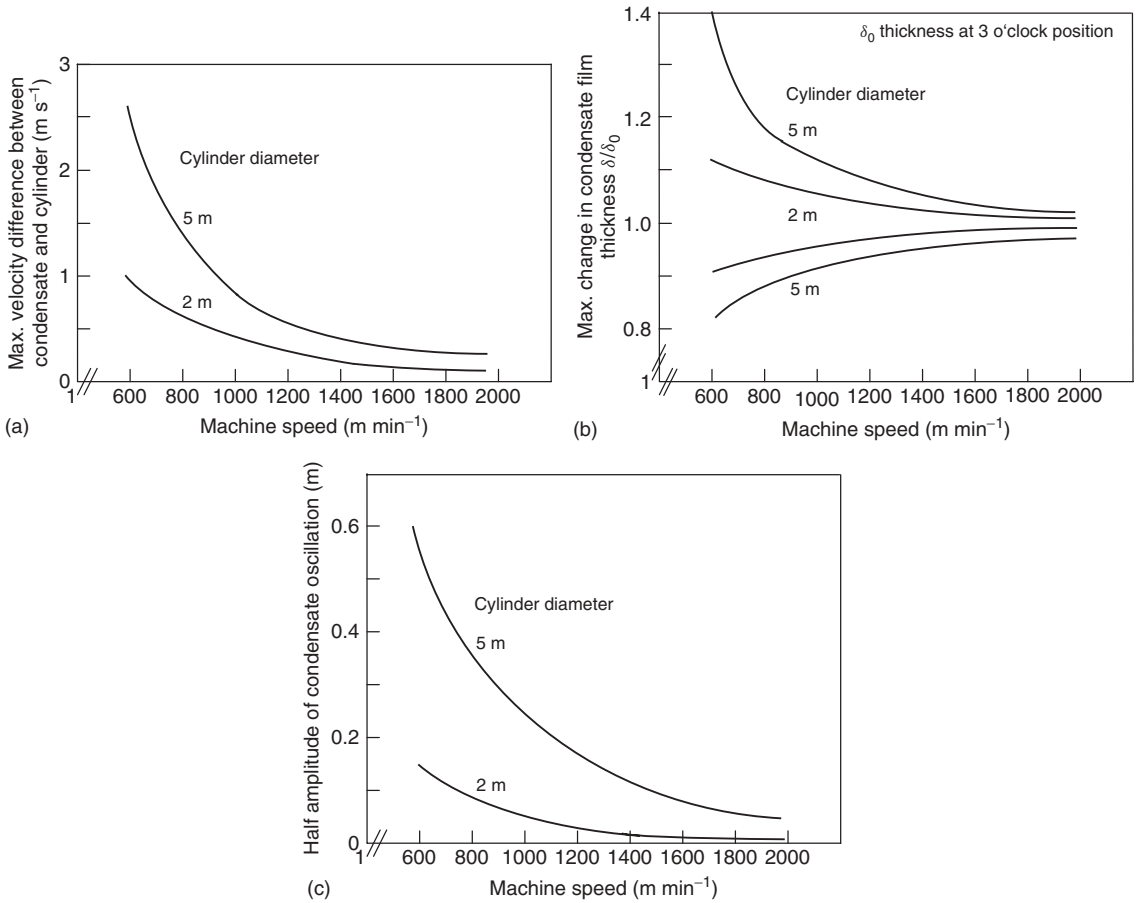


Figure 16.4 Condensate behavior in a 2 and 5 m diameter dryer during rotation (friction is neglected). [4].
 (a) Maximum relative velocity between wall and condensate ring. (b) Maximum variation in condensate ring thickness, and
 (c) Half amplitude of the condensate ring oscillation as a function of machine speed.



Figure 16.5 View inside a drying cylinder equipped with spoiler bars. (Source: Voith.)

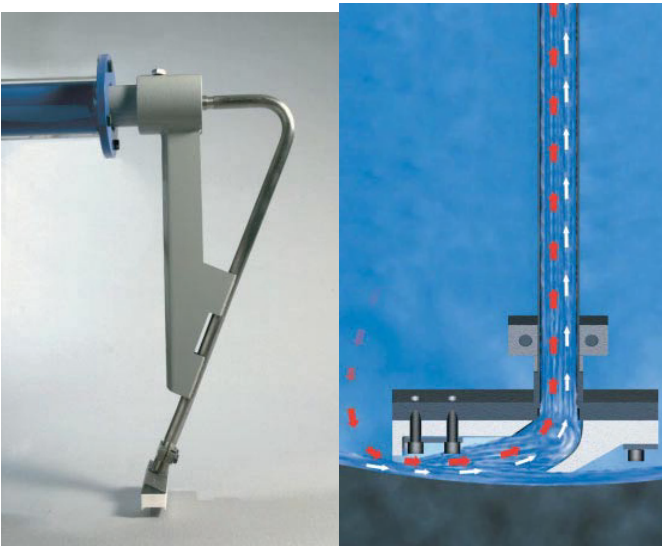


Figure 16.6 Siphon for removing condensate (white arrows) by blow through steam (red arrows).

are installed. As the condensate has to flow a certain distance to the siphon, there is a difference in film thickness and flow velocity across width. The effect on the uniformity of drying in CD usually can be neglected.

In multicylinder dryer sections, the paper web undergoes repeated actions from cylinder to cylinder. It is heated up during the contact with the cylinder surface

whereby evaporation through the dryer fabric is restrained, followed by a draw with free evaporation and cooling down. As a consequence, the surface of the rotating cylinders is subjected to nonstationary heat transfer. For large cylinder diameters, this leads to the effect that the temperature at the cylinder surface and close to it can swing by some degrees Celsius around a mean value.

16.2.3

Air Impingement Drying

Air impingement drying is mainly used where noncontacting drying, for example, after coating, or where additional drying capacity, for example, in tissue drying, is necessary. An impingement drying hood blows hot air through a nozzle plate or nozzle bars with high velocity onto the paper. The impinging air transfers heat to the web and simultaneously takes up the evaporated water. The air that is now cooled down and loaded with water vapor is then sucked back into openings of the hood. It is recirculated to the burning chamber (or to the air/steam heat exchanger) and the pressure fan where it is heated up and pressurized again. A small amount of the air needs to be exhausted and to be replaced by make up air, in order to control the water content of the impingement air. Heat transfer in impingement drying increases with higher air temperature, velocity, and mass flow and with reduced distance between nozzle plate and paper surface. The lower the air humidity, the higher the mass transfer and thus the drying rate, but with low air humidity the energy demand increases. The heat transfer Q to the area A is calculated as

$$Q = \alpha_i \times A \times (t_{\text{air}} - t_{\text{paper}})$$

with a heat transfer coefficient α_i in the range of about 250–350 W (m² K)⁻¹ for 100 m s⁻¹ air impingement velocity and a spacing of about 25 mm. Figures 16.7–16.9 indicate how far the variation of the parameters air temperature and humidity, air jet velocity at the exit of the nozzle, and spacing between nozzle plate and paper surface influence the heat transfer [5, 6].

Normal operation conditions for impingement hoods are air velocities between 70 and 120 m s⁻¹ and air temperatures between 200 and 400 °C (gas heated). Steam heated hoods can only achieve up to 150 °C. High efficiency hoods (used mainly in tissue drying) can be designed for air velocities of up to 210 m s⁻¹ and air temperatures up to 700 °C (gas fired). With the high air temperature, the contribution of radiation of the nozzle plate to hood heat transfer can be between about 4 and 9%. For tissue drying, the impingement hood is arranged around a Yankee dryer.

For coat drying, the impingement hoods are built as flotation dryers. Here, not only the drying is enforced by the air impingement, but also the web is guided by using the air cushion pressure of the nozzle bars.

The impingement drying principle is also applied in a few machines after the press section to enhance the web dryness and hence the web strength before the first free draw in the dryer section [7]. Sometimes it is used for curl control, after single-tier multicylinder dryer sections.

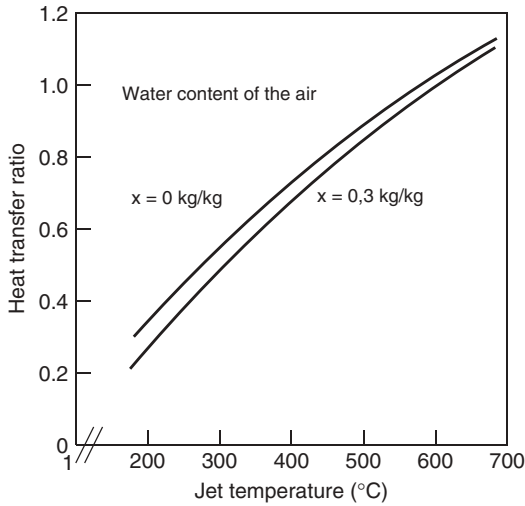


Figure 16.7 Influence of varying temperature and humidity of the air in impingement drying on heat transfer [5, 6].

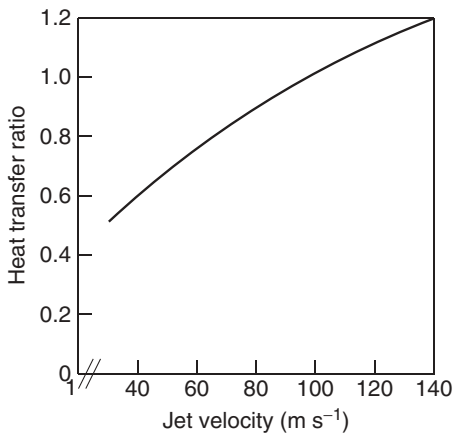


Figure 16.8 Influence of varying jet velocity at nozzle exit in air impingement drying on heat transfer [5, 6].

16.2.4

Through Air Drying

This method is used for drying of tissue and nonwovens. Hot air is sucked or blown through the air-permeable paper web supported by a heat resistant fabric. Heat is transferred directly into the fiber network and the evaporated water is carried off. Through air drying (TAD) results in the highest drying rates but it is only applicable for highly permeable webs such as tissue grades and it has a quite high energy

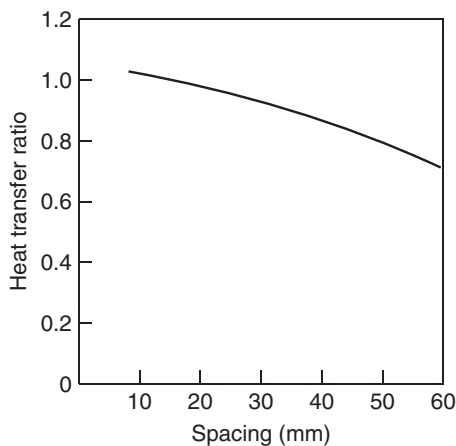


Figure 16.9 Influence of varying spacing between nozzle plate and paper in air impingement drying on heat transfer [5, 6].

demand because of the high capacity vacuum fan. For tissue, this usually pays off by achieving premium quality regarding softness and bulk. Here, TAD replaces mechanical press dewatering.

16.2.5

Infrared Drying

This heat transfer method is mainly used after coating because of its high intensity that is preferred for drying of the coating layer up to its immobilization. Infrared heaters are usually gas fired. The gas burners heat up a metal or ceramic emitter plate covered by a mesh to a temperature of about 900–1100 °C. The low thermal inertia of the thin emitter plates and of the mesh allows fast control of temperature and heating rate as well as preventing fires in the case of sheet breaks. In some cases, electrical heaters are in use with temperatures up to about 700 °C exhibiting a fast cool down of the emitter plates.

In infrared drying the heat flux Q transferred by radiation is

$$Q \sim T_2^4 - T_1^4$$

where T is the absolute temperature in K (Kelvin), T_2 is the temperature of the infrared heat source, and T_1 is the temperature of the material to be dried, for example, the paper. Taking the maximum temperatures of the gas fired and electrical infrared heaters, the heat transfer of the gas fired heater is about three to four times the heat transferred by the electrical heater. IR drying provides very high drying rates, but the energy efficiency is quite low. The efficiency can be improved when it is combined with a small impingement dryer using the hot exhaust air of the IR dryer. Infrared drying units need sufficient air flow in order to carry off the evaporated water and to prevent coat quality problems. Infrared heaters are also used for CD moisture profile control of the paper web.

16.2.6

Press Drying

In this process, the paper web is compressed by mechanical pressure during drying. The web runs around a large heated cylinder and is wrapped by a cooled steel belt or it runs between two steel belts of which one is heated and the other is cooled. A water pressure compartment presses the cooled steel belt against the heated cylinder or against the heated steel belt. Between the cooled steel belt and paper web, a permeable felt or wire is installed. So the vapor can escape to the permeable cover to be stored therein, in condensed form.

Drying under pressure can increase the strength properties of the web and if fibers can be saved, this can justify the higher expenses. There are only a few installations of this dryer type worldwide in packaging paper production. An application for writing and printing grades are less probable because of marking (Chapter 15).

16.2.7

Impulse Drying

This method is also a combination of pressing and drying. The process takes place in a press nip (for instance, with a shoe press) where one surface, which is in direct contact with the web, is heated. The other web side is in contact with a felt. The wet web is compressed and thus mechanically dewatered. Additionally, the vapor pressure generated at the hot surface pushes some liquid water out of the web, which results in improved dewatering. The paper web is expected to have higher strength and higher bulk. Despite lot of scientific work in the last decades, this kind of process has not found commercial application owing to paper delaminating problems (Chapter 15).

16.2.8

Air–Water Mixture in the Mollier Diagram

The Mollier diagram allows describing the change of air conditions as regards changes in enthalpy, temperature, and water content of the air. It can be used, for example, in convection drying when hot air impinges the wet paper surface or in through drying. It is also well suited for description of processes in humid air handling in drying hood air systems. Figure 16.10a shows the diagram in principle with the axes, enthalpy h and water content x of the humid air, as well as lines of constant temperature t , and relative humidity φ . The saturation curve (here, the relative humidity is 100%) indicates where the air is saturated and cannot take up more water. Above the curve the air is not saturated and below the curve it is oversaturated (which means fog area). Both the h -lines (constant enthalpy) and t -lines (constant temperature) are inclined for better resolution. The t -lines end at the saturation curve. The φ -lines (constant relative humidity) indicate constant

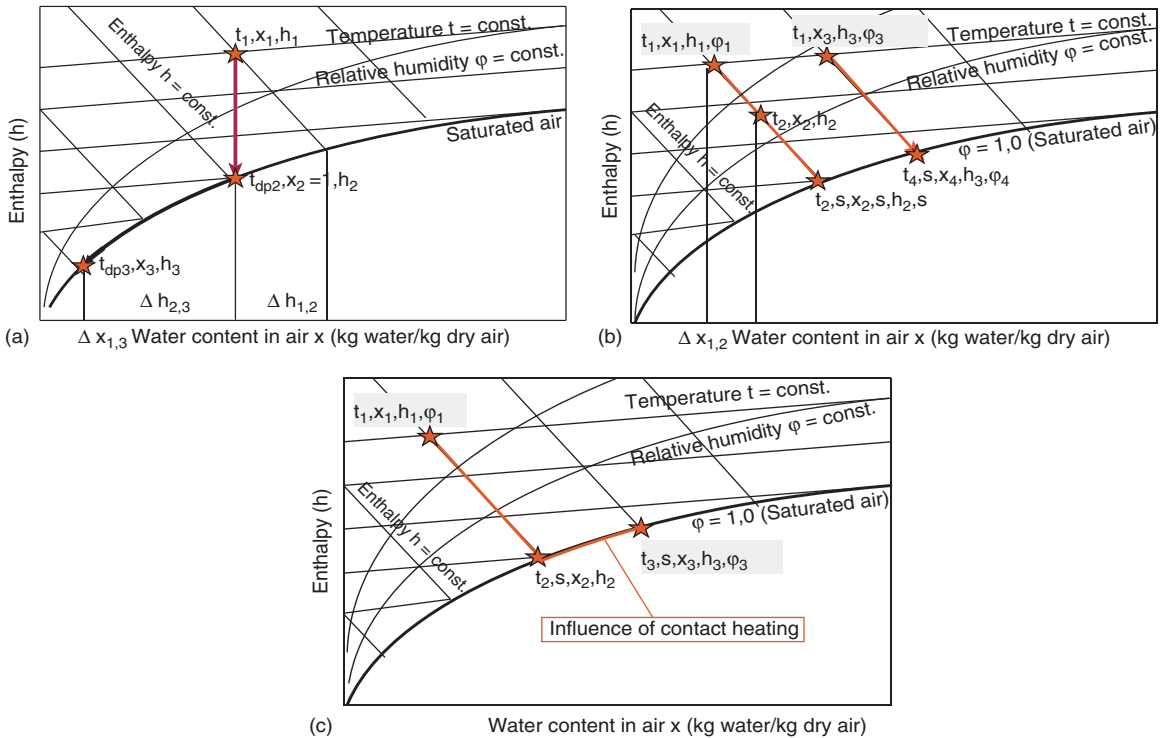


Figure 16.10 (a) State change of humid air when cooling down. (b) Change in enthalpy, temperature, and moisture content of the air at impingement drying. (c) Change in enthalpy, temperature, and moisture content of the air at impingement drying, coupled with additional contact drying.

ratios of partial pressure of water vapor in the air. The relative humidity decreases with increasing distance above the saturation line $\varphi = 1.0$.

When hot humid air (t_1, x_1) is cooled down (e.g., at the surface of the dryer section hood or in a heat exchanger), it may reach the saturation line at the temperature $t_{2,dp}$, which is the dew point temperature for (t_1, x_1). Effective heat recovery is given by condensation of the water vapor of the saturated air when cooling the air down to a temperature of t_2 . Here, the latent heat $\Delta h_{1,3} = h_1 - h_3$ due to $\Delta x_{1,2} = x_1 - x_2$ can be gained. Heat recovery makes most sense for air conditions of high humidity and high temperature. Higher relative humidity of the air (at constant temperature) results in higher amount of heat recovered at a given lowest temperature t_2 as shown in Figure 16.10a.

When hot air (t_1, x_1) impinges on the wet web surface, it transfers heat and takes up a certain amount of water vapor ($\Delta x_{1,2} = x_2 - x_1$). Thereby, the temperature will be decreased to t_2 . The air would be capable to take up more water vapor ($\Delta x_{1,2,S} = x_{2,S} - x_1$), before it gets saturated (when reaching the wet bulb temperature $t_{2,S}$ on the saturation curve). This saturated state of the air will never be reached in impingement drying but the temperature $t_{2,S}$ corresponds to the temperature of the wet (water saturated) paper surface. Higher air humidity results in higher wet bulb temperature, as can be seen from Figure 16.10b. For only impingement drying with high air temperature, the decrease in drying capacity due to the increase in wet bulb temperature – and thus decrease in temperature difference – can be neglected.

In tissue drying, both impingement and contact drying are applied. So, an additional heat source is available, which increases the wet surface temperature to $t_{4,S}$ (Figure 16.10c). More additional heat means higher $t_{4,S}$. The increase in wet surface temperature is lower with increasing mass transfer coefficient (higher velocity) of the impinging air. In contact drying, the temperature difference between steam and paper surface is usually much smaller than that for air impingement drying. Therefore, an increase in paper surface temperature may decrease the contact drying rate considerably, which is especially true for multicylinder drying.

16.3 Basics Related to Paper Drying

16.3.1 Drying Curve

Paper shows some kind of hygroscopic behavior. In drying under lab conditions, three periods of evaporation rate can be clearly distinguished: a heating up period, a constant rate period, and a falling rate period, which may be divided into two sections A and B. This principal behavior is due to the kind of distribution of the water in the paper sheet. The drying curve describes the drying rate over time for constant drying conditions (Figure 16.11):

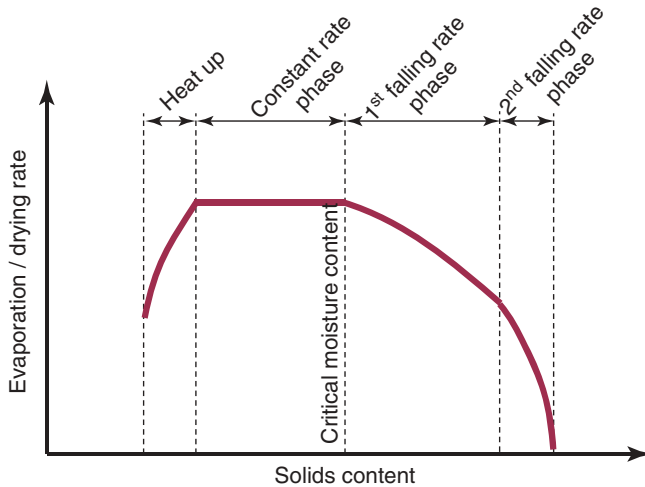


Figure 16.11 Principle drying curve of a lab sheet on a heating plate with constant temperature.

- In the heat-up phase, the transferred heat is only partly available for evaporation as it is mainly used for temperature elevation of the paper.
- During the constant rate period, there is free water on or close to the surface. So, good heat transfer and easy vapor escape are given. The surface temperature is constant for constant heating.
- In the 1st falling rate phase (falling rate period A), the water stored inside the paper is removed. This water is bound by capillary forces between the fibers or solids and the vapor has a longer way to get to the sheet surface. Furthermore, the heat conduction within the sheet is reduced. The paper surface temperature increases.
- In the 2nd falling rate phase (falling rate period B), water that is stored inside the fiber is driven out. That needs more time as the water is even better bound by higher capillary forces. This increases the partial pressure what needs higher energy to evaporate. The vapor has higher flow resistance when escaping. The heat conductivity at lower water content in the sheet is lower. The paper surface temperature increases further.

The position of transition from one to the next period is mainly depending on the kind of fibers and their preparation, kind of fillers and chemical additives, the basis weight and the drying intensity [8], and is not given as a sharp edge.

In a multicylinder dryer section of a paper machine, the paper web does not experience constant drying conditions as there is a fast change between heat transfer and pure evaporation phases. Therefore, the principle of the drying curve is more hidden. In tissue drying on a Yankee dryer, the paper drying curve of Figure 16.11 can be found to be more pronounced.

16.3.2

Paper Shrinkage

During drying, the paper web shrinks because of fiber shrinkage. The fibers themselves shrink in thickness (up to 30%) much more than in length (up to 2%). The unrestrained shrinkage of a paper sheet is proportional to the number of fiber bonds. At such a bond of two fibers, the fiber is compressed in longitudinal direction because of the shrinkage in thickness of the other fiber perpendicular to it or under a certain angle [9]. A paper sheet with randomly oriented fibers (like a hand sheet from the laboratory) will shrink equally in all directions when dried without restraint. When fibers in a paper sheet are more oriented in one direction (e.g., in machine direction as usually given in the paper machine), shrinkage will be higher in cross direction. Generally, the extent of shrinkage depends on the type of stock, degree of beating, the fiber orientation, and on forces that restrain the shrinkage.

Figure 16.12 gives an example of the amount of unrestrained shrinkage of a lab sheet made from unbleached kraft pulp over the dry content showing the maximum shrinkage at the highest dry content [10]. In Figure 16.13, the influence of the stock on unrestrained shrinking is shown taking as example TMP, DIP, and a mixture of both stocks.

The shrinkage in machine direction is restrained by the draws in the press and dryer section between the drive groups. These draws lead to respective strain and build up web tension. A low shrinkage during drying is accompanied with low wet extension and high dimensional stability.

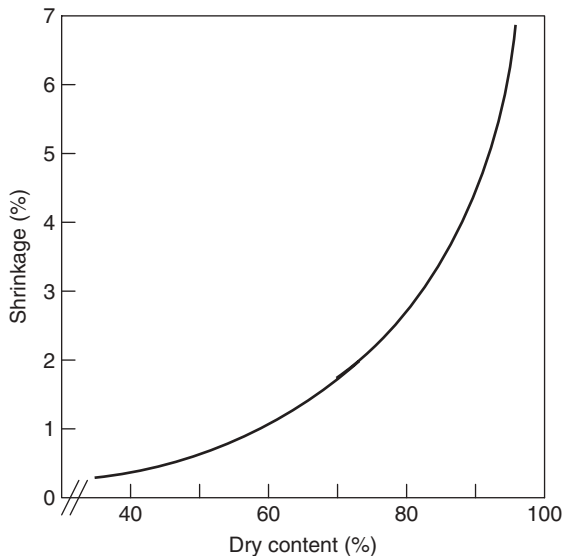


Figure 16.12 Example for the shrinkage of a paper lab sheet made from unbleached kraft pulp over the dry content [10].

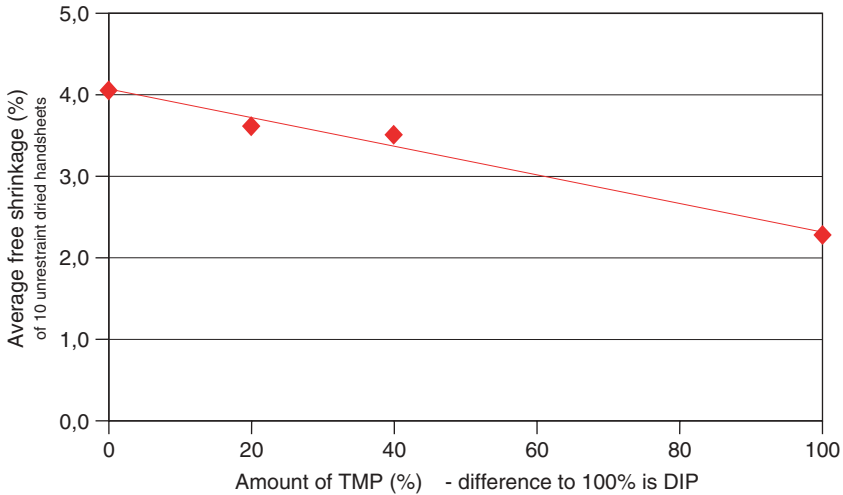


Figure 16.13 Influence of furnish on the shrinkage behavior of lab sheets. (Source: Voith.)

16.3.3

Change in Wet Strength of a Paper Sheet during Drying

The web strength increases with increasing dryness because of the build up of hydrogen bonds between the fibers. The increase in strength from about 50 to 95% dryness is a factor of approximately 10 and more depending on the furnish. Figure 16.14 gives an example for the paper wet strength increase with dry content showing very low web strength at the dryness at which the paper web enters the dryer section. Figure 16.15 shows a principle stress/strain curve (in the small

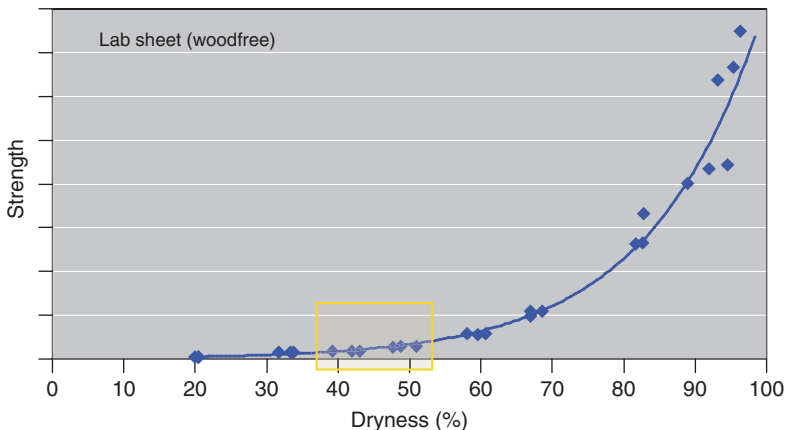


Figure 16.14 Example for strength increase with dry content of a paper lab sheet. (Source: Voith.)

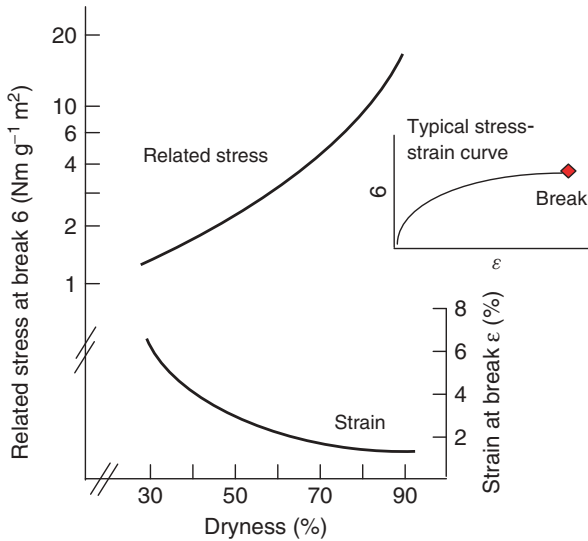


Figure 16.15 Typical stress–strain curve and example of stress and strain at rupture for different dry contents [11, 12].

diagram) and an example for breaking strength and strain for different dry contents [11, 12].

As the web undergoes tension and elongation during the run through the paper machine, the tensile energy absorption (TEA) is also an important property. TEA means the mechanical energy necessary to rupture the sheet (force and elongation). Stretch before rupture decreases with dryness and also depends on the web structure and how far the web was allowed to shrink.

16.3.4

Paper Curl

Paper curl is an undesirable effect when paper undergoes nonsymmetrical heating or moistening, for example, in copy machines or in printing. Curl is due to nonsymmetrical residual stresses in the z -direction of the web that date back to nonsymmetrical main fiber orientation (Chapters 13 and 14) or to nonsymmetrical drying of its top and bottom sides. The amount of curl is influenced by the degree of nonsymmetry of both influences (Chapter 23). The highest impact occurs at the end of the drying process, as can be derived from the free shrinkage curve in Figure 16.12. The direction of curl (MD, CD, or diagonal curl may occur) is determined by the paper and fiber structure. Curl can be reduced by adjusting the steam pressure of the top and bottom drying cylinders in a double-tier dryer group. In a single-tier dryer section curl can be controlled by additional tools, such as moistening (water, steam) or additional nonsymmetrical drying, for example, by air impingement drying.

16.4 Dryer Sections

16.4.1 Multicylinder Dryer Section

16.4.1.1 Types of Multicylinder Dryer Section

Multicylinder dryer sections consist of single-tier groups, double-tier groups, or a combination of single-tier and double-tier groups. The number of cylinders is up to about 60 in graphic paper machines and up to about 90 for board and packaging paper machines. Cylinder diameters today are usually 1.8 m, in older machines they are also 1.5, and sometimes 2.2 m. Table 16.2 gives an overview how drying rates increased and cylinder diameter were optimized in the past. For a single-tier dryer section, for example, of a newsprint machine, investment costs are about 1/3, electrical power consumption about 1/6, and thermal energy consumption (steam) about 3/4 related to the overall costs and consumption of the paper machine. Today approximately, 1.2 kg steam/kg evaporated water is consumed. In Figure 16.16, an example is given how the paper web temperature increases with time (on the abscissa) when running through the dryer section. It also can be seen how the cylinder mean surface temperature is changing and the solids content (dryness) increases along the dryer section, with a given steam pressure curve.

In double-tier dryer groups (Figure 16.17), the paper web runs around the cylinders arranged in a top and a bottom row. The paper web is in contact with each cylinder at an angle of about 220–240° alternating with the top and the bottom side. Dryer fabrics, one for each top group and one for each bottom group of cylinders, press the paper against the cylinder surface for improved heat transfer and web guiding. Even together with stabilizers, the dryer fabrics can only partly support the paper web on its transfer to the next cylinder. It remains a free draw.

The state-of-the-art dryer section for a high-speed graphic paper machine consists of only single-tier groups with steam heated cylinders in the top row and suction rolls in the bottom row. The paper web runs together with the dryer fabric alternating around the cylinders and the suction rolls and is always supported by the fabric (Figure 16.18). In the top row, the paper web is pressed against the drying cylinders by the dryer fabric. In the bottom row, it is held on the fabric by vacuum

Table 16.2 Overview on the increase of drying rates over the years for newsprint production.

Time	Boundary conditions	Typical drying rate
Before 1820	Drying loft for single sheets	$\ll 0.1 \text{ kg (m}^2 \text{ h)}^{-1}$
~1950	52 g m^{-2} , 500 m min^{-1} , 50 dryers ($\varnothing 1500 \text{ mm}$)	$\sim 6 \text{ kg (m}^2 \text{ h)}^{-1}$
~1970	52 g m^{-2} , 1000 m min^{-1} , 54 dryers ($\varnothing 1500 \text{ mm}$)	$\sim 12 \text{ kg (m}^2 \text{ h)}^{-1}$
~1996	48 g m^{-2} , 1700 m min^{-1} , 31 dryers ($\varnothing 2200 \text{ mm}$)	$\sim 20 \text{ kg (m}^2 \text{ h)}^{-1}$
~2009	45 g m^{-2} , 2000 m min^{-1} , 32 dryers ($\varnothing 1800 \text{ mm}$)	$\sim 25 \text{ kg (m}^2 \text{ h)}^{-1}$

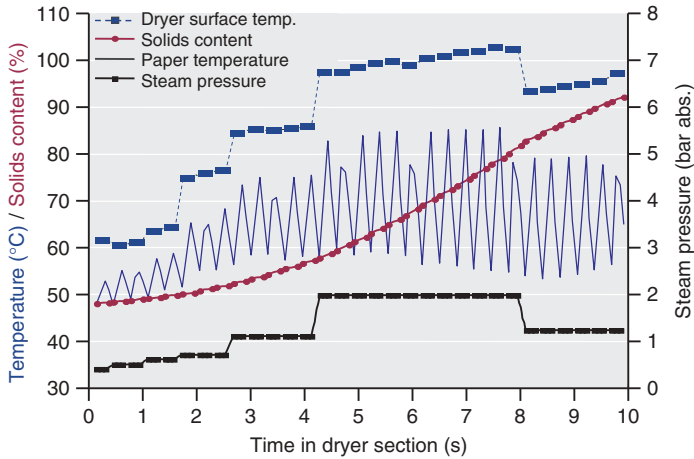


Figure 16.16 Example for a steam pressure curve, the related paper and cylinder surface temperature and the solids content along a multicylinder dryer section. (Source: Voith.)

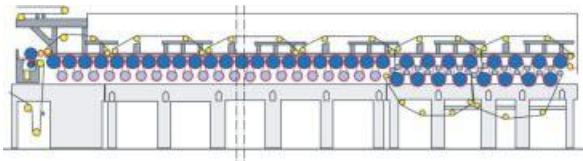


Figure 16.17 Double-tier dryer section. (Source: Voith.)

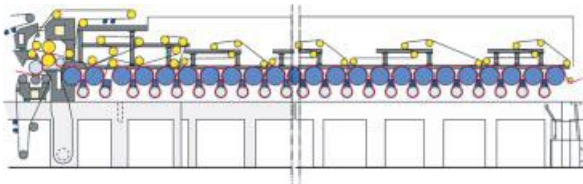


Figure 16.18 Single-tier dryer section. (Source: Voith.)

in the suction rolls. Stabilizers installed in the pockets ensure a reliable web run along its path between cylinder and suction roll.

Many paper machines have some single-tier groups for runnability reasons, where the web is still wet, followed by double-tier dryer groups. Double-tier dryer groups have the advantage of symmetrical drying of top and bottom sides and of higher drying rate per length, especially for paper and board grades with higher basis weight.

The dryer section is split into several drive groups to control web tension and to account for web stretch and shrinkage. Each group has its own dryer fabric and separate drive.

The CD shrinkage profile over width shows a U-form. At the edges, there occurs a higher shrinkage than in the center part, where the web is much more restraint compared to the edges. Higher draws in MD cause additional CD shrinkage, especially at the edges because of cross contraction of the web. Compared to a double-tier dryer section, a single-tier dryer configuration leads to more restraining in the middle part, and therefore, to a flatter CD shrinkage profile in this position, and to higher shrinkage gradients at the edges of the web (Figure 16.19).

With increasing machine speeds the air permeability of the fabrics had to be lowered in order to reduce the excessive amount of air carried by the fabric. Modern dryer fabrics provide high contact area, low caliper, high stability, and abrasion resistance. Good cleaning of the dryer fabrics ensure uniform evaporation, less sheet picking, and improved effectiveness of the web run stabilizers. Shutdowns for cleaning can be avoided or cleaning intervals increased by appropriate cleaning devices (Figure 16.20).

16.4.1.2 Tail Threading and Web Handling

Tail threading in double-tier dryer sections was done in the past by means of ropes. Modern machines use double-tier groups ropeless threading, where the tail is guided by tail doctors with air nozzles from one cylinder to the next one

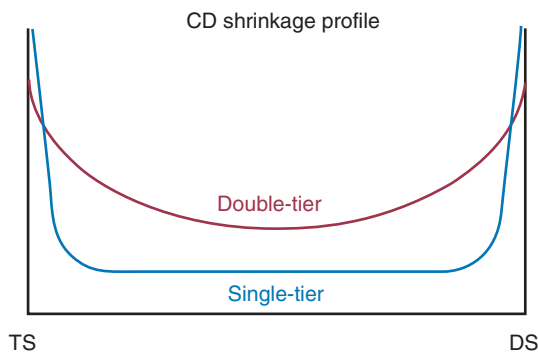


Figure 16.19 Typical CD shrinkage profiles of single-tier and double-tier dryer sections.

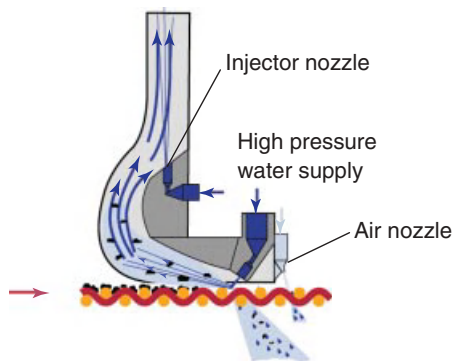


Figure 16.20 Dryer fabric cleaning device. (Source: Voith.)

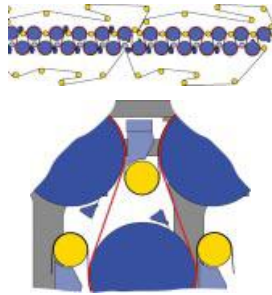


Figure 16.21 Ropeless tail threading in double-tier dryer sections by doctors with air nozzles. (Source: Voith.) (RM).

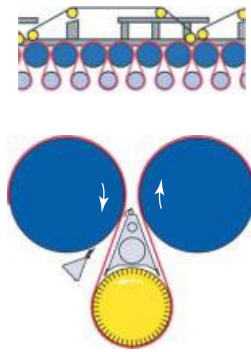


Figure 16.22 Tail threading in single-tier dryer sections by air nozzles installed in the doctor holder. (Source: Voith.)

(Figure 16.21). For single-tier dryer sections, ropeless tail threading by air nozzles installed in the doctor holder is standard (Figure 16.22).

The forces acting on the web when the web is transferred between two guiding elements (e.g., cylinders or rolls) are listed in Figure 16.23. It shows, in principle, the web transfer from a drying cylinder surface to the dryer fabric. The kind, origin, and effect of the forces for high machine speeds are summarized in Table 16.3.

- **Peeling off:** The web adheres to the surface. To peel it off, a certain force is required. The angle of detachment (between web direction and tangent at peeling line) depends on the forces of adhesion and draw.
- **Inertia:** This force is always present when a free draw is given. It does not depend on its length. The force increases with machine speed, web bending radius (due to its bending stiffness), and depends on the total mass (basis weight and moisture content).
- **Vacuum:** The faster the machines speed, the higher is the vacuum force. The active length of the vacuum effect is short.

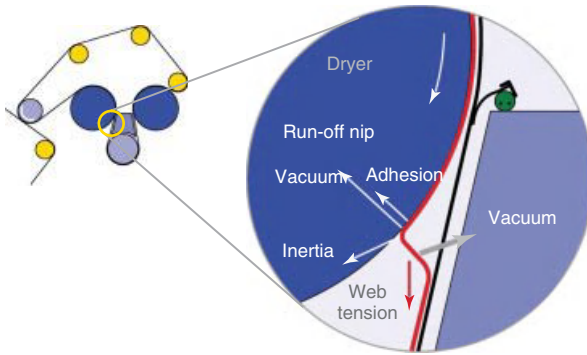


Figure 16.23 Forces acting on the paper web in a free draw [12].

Table 16.3 Forces on the web in a short free draw at high machine speeds, their causes, and importance.

Force		Induced by . . .	Increasing with . . .
Peeling off	F_P	Adhesion	Machine speed Moisture content Poor release properties
Inertia	F_I	Machine speed	Machine speed Smaller web bending radius Moisture content
Vacuum	F_V	Web detachment	Machine speed
Air pressure	F_{AP}	Entrained air flow Free air movement	Machine speed Air flow velocity
Draw	F_D	Speed difference	Higher required web tension

- **Pressure by entrained air:** Air is carried by the web in a boundary layer. The longer the free undisturbed run, the thicker is the boundary layer. When the air hits the next contact (as a barrier), a pressure is built up stressing the web. The force increases with machine speed and free draw length.
- **Pressure by air flows:** When air flows “uncontrolled” within the machine and hits the web in the free draw, the resulting force depends on the air velocity and impinged web length.
- **Draw force:** The speed difference between two adjacent rolls defines the strain and thus the web tension.
- **Friction:** As this force is pretty low, it can be neglected.
- **Weight:** The longer the free draw and the higher the web moisture content, the higher is this force. For today’s high speed paper machines the weight is mainly relevant for the inertia forces.

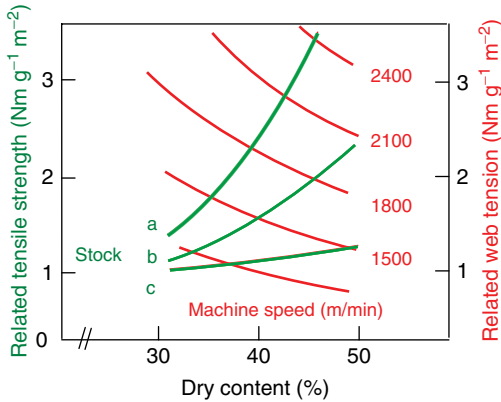


Figure 16.24 Estimation of the maximum speed depending on web dryness and stock type. [12, 13]. (a) Spruce sulfite (19SR), (b) Ground wood, and (c) Spruce sulfite (14SR).

The draw force has to be higher (at least equal) than the sum of all forces in the free draw (i.e., without peeling force) to ensure reliable web transfer without web fluttering. The higher the draw force, the smaller is the angle at the web peeling line. In a very short draw, the centrifugal force is determinant. Figure 16.24 shows how the maximum speed can be estimated taking into account the web strength (of different furnishes) and only the centrifugal force both depending on moisture content [12, 13]. Here, bending strength is neglected.

In a multicylinder drying section, the web tension is built up by the draws between the drive groups. The necessary minimum draw increases with speed and decreases with dryness of the web. The maximum draw the web can resist without break depends on grade, fiber properties, filler content, dryness, and MD/CD ratio. The draws have to be adjusted very sensitively.

In order to further reduce the forces acting on the web and to reduce the necessary draws at high machine speeds, single-tier dryer groups are equipped with high vacuum stabilizers. In the critical area, where the web has to be released from the cylinder surface, the stabilizer has a separate high vacuum zone, where a vacuum of up to 2000 Pa is applied. In the rear dryer groups, where the paper web has higher dryness, standard vacuum stabilizers are installed.

Stabilizers are also used in double-tier dryer sections to hold the paper web on the fabric and to reduce the length of the open draw.

16.4.1.3 Steam and Condensate Systems

The steam and condensate system is also split into groups to control the heating curve. Temperature of the cylinders and hence steam pressure in the different heating groups have to be adjusted to optimum paper web temperature and dryness. The steam pressure needs to be increased along the dryer section. Only in the last group the steam pressure often is lower than in the previous one. The most economic steam and condensate system is a cascade system, supplying only the last (called “main”) group with fresh steam and supplying its blow through

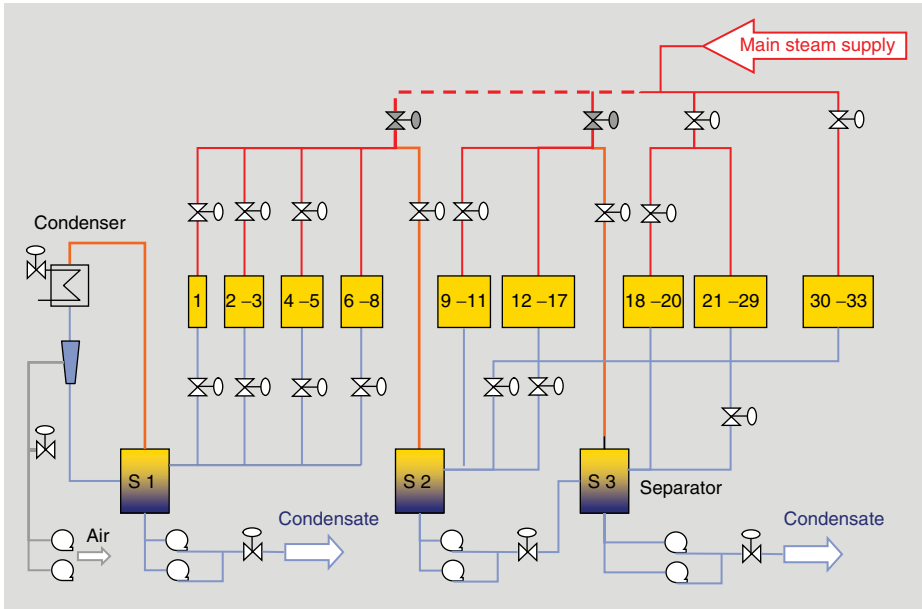


Figure 16.25 Steam and condensate system with steam supply to the dryer groups in cascading sequence. (Source: Voith.)

steam to the last but one, and so on. The blow through steam of the heating group with the lowest pressure (often below 1 bar) is fully condensed and remaining air is exhausted from the steam–condensate system by a vacuum pump. In Figure 16.25, a steam and condensate system is shown with cascade for the predryer groups.

16.4.2

Ventilation Systems

The ventilation system has to supply fresh air of the required temperature to the places where water vapor is generated and from where it has to be carried off. It should improve production capacity and quality, avoid air condensation problems, and also take care for a decent machine room climate.

16.4.2.1 Pocket Ventilation

Pocket ventilation is needed for carrying off the evaporated water from the pockets in the dryer section. This decreases the partial pressure which results in a higher mass transfer respectively drying rate. It also has to assure equal drying conditions in CD and improved paper quality regarding moisture profile. “Pockets” are the space between adjacent cylinders or cylinders and suction rolls. A certain amount of air is required to ensure an even paper surface temperature profile across the width. More air is needed where a high evaporation rate is given, and less toward the end of the dryer section.

The air is blown into the pockets by boxes installed below the suction rolls, by ventilation stabilizers that support the web run and supply air to the pocket, or by blow rolls as guide rolls. Also doctors with additional function of air supply are in use. The air carrying the evaporated water escapes to tender and drive side and is exhausted by the hood ventilation system.

16.4.2.2 Dryer Hood Ventilation

The whole dryer section is enclosed in a dryer hood to control the climate and to allow effective heat recovery. The hood is made of insulation panels on a frame. Doors on tender and drive side give access for inspection. Hot air of up to 110°C is blown into the hood by means of the pocket ventilation and exhausted via openings under the hood roof. The exhaust air is led to the heat recovery system. Normally, two or three separate hood ventilation systems are installed along the dryer section.

The “0-line” describes the position in the hood with ambient pressure, below toward the cellar is under-pressure and above is over-pressure. The 0-line position can be adjusted by changing the supply/exhaust air ratio in order to avoid uncontrolled sucking of ambient air into the hood, or to blow out hot and moist air into the machine room. The ratio between evaporated water and supply air influences the dew point. The higher the dew point, the more effective is the heat recovery, but too high a dew point may result in condensation problems at the walls and the roof of the dryer hood.

To prevent condensation at the hood walls, they are insulated and make up air is often supplied along both hood sides from underneath. These measures allow a low amount of make up air, a high air dew point of the exhaust air, and effective heat recovery. Today, usual dew point temperatures of the air are about $50\text{--}60^{\circ}\text{C}$ and even up to 65°C for a hood with good insulation. The air system for the dryer hood is dew point controlled. This means that best heat recovery and no condensation is assured for all paper machine operating conditions. Figure 16.26 gives a view on a closed dryer hood with windows and doors to be opened for inspection.



Figure 16.26 View on a closed dryer hood with windows and doors to be opened for inspection. (Source: Voith Krieger.)

16.4.2.3 Machine Room Ventilation

The aim of machine room ventilation is to improve working conditions in the machine room and to protect the building structure. The air is blown into the room at floor level. When it is directed into the working area of the personnel, the air velocity should be below 0.5 m s^{-1} , the air temperature about $22\text{--}25^\circ\text{C}$ for their comfort. All the air goes toward the machine room roof, where it is collected. Figure 16.27 gives an overview where heat and humid air should be carried off. The machine room ventilation is part of the overall air and heat recovery system.

16.4.2.4 Heat Recovery System

The heat existing in the exhaust air has to be recovered for economic and ecological reasons. The heat recovery system recovers most of the heat in the exhaust air of the dryer hood. It often also makes use of the heat in the Turbair blower or the infrared heater exhaust. The heat is used for preheating of the supply air and for heating up of process water. The supply air is used as fresh air for pockets, dryer hood, and machine room ventilation. Figure 16.28 shows an example of a state-of-the-art

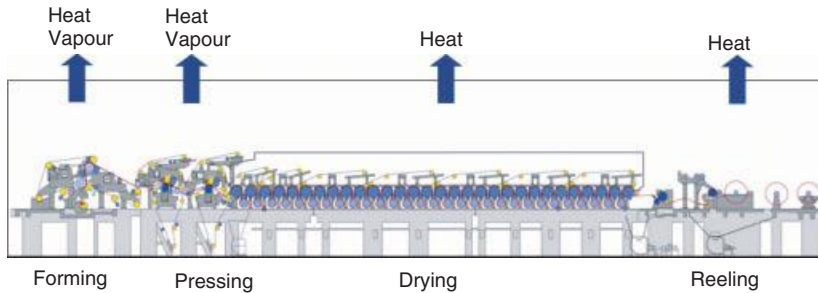


Figure 16.27 Overview where heat and humid air has to be carried off in a machine room. (Source: Voith Krieger.)

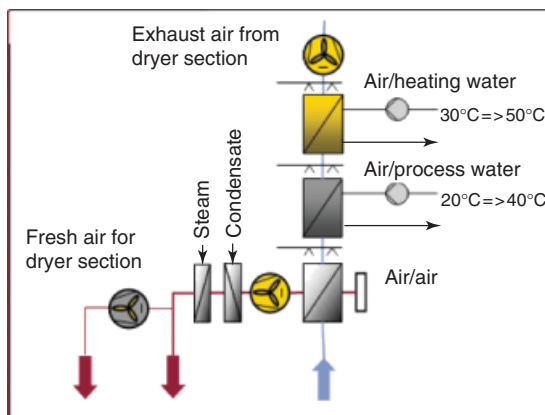


Figure 16.28 Air system coupling pocket, hood, and machine room ventilation as well as process water heat up. (Source: Voith Krieger.)

multistage air system coupling pocket, hood, and machine room ventilation as well as process water heat up.

At heat recovery, special attention has to be paid to the fouling of heat exchangers due to condensation of the air, which may contain particles and condensing matters entrained from the dryer section.

16.4.3

Tissue Dryer Section

Conventional tissue drying is a combination of contact drying by one large tissue cylinder and impingement drying by a high velocity hood. At present, a combination with TAD is used for premium grades. The tissue cylinder with impingement hood follows after the through air dryer section which replaces the press section. In some cases, only through air dryers are used.

Cogeneration of electrical power (for drives) and heat energy (hot air and steam) saves energy. A gas turbine provides electrical energy. The exhaust gas of the turbine is coupled with the air system of the dryer hood. With the exhaust air of the hood steam is generated for the tissue cylinder.

16.4.3.1 Tissue Cylinder

Tissue cylinders (Figure 16.29), also called *Yankee dryers*, have a width of up to 8.2 m and a diameter of 3.6–5.5 m, and in special cases even up to 6.3 m. The inside of a tissue cylinder shell is usually ribbed for maximum drying rates. A ribbed shell provides about 20–25% higher drying capacity than a plain shell dryer at the same safety. The drying rate is further enhanced by turbulence generators. Condensate removal is performed by two-phase flow through a rotating soda straw syphon

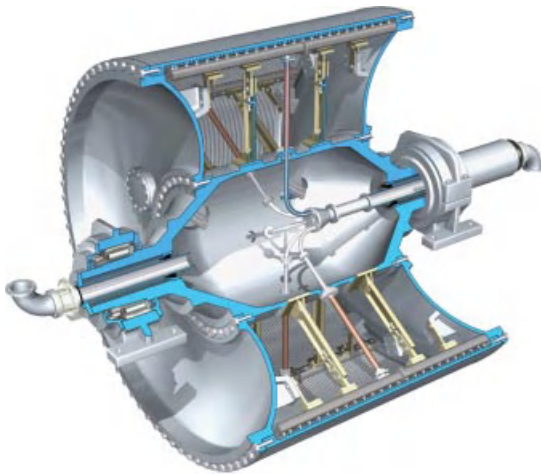


Figure 16.29 View inside a ribbed tissue drying cylinder with soda straw siphons. (Source: Andritz.)

system. The cylinder shell, made of special gray cast iron or sometimes steel is the most sensitive part as regards safety against catastrophic failure. It undergoes a mainly two-dimensional combined static and dynamic stressing. This is due to inside steam pressure, high temperature gradient across the shell thickness, high centrifugal forces, and dynamic stress due to press roll loading. So, the admissible steam pressure has to be limited. Safe Yankee dryer operation conditions depend on adequate stress calculation, including the influence of nonconformities in the dryer shell, and a continuous thorough inspection of the cylinder [14, 15].

For good creping effect, a coating consisting of hemicellulose and/or synthetic agents has to be established on the cylinder shell surface. This also reduces wear. Prolonged cylinder lifetime can also be achieved by covering the surface with a metal spray coating. One (or two) press roll(s), dewater the web and bring it into good contact with the cylinder surface for intense heat transfer.

The shell shape in CD depends on the operating conditions. These must be defined in advance, in order to grind the adequate crowning on both cylinder and pressure roll(s) for uniform web pressing and dewatering in CD. As operating conditions may vary in a certain range, the cylinder shape and the moisture profile in CD may also show some deviations (Chapter 23). To end up with a uniform moisture profile and creping quality, modern tissue drying includes a press roll that can better adjust to cylinder shape deviations as well as a dryer hood with a CD moisture profiling system.

Yankee dryers are also used for drying of one-side glazed paper or coated board, typically with a plain shell.

16.4.3.2 Tissue Dryer Hood

The tissue dryer hood is also called *high velocity hood*, high temperature hood or high efficiency hood. It spans the tissue cylinder by about 220–260° and consists of two halves both of which are retractable. The nozzle plate is concentric to the cylinder and includes exhaust openings. The diameter of the nozzles is about 5–7 mm depending on the spacing between the nozzle plate and the cylinder. The ratio of nozzle diameter to spacing has to be optimized with regard to minimum fan energy consumption and maximum drying rate. The minimum spacing is limited for runnability reasons to about 20 mm. Air temperatures of up to 700 °C and air blow velocities of up to 210 m s⁻¹ can be used. Usual operating conditions are around 350–500 °C and 100–150 m s⁻¹.

For CD moisture profile control, the hood is divided in several sections across its width and is insulated. Its design has to account for the large temperature differences when heated up. The air system with burners, fans, and heat exchangers for heat recovery is located in a separate place outside the hood. A tissue dryer hood and its air system are shown in Figure 16.30. Such hoods are also used in the production of one-side glazed paper, typically, as steam heated hood.

16.4.3.3 Through Air Dryer

This type of cylinder can be built with diameters up to 5.5 m, or in special cases up to 6.7 m, and widths of up to 9 m. It has a free outside surface area of up

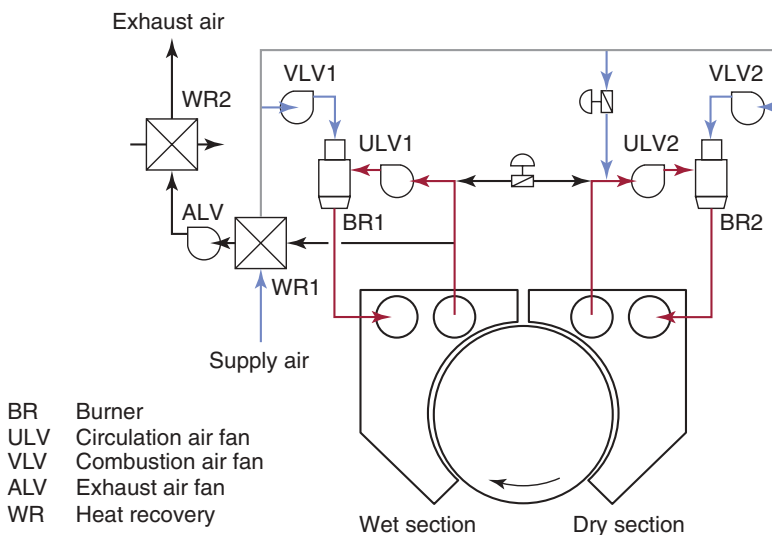
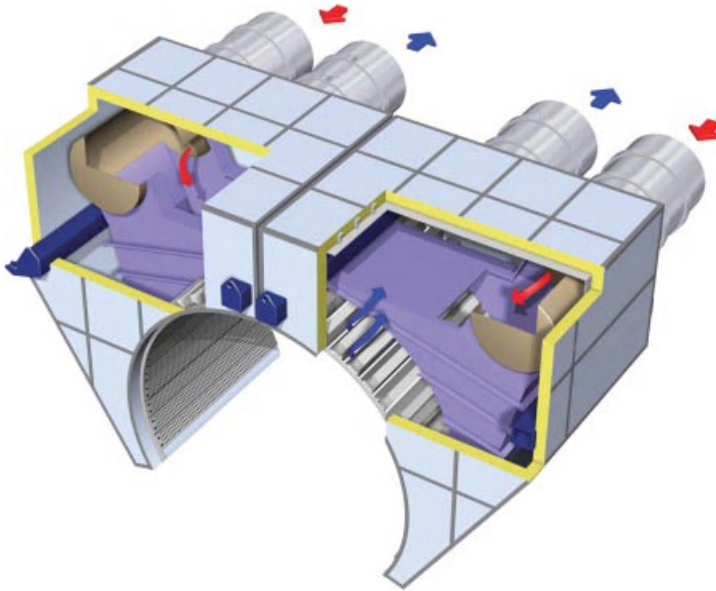


Figure 16.30 Schematics of a tissue dryer hood and an air system. (Source: Andritz.)

to 96%, in order to have a uniform air flow through the paper web. During its contact with the cylinder, the paper web is supported by a revolving wire. The cylinder can run at speeds of up to 3000 m min^{-1} . Air is usually sucked into the cylinder by reduced pressure and is supplied by a hood wrapping the cylinder by about 250° . The temperature can be up to 300°C . The design has to withstand the heat-up and cool-down cycles during its operational life and always has to ensure

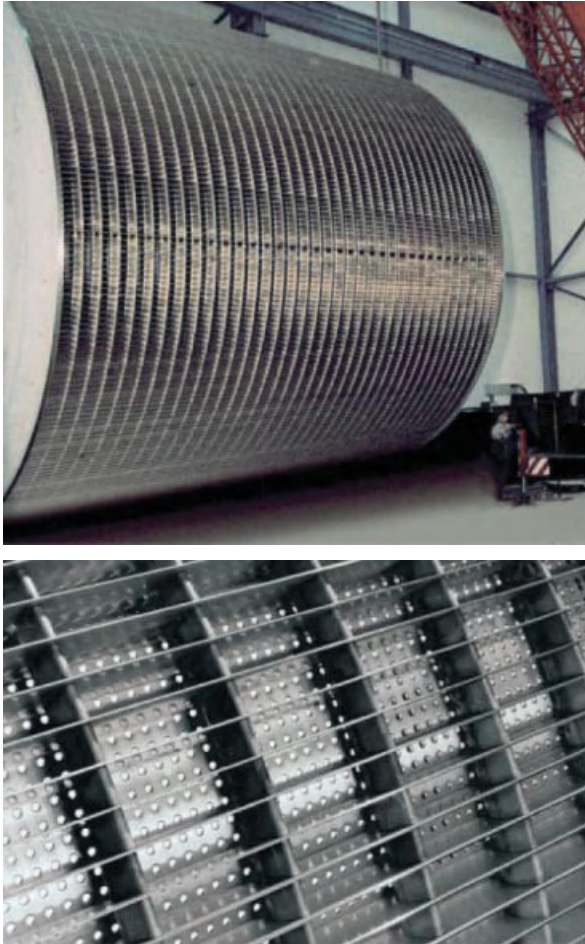


Figure 16.31 Overall view of a cylinder for through air drying with a highly open surface and some construction details. (Source: Fleissner.)

a uniform geometry and drying conditions. Figure 16.31 gives an overall view of a TAD cylinder and a closer look at the construction.

16.4.4

Drying of Coated and Surface-Sized Paper and Board

Drying of coated paper and board has to take into account the special characteristics of the coating color. Some water penetrates into the pores of the paper sheet. Fast heat up and high evaporation rate is admitted until a first critical concentration. The binder is then immobilized. From here on, the evaporation rate has to be reduced in order to avoid concentration gradients, which for example, may lead

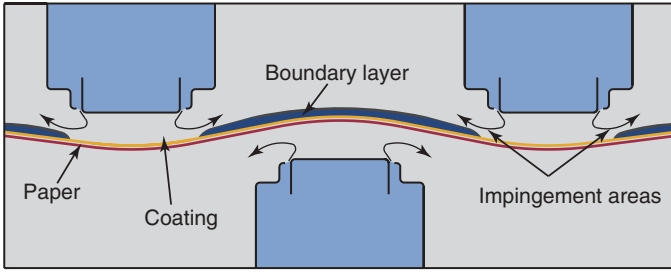
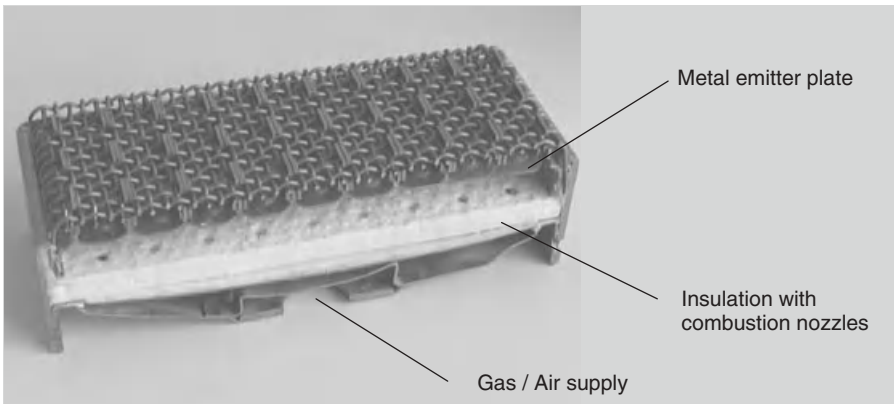
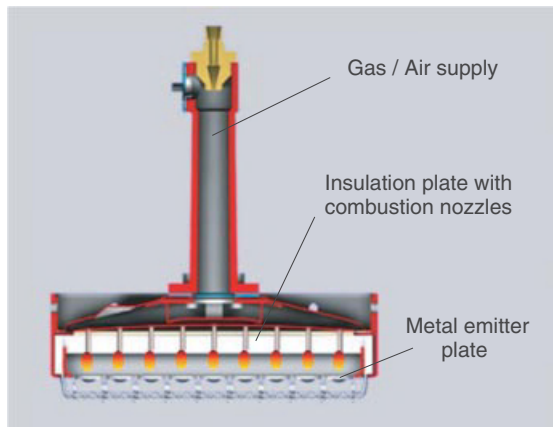


Figure 16.32 Air flotation dryer with web stabilization by sinus wave web run. (Source: Voith.)



(a)



(b)

Figure 16.33 Principle of a gas fired infrared dryer emitter and an example of an emitter. (Source: Voith Krieger.)

to mottling in wood-free coated papers. The most compact structure is reached at the second critical concentration, where the water in the coating layer has been displaced by air. On the other hand, sufficient high temperature has to be reached in the coating layer and paper to cure the latex binder.

With contactless drying, sticking of the coating color to the cylinder surface is avoided. Contactless drying is done by combined infrared and air flotation drying. In Figure 16.32, the principle of an air flotation dryer is shown, where the web run is stabilized by sinus wave configuration. The impinging air breaks down the boundary layer for improved drying. For curl control of surface-sized copy paper, a double-tier dryer group usually follows the air flotation drying section. The principle of a gas-fired infrared dryer emitter and an example of an emitter are shown in Figure 16.33.

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17

Surface Sizing and Coating

Reinhard Sangl, Werner Auhorn, Werner Kogler†*, and Martin Tietz**

17.1

Surface Sizing

Surface sizing is usually an on-line process in the paper machine, where a starch solution, a sizing agent, or a mixture of both is applied to the paper web. The common application principles used for surface sizing are the pond size press and the film press or metered size press.

17.1.1

Objectives of Surface Sizing

The adhesive properties of the sizing solution, which is pressed into the fibrous network, lead to a considerably higher strength of sized papers than of unsized papers. This is, for instance, important for liner and corrugated media and also for other packaging papers as well as graphic papers. For increase in tensile strength, penetration of the size into the paper is desired. If the main objective is to increase surface strength, for example, for printing, the size should remain on the surface.

Sizing also reduces the penetration of liquids into the paper; for example, sizing limits the ink spread when writing or printing onto the paper. The same effect is desired for coating base papers, since sizing improves the coating holdout in the subsequent coating process.

17.1.2

The Sizing Principle

Starch solution, a sizing agent, or a mixture of both is applied to the paper web in a size press or a metered size press (MSP). In a pond size press (Figure 17.1), the web is passed through a pond of the sizing agent, which is located above a roll nip. As a result of both capillary action in the pond and the hydraulic pressure in the roll nip, the paper web absorbs the sizing liquor.

† Deceased.

* Contributed to the First Edition.

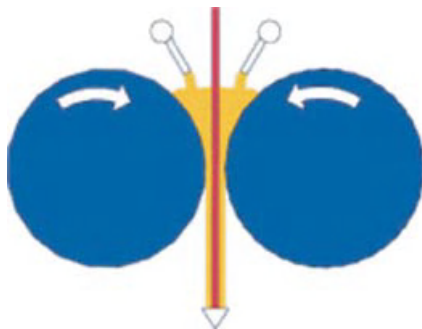


Figure 17.1 Size press. (Source: Voith.)

The amount of size pickup and the degree of penetration depend upon

- the pond height
- the concentration and viscosity of the sizing solution
- the absorption behavior (porosity, moisture content, temperature, etc.) of the paper web
- the nip pressure and nip length.

The size pickup is mainly controlled by variation of the size concentration and also by variation of the pond height or nip pressure. Typical size concentrations lie between 5% and 15%; concentrations of 25% or more can also be reached. The pickup is usually $0.8\text{--}3\text{ g m}^{-2}$ dry substance in total, and pickups of 7 g m^{-2} and more are possible. Nevertheless, size concentration and pickup are limited.

In the MSP or film press (Figure 17.2), the required quantity of the sizing agent is predosed on the application roll as a film and transferred from there to the web in a press nip.

The water applied in the size or film press increases the moisture content of the paper web from around 2–4% to 60–75%. The water is evaporated in the after-dryer section. The first cylinder, in particular, must be protected against the buildup of coatings.

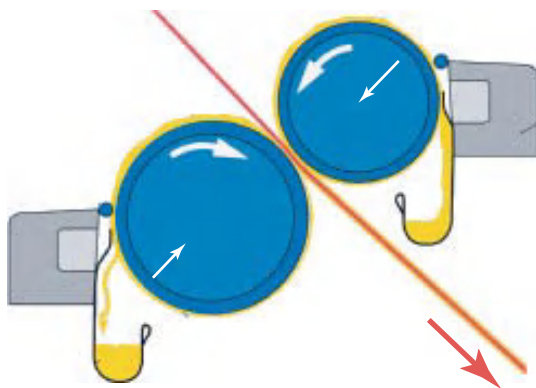


Figure 17.2 Metered size press or film press. (Source: Voith.)

17.1.3

Application of the Sizing Solution

In a traditional size press, the web is passed through a pond of the sizing agent above the roll nip. This was the standard principle for a long time. With higher machine speeds, the turbulence in the pond became unacceptable. The limit is approximately 1000 m min^{-1} . To reduce these turbulences, foils (“size wings”) that dip into the pond can be applied. Thus, the pond level or machine speed can even be increased.

The MSP, introduced in the 1980s, overcomes the speed limitations of a traditional size press. Here, the necessary amount of sizing agent is predosed as a film on the rolls and then transferred to the paper web in the press nip. Predosing for high speeds is done on the press rolls with the help of rotating rods. Unlike pigment-based coating colors, pigment-free sizing solutions do not tend to cause abrasion. This allows the use of profiled (or grooved) rods for metering. The profile geometry controls the film thickness. The application weight or pickup therefore is (almost) independent of the concentration of solids in the sizing solution. A limited variation of the size pickup is possible by adjusting the rod pressure without changing the rod profile. At present, the size presses in use do not limit the speed of the production line, and speeds of 1700 m min^{-1} and more can be achieved.

Spray sizing (similar to spray coating) is now in development and might be applied as a low-cost sizing solution in the future.

17.2

Coating

17.2.1

Overview

During coating, a water- and pigment-based dispersion is applied to the web in order to enhance its surface quality. At present, coating is done off-line or on-line. The process of coating was developed in the United States in the nineteenth century, and it has been in use since then. The real boom worldwide for coating application came in the second half of the twentieth century. Coating application is partly done using equipment similar to that used for sizing, which makes use of rolls or jet applicators.

- **Blade coating:** Usually, coating color is applied in excess, using roll, pond, or jet applicators (Figure 17.3). Here, it is necessary to meter and level the coating color, using stiff or bent blade, metering rod, or air knife (Figure 17.4).
- **Film press coating:** With a film press, metering is performed on the applicator roll and not on the web. When film presses are used for coating, the applicator rolls are softer and the line load is lower than for sizing because a lower nip pressure allows retention of the coating on the surface of the coated paper.

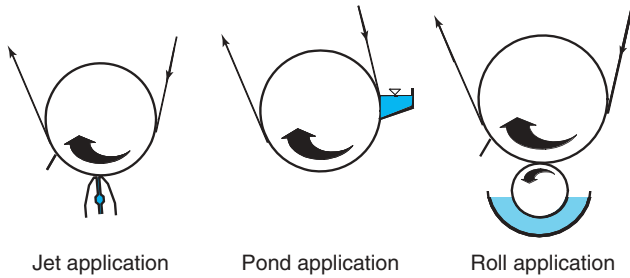


Figure 17.3 Application of coating color in excess (metering required).

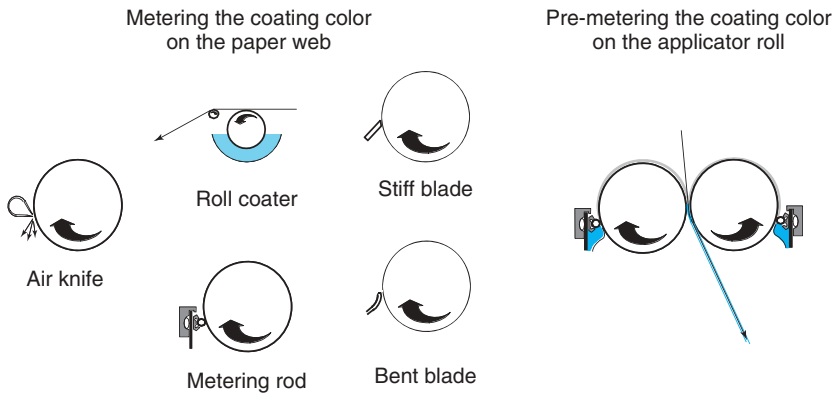


Figure 17.4 Metering elements to dose and level the coating color.

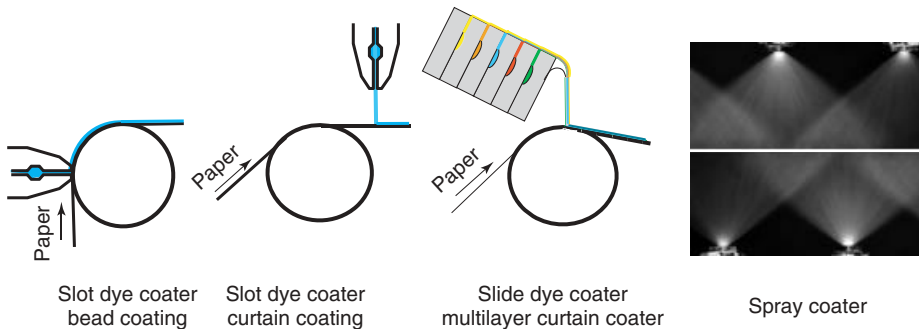


Figure 17.5 "Contactless" application of coating color (no metering but predosing).

- **"Contactless" coating:** For direct application of the coating color in the desired amount (Figure 17.5), either slot dye coaters in bead-coating mode (requiring close proximity to the substrate) or curtain-coating mode (requiring a stable film) or slide dye coaters can be used. In slide dye coaters, especially when operated in multilayer mode, the curtain is smaller than the web width and the edges of the curtain remain on the paper ("in-board" operation). These edges require

special care. Slot dye curtain coaters can also be operated in “overboard” mode, where the curtain is broader than the web width. Spray coating has not been implemented as an alternative for pigmented coating in the paper industry.

17.2.1.1 History of Paper Coating

Some historical steps in the paper coating process are listed in Table 17.1.

There have been significant changes in the coating process since the 1920s (Figure 17.6):

- The machine width increased from 1 to a maximum of more than 10 m.
- The speed increased from about 50 up to about 1800 m min^{-1} .
- The length of the coating machine, however, increased from about 80 to only 115 m.

Table 17.1 Some historical steps in the development of paper coating.

Middle Ages	First hand-coated sheets (clay dyes and carbonate), brush technique
1886	First coating machine in Dresden (Germany)
1933	Roll coating
1938	Air knife metering
1945	Blade metering
Until World War II	Further developments in the United States
1950	US techniques introduced in Europe
1990	Film press for coating grades
2000	Spray coating for commodity grades installed without a breakthrough
2000	About 50 installations of curtain coaters for specialty grades

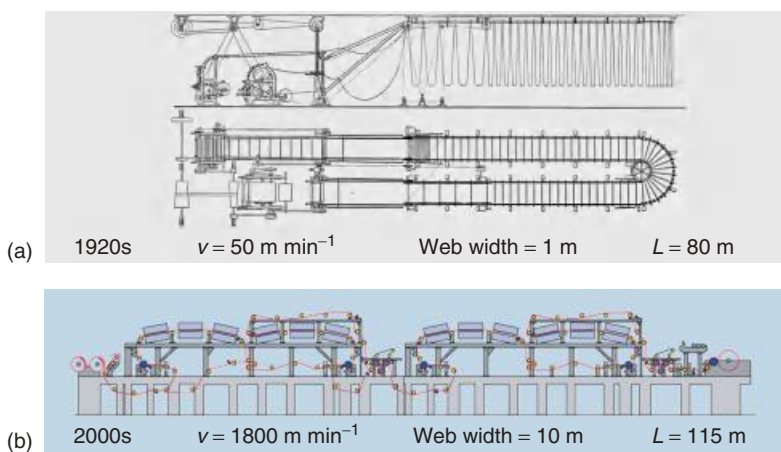


Figure 17.6 Early (a) and recent (b) coater designs. (Source: Voith.)

In the earlier machines, the web was draped during drying like an oversized undulating band suspended on rails, filling most of the machine hall. At present, drying of the wet coat is usually done first by infrared and air float dryers; this is followed by final contact drying on steam-heated cylinders.

17.2.1.2 Technological Developments

Figure 17.7 summarizes some of the technological developments and their drivers during the past 50 years. Of course, the developments in various paper grades have been different. However, the general direction toward low-cost production of commodities with recent emphasis on the importance of sustainability is outlined.

17.2.1.2.1 Pigment Development The lower section of Figure 17.7 indicates that during the 1960s and 1970s, clay was more or less the exclusive pigment used for paper coating. This was true especially for secondary kaolin types, which require comparatively little upgrading. As wet grinding was improved, ground calcium carbonate (GCC) entered the market in the 1980s. Various advantages in terms of costs and performance (brightness and solid content) have turned it into the most important mineral for paper coating at present. The instability of this mineral at lower pH values, however, required revolutionary changes in the papermaking process, which had been performed at acidic conditions until then. In many cases (with exceptions, e.g., for lightweight coated (LWC) paper for rotogravure printing), platy clay particles are at present used to tune coverage, smoothness, and gloss into

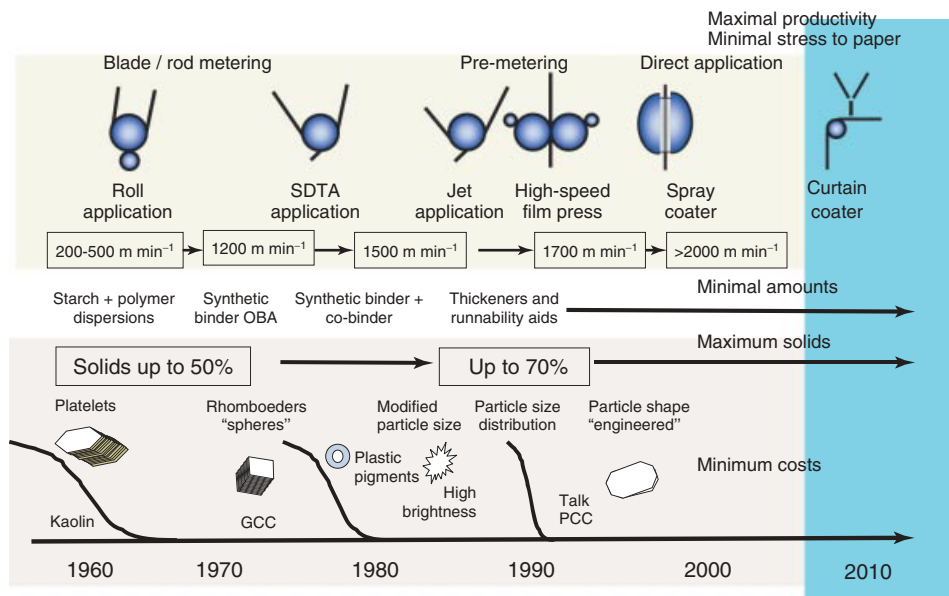


Figure 17.7 Some of the major developments in paper coating since 1960. GCC, ground calcium carbonate; PCC, precipitated calcium carbonate.

the desired direction, while GCC serves as the pigment body. Pigment development then turned toward further improving brightness and gloss, for example, by using plastic pigments. For maximum pigment performance, particle size was adapted in terms of median particle size and size distribution. The development of jumbo rolls for rotogravure grades in the 1990s enhanced the importance of talc as a coating pigment even in regions where this mineral is not so easily available. Reduced friction helps avoid cracking and creeping close to the core of jumbo rolls during roll handling, which compensates for higher costs due to logistic reasons. Many efforts toward engineered particle shape have been reported. “Ideal” pore size distributions are possible with these specific developments. However, the increasing importance of and competition from electronic publications has led to pressure on manufacturing costs of paper. Therefore, over the past decade, costs have been dictating the use of coating color components more than ever before.

Pigments, as the “body” of the coating color, exert a major influence on the solid content of the coating colors, which can be further processed on the coater. The compact habitus of rhombohedral GCC particles, especially, helped develop coating colors in industrial use with a solid content close to or even above 70% by weight.

17.2.1.2.2 Developments in Binders and Chemical Additives In the 1960s, starch was the main coating binder, only complemented with polymer binders and other chemical aids; latex gained in importance later on. Long polymer chains provide the binding power of starch, but they give rise to a comparatively high viscosity. This allows only for low solid contents in starch-based coating colors. Long polymer chains with a high binding power are also inside the latex spheres. The cores of these spheres hinder these polymers from unfolding before the drying process starts and allow latex dispersions to be delivered at a solid content of ~50% by weight and with a waterlike viscosity. Latex also exhibits a high flexibility for tailor-made binder properties by changing the monomer composition, particle size and size distribution, and manufacturing process, including emulsion systems, to control properties such as brittleness, glass transition temperature T_g , and many others. Therefore, latex has become the most important binder type for paper coating. Optical brighteners and rheology aids are added to improve product quality. Polyvinyl alcohol (PVOH), with its high binding power and good stabilization of optical brighteners, has also gained importance.

The consolidating costs of coating color components as well as the increasing demand for sustainable manufacturing processes and products are the use of tailor-made starches in coating colors in use at present.

17.2.1.2.3 Developments in Coating Machinery The possibility to increase production speed was a major reason for the further development of the coating colors and their components. During the twentieth century and the years thereafter, a higher efficiency was successfully translated into an increased manufacturing speed. An extraordinary growth in paper demand allowed for this development,

and overcapacities due to new, fast paper machines were “swallowed” immediately by the growing demand for paper products.

The ability of the application systems to run at high speed was one of the driving factors in these developments. The reliability of roll applicators proved to be limited to coating speeds of about 1200–1500 m min⁻¹. Exceptions with much higher speeds are known, but not usual. The long contact time of the coating color between application and metering was detected as one possible reason for web breaks due to insufficient wet strength of the paper. Short dwell time applicators (SDTAs) were designed to overcome this problem. But turbulences within the chamber may induce severe quality problems, so that this system is not common in new installations. At present, a jet applicator with subsequent blade metering is the system of choice for many grades of paper and allows for a good runnability and high quality due to the leveling effect of the blade.

A blade “scratching” on the paper surface at very high speeds, however, seems a natural reason for web breaks in case of irregularities in the web. Metering has therefore been removed from the paper web and placed on the transfer roll in film press applications. With MSP application, the stress on the web is reduced considerably when the blade is not working on the web. However, film split after the transfer nip and the metering element needs to be controlled at high speeds.

A further reduction of the stress applied to paper is possible with “contactless” application systems, where the exactly desired amount of coating color is directly applied to the web. This can principally be done using spray devices, which have not really established themselves for coating beyond one industrial application. Curtain coating, where a falling film is placed on the web, seems more promising and at present is common for many specialty grades. The inherent requirements of curtain coaters such as a degassing to a very high degree, stable curtains, homogeneous edges, and contour-like coating with less smoothness continue to prevent higher market penetration of commodity papers. Further, curtain coating is a one-sided application, whereas a film press allows simultaneous application of a coating layer on both sides of the paper web, thus saving on energy required for drying.

17.2.1.3 Why Paper Is Coated

The main purpose of coating is to improve the surface quality of the paper or board. Quality improvement can aim at optical properties such as brightness, gloss, or opacity; tactile properties such as smoothness; and, most importantly, printability and print image quality.

The application of pigments (usually white) to the base paper surface enhances the brightness of the paper. In addition, the opacity increases because of high light scattering by the pigments. This improves the optical appearance because the shine through of the printing on the other side of the paper is reduced. Further, the coat layer evens out the surface topography of the sheet, resulting in an improved smoothness, which in turn gives a better gloss.

The coat layer reduces the penetration of ink into the paper sheet. Therefore, the ink does not spread as much, and the print image is clear and sharp. Print density

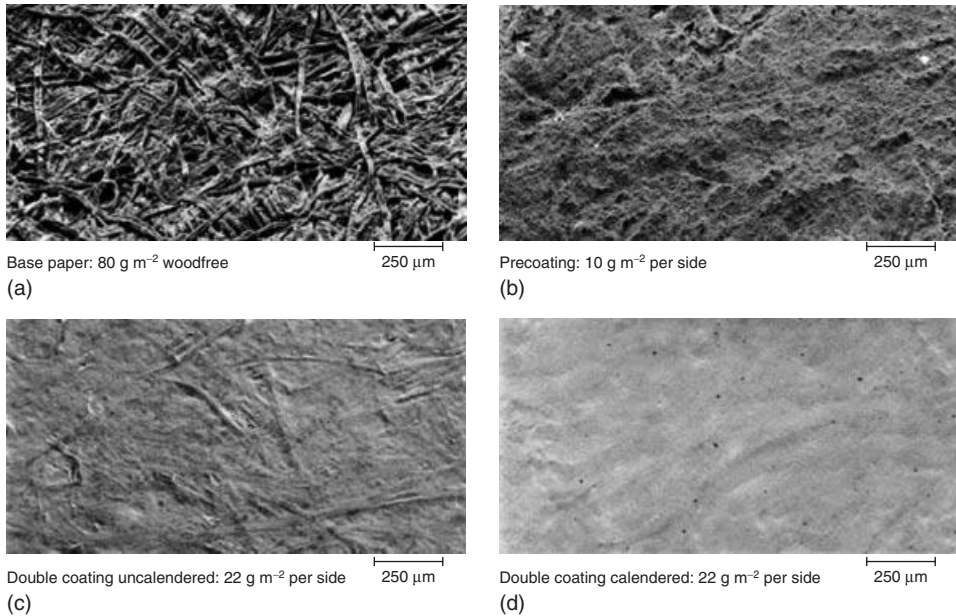


Figure 17.8 Comparison of (a) base paper, (b) precoat, (c) topcoat uncalendered, and (d) topcoat calendered. (Source: Omya.)

and the print gloss are enhanced, and the ink demand is reduced compared to that in uncoated papers.

For specialty papers, the coat layer can have functional properties. Examples are the thermosensitive layer of thermal papers or the capsule-containing coat layer of carbonless papers.

The benefits of applying a coating layer become very apparent when comparing paper surfaces with different coatings. The scanning electron microscope (SEM) micrograph of an 80 g m⁻² woodfree (WF) base paper shows multiple layers of intersecting fibers (Figure 17.8). The paper surface is characterized by hills and dales formed by the fiber mesh (Figure 17.8a). The voids between the fibers impair the smoothness and uniformity of the paper surface. The next micrograph (Figure 17.8b) shows a precoated paper at the same magnification for comparison. A precoating of just 10 g m⁻² per side suffices to cover up the majority of voids and fiber crossings. This helps to smooth and even out the paper surface. Paper surface quality can be further enhanced by the application of a topcoat. Coating the paper with another 12 g m⁻² per side distinctly enhances the existing precoated surface quality, with a number of dominant fiber structures and valleys still remaining visible (Figure 17.8c). Subsequent calendering achieves an additional quality gain by enhancing smoothness and gloss. The resulting surface is flat, with a minimum of irregularities (Figure 17.8d).

An electron microscopic image of a microtome cut from a coated paper sample is shown in Figure 17.9.

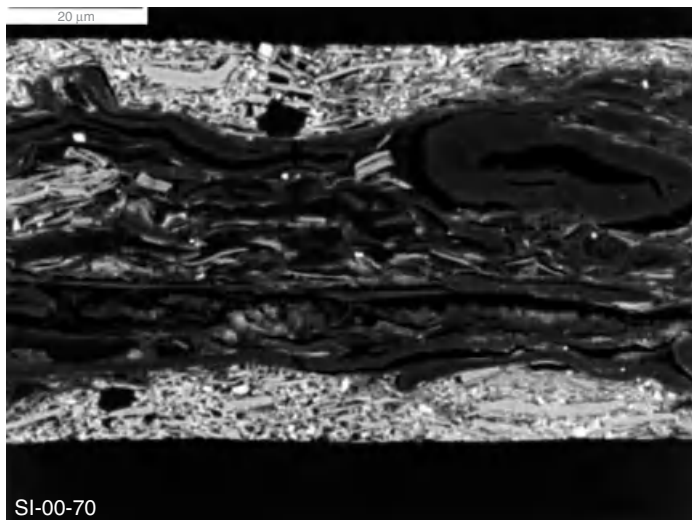


Figure 17.9 Microtome cut of a coated paper sheet. (Source: Voith.)

The fibers can be seen at the center of the sheet. The lighter and more densely packed structure outside the paper sheet is that of the pigments of the coat layers. The caliper of the coat layer varies according to the changing thickness of the base sheet. The surface is smooth; so, by coating, paper and board can be upgraded to a higher quality with added value. Furthermore, raw material costs are also an important factor for coated papers, and coating colors are in most cases cheaper than chemical or mechanical pulp. So, an optimum ratio of coating layer/fiber web has to be found.

Some general reasons for coating paper are

- **To improve the appearance:** whiteness, brightness, gamut, brilliance of colors, and so on; for example, for packaging paper or paper used in promotional items;
- **To improve performance in converting and printing:** uniform absorbency of fluids, for example, in printing, and for good adhesion and release properties;
- **To protect the coating base:** for example, for preventing interactions with fluids;
- **To protect packaging goods:** forming barriers for oxygen, water vapor, fats, oils, and so on;
- **To functionalize surfaces for specialty grades of paper:** for example, release paper.

Some reasons for coating printing papers are

- **To improve printability:** better morphology (uniform surface, especially, in terms of smoothness and penetration);
- **Other qualitative advantages:** ease of varnishing, less dusting;
- **Economic advantages (product-specific):** lower manufacturing costs (pigment price is lower than fiber costs) and lower printing ink demand.

17.2.1.4 Requirements for Coated Paper and Board from Consecutive Processes

Paper requirements are usually defined by the consecutive steps of paper use. For printing paper, this is the printing process; for other paper grades, other or additional converting steps may determine the paper properties. Quite often, coating is the process that satisfies these requirements (Table 17.2).

Carton boards often have to meet additional requirements, as listed in Table 17.3.

17.2.1.5 Requirements for Coating Colors from Consecutive Processes

The product requirements mentioned in this chapter can only be met if the coating color is designed appropriately. Important color requirements are given in Table 17.4.

The coating color needs to be designed in order to meet these requirements. The component pigments and pigment blends, binders and combinations of binders, additives to enhance runnability and quality, as well as the amount of water need to be selected accordingly.

Table 17.2 Requirements for coated paper and board from the printing process.

Printing process	Specific requirements
All printing processes	Uniformity in smoothness and sorptive properties⇒ <ul style="list-style-type: none"> ● Strength (especially tear growth resistance) ● Stiffness ● Flatness and dimensional stability
Letterpress printing	Low-viscosity printing ink is transferred from raised areas of the printing plate to the paper (At present: especially flexo printing) ⇒ <ul style="list-style-type: none"> ● Porosity, ink setting
Rotogravure printing	Printing ink of low viscosity is absorbed by the paper from etched or machined cups in the printing plate. Good contact required ⇒ <ul style="list-style-type: none"> ● Smoothness ● Absorbency, compressibility
Sheet-fed offset printing	Viscous printing ink and water are transferred from hydrophobic and hydrophilic zones to the paper ⇒ <ul style="list-style-type: none"> ● Ink setting ● Piling ● Water resistance ● Print evenness, print gloss ● Drying of printing ink
Heat-set web offset printing	Higher speed than sheet-fed offset requires thermal drying of the printing ink ⇒ <ul style="list-style-type: none"> ● Blistering
Inkjet printing	Small droplets are shot to the paper from a nozzle. Color needs to develop on the surface, while high amounts of water need to be absorbed by the paper (no thermal drying) ⇒ <ul style="list-style-type: none"> ● For porosity and absorbency (swelling), it is necessary to remove the fluid from inkjet ink surface charge (usually cationic) to allow for color development on the surface

Table 17.3 Additional requirements for carton boards.

Parameter	Specific requirements
Universal printability	Offset printing Rotogravure printing Flexo printing Often also digital printing for individualization (bar codes, etc.) <ul style="list-style-type: none"> • Porosity • Ink setting
Converting	Creasing, folding, bending, and so on without breaks; sufficient stiffness
Glueing	Often also heat sealable
Varnishing	Lacquer adhesion
Barriers	Water vapor, oxygen, fat, and aromas
Mechanical protection	High stiffness at low grammage
Special effects	For example, extreme smoothness for electronic printing, RFIDs, or sensors
Food contact	Odorless coating (minimum of volatile compounds); must meet requirements for food contact (e.g., FDA approval)

Table 17.4 Color requirements derived from the coating principle.

Parameter	Specific requirements
Chemical stability	Undesired interactions of coating color components should be avoided, for example, stability to Ca ions
Rheology	Transport and metering processes require a good processability, for example, shear thinning behavior and no dilatancy
Water retention	The coating color should not lose soluble or mobile components during the contact with paper when recycled
On-line coating	<ul style="list-style-type: none"> • Good water retention at elevated temperatures • minimal yellowing at high temperatures • quick film formation
Precoat	The coating base surface roughness (pigments) should be smoothed The precoat should have high binding power (binder penetrates into the coating base)
Middle layer	This layer should cover the lower layers and provides uniform surface
Top layer	This layer should functionalize surface, for example, good printability
Calendering	For effective improvement of gloss and smoothness at calendering conditions, the following properties should be satisfied: <ul style="list-style-type: none"> • Low adhesiveness to calender rolls • Minimal thermal yellowing
Coating speed	High shear stability of all components

17.2.2

The Process of Coating**17.2.2.1 Penetration and Migration**

Soluble and mobile components of the coating color will penetrate into the coating base when the color is applied. The different steps of penetration, listed below, are illustrated in Figure 17.10:

- application, when the color is put on the coating base;
- immobilization, when a filter cake forms and the excess water together with dissolved and mobile color components penetrates the coating base;
- drying, when water inside the coating base and the coating layer moves toward the surface and is evaporated there.

Small binder particles penetrate into the base paper together with water and they also migrate during drying. Any nonuniformities of the porous structure of the coating base will lead to nonuniformities in the concentration of soluble and mobile substances on the surface and these may even be enhanced during printing.

17.2.2.2 Absorbency and Porosity Influence Quality and Runnability

The processes during metering (blade coating) and film transfer (film coating) are explained in greater detail in Figure 17.11. The mobile coating color, which is applied in excess to the web (for blade coating, about 20–25 times more than will stay after metering), will immobilize close to the web surface. Soluble and mobile components of the coating color start penetrating directly after application. The pressure impulse from the metering element will enhance this penetration when

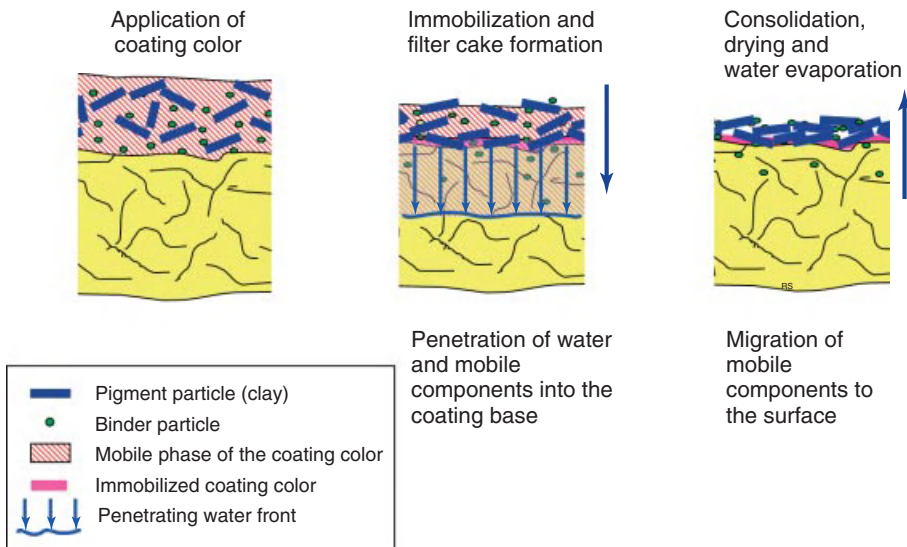
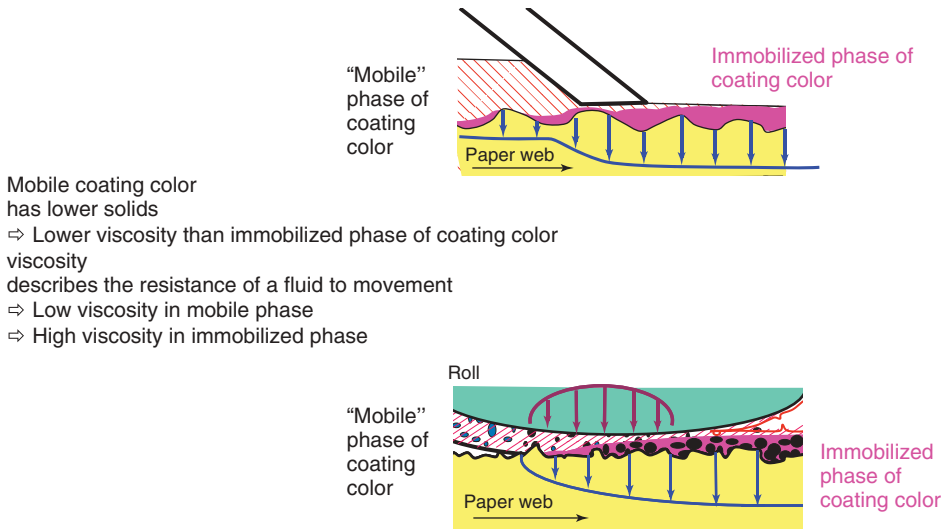


Figure 17.10 Interactions between coating base and coating color.



Mobile coating color

has lower solids

⇒ Lower viscosity than immobilized phase of coating color

viscosity

describes the resistance of a fluid to movement

⇒ Low viscosity in mobile phase

⇒ High viscosity in immobilized phase

Figure 17.11 A thin mobile phase of the coating layer is required for blade and film coating after the film split/metering. (Source: PTS.)

the blade meters the color. The immobilized coating color has a higher viscosity than the mobile color with lower solid content. A higher viscosity means a higher resistance to movement. The objective in blade coating is to keep the blade working in the mobile phase.

Similar processes occur during film transfer in a film press or MSP. Penetration and immobilization start with the contact between coating color and base paper, that is, at the beginning of the transfer nip. The objective is to maintain a thin mobile phase at the film split at the end of the nip. Problems such as misting or orange peel can be controlled if this thin mobile phase can be stabilized during film transfer, as shown in Figure 17.11.

Figure 17.12 illustrates in greater detail how deep the waterfront penetrates into the paper, how thick the mobile and immobilized phases of the coating color are, and what happens if paper and coating colors are not adapted properly in blade coating. The consequences of an insufficient adjustment between base paper and coating color are described explicitly in this figure.

For film-coating, coating color and coating base have to be adapted as well (Figure 17.13). Typical problems such as misting or orange peel can be avoided if this adaption is done properly.

Owing to different conditions in terms of temperature, coating speeds, and consequently hydrodynamic conditions and pressures, as well as machine settings (e.g., blade thickness also results in different pressures), it cannot be expected that the same coating colors will behave identically on different machines, even if the base paper is the same.

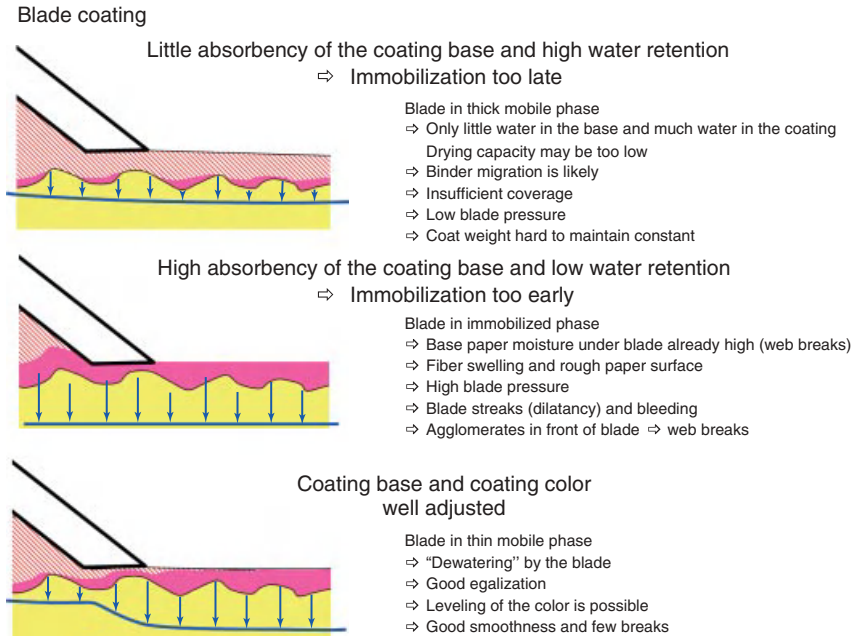


Figure 17.12 Absorption, penetration, and immobilization during blade coating. (Source: PTS.)

17.2.2.3 Means to Adapt the Coating Base

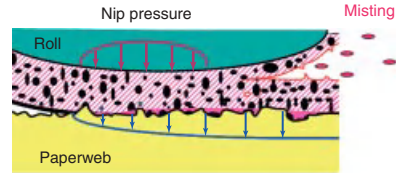
The interactions between coating base and coating color can be controlled by changes in the paper base as well as changes in the coating color. Fibers, fillers, and additives as well as the machinery for papermaking have a large influence on the absorbency of the paper web (Table 17.5).

- **Fiber base:** Generally, WF paper is more open than paper based on mechanical pulp or based on secondary fibers (Figure 17.14). Recycled fibers (RCFs) are the dominant source of raw materials for papermaking, for example, in EU countries or Japan, and can replace virgin fibers in many cases (Section 2.4). However, not all products can be manufactured from RCF, and the system always requires fresh fiber supplements. There are some limitations to the use of RCFs; these are listed in Table 17.6.
- **Fiber treatment:** The most important process defining the absorbency of the base paper is refining (Chapter 7).
- **Fillers:** The content of minerals as fillers or coating pigments in commodity papers has reached values of 50% and higher. In Figure 17.15, the typical range of mineral content is given for selected paper grades in Europe. For some specialty grades, even higher amounts of minerals in a paper product are desired and reached.
- **Additives:** More details on the influence of additives can be found in Chapter 4.

Film coating

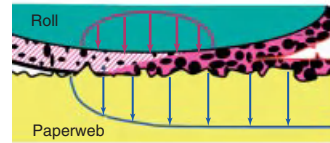
Little absorbency of the coating base and high water retention
 ⇒ Immobilization too late

Film split location (zone of minimal cohesion) undefined
 Low viscosity/cohesion in coating color
 A lot of material for misting



High absorbency of the coating base and low water retention
 ⇒ Immobilization too early

Film split location (zone of minimal cohesion) undefined
 Orange peel surface (no leveling)
 Dry film on roll => break



Coating base and coating color
 well adjusted

Film splits in thin mobile phase
 Good quality (leveling after film split)
 Good runnability

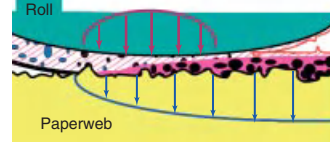


Figure 17.13 Absorption, penetration, and immobilization during film coating. (Source: PTS.)

Table 17.5 Control of web absorbency in the papermaking process.

Fiber base	Chemical/mechanical pulp and secondary fibers
Fiber treatment	Refining, sorting, and so on
Fillers	Nature, mineralogy, particle size distribution, and amount (ash content)
Additives	Hydrophoby, sizing, wet strength agents, and so on
Machinery	Forming, dewatering, pressing, and so on

- **Machinery:** Any device that influences base paper structure in terms of permeability and porosity can be used to control the interactions of base paper and coating color. Examples are formers, dewatering devices, press section design, and so on.

17.2.2.4 Properties of Base Paper in Order to Meet the Requirements of the Coating Process

Coated papers are classified as wood-containing or mechanical papers, and fine papers, which are also called *WF papers*. Wood-containing papers are made of a fiber furnish such as groundwood or other mechanical pulps. RCFs are also an

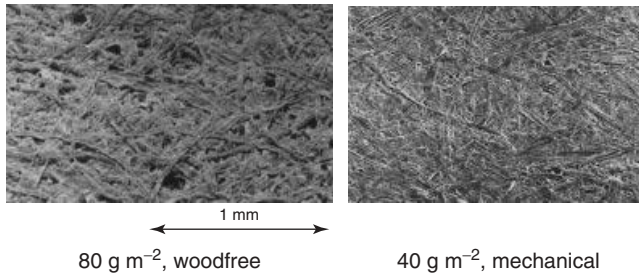


Figure 17.14 Microscopic photographs of a paper made from (a) woodfree and (b) mechanical pulp. (Source: Omya.)

Table 17.6 Limitations in the use of recycled fibers.

Paper machine	Whiteness Ash content Strength (also for folded products) Dirt counts Stickies runnability
Coater	Streaks Fibers in coating color bleeding Coverage Runnability
Calender	Blackening
Printing machine	Picking and negative buildup Short washing intervals Folding strength Runnability Blistering

important and steadily growing raw material for coated base papers. WF papers are made of a fiber furnish of only chemical pulp, or only very little mechanical pulp (no more than 10% of the fiber material). Typical mechanical coated papers are LWC papers, ultralightweight coated (ULWC) papers, medium-weight coated (MWC) papers, and high-weight coated (HWC) papers. Art printing papers are typical WF-coated paper for the highest printing quality (Figure 17.16). Coated folding boxboard (FBB) is an example of coated board, which is used in packaging goods. In North America and Japan, there exists a classification system that is based on the brightness of coated papers.

The base paper in coating must ensure trouble-free running of the coater, provide an optimal basis for paper finishing, and form a base for fixing the coating layers demanded by the end users. The lower the basis weight, the more important are the properties of the base paper. Generally, the best coated paper surface is achieved with the best and most uniform base paper. Variations in formation, absorption, thickness, moisture, and roughness of the base paper have a great influence on

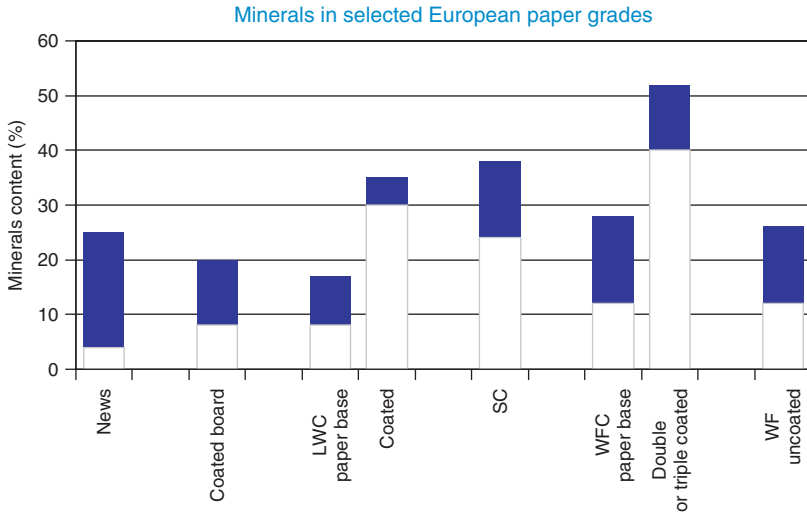


Figure 17.15 Minerals in selected European paper grades; blue = typical range. (Source: Omya.)

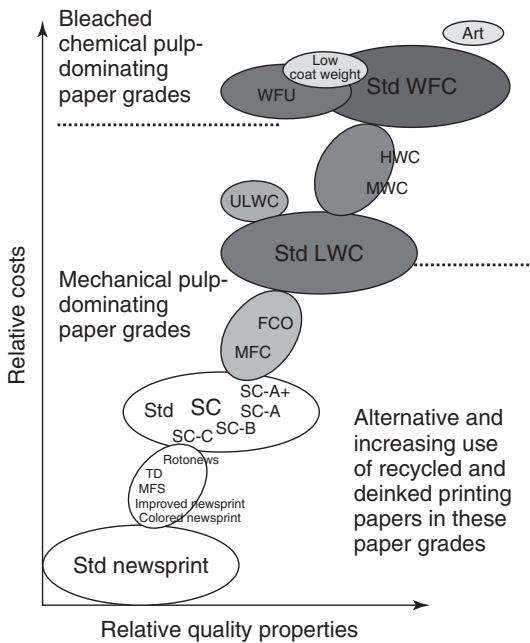


Figure 17.16 Range of printing papers (quality vs costs). (Source: Metso.)

the properties and the uniformity of the coating layer. Nonuniform coat weight distribution is the most important factor in generating uneven print image called *mottling*.

Further critical properties are paper web profiles in the machine and cross-machine directions as regards basis weight, filler distribution, caliper, and moisture. The paper web has to be free from faults, holes, and impurities, and have low fiber roughening potential (for web offset grades), low porosity with a uniform pore distribution, high smoothness, opacity and brightness, minimal two-sidedness, sufficient tensile, and tear strength, as well as sufficient stiffness. Stiffness is related to the bulk of the coated paper. Stiffness, especially, becomes a critical property with low basis weights, high filler content, and high coat weight, and in sheet printing. Bulk can be improved by choosing coarse, bulky fibers, careful wet pressing, and by calendering as little as possible. In sheet-fed printing, the stiffness in the cross-machine direction is more critical. This can be influenced with fiber furnish and by controlling fiber orientation with the jet : wire ratio in web forming.

Good internal bond strength is required both in heat-set web offset (HSWO) and sheet-fed offset. If the internal bond strength is good in HSWO, the blistering temperature increases. In this printing method, printing ink is dried by external heat, while, at the same time, the remaining water in the base paper starts to evaporate. If the internal strength and formation are poor, steam pressure inside the paper web can rise locally, causing bubbles; this is called “*blistering*.” In high-quality printed jobs with colorful printing, it is very important that there is no cracking in the fold. The tendency to crack is higher with stiff mechanical pulp fibers (e.g., TMP) than with chemical pulp fibers, but it remains a problem in WF papers – especially those with high basis weights. Folding properties can be affected by pulp refining, pulp and pigment types, and the amount of starch used in the coating formulations.

The base sheet of board mostly consists of several layers (multiply); therefore, sufficient ply bond and crack fold are additional important parameters besides a uniform and bright surface to achieve a good quality of coated board.

Faults in the coating base usually cannot be overcome by coating – sometimes, they are more severe after coating. Possible faults and their effects are listed in Table 17.7.

The most important base paper properties affecting the coating are described in the following:

- **Strength properties:** To guarantee a good runnability of paper web in coating, different strength properties are needed. Because base paper is wetted in coating units, it requires good temporary wet strength. Wet tensile strength, in principle, is measured using similar methods as for measuring tensile strength, but the sample is prepared differently. Other strength properties related to coating are tear strength and edge-tearing resistance as well as bursting strength.
- **Basis weight, caliper, and moisture profiles in the cross-machine and machine directions:** These have a strong influence on the uniformity of coating, for example, calendering very often controls caliper, which means that in the

Table 17.7 Possible faults in the coating base.

Faults in coating base	Possible effects on the coating process
Holes	Web adheres to the backing roll ⇒ Web break
Hickies and stickies	Humid hickies are torn off ⇒ Web break
Adhesive joints	Strength too low for blade coating ⇒ Web break
Torn/hurt edges	Tear growth resistance too low ⇒ Web break
Low surface strength	Enrichment of fiber material in coating color (blade coating) ⇒ Bleeding
Vessel cells	Little adhesion ⇒ Coating disrupted
Fluctuation in profile (MD or CD) (formation, smoothness, structure, basis weight, strength humidity, surface tension, porosity, and so on)	Cloudiness and dimensional stability ⇒ Quality ⇒ Printability ⇒ Customer complaints

cross-machine direction, some parts of the web are pressed more than others to reach a uniform caliper profile. These more-compressed parts will differ in porosity and smoothness of base paper, which affects the coating amount. Caliper before coating can be measured on-line for control. Basis weight variations usually cause caliper variations; these can be seen as streaks in the machine direction. Moisture variation will affect coating amounts with risks of wrinkles if moisture variations across the web are high. High moisture before coating can affect coating color penetration and the gloss of coated paper and, subsequently, ink settling in printing.

- **Porosity:** If porosity is very high, absorption of coating is also high and coating weight can increase dramatically; drying problems may also occur.
- **Formation:** This property refers to small-scale basis weight variations in paper. There are areas that are denser and less absorbent to the coating than other areas. To reach uniform coating penetration, the base paper requires even formation, otherwise mottling may occur in printing.
- **Smoothness:** A smooth base paper gives a uniform and closed coated surface. The various coating processes have slightly different smoothness requirements. Air knife coaters require a relatively smooth surface because, in that method, coating is applied in a layer of rather uniform thickness, regardless of the base paper contour. Blade coating fills the cavities and leaves the high spots uncovered.

17.2.3

Components and Properties of Coating Colors

Coating colors have a very simple composition, although the interactions between ingredients are far from simple. A coating color consists primarily of pigments dispersed in water, plus binders, cobinders, and additives. Calculations are, as

a rule, based on the dry product, even if the actual ingredients deployed are mainly liquid commercial products with differing dry contents (proportion of active substances). The basis of calculation is 100 parts of pigment, to which all additions are referred. As an example, 24 kg of commercial product binder must be added to 100 kg of dry pigment to obtain 12 parts of dry binder in the formulation if the synthetic binder has 50% dry content.

Coating color components and their properties are described in detail in Section 5. In the following sections, the most important contributions of pigments and binders on processes and quality are mentioned; cobinders and additives are only briefly summarized in Table 17.10.

17.2.3.1 Pigments

The pigment is the most abundant component in the coating; so, it is naturally the most important factor affecting the properties of the coating.

An ideal pigment would have the following properties:

- appropriate particle size and narrow particle size distribution;
- no impurities;
- good dispersibility for easy mixing with water and low water absorption;
- high chemical stability and low solubility in water;
- good compatibility with other coating components;
- good light reflectivity at all wavelengths for high brightness;
- high refractive index for good opacity;
- good glossing properties for eye-pleasing coating gloss and high print gloss;
- low binder demand;
- good flow properties in an aqueous suspension and low abrasiveness;
- low cost.

There is of course no pigment that could meet all these requirements; however, different pigments meet different combinations of these properties. The main coating pigments are clay (kaolin), GCC, precipitated calcium carbonate (PCC), and talc.

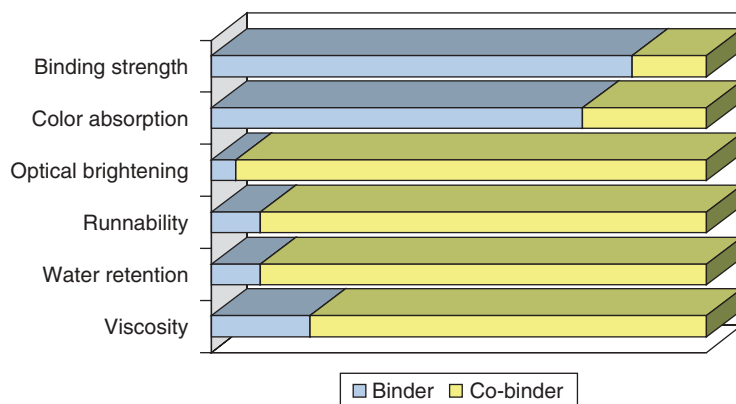
Some pigment properties and their influences on coated paper are given in Table 17.8.

17.2.3.2 Binders

Binders serve as pigment–pigment bonders to anchor the pigments to the base paper surface. They are also expected to prepare the coated papers for the printing and converting stages. At present, synthetic binders are preferred in coating kitchens. They are polymerized petroleum products that are available in the form of dispersions in very fine distributions, often with 50% solids. Some typical starting materials are monomeric styrene, butadiene, acrylic acid, and their derivatives from which products such as styrene butadiene latexes, acrylic acid esters, and polyvinyl acetate are obtained. Besides synthetic binders, natural binders are also used. They are often multifunctional, in that they contribute to bond strength, water retention (WR), and improved runnability. Natural binders include starch and its derivatives,

Table 17.8 Pigments influencing papermaking processes and paper quality.

Pigment characteristics	Pigment property	Influence on processing	Influence on paper property
Optics	Brightness, CIE values, refractive index, and so on	–	Brightness, CIE values, opacity, and so on
Tribology	Particle size, size distribution, and specific surface area	Rheology, solids content, and abrasivity	Binder demand, smoothness, gloss, opacity, abrasivity, ink setting, and so on
Habitus and morphology	Crystal structure, aspect ratio, and so on	Rheology and solid content	Smoothness gloss, opacity, abrasivity, and so on
Solid-state characteristics	Hardness and purity	Abrasivity	Abrasivity
Surface chemistry	Surface charge, surface energy, polarity, and reactive groups	Stability, dispersing, swelling, and solubility (salt concentration),	Printability and runnability in the printing machine

**Figure 17.17** Contribution of binder and cobinder to different properties of coating color and coated papers. (Source: PTS.)

and with some restriction, carboxymethyl cellulose (CMC). These products are normally supplied dry and need to be dissolved during color preparation.

The contribution of the binder to coating color properties is usually small when compared to that of the cobinders, while coated paper properties often depend on the binder system used. This is illustrated in Figure 17.17.

However, the binder does influence the coating color properties:

- **Before application:** compatibility with other components, stabilization of pigments, and rheology;
- **During application:** WR, shear stability, migration during drying, and drying rate;
- **After application:** printability, permeation.

Latex properties can be used to control the properties of coated paper. Table 17.9 shows some binder characteristics and their influence on paper properties.

Among binders, styrene–butadiene latexes dominate besides modified starches. Styrene–acrylate dispersions are specialties and of high importance for impressive prints. Additionally, acrylate dispersions have an excellent brightness and aging resistance and are less odorous. Future requirements of coating process conditions on paper characteristics and printing technologies forced the production of tailor-made binders with very specific property profiles.

17.2.3.3 Requirements Based on Coating Color Components

Table 17.10 summarizes the important requirements of coating color components concerning coating color and coated paper properties and gives, with some examples, some keywords related to the mechanism that helps meet these requirements (Chapter 5).

Table 17.9 Latex properties.

Binder characteristics	Influence on paper property	Example
Monomers used	Pigment binding strength	Styrene
	Print evenness	Butadiene
	Drying of printing ink	Acrylate
	Porosity	
	Hardness and stiffness	
	Print gloss	
	Odor	
Glass transition temperature T_g /minimal film forming temperature	Pigment binding strength	Butadiene: $T_g = -108^\circ\text{C}$ (soft)
	Print evenness	Styrene: $T_g = 100^\circ\text{C}$ (hard)
	Hardness and stiffness	
	Gloss	
Particle size	Pigment binding strength	Approximately 100–200 nm
	Porosity	Small size \Rightarrow high strength
	Printing ink holdout	
Degree of cross-linking	Pigment binding strength	–
	Porosity	
	Water fastness	

Table 17.10 Important requirements for coating color components.

Important requirements placed on	Concerning coating colors	Concerning coated paper characteristics	Important mechanisms	Examples
Pigment	Costs, rheology, and maximum solids	Brightness, gloss, whiteness, opacity, structure, and printability	Brightness, particle size, and PSD aspect ratio	GCC, clay, and PCC TiO ₂
Binder	Solid content	Strength, printability, and water resistance	Polymer structure and spherical packing	XSBRSA
Cobinder	Rheology and water retention	Structure, printability carrier, and water fastness	Pigment affinity and molar mass	Starch, CMC, and PVOH
Thickeners	Rheology and water retention (lower dosage)	Structure	Molar mass, cross-linking, intra- or intermolecular association	CMC, PVOH, acrylic copolymers, and associated thickeners
Lubricants	Reduced friction	Reduced dusting gloss	Particle size and PSD aspect ratio	Stearates, PEG, wax emulsions, and soy lecithine
Defoamers	Reduced number of bubbles	Reduced faults	Surface activity	Surfactants and insoluble hydrophobic additives
Insolubilizers	–	Water resistance	Cross-linking	Glyoxal, MF, UF resins, and ammonium zirconium salts
Dyes	–	Tinting and shading	–	Basic, substantive, and pigment dyes
OBA	–	Brightness	Sulfonic groups	Stilbene

17.2.4

Coating Color Formulations

Coating colors in use at present are different from earlier formulations. Some reasons for this development are given in Chapter 5. They can be summarized as follows:

- changed customer needs
- increased or changed quality demands
- new manufacturing possibilities
- increased environmental requirements.

These were the driving forces that did lead to the following developments:

- Coating color with
 - fewer components
 - higher solid content
 - smoother rheology (less tendency to dilatancy)
 - adapted WR.
- Lower costs of the formulation
- Lower operating costs.

Coating color formulations and their solid content and properties differ according to the application system used and the coating process. Typical ranges of coating weight applied to the paper as well as solid content of the coating color for the various principles of pigmenting and coating are listed in Table 17.11.

17.2.4.1 Model Composition of a Coating Color

Pigments are the body of the coating color and are used as the base. Standard descriptions of coating colors refer all components to 100 parts of pigments by weight. Typical formulations for offset printing grade would therefore have 100 pph pigments (CaCO_3 and clay), 8–12 pph binder (styrene butadiene or styrene acrylates), and 0.5–2.5 pph additives such as thickeners and lubricants (Figure 17.18). The calculation is based on dry weight.

This description, however, does not include water as the transporting liquid of coating colors. Table 17.12 lists the different ways to describe the composition of a coating color using

- shares by dry weight (pph), which is convenient if changes in composition need to be obvious, because the value of unchanged components remains constant (note: the amount of water needs to be indicated by the solid content);
- weight percentage of traded products, which provides the quantities for mixing a batch of the desired coating color;
- volume percentage of components, which is the basis if the mechanics of movement are taken into consideration. Here, air needs to be included as well.

Table 17.11 Coat weights and solid contents of coating color for different coating methods.

Coating method	Coating color solids content (%)	Coating speed (m min^{-1})	Coat weight (g m^{-2})	Remarks
Size press	20–30	100–1000	2–5	Pigmented surface sizing
Fim press	35–68	100–2000	6–12	–
Blade coater	45–72	100–3000	7–20	–
Metering bar coater	60–65	100–800	3–12	Pigmented surface sizing or coating
Air knife	30–50	100–500	8–12	Mainly board coating
Spray coater	45–55	100–2000	5–12	–
Curtain coater	45–68	100–2000	8–20	–

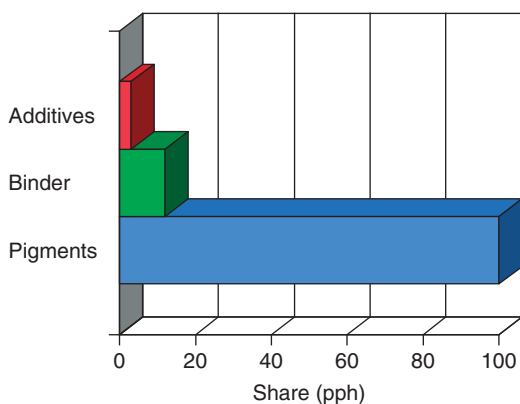


Figure 17.18 Components of a coating color for offset paper.

Table 17.12 Different methods to describe coating color composition.

	Formulation $m_{\text{comp}}/m_{\text{pigments}}$ (pph)	Weight percentage $m_{\text{comp}}/m_{\text{total}}(\%)$	Mixing rule $m_{\text{traded product}}/$ $m_{\text{total}}(\%)$	Volume percentage $\text{Vol}_{\text{comp}}/\text{Vol}_{\text{total}}(\%)$
CaCO ₃	80	46.7	63.9	21.2
Clay	20	11.7	16.7	5.3
Latex	8	4.7	9.3	7.1
Starch	4	2.3	7.8	3.6
Additives	2	1.2	2.3	1.8
Water	–	33.5	0.0	41.0
Air/gas	–	–	–	20.0
Total	114	100	100	100
Solid content	66.5%	–	–	–

pph, parts per hundred part of pigment; comp, component.

Another crucial factor in coating color formula design is the intended use, that is, the envisaged paper type and printing process. Formulations differ between matt and glossy grades, as well as for single or double coats with pre- and topcoats, and triple coats with precoat, intermediate, and topcoat. All coating color formulations aim for maximum solid content for quality and economic reasons. The coating color formulations presented in Tables 17.13 and 17.14 are examples of those commonly used in Europe at present. However, they must usually be adapted to suit the particular conditions in the individual paper and board mills. All formulations are in dry parts of the individual substances. In many cases, coated web offset paper has to have high stiffness of paper and freedom from blistering and creasing, the latter especially for HSWO. Manufacture of higher weight papers such as MWC and HWC involves formulations similar to those used for WF grades.

Table 17.13 Typical formulations of coating colors for various paper grades.

Number of coating layers	Offset wood free (wf)		Offset wf		Offset wf glossy		OD wf glossy		Roto LWC glossy		Roto LWC		ODweb LWC	
	1	pph	1/2	2/2	1/2	2/2	1/2	2/2	1	2/2	1	1	1	1
	pph	pph	pph	pph	pph	pph	pph	pph	pph	pph	pph	pph	pph	pph
GCC (60–75% < 2 μm)	–	100	–	–	–	–	80–100	–	0–20	–	40–60	–	–	
GCC (60–90% < 2 μm)	80	–	–	60–80	–	–	–	–	–	–	–	–	–	
GCC (90–99% < 2 μm)	–	–	80	–	–	80–100	–	–	–	–	–	–	60–90	
Kaolin	20	–	–	–	–	–	0–20	–	60–80	20	–	–	10–40	
High glossing kaolin	–	–	10–20	20–40	–	0–20	–	–	–	–	–	–	–	
Talc	–	–	0–10	–	–	–	–	–	0–30	–	20–40	–	–	
Calcined kaolin	–	–	–	–	–	–	–	–	–	–	–	–	–	
Titanium dioxide	–	–	–	–	–	–	–	–	–	–	–	–	–	
Synthetic binder	10–12	6–8	10–12	12	6–8	12	6–8	4.5–50	–	–	5.0–5.5	–	10–12	
Starch	–	4–8	–	–	4–8	–	–	–	–	–	–	–	–	
Cobinder and thickener	0.5–1.0	–	0.5–1.0	0.5–1.0	–	0.5–1.0	–	0.5–1.0	0–0.5	0–0.5	0–0.5	–	0.5–1.5	
Optical brightener OBA	0.5–1.0	–	0.5–1.0	0.5–0.8	–	0.5–0.8	–	0.5–0.8	0–1.0	0–1.0	0–1.0	–	0–2	
Stearate	–	–	–	–	–	–	–	–	0.4–0.8	0.4–0.8	0.4–0.8	–	0.4–1.0	
Solid content (%)	65–68	66–68	66–70	65–70	65–68	66–70	65–68	66–70	48–60	50–62	50–62	–	64–70	

Source: Omya and AKW.

Table 17.14 Typical formulations of coating colors for various board grades.

Number of coating layers	Solid-bleached board (SBS)		White-lined chip board (WLC)		
	1/2	2/2	1/3	2/3	3/3
	pph	pph	pph	pph	pph
GCC (60–75% < 2 μm)	–	–	80–100	–	–
GCC (60–90% < 2 μm)	80–100	–	–	70–90	–
GCC (90–99% < 2 μm)	–	80–100	–	–	80–100
Kaolin	0–20	0–20	0–20	0–10	–
High glossing kaolin	–	–	–	–	0–20
Talc	–	–	–	–	–
Calcined kaolin	–	–	–	0–20	–
Titanium dioxide	–	–	–	0–10	–
Synthetic binder	12–14	12–15	10–14	14–18	12–14
Starch	–	–	–	–	–
Cobinder and thickener	0.5–1	0.5–1.5	0.3–1	0.5–2.0	0.5–1.0
Optical brightener OBA	–	–	–	–	–
Stearate	–	–	–	–	–
Solid content	55–68	65–70	50–65	45–60	66–70

Source: Omya and AKW.

17.2.5

Coating Machines

17.2.5.1 Overview

In contrast to coating applicators placed on-line in a paper machine, off-machine coaters (OMCs) are separate machines in which a previously produced dry base paper is unwound, coated, dried, and then reeled again (Figure 17.19). Here, web defects may be removed during re-reeling. If coating is done on machine, then the coating will immediately follow the manufacturing of the base paper without intermediate reeling.

In a paper mill, one off-line coater is usually associated with one paper machine. Sometimes, however, one OMC receives paper from different paper machines. In most cases, the off-line coater has the same width as the corresponding paper machine (except for the edge trim). Some coaters with half width are in operation, where the jumbo reels from the paper machine are split and the two halves are coated separately.

Off-line coating has the advantage that the paper machine can continue production when the machine stops on the off-line coater. These stops can be, for instance, due to coating color changes, which are especially important for machines with a very broad product range. Since off-line coaters operate faster than the paper machine to which they belong, the time efficiency of the entire line is higher than for on-line installations.



Figure 17.19 Off-line coater. (Source: Voith.)

17.2.5.2 Applicators

Historically, papers used to be coated in much the same way as painting a wall: the color was applied and distributed with a brush, then dried, and smoothed. The process has remained essentially unchanged to the present day, although it has undergone major improvements over time. Today, roll or jet applicators are employed instead of a brush, and the color layer is leveled out using either a pneumatic or mechanical system, such as a blade or a metering bar. The moist sheet then passes between infrared dryers before being conveyed to high-temperature air floats and/or drying cylinders.

In principle, the coating process can be divided into different phases:

- Application of the coating color onto the base paper. Either the exact amount or a surplus of coating color is applied depending on the coating methods.
- Metering of the coating, where metering may take place before (pre-metering), during (simultaneous metering), or after (post-metering) the application.
- Drying of the coating.
- Smoothing of the surface, for example, by supercalendering or soft calendering.

17.2.5.2.1 Metering Pre-metering, or metering before application, takes place, for example, in the MSP or film press and in the gate roll press. Simultaneous metering, or metering and application at the same time, take place in the SDTA and the conventional pond size press. Post-metering, or metering after application, takes place in the blade coater, the rod coater, and the air knife coater. Figure 17.20 depicts a schematic arrangement of backing roll, roll applicator, and doctor together with the coating base paper. The applicator roll runs at a slower rate than the paper sheet and applies a generous amount of color (20–30 times in excess) to the base paper.

After wetting the base paper, the waterline migrates into the coating base. This penetration is assisted by hydrodynamic pressure building up in the nip as a result of the web speed. Consequently, the kinds of application and metering characterize the various coating methods. In MSP application, metering takes place on the

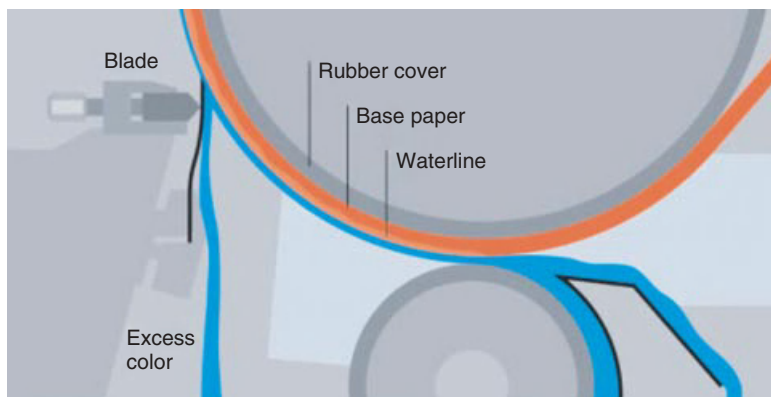


Figure 17.20 Principle of coating color application. (Source: Omya.)

surface of a roll, and the coating film is then transferred onto the paper in the nip between two rolls.

Coating can be done double-sided, that is, both sides of the paper are coated simultaneously (e.g., in a MSP), or on only one side at a time. Printing papers are usually coated similarly on both sides, and boards often on one side only.

Single coating means that only one coating layer is applied per paper side; in multiple coating, several coating layers are applied per paper side. The most common multiple coating is double coating. So-called art papers may be triple-coated, that is, three coating layers per paper side.

17.2.5.2.2 Effects during Coating During coating, liquid is removed from the color, which then adheres to the base paper. As the liquid phase strikes the base paper, water-containing dissolved substances and other color components (mainly binders, cobinders, and additives) migrate into the base paper. Actually, filtration of the coating components takes place in the z -direction, that is, perpendicular to the sheet plane. This anchors the color to the paper surface. If the color strike-in is too intense, the coating layer may become depleted of binder. This may in turn give rise to undesirable phenomena such as dusting or picking. If the color is dewatered extremely quickly, solid content and, hence, viscosity, will increase. This increases, for example, the blade pressure in blade coating; so, the coating color needs dilution – a measure that may result in poorer surface quality. Another key phenomenon is the mechanical shear stress experienced by the color in the clearance between the stationary doctor and the paper sheet as it passes by. The shear rate D (rate of application of strain) on the color may be calculated from the velocity v of the paper and the clearance d between paper and doctor as follows:

$$D = \frac{v}{d} (\text{s}^{-1}) \quad (17.1)$$

The clearance d is difficult to measure because of the flexible cover of the backing roll and the compressibility of the base paper. The shear rate D may attain a multiple of 10^6 s^{-1} . This value plays a crucial role in coating color rheology and

runnability. More recent analysis shows that at high speed, the above simple shear generation model may no longer be applicable. Boundary slip conditions can occur, leading to a pseudo-plug-flow under the doctor nip initiated by the rapid change in shear rate upstream from the nip. Under these circumstances, the coating color behaves partially elastically, in contrast to the classical viscous flow described here.

Appropriate absorbency of the coating base paper, WR of the coating color, as well as its rheology or viscosity ensure good coating quality and runnability. These mechanisms take place within fractions of a second: at a coater speed of 1500 m min^{-1} , for example, the paper web reaches the doctor just 0.04 s after the moment of color contact. Under adverse drying conditions, the binder may distribute nonuniformly into the coating surface. Along with local variations in surface porosity caused by nonuniform coating consolidation during drying, this is a typical cause of print mottle as a result of irregular ink absorption.

17.2.5.2.3 Blade or Rod Coating In direct coating, the web is supported by a backing roll and the coating medium is fed in excess onto the web. After a certain distance, defining the “dwell time,” the coat layer is metered down to the final thickness, which is the desired coat weight.

In the “roll applicator” or “long dwell time applicator” (LDTA), feeding is done with a roll, which draws the coating medium from a pan onto the web (Figure 17.21). The applicator and the backing rolls form a nip. The nip pressure and, consequently, the nip gap are adjustable, determining the amount of coating medium fed to the web. The nip load also yields an external penetration pressure which, together with the capillary pressure, causes penetration of some coating medium or components thereof into the paper or board web. This is to a certain extent desirable because it anchors the coating to the base paper and gives surface strength. Excessive penetration, however, would reduce the gain in surface properties, such as smoothness or gloss.

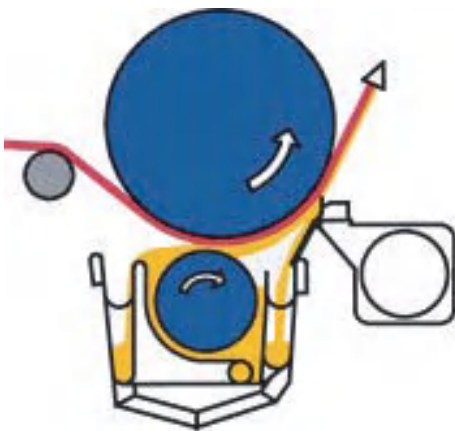


Figure 17.21 Roll applicator (Source: Voith.)

Penetration of the coating into the base paper can be controlled with the “WR” of the coating medium. At elevated machine speeds, for example, above $\sim 1500 \text{ m min}^{-1}$, the splitting of the coating color between applicator roll and paper at the nip exit shows irregularities, which negatively influences the homogeneity of the coat layer. Further, the relatively short nip and the considerable penetration caused by the nip load cause runnability and quality problems.

To overcome these limitations, the application of the coat medium to the paper can be performed with a free jet. In a “free jet applicator” (Figure 17.22), the jet usually has a thickness of less than 1 mm and a length of a few centimeters. The resulting coat layer (still before final metering) is much more homogeneous than that of a roll applicator, and, since the external pressure at the impingement point is considerably less than in the roll nip, the penetration of the coating medium into the base paper is reduced. This improves the so-called “coating holdout,” which results in a better surface quality of the coated paper.

The final metering of the applied coating is often performed with a blade. With this blade, most of the coating medium is removed and returned to the working tank. The coat layer remaining on the paper or board is evenly distributed. The blade pressure ensures that the surface voids of the web are filled with coating. Owing to the blade geometry, the coated web has a good smoothness. The blade usually has a thickness of less than 1 mm, typically $\sim 0.4 \text{ mm}$. The stick-out length (or unsupported length) is usually a few centimeters. The operating angle between blade and paper web is usually $20\text{--}35^\circ$. Under these conditions, the blade is considered a “stiff blade” because its bending is negligible with respect to the operating principle. If, however, a blade geometry is chosen, where the bending of the blade results in an operating angle close to 0° , the mode is called “*bent blade*.” The bent blade gives – in comparison to the stiff blade – an even smoother

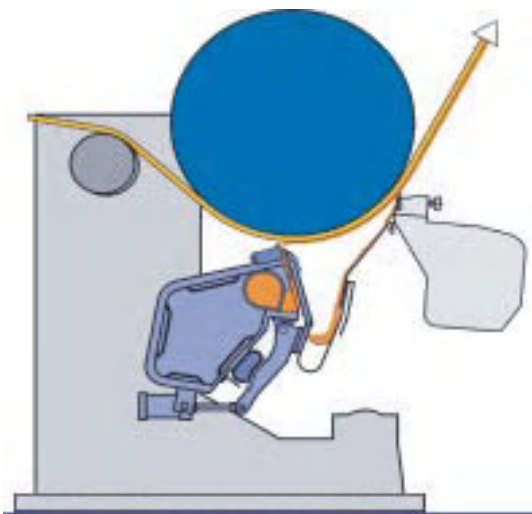


Figure 17.22 Jet applicator. (Source: Voith.)

surface, but it is more prone to surface defects, such as blade scratches, and is more difficult to operate. As the web has a considerably reduced roughness after coating, the coat layer itself must be nonuniform in caliper to even out the base paper roughness. On certain grades, especially board, this nonuniform layer thickness can be seen as inhomogeneous coverage or mottling. If coverage is desired rather than smoothness, metering can be done with a rod rather than with a blade. Rod metering is typical for the precoat of board and specialty papers, where the base web has to be evenly covered with a specialty coat.

In most cases, the metering blade (or rod) is placed against the same backing roll as the coat applicator. The angle between the point of application and point of metering is then $\sim 60^\circ$. This results in a dwell length of 400–600 mm, depending on the backing roll diameter. The resulting “dwell time” depends strongly on the machine speed. It is in the range of 10–200 ms.

An “SDTA” was tried in order to reduce the dwell time to much shorter values. This SDTA consists of a closed chamber that incorporates the coating feed and the metering blade. However, vortices in the chamber caused a streaky appearance of the coat layer at elevated machine speeds. Therefore, the SDTA has not received much attention outside North America.

17.2.5.2.4 Film Coating As an alternative to direct coating, a film press can be used for the application of coating media. The film press was derived from the size press, which is used for the application of starch or size solutions. At present, a wide variety of coating media are applied, including pigment dispersions with high solid content. In a film press, a film of the coating medium is formed and metered on a large-diameter roll. This roll forms a nip with another roll. The paper or board web passes this nip and picks up a certain portion of the film. Application can be – but does not have to be – simultaneous on both sides.

Metering is performed using metering rods. These can be either smooth or profiled. Profiled rods provide a certain volume of coating medium because of the open cross section in the profile. A deeper or coarser profile gives a higher coat weight than a fine profile. The application weight is mainly adjusted by choosing an adequate profile. Fine tuning of the application weight can be done by modifying the rod pressure. Profiled metering rods are mainly used for low viscosities (i.e., low solid content of the coating medium) and low machine speeds.

With increasing viscosity and speed, the rod loses contact with the roll because of the hydrodynamic forces of the coating medium, comparable to aquaplaning. Then, the application weight depends less on the profile and more and more on the hydrodynamic conditions, such as rod pressure, rod diameter, viscosity, and speed. Consequently, a smooth metering rod is used. Typical rod diameters are 14–38 mm for smooth rods. Larger diameters yield higher application weights. Higher viscosities and machine speeds require smaller rod diameters for the same application weight than lower ones. The coating medium is not transferred completely to the web. A certain amount remains on the roll and returns to the application unit, where it is mixed with fresh coating medium. The transfer ratio depends on the acceptance behavior of the web, the properties of the coating

medium, and – to a limited degree – the surface properties of the roll. For starch, where the absorptivity of the web is high, the transfer ratio can be more than 90%. For pigment coats, it can be as low as 50%.

The pre-metered films usually have thicknesses of 7–20 μm (or ml m^{-2}). Lower values would require very high rod pressures and coverage of the web would also be insufficient. Higher values are not meaningful as the web has a limitation with respect to coating acceptance. If the amount of pre-metered coating medium is too high, the surface of the coated web appears uneven, with an “orange peel” character. At elevated machine speeds, the film split at the nip exit can create a fine mist of coating medium. This mist deposits on machine parts or even on the paper or board web. This misting increases with film thickness, so it is the major limitation for the application weight at high speed. For typical applications, misting becomes a limitation above 1500 m min^{-1} . At 1800 m min^{-1} , for example, coat weights above 7 g m^{-2} are difficult to achieve without disturbing misting.

17.2.5.2.5 Curtain Coating Besides film and blade coating, curtain coating is used for the application of coating media onto paper surfaces. Although curtain coating is a very old application technique, going back to the end of the nineteenth century, it has only been used for coating of paper since the 1990s. Curtain coating is mainly used for specialty papers. Specialty coats are usually very expensive. Therefore, the application amount must be kept to an absolute minimum. On the other hand, a certain amount is required to achieve the desired function of the coat. In a curtain coater, a thin film of coating medium is formed, which falls by gravity onto the paper surface. The only metering device for the coating color is the nozzle slice. The slot opening is about 20–50 times larger than the actual coating color thickness. Thickness is reduced by gravity forces while the jet is moving toward the web and by the shear forces exerted by the high speed difference between the jet and the running web (Figure 17.23). Owing to the homogeneity of the film, the coverage of the paper by the coating medium is very uniform.

Unlike film and blade coaters, the application is contact free. This considerably reduces the risk of web breaks and, therefore, improves runnability. It is expected that the significance of curtain coating will increase.

This is especially true, when making use of multilayer curtain coating (Figure 17.24), where more than one layer can be applied wet-in-wet, which

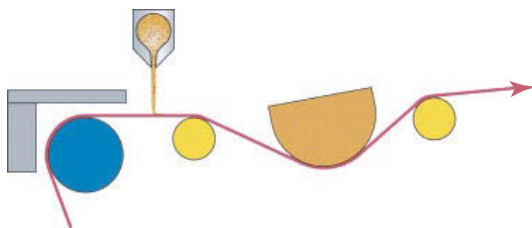


Figure 17.23 Principle of curtain coating. (Source: Voith.)

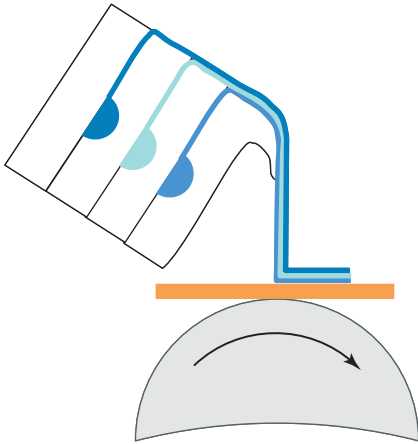


Figure 17.24 Multilayer curtain coating.

can save drying steps and energy. For example, in photo paper manufacturing, industrial practice is to apply more than 10 layers at a time.

17.2.5.3 Typical Applications

Typical coat weights for graphic papers are given in Figure 17.25, plotted against the basis weight of the base paper. The coat weight is typically 25–40% of the final basis weight of the paper.

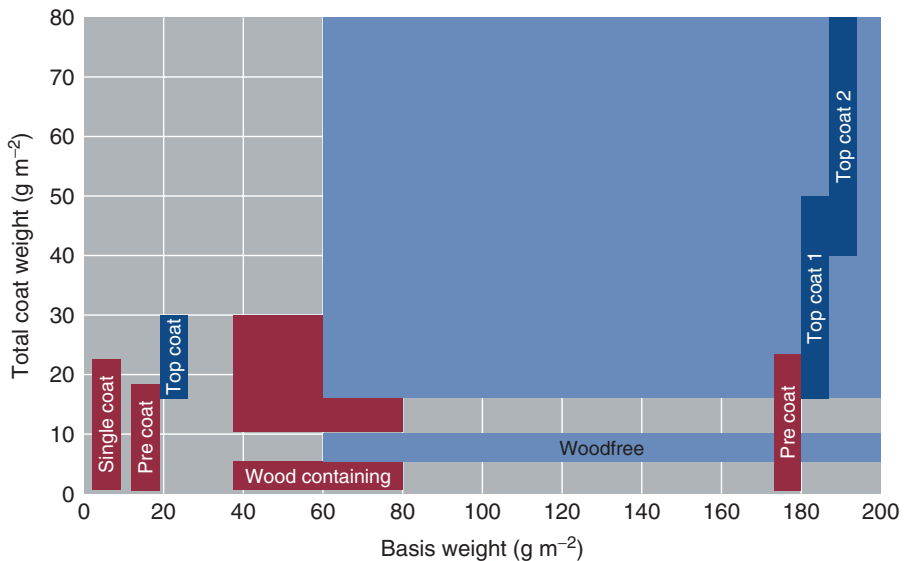


Figure 17.25 Typical coat weights for graphic papers. Basis weight includes base paper + coat weight. (Source: Voith.)

Wood-containing papers are mainly single-coated (LWC). Coat weights are usually between 6 and 10 g m⁻² per side. Traditionally, the coat is applied with a blade coater. More modern installations use a film press for the single coat.

At higher basis weights (MWC), two coat layers may be applied per paper side. Here, the topcoat is usually a blade coat. The precoat may be either a film or a blade coat.

WF papers cover a very wide basis weight range. Depending on the basis weight, the application can be single coat, double coat, or triple coat. The coat weight per layer can vary in a wide range between ~8 and 20 g m⁻².

For board grades, the coat weight depends on the requirements of the final product and the quality of the base board. Coverage, brightness, and smoothness are the main properties that are improved by the coating. Depending on the required coat weight, two or three coat layers are applied.

Depending to their functions, different formulations are used for the individual coat layers. For instance, pigments with high opacity are used in the first layers, whereas very fine pigments with good smoothness potential are used for the topcoat.

17.2.6

Drying

After its application, the wet coat must be dried. Three different drying principles are used: radiation (infrared), convection (hot air), and contact (cylinders).

Infrared drying yields a very good energy transport, whereas mass transfer is inferior. Therefore, infrared is especially suitable for heating the paper or board web to temperatures where considerable drying occurs. Heating of the infrared radiators can be by electricity or gas. Gas-heated infrared dryers reach higher temperatures and are usually cheaper. Electrical infrared dryers are easier to control and are, therefore, often used for moisture profiling in the cross-machine direction. The mode of heating depends on the local conditions at the mill site, such as availability and prices and the heating principle that is used for infrared drying.

Air flotation dryers are widely used for drying of the coat. In an air flotation dryer, hot air is blown onto the paper surface. Air temperature can be as high as 350 °C, sometimes even higher. The impingement velocities of the air can exceed 40 m s⁻¹. The impingement effect gives very effective heat and mass transfers between air and paper surface. The blowing nozzle sections in the dryer are alternately placed on either side of the paper. This gives a sinusoidal web run through the dryer with a web-stabilizing and wrinkle-avoiding effect.

Cylinder drying of the coat is possible, as soon as the freshly coated surface is dry enough that the coating color does not stick on the cylinder surface. Therefore, drying cylinders are only found after a certain amount of contact-free drying, that is, toward the end of the dryer section after a coater station. In modern coating machines, cylinder drying does not contribute much to the total drying capacity, sometimes less than 20%. Contact drying has usually the lowest specific cost. Furthermore, the cylinder group is an excellent fix point for the web run. When

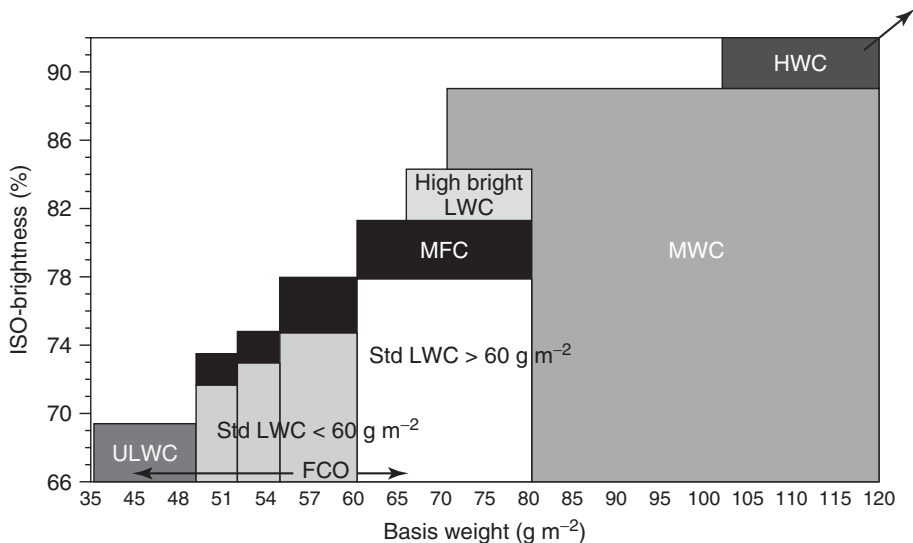
Table 17.15 Overview of coated paper and board grades and their most important characteristics; board grades (mainly top side only coated).

Paper/board grades	Base paper main fiber furnish	Basis weight base paper (g m^{-2})	Coat weight per side (g m^{-2})	Number of coating layers	ISO brightness (%)	Main uses of paper/board grades
ULWC (ultra light weight coated)	MP, CP, and DIP	25–35	5–7	Single	69–72	Catalogs and magazines
LWC (light weight coated)	MP, CP, and DIP	35–45	6–12	Single	72–78 (84)	Magazines and inserts
MFC (machine finished-coated)	MP, CP, and DIP	35–60	5–15	Single and double	72–78	Magazines and catalogs
FCO (film-coated offset)	MP, DIP	30–45	4–10	Single	72–78	Inserts, flyers, and advertising
MWC (medium-weight coated)	MP, CP, and CP	45–65	12–25	Double	80–88	Special magazines and advertising
HWC (high-weight coated)	MP, CP, and CP	65–100	25–35	Double and triple	82–90	Magazine covers and advertising
WFC (woodfree-coated fine papers)	CP	60–120	25–35	Single, double, and triple	88–98	Magazines, image brochures, and labels
Art paper	CP	60–150	20–40	Double and triple	94–98	Illustrated books, calendars, and so on.
FBB (folding box board)	DIP, RP, MP, and CP	135–425	12–35	Single, double, and triple	72–86	Packaging of food and book covers
WLC (white-lined chipboard)	DIP, RP, MP, and CP	170–425	10–30	Single and double	76–92	Shoe and wine boxes and protection packaging
SBS (solid-bleached sulfate)	BHSP and BSSP	120–250	15–25	Double	84–98	Packaging of chocolate, cigarettes, and cosmetics
LPB (Liquid packaging board)	BSSP and UBSSP	280–330	10–15	Single	76–86	Milk and juice packaging

MP, mechanical pulp; DIP, deinked pulp; CP, chemical pulp; RP, recovered paper; BHSP, bleached hardwood sulfate pulp; BSSP, bleached softwood sulfate pulp; UBSSP, unbleached softwood sulfate pulp.

Table 17.16 Overview of coated paper and board grades and their most important characteristics; board grades (mainly top side only coated).

Paper/board grades	Base paper main fiber furnish	Basis weight base paper (g m^{-2})	Coat weight per side (g m^{-2})	Number of coating layers	ISO brightness (%)	Main uses of paper/board grades
FBB (folding box board)	DIP, RP, MP, and CP	135–425	12–35	Single, double, and triple	72–86	Packaging of food and book covers
WLC (white-lined chipboard)	DIP, RP, MP, and CP	170–425	10–30	Single and double	76–92	Shoe and wine boxes and protection packaging
SBS (solid-bleached sulfate)	BHSP and BSSP	120–250	15–25	Double	84–98	Packaging of chocolate, cigarettes, and cosmetics
LPB (liquid packaging board)	BSSP and UBSSP	280–330	10–15	Single	76–86	Milk and juice packaging

**Figure 17.26** Classes of wood-containing coated printing paper and their positioning according to their basis weight (base paper+coating layers) and brightness [7].

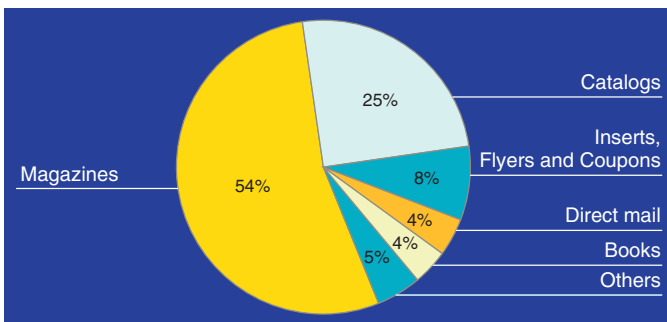
no cylinders are used, a separate fix point between the coater stations has to be included, such as an S-wrap or a pull stack.

In some machines, the last cylinders are used to cool down the web rather than for drying. After drying, the web can reach temperatures well above 70 °C and does not cool sufficiently before the next coater station. Too high a web temperature causes excessive penetration of the coating color into the web; so, cooling provides a higher product quality.

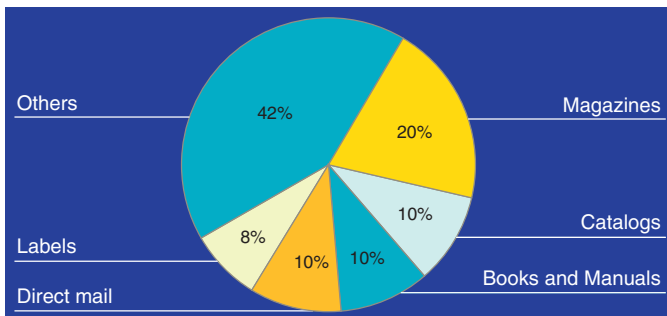
17.3 Coated Paper and Board Grades

Coated paper and board grades are described in Chapter 28. Tables 17.15 and 17.16 give a concentrated overview of coated paper and board grades as related to the main components of base paper, basis weight, coat weight, brightness, and their main uses.

Figure 17.26 illustrates the relative positions of mechanically coated printing papers in basis weight and brightness. Figure 17.27 presents typical end uses for coated mechanical papers and coated fine papers worldwide.



(a)



(b)

Figure 17.27 Worldwide use of (a) all coated mechanical paper grades and (b) coated fine paper grades for printing.

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18 Calendering

Rüdiger Feldmann

18.1 Objective and General Description of the Calendering Process

The objective of calendering is to modify the surface characteristics of paper for its further use, for example, printing. Depending on the individual grades, the focus is put on different technological properties. These are mainly

- gloss
- smoothness/roughness
- density
- blackening
- brightness
- opacity.

Printed gloss and printing smoothness are the major prerequisites for a good print quality. Both are generally dependent on the gloss of the paper and its smoothness/roughness as well as its levelness and compressibility. High printed gloss gives the printed product the desired shiny appearance, while high (printed) smoothness is decisive for the evenness of print and print density, for example, reduced number of missing dots.

As to the theoretical basis of calendering, a series of explanations exist. Some scientists hold the view that smoothness and gloss result from slipping of the paper in the nips. Others maintain that calendering is a flattening process where the smooth surface of the hard rolls is replicated on the side of the web that contacts the hard roll. Still others argue that it is the shearing action in the nip which causes gloss and smoothness by “aligning” the surface particles of the web. Not in dispute is the influence of heat: thermal energy transferred to the web softens the cellulose fibers (glass transition point) and thus enhances the development of gloss and smoothness.

Smoothing the surface and increasing gloss are accompanied by reduction in caliper, strength properties, brightness, and opacity to a certain degree.

The strength properties of the paper are peremptory for the runnability of the web in the printing machine. Brightness and opacity have a distinct impact on the print

quality. Blackening is found when parts of fibers have collapsed under pressure. Under transmitted light the respective areas appear glassy, whereas under incident light they appear as darkened areas. This is still intensified by the printing process, that is, the light full tone areas turn a murky gray.

Calendering is done by pressing the paper web in one or more “rolling” nips formed by rolls with special properties. The main factors in calendering – apart from furnish and paper properties such as moisture, temperature, and coating – that influence the above-mentioned technological result are

- nip pressure/load
- nip dwell time
- roll elasticity
- roll surface temperature and smoothness.

Details concerning the rolls and roll covers, the roll configuration, and other important components of the calenders are treated below.

18.2

History of Calendering

From the very beginning there was a desire to glaze the rough surface of paper. The procedure then was to lay each hand-made sheet on a smooth surface and treat it with an agate or pumice stone. Nothing changed in this tedious procedure for centuries. Later, water-driven hammers came into use for smoothing. These hammers were superseded in the course of the seventeenth century by roll presses like those that had been used since the late Middle Ages for copper rotogravure printing. This was the first step toward smoothing in the “rolling press nip,” that is, calendering. Today, this method still determines the surface treatment of paper.

In 1798, Nicolas Louis Robert invented the paper machine. It took more than 50 years, however, until calenders were installed in the paper machine. These calenders – also called *machine calenders* – consisted of at least two hard rolls. A decade later, the supercalender appeared with a large number of alternating hard and resilient rolls. The resilient rolls were often termed *filled or paper rolls* as rounds made of fibrous material (cotton, wool) were pushed onto the roll shafts where they were pressed together under high pressure and secured with closure elements. Paper rolls are highly prone to marking. They must therefore be replaced at regular intervals and finish-turned. This is why these supercalenders could only be operated offline.

Conventional rolls deflect under the influence of the load and their dead weight, which would result in a nonuniform distribution of linear load in the press nips. To avoid this, the rolls had to be crowned, that is, ground with a camber. The selected crown does, of course, only apply to a certain load. If it were desired to alter the load, the rolls had to be recrowned.

Hence, the introduction of the “Swimming Roll” in the 1950s by Küsters was of decisive importance for the further development of both the machine calender and

the supercalender. This roll consists of a fixed shaft with a shell rotating around it. Between the shaft and the shell is an oil-filled chamber. By adjusting the oil pressure in this chamber the shape of the roll shell can be changed (Figure 18.1). Thus the “operating window” of calenders was suddenly expanded.

The swimming roll allows control of the linear load distribution across the width only in a given overall shape. This limitation was overcome with the next generation of nip control rolls introduced in 1974 by Escher Wyss, the Nipco roll (Figure 18.2). Here the load distribution can be controlled locally zone wise. On this roll, the rotating roll shell is carried by a large number of hydrostatic supporting elements, which in turn are supported on a fixed shaft. The hydraulic control unit combines several supporting elements into one zone. In all, there are six to eight effective hydraulic zones. As they can be controlled individually, the linear load can be specifically adjusted across the width of the calender. It is, therefore, possible not only to uniformly distribute the linear load across the roll width but also to increase or reduce it locally. Zone-controlled deflection rolls are meanwhile

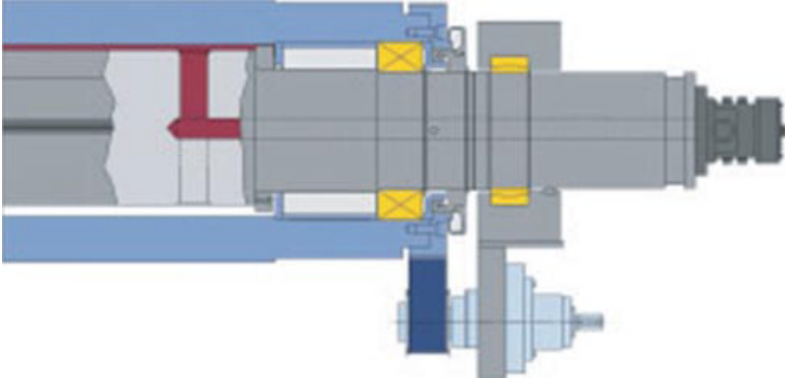


Figure 18.1 Overall control roll, swimming roll. (Source: Voith.)

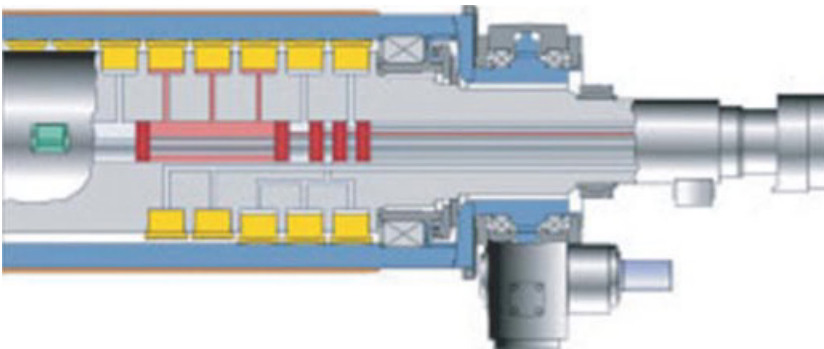


Figure 18.2 Zone-control roll, Nipco roll. (Source: Voith.)

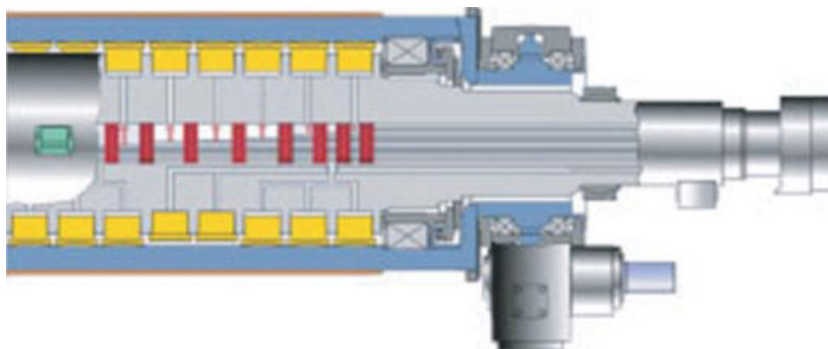


Figure 18.3 Multizone roll, Nipcorrect roll. (Source: Voith.)

available in the marketplace under different names and designs by Küsters, Metso, and Voith.

Since 1994, multizone control rolls have been in operation with up to 60 supporting elements arranged horizontally close together. These can be individually controlled so that even more precise profile corrections can be made (Figure 18.3).

Machine calenders and supercalenders with width about 5000 mm and above are today equipped with zone-controlled rolls as standard. Narrower machines still use the simpler overall control type rolls.

Supercalenders are classic offline machines as they have downtimes of 25–30% because of the filled roll change. To be able to keep pace with a high-speed paper machine, at least two, sometimes even three, supercalenders were therefore required. This disadvantage of the supercalender led, at the beginning of 1980, to the development of the soft calender. The soft calender consists of at least one heated roll and one resilient roll covered with synthetic material. Because synthetic rolls are much more resistant to marking than the filled rolls of the conventional supercalender, the soft calender was also able to be used online. In many cases, the online soft calender was very successful. However, not all quality demands on the paper surface could be met with it. For demanding papers, the supercalender equipped with filled rolls and which therefore could only be operated offline remained the only alternative.

Things changed in the middle of the 1990s with the emergence of improved synthetic covers. In 1994, the first calender of the new type (Janus Concept calender of Voith Paper) was built with all resilient rolls covered with special synthetic materials. At a first glance, this new calender looks like a conventional supercalender. In reality, it differs in many respects, for example, by the reduced number of nips, less energy input and – most noteworthy – suitability for online operation. Thanks to a suitable combination of pressure, roll surface temperature, roll surface quality, and number of nips, it was now possible to calender even highly demanding paper qualities online. Other machine builders followed (Küsters and Metso). The latest development is a calender (Voith's Janus MK 2), on which the roll stack is no longer arranged vertically but at an angle of 45°. The

modern online-capable multiplex calenders have extensively ousted the classic supercalenders. The few cases in which it is still used for technological reasons are treated in Section 18.4.

18.3

The Different Calender Types

18.3.1

Machine Calenders

Machine calenders consist of two or more hard rolls and are practically always installed online. They are primarily used for paper that only requires moderate finishing or for precalendering grades that need further finishing treatment in order to obtain higher gloss and/or smoothness. Machine calenders are equipped with overall deflection or zone-controlled deflection rolls (Figure 18.4).

18.3.2

Supercalenders

Supercalenders are off-machine multiroll-calenders consisting of an unwind stand, a roller stack, and a rewind stand. The usual number of rolls is 9–12. For specialty papers – such as silicon based papers for instance – the number can reach 18. The rolls are hard and elastic in turn. When the number of rolls is even, there will be a so-called reverse nip having two adjacent elastic rolls. The elastic rolls are filled rolls. The filling consists of a multitude of specialty paper sheets slid onto a steel shaft, compressed to the required hardness and then locked by nuts. The hard rolls are steel or cast chilled iron rolls and are often heated. The top and bottom roll are either overall deflection or zone-controlled deflection rolls.

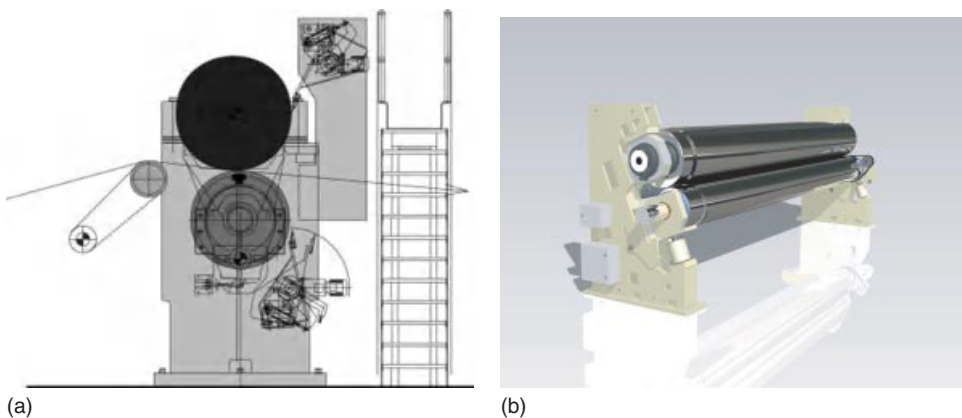


Figure 18.4 (a) Machine calender, principle and (b) a modern design. (Source: Voith.)

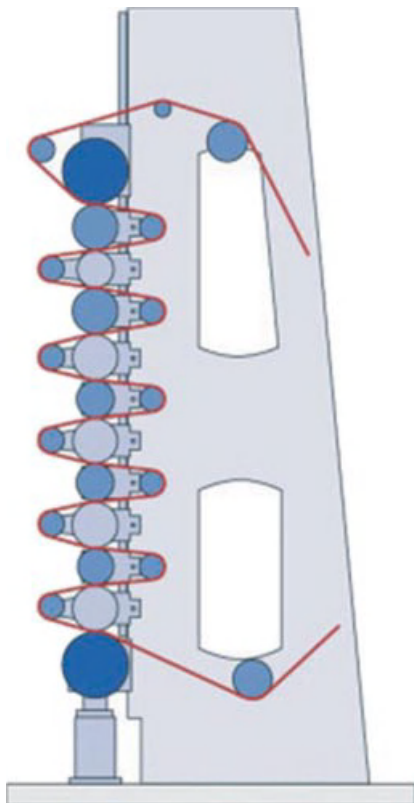


Figure 18.5 Supercalender. (Source: Voith.)

To prevent the filled rolls from getting marked by the web following a web break, the stack is equipped with a device for quickly opening the nips. Further important features are the spindle system, the overhanging load compensation system, doctors, web cutting and oscillating devices, flying splice devices, inner and outer lift platforms, and so on. The maximum working speed of supercalenders is approximately 800 m min^{-1} and the maximum line load approximately 450 N mm^{-1} . However, maximum speed, line load, and maximum surface temperature cannot be applied at the same time because of the delicate nature of the filled rolls (Figure 18.5).

18.3.3

Soft calenders

The basic version of the soft calender is the two-roll soft calender. Its main components are the soft covered deflection control roll and the heating roll. The linear pressure of a soft calender ranges from approximately 10 to 350 N mm^{-1} and the surface temperature of the heated roll can be up to 230°C . For two-sided

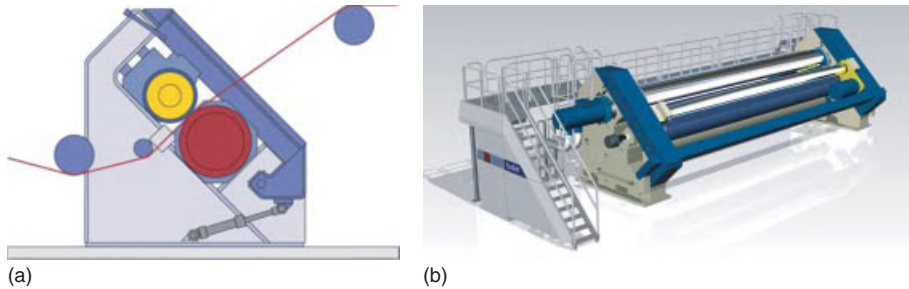


Figure 18.6 (a) Soft calender, principle and (b) a modern design. (Source: Voith.)

calendering, two stacks with an inverted roll configuration are combined. In cases where one hot calendering nip per web side is not sufficient to obtain the desired finishing result, more calendering capacity is achieved by adding further soft nips. In contrast to supercalenders, soft calenders can also be installed online because the soft covers can withstand line loads, load cycles, and temperatures that are much higher than those witnessed with conventional filled rolls (Figure 18.6).

18.3.4

Modern Multinip Calenders

Modern multinip calenders are similar in function to supercalenders. The main difference is that the filled rolls are replaced by polymer covered rolls. As a result, modern multinip calenders can be installed online and can be run more than twice as fast as supercalenders and with much higher surface temperatures and line loads.

Presently, there are three calender designs which make use of the new technology (Janus MK 2 calender of Voith, ProSoft calender of Küsters, and the OptiLoad calender of Metso).

Voith's Janus calender was the first multinip calender that could be integrated into a fast running paper machine. Various roll configurations were possible, that is, 6–10 rolls in one vertical stack, 2×5 rolls in two vertical stacks, and so on. As the polymer cover of the elastic rolls is less thick than the filling of the conventional paper rolls, no slideways and spindles are necessary. The intermediate rolls are supported by loading arms that incorporate the overhanging load compensation function. Depending on their design, the heated rolls can produce surface temperatures of up to 170 °C. Line loads in the range 250–500 N mm⁻¹ are possible. When installed in-line with a paper machine, the Janus calender is featured with a special tail threading device. Similar parameters are found in the OptiLoad calender of Metso and Küsters's ProSoft calender.

On the basis of the Janus Concept calender, Voith developed the Janus MK 2. This latest multinip calender version is mainly characterized by the stack being no longer arranged vertically but inclined at a 45° angle offering operational and technological advantages (Figure 18.7).

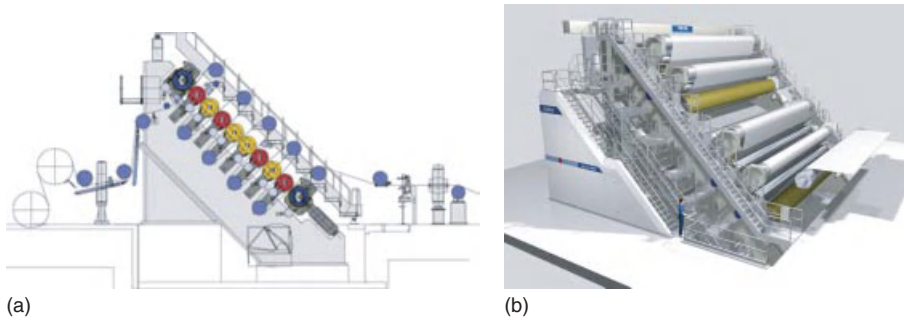


Figure 18.7 (a) Multinip calender, principle and (b) a modern design. (Source: Voith.)

18.3.5

Extended Nip Calenders

Jörg Rheims and Rüdiger Feldmann

Since the mid-1990s, new calendering technologies utilizing an extended nip were introduced. Generally, they can be discerned in two categories: shoe calendering and belt calendering. Both methods target at an improved ratio of surface quality versus bulk. This is achieved by increasing the influence of moisture and temperature on the calendering process by higher operating temperatures and by moisturizing the paper surface. If dwell time, moisture, and temperature gradients are set properly, the surface can be plastified and pressure can be reduced so that bulk loss is minimized and fibers can be saved.

A shoe calender (Figure 18.8) consists of a heated metallic roll acting against a soft sleeve rotating around a shoe roll [1]. Optionally, a moisturizing device is

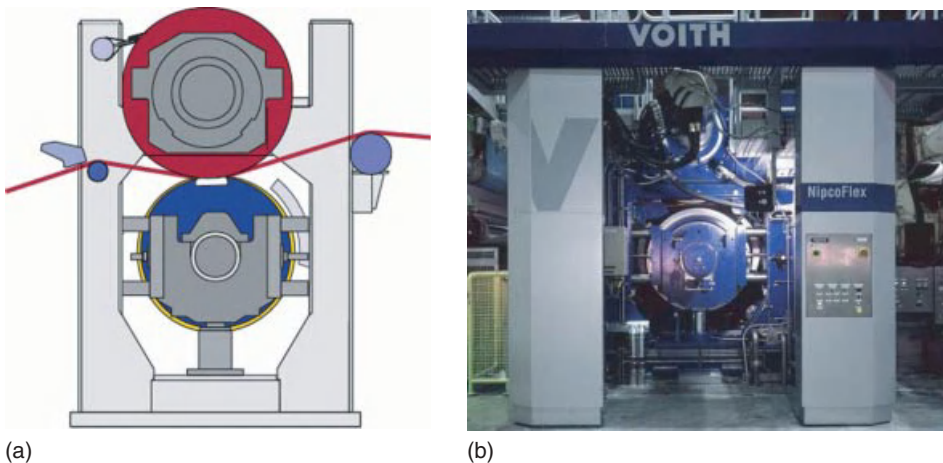


Figure 18.8 Shoe calender as an example of an extended nip calender, (a) schematic, (b) photo. (Source: Voith.)

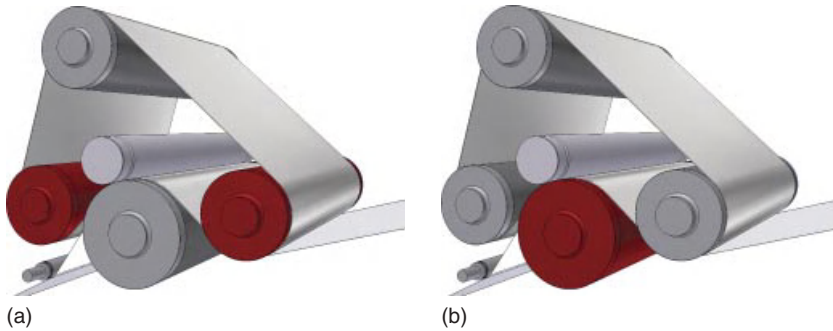


Figure 18.9 Belt calender (after [2]), heating and calendering of top (a) or bottom (b) side.

directed against the side of the web to be surface-treated. When passing the shoe nip, the web is calendered on the side contacting the heated metallic roll. The nip length is determined by the length of the concave shoe. Depending on the grade to be calendered and the operating conditions it varies between approximately 75 and 250 mm. The first shoe calenders were installed in board machines. Typically, these calenders are operated at surface temperatures between 150 and 250 °C. Other applications are with thermal paper at roll surface temperatures of approximately 60 °C.

At around 2005, belt calendering was introduced. This type of calender can be described as a combination of a hard nip calender with a thin belt (Figure 18.9). The belt clasps the counter roll before and after the nip at low pressure and thereby improves heat transfer to the web [2]. If a metal belt is used, it can be heated, and the counter roll can be heated, too. In this configuration, either one or both paper sides can be heated and thus calendered. In the nip section, pressure is less than that in a conventional nip; temperature typically is between 150 and 200 °C. Belt calendering also improves the ratio of surface and print quality versus bulk. Several installations are known for board grades, and one metal belt calender is running with copy paper (as of 2012). It is also known from patent applications that a polymer belt could be used instead of a metal belt and the heating zone before or after the nip could be omitted.

Figure 18.10 shows the calendering pressure over dwell time for shoe and belt calenders in comparison to a hard or soft nip calender. The years to come will show where and how extended nip calendering finally will find its place.

18.3.6

Embossing Calenders

Rüdiger Feldmann

The objective of embossing is to give the paper a three-dimensional pattern. This is achieved by means of a single nip calender. There are three different

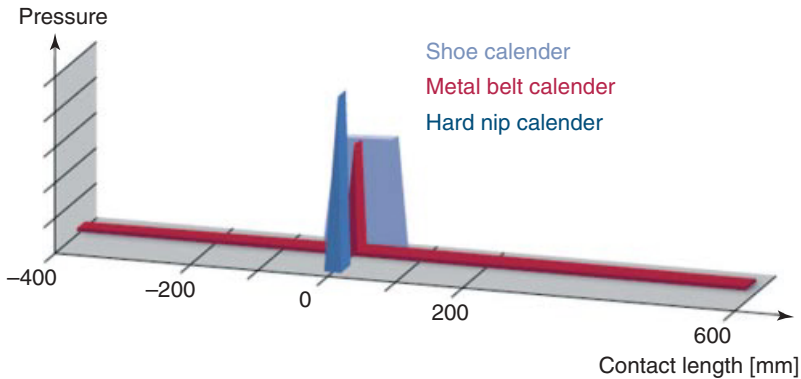


Figure 18.10 Calendering pressure over dwell time for different calendering principles. (Source: Voith.)

embossing methods, namely “matrix” embossing, “flat-back” embossing, and “union” embossing.

Machines for “matrix” embossing consist of an engraved ridged heated and sometimes chromium plated top roll and a soft covered bottom roll whose diameter is exactly double that of the top roll. By pressing both rolls together and running them at low speed, the pattern of the top roll is imprinted on the bottom roll. As a result, a paper web passed through the nip will have an embossed laid pattern on both sides. Matrix embossing is applied for graphic papers, wallpapers, and so on.

Flat-back embossers are similar to the above-mentioned calenders for geared embossing except that the diameter relation of the top and bottom roll is bigger or smaller than 1 : 2. With this type of calender, only the top side of the web receives a pattern. If both sides require a three-dimensional structure, the web has to be passed through the nip again with the former bottom side now turned against the top roll and with a reduced nip pressure. Flat-back embossing is applied for writing and printing papers, photographic papers, car body boards, and so on.

Union embossing calenders differ from the above-mentioned machines in so far as they consist of two rigid rolls of the same diameter. The rolls mesh. The distance between the two rolls is always adjusted in such a way that it is identical with the thickness of the web to be embossed. The result of union embossing is a web having a corrugated shape.

18.3.7

Friction Calenders

The purpose of friction calendering is to impart glazing to the paper. Friction calenders are single or double nip machines in which all rolls are driven separately at speeds that differ by 10–30%. They are mainly used for glazing playing cards.

18.4

The Main Calendering Methods for Various Paper and Board Grades

18.4.1

Wood-Containing Paper Grades

18.4.1.1 Newsprint

Newsprint belongs to the group of uncoated, wood-containing printing papers. Nowadays, it consists of up to 100% DIP (deinked pulp), basis weight around 45 g m^{-2} . These papers are produced on machines at speeds of up to about 1900 m min^{-1} and are equipped with machine calenders or online soft calenders. Modern paper machines equipped with just two double-felted press nips produce a base paper whose top side is slightly rougher than the bottom side. If a soft calender is used, its heated roll is always installed in the top position, as the contact of this roll with the rougher top side reduces the two-sidedness. The shrinkage-preventing, single-tier dryer section of a modern newsprint machine causes a more or less pronounced upward curl. To eliminate this curling, a steam moisturizer is installed in front of the first calender nip. As optimal CD caliper profiles are a basic prerequisite for a smooth-running printing process, particularly with lightweight newsprint, deflection control rolls are used in calenders that allow zone-controlled, short-wave caliper profiling and ensure 2σ values of below $0.5 \mu\text{m}$ in the caliper. As far as the printing process is concerned, offset printing is becoming more and more popular. A differentiation is made between cold offset and heat offset. Each method places a different demand on the paper.

For cold offset printing, Bendtsen roughnesses of the order of $150\text{--}200 \text{ ml min}^{-1}$ are required. This roughness level can easily be achieved on a two-roll online soft calender. The linear loads here are between 40 and 100 N mm^{-1} . The calendering temperature corresponds approximately to the web temperature.

For heat offset printing, lower roughness is required, that is, Bendtsen values of approximately 100 ml min^{-1} . To meet this requirement, online soft calenders with a total of two nips are used, so that each side of the web contacts a heated roll once. With a suitable layout – linear load, roll surface temperature – even rotogravure-capable SC-B papers (see later) can be produced.

18.4.1.2 SC-B/Offset and Rotogravure

SC papers can be subdivided into two main grades, SC-B with a high percentage of recovered paper (up to 100%) and SC-A with a high percentage of wood pulp (TMP or groundwood; up to 80%).

In contrast to SC-A top grades (see later), SC-B papers with a partially 100% DIP portion are already being calendered online today on 6-, 8-, or 10-roll calenders. The large percentage of DIP means that the papers are very quickly prone to increased black calendering. This trend continues with increasing web moisture. For this reason, cooling rolls are indispensable here. These reduce the moisture losses and therefore allow running into the calender at approximately 9% moisture. Online calendering of course places special demands on the availability of the machines,

especially on the service life of the resilient rolls and thermo rolls and presupposes a properly functioning tail threading system.

18.4.1.3 SC-A/Offset and Rotogravure

SC-A top grades are calendered on 10–12-roll multinip calenders in the off-line process, allowing speeds of up to 1500 m min^{-1} . Owing to the much higher calendering temperatures compared to the supercalendering process, the web running into the calender must be significantly moister. To achieve approximately 5% end moisture after the calender, ingoing moistures of 8–10% are necessary. Still higher web moistures do not produce any additional increase in the effect; on the contrary, they worsen the optical properties. The moisture losses between the calender and the rewind should therefore be kept as low as possible. The use of cooling rolls has proven useful in these cases. These are installed shortly after the last nip. In this way, the web temperature is suddenly cooled down by approximately 20°C and the moisture loss is reduced accordingly.

Owing to the previously mentioned high calendering temperatures in conjunction with significantly higher steam rates – up to five steam moisturizers are used – offset papers can be produced that already come very close to the LWC grades and are characterized by high gloss, a very uniform surface – no more “print mottling”! – and greatly reduced black calendering.

The calendering of rotogravure-capable SC papers proves to be more difficult, because rotogravure calls for very smooth paper surfaces in order to minimize the number of missing dots. A certain compaction is necessary for this, which is produced by the number of nips, linear load, temperature, and addition of steam. With increasing calendering speed it is of course more and more difficult to achieve the desired compaction. For high-quality rotogravure papers, the maximum possible calendering speed is therefore around $1100\text{--}1200 \text{ m min}^{-1}$.

18.4.1.4 Blade-Coated LWC/Offset and Rotogravure

LWC papers are either blade-coated or film-coated. In both cases it is recommended to calender the base paper before coating. The objective of this precalendering is to optimize the CD caliper profile, to compact the sheet structure and to easily smooth the web surface. In this way, the end result of calendering can be improved in Gardner gloss by up to 5% and in PPS-10S roughness by up to $0.2 \mu\text{m}$. The precalendering mostly takes place on a two-roll machine calender, that is, in a hard nip. It is, however, also possible to use a two-roll soft calender. Both types of calender are equipped with a deflection control roll. The calendered LWC papers go either to offset printing or to rotogravure printing.

LWC papers with a typical basis weight of $50\text{--}70 \text{ g m}^{-2}$, which are blade-coated on off-line coating machines, are still calendered off-line today. The extreme demands made on the smoothness of these papers provided with coating of only $6\text{--}8 \text{ g m}^{-2}$ per side – the PPS-10S roughness values are around $0.7\text{--}0.8 \mu\text{m}$ – have until now prevented online calendering at high speed. For the offline calendering of these papers generally modern 10–12-roll multinip calenders are used. The

calendering temperatures are up to 130 °C. The linear loads range between 300 and 400 N mm⁻¹.

18.4.1.5 Film-Coated LWC Offset

On LWC offset grades of typically 45–70 g m⁻² basis weight, the online-capable two-sided simultaneous film-coating method is becoming more and more popular, even at the highest speeds. Owing to film splitting, the surface of the paper is distinctly rougher than with the blade coating method and hence harder to smoothen. As offset papers do not require such high smoothing as rotogravure papers, they can be calendered online. Modern 6-, 8-, or 10-roll multinip calenders are used for this purpose. The calendering temperatures partially lie above 60 °C. The linear loads can reach 450 N mm⁻¹. Gardner gloss values of 55% are not infrequent. The PPS-10S roughnesses are between 1.4 and 2.0 μm. Today's base papers for LWC offset may contain up to 90% recovered paper. It should be noted that greater efforts are also being made to produce LWC rotogravure grades by the film-coating method. These film-coated LWC rotogravure papers can then be calendered online.

18.4.2

Woodfree Paper Grades

18.4.2.1 Woodfree Uncoated Papers

Woodfree uncoated papers include, above all, office papers, which are in turn subdivided into writing and printing papers as well as copy papers. In the past, these papers were not supercalendered. Simple machine calendering was considered satisfactory. However, the demands made on the surface quality of these papers have now increased considerably.

Besides the standard copy papers with a Bendtsen roughness of 220–280 ml min⁻¹ there is also a smooth paper for color copies with a roughness of less than 80 ml min⁻¹. For standard copy papers, a low-loaded machine calender with two hard rolls continues to be sufficient. As these papers require only a low sheet compaction, calendering in the hard nip does not lead to detrimental mottling. In the case of copy papers with a Bendtsen roughness of below 150 ml min⁻¹, sheet compaction by a two-roll machine calender is already so high that distinct mottling occurs here. To avoid this, a 2 × 2-roll online soft calender is required. As, in this case, each side of the web contacts a hot nip once, the roughness values are low for the top and bottom sides. It has been found that linear loads of 150–250 N mm⁻¹ and roll surface temperatures above 140 °C provide the optimal calendering conditions. Copy papers are cut-size papers, therefore uniform calipers are of special significance. Thus, irrespective of whether a machine calender or a soft calender is used, it is recommended to equip the calender with a multizone deflection control roll to optimize the caliper profile.

18.4.2.2 Woodfree Coated Paper Grades

With these papers a differentiation must be made between single-coated, double-coated, and triple-coated papers. In addition, it is also of significance whether the papers are to be used in rolls or as cut-size sheets.

Single-coated, woodfree papers are generally calendered online. The machines used for this are mostly 2×2 -roll soft calenders. At speeds up to 1300 m min^{-1} , Gardner gloss values of 55–65% can be achieved. To insure good flatness – this applies above all to cut-size sheets – the papers must be subjected to only moderate linear loads.

Up to the mid-1990s, double or triple blade-coated woodfree high-gloss papers with coating per side of $20\text{--}30 \text{ g m}^{-2}$ were calendered on supercalenders. Even today, they are still calendered off-line. However, 8–10-roll multinip calenders, whose resilient rolls are covered with synthetic material, have ousted the classic supercalenders. In contrast to conventional supercalenders, these new types can be operated at higher temperatures, that is, temperatures of $100\text{--}130^\circ\text{C}$. Consequently, the desired calendering parameters – PPS-10S roughness $0.7\text{--}0.9 \mu\text{m}$ and Gardner gloss 75–85% – can now be achieved at much higher speeds, around $700\text{--}1000 \text{ m min}^{-1}$. A further increase in speed would theoretically be possible, but presupposes an increase in the linear load. With rising linear load, however, the flatness, which is particularly important for cut-size paper, would be negatively affected. Linear loads of $200\text{--}300 \text{ N mm}^{-1}$ have proven to be optimal. Usually, these calenders are equipped with two cooling rolls.

It goes without saying that in this premium segment, there is, in addition to high-gloss paper, always a certain portion of matte or satin papers. Two different calendering processes exist for these. Either an online soft calender with two synthetic-covered rolls is built into the coater – by this soft/soft calendering the matte character of the paper is hardly changed, but the abrasion resistance is significantly improved – or the above-mentioned multiroll off-line calender is used by calendering the web in its uppermost and lowermost nips while the intermediate nips are “run through” – in this case both the gloss and smoothness of the web are increased.

18.4.3

Specialty Papers

18.4.3.1 Silicone Base Paper

Silicone base papers are used as carrier papers for the later application of a one-sided or two-sided layer of silicone, onto which, in the following operations, further layers, for example, adhesive in combination with label paper, are applied. Silicone base papers presuppose special quality features. These include, above all, high compaction, uniform caliper and moisture, high transparency, strength, good flatness, and a low surface roughness which ensures that the later application rates of the cost-intensive silicone are minimized. The basis weight of the silicone base paper is between 60 and 160 g m^{-2} . As in the past, these papers are calendered offline on special supercalenders with at least 15 rolls. The resilient rolls consist of

a cotton/linen mixture. The surface temperatures are around a maximum of 150 °C and the linear loads around 450 N mm⁻¹. The operating speed is 600 m min⁻¹. It is only in instances where not such high demands are made that modern offline multinip calenders with synthetic-coated resilient rolls are taken into consideration.

18.4.3.2 Laminated Base Paper

Laminated base papers are highly absorbent papers for the production of layered materials saturated with synthetic resins. The basis weight of these papers with an extremely high percentage of fillers – up to 40% – and correspondingly low strength, lies between 40 and 80 g m⁻². Laminated base papers are very dry. Their moisture content is only 1–2%. Characteristic of the production process of laminated base papers is that the trim widths change frequently and to a great extent. The base papers must be opaque and require one-sided smoothing to Bekk smoothness values of 400–600 s. For this purpose, 5-roll online multinip calenders with a linear load of 300 N mm⁻¹ are used. The roll surface temperatures of the heated rolls are around 150 °C. The resilient rolls are covered with synthetic materials. A steam blow box is also used.

18.4.4 Board

Jörg Rheims and Rüdiger Feldmann

18.4.4.1 Uncoated Board

Uncoated boards include a large variety of subgrades such as test liner, kraft liner, white top liner, and liquid containerboard. Some of these grades need no calendering at all. Where calendering is required to achieve better surface properties, Yankee cylinders and soft calenders have been used. As with coated grades, it is currently being discussed whether these traditional technologies can be replaced by extended nip calendering (Section 18.3.5).

18.4.4.2 Coated Board

Coated board grades range from one- to five-ply boards and can consist of virgin fibers and/or recycled fibers. The most important properties are high bulk, stiffness, and smoothness. The board is usually one-side coated. In some cases, however, it can also be coated on both sides.

Usually, the quality of the board surface before coating is adjusted by a Yankee cylinder or a machine calender; in some board machines a wet stack or a soft calender is used instead. In view of the bulk saving, these classical technologies may be replaced in certain cases by extended nip calendering (Section 18.3.5). For high demands on board quality, the coated surface can be smoothed by a soft calender, too.

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19

Reeling

Matthias Wohlfahrt

19.1

Objectives and Basics

The purpose of reeling is to wind up the continuously produced paper web on reel spools building up paper rolls of diameter up to 4.8 m. The paper rolls have to fit the requirements of any of the following process steps. These mainly concern the paper roll structure such as hardness and overall shape. As reeling is a discontinuous process, economic aspects as regards broke due to roll change/turnup are important as well. This concerns the so-called top broke outside the finished parent roll and the bottom broke at the inner layers of the spool.

There are only a few key parameters that influence the hardness of a roll (Figure 19.1). These are web tension, line force, and center torque. As, for example, some paper grades only allow low web tension to avoid breaks at the winder; this parameter often cannot be used for optimization of roll hardness. So, the main parameter is the line force, which usually varies between 1 and 6 kNm⁻¹. Line force can be applied either by the reel drum or the paper roll. The center torque applied on the reel spool is the third tool to build a good roll structure. There are different reel types combining these parameters in different ways depending on the special requirements of the individual paper grades to be reeled.

For certain ranges, roll hardness can be described by a linear equation as

$$s_{\text{rad}} = f_{\text{const}} + (f_{\text{WT}} \times \text{web tension (Nm}^{-1}\text{)}) + (f_{\text{CF}} \times \text{circumferential force (Nm}^{-1}\text{)}) + (f_{\text{LF}} \times \text{line force (kNm}^{-1}\text{)})$$

with the radial pressure s_{rad} defined as a positive value.

The f -factors can be determined, for example, by trials on a pilot reeler, where the same paper roll is wound several times by varying the above-mentioned parameters and measuring the resulting roll hardness.

As given in Table 19.1, the f -factors depend on paper grades, which can be explained by their individual quality parameters.

The negative value of f_{const} signifies that for every paper grade and velocity, the combination of the parameters web tension, circumferential force, and line force has to reach at least a minimum value below which the roll could not be wound.

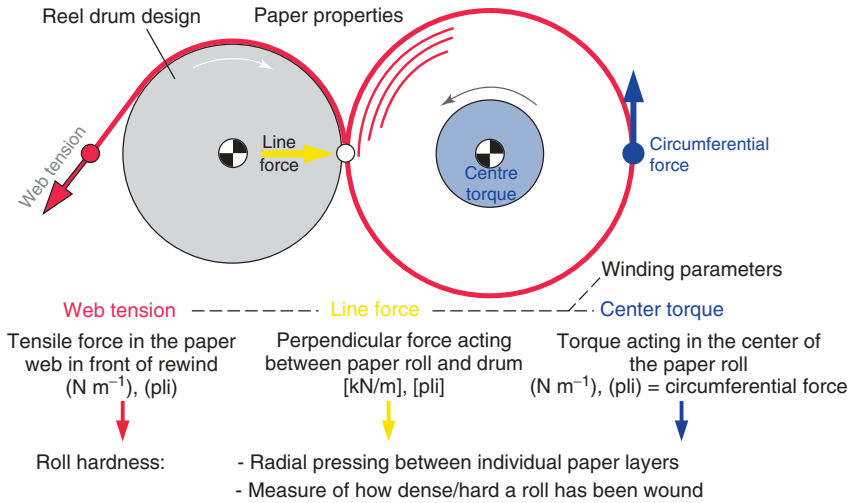


Figure 19.1 Variables influencing the structure of a roll. (Source: Voith.)

Table 19.1 Influence of winding parameters on roll hardness for constant velocity.

Factor for $v = 1200 \text{ m min}^{-1}$	Unit	Heavyweight-coated paper	Lightweight-coated paper
F_{const}	N mm^{-2}	-0.6	-0.26
f_{WT}	$\text{N mm}^{-2}/\text{N m}^{-1}$	8.2×10^{-4}	7.4×10^{-4}
f_{CF}	$\text{N mm}^{-2}/\text{N m}^{-1}$	5.8×10^{-4}	3.7×10^{-4}
f_{LF}	$\text{N mm}^{-2}/\text{kN m}^{-1}$	3.0×10^{-1}	9.6×10^{-2}

The main influencing paper properties in winding are porosity, smoothness, Young's modulus, density, friction coefficient, and cross-machine direction (CD) caliper profile. The reel drum is a design parameter, which cannot be changed during Reeler operation. On the other hand, its design has to be reviewed and possibly adapted when the paper grade produced is changed fundamentally as regards the above-mentioned quality properties.

19.2 History

The hasp, as shown in Figure 19.2, was one of the first simple units to store the continuously wound paper web. The next development concerning reeling came from Charles E. Pope. Figure 19.3 shows an extract of his patent from the year 1917. This was the first reel with all necessary components for online reeling and turnup

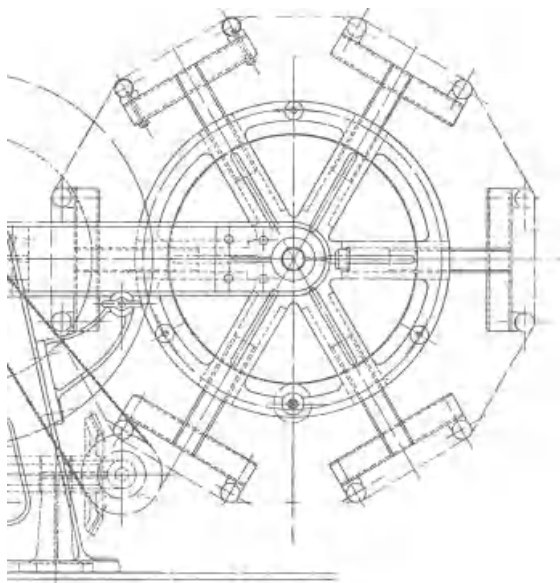


Figure 19.2 Hasp with adjustable diameter.

C. E. Pope
Winding reel for paper,
application filed July 13, 1915.

1,248,542.

Patented Dec. 4, 1917.
2 Sheets—Sheet 1.

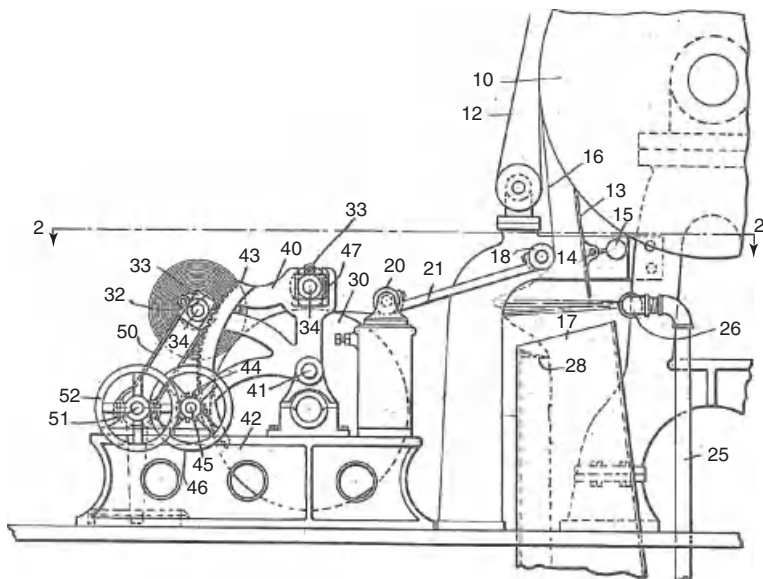


Figure 19.3 US Patent 1,248,542 granted to C. E. Pope.

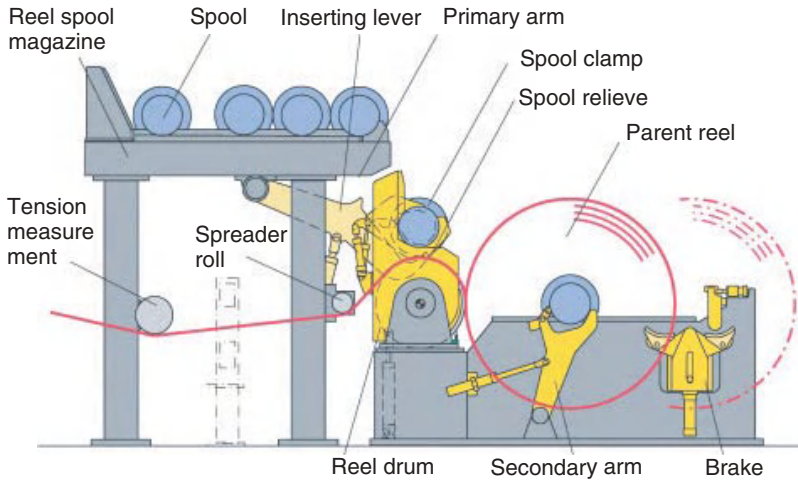


Figure 19.4 Standard Pope reel from 1990. (Source: Voith.)

at full machine speed. The development has been so fundamental, that in the next decades, only small modification has been done at this section. Figure 19.4 shows a reel used since 1990 with the modified components as primary, arm secondary arm, and reel spool clamp. Till now, the worldwide name used for this equipment is still “Pope reel.”

In the 1990s, demand increased dramatically. For example, in lightweight coated (LWC) production, coating has been changed from an off-line to an online process. This means that paper grades with critical properties (very high smoothness and high density) have to be wound on the reel at high machine speeds. Furthermore, the reel diameter has been increased from, for example, 2.8 m to more than 3.2 m for better efficiency of the paper machine. This required the development of new reel types.

19.3

New Generation Reels

19.3.1

Center Drive

A common characteristic of the reels of the new generation is the center drive in the reel spool applied during the whole winding process. Especially, for paper grades with sensitive surfaces, the center drive allows one to reduce the nip load and generate sufficient roll hardness at the same time.

19.3.2

Nip Load System

In modern wide machines, the nip load system uses hydraulic cylinders. Here, the nip load system is still a distinguishing factor. Type A shown in Figure 19.5 has a nip load system in the primary and secondary arms. When the nip load is applied by the parent reel, which may have a weight of up to 140 t, the friction forces can no longer be neglected; so, type A reels sometime use a low-friction linear guide for the parent roll to reduce these forces. As a further possibility, the nip load may be controlled by force sensors as part of a force-controlled system instead of the pressure in the hydraulic cylinders. One disadvantage is still given: the change of nip load application from the primary to the secondary arm.

The next two reel types have a movable reel drum to generate the nip load. The advantage is that there is no change of nip load system as in type A. Type B has a drum movable in the vertical direction. Here, the weight of the drum has to be compensated, as there is a large load component in the vertical direction, but only a small part of it is used for nip load control. This reduces the accuracy of this kind of control system. Type C has a drum movable in the horizontal direction. Here, the force direction of the nip load is orthogonal to that of the drum weight. Using low-friction carriages, line force deviations due to friction are low.

With this system, very low line forces can be realized with high accuracy. For example, now the sensitive NCR (No Carbon Required) papers can be wound up with a nip allowing about double the speed.

	Type A	Type B	Type C
Reel drum	Stationary and fixed	Vertically movable	Horizontally movable
Parent roll	Horizontally movable	Horizontally movable	"Stationary"
Line force system	Tow systems: primary arm for spool clamp and secondary arm for transfer	One system: reel drum carriage angle not constant	One system: reel drum carriage
Spool weight	Influence on line force in primary arm operation	No influence on line force	No influence on line force

Figure 19.5 Comparison of new generation reels. (Source: Voith.)

19.3.3 Oscillation

At Type C the reel spool in the secondary arm is way controlled. It has to compensate for the growth of the roll diameter. The reel drum is force controlled and follows the movement of the nip. When the secondary arm gets an overlay of a sine movement in the machine direction counteracting at Front Side (FS) and Drive Side (DS), the drum follows without changing the nip load and its CD uniformity. This requires a vertical web run before the reel drum, in order not to influence web tension over the width. The result is an oscillated paper roll (Figure 19.6), realized with only a few small further hardware components. This feature is very useful for “hard” paper grades with high Young’s modulus. Deviations in CD caliper profile cannot accumulate so easily, which allows one to wind larger diameters without winding defects.

19.4 Reel Drum Design

The structure of the wound paper roll is also influenced by the design of the reel drum. As shown in Figure 19.7, two kinds of air bubbles may occur at the reel. The boundary layers below the web and on the reel drum are mainly influenced by the web speed. Low paper porosity leads to air accumulation (air bubble) between

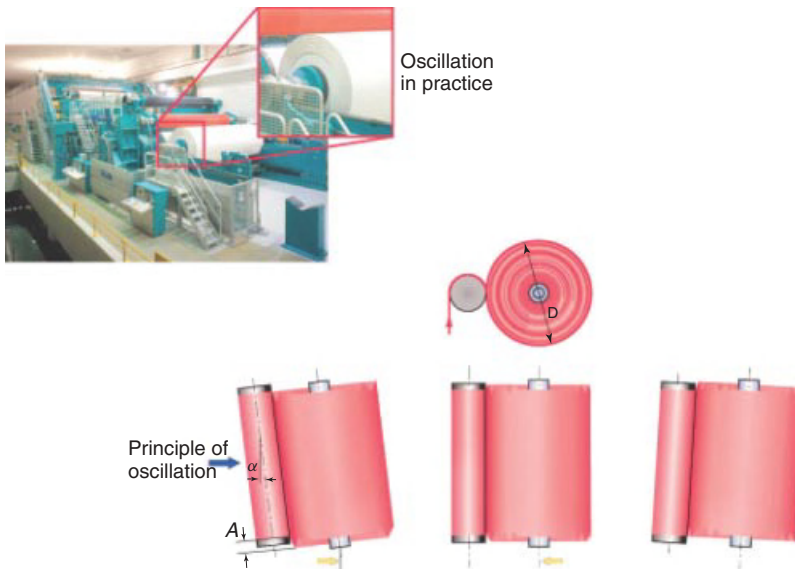
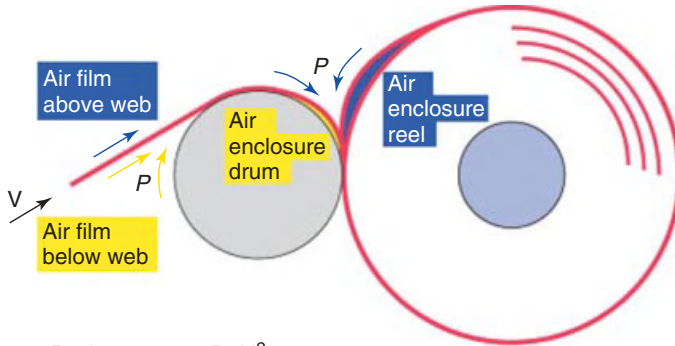


Figure 19.6 Oscillation in reeling. (Source: Voith.)



Back pressure: $P \sim V^2$

Figure 19.7 Influence of air boundary layers on winding result. (Source: Voith.)

the web and the drum before the nip. The web is no longer firmly fixed in the CD and can float in CD, which will lead to uneven edges. A critical situation occurs when the air bubble gets too big and even goes through the nip. The resulting wrinkles cause broke. The air bubble problem can be avoided or reduced by two measures. First, narrow grooves in the drum surface allow the air to pass the nip. Practical experience has shown that for higher speeds and lower paper, web porosity through-drilled drums have the highest efficiency. Here, the air is not compressed as it goes through the drills into the drum and can leave below the drum.

Deviations in the CD caliper profile lead to a noncylindrical roll shape. This means that the nip is not closed over the whole width, and air can be easily wound into the roll between the outermost two layers. When paper porosity is high, the air can escape before coming again through the nip. If not, the air will also accumulate between two layers of the paper web in the parent roll before the nip. Sometimes there exist more bubbles between several layers. If the bubbles are almost stationary and not too large then generally no problems occur, but when they are pulsating irregularly in the CD, they can cause wrinkles and broke.

With the groove design on the reel drum, the wind-in of air cannot be avoided, but the air can be moved steadily to the edges, resulting in a stable balance of air in the roll. Here, a pressure relief groove or wide grooves will be applied. The groove has to be a spiral, changing its direction in the middle of the drum. The arrow of the groove has to show in the web run direction; otherwise, the air would be transported toward the machine center.

A possibility to reduce the amount of wound-in air in the parent roll is to use a rubber-covered reel drum. This drum can adapt to the uneven surface of the roll to a certain degree and thus close the nip over the whole width. At the same time, line force distribution with the rubber-covered drum is more even over the whole machine width, thus avoiding the high-pressure areas that can occur with a steel drum.

19.5 Turnup Systems

19.5.1 General

The continuous process of paper production is interrupted at the reel when the required roll diameter or web length has been reached. Now, the paper web has to be cut, a fresh reel of spool started, and the finished parent roll discharged. So first the empty reel spool has to be accelerated to machine speed. With a standard Pope reel, the empty reel spool will now be lowered till the nip is closed (Figure 19.4). The reel is now ready for the turnup, which is described separately.

Some new generation reels show a different sequence. They first open the nip by moving the parent roll (Figure 19.8). In order to avoid too much air being wound in an air-squeezing element, a small roll or a brush on the parent roll is applied. After the parent roll is in its end position, the primary arm can be lowered to the turnup position and the primary nip is closed. The turnup position of the primary arm can now be varied between the position of a standard Pope reel and the position on the rails, depending on the demand of the turnup system and the paper grade. The turnup is easier and faster with self-threading concepts when the empty spool is already partly wrapped by the web.

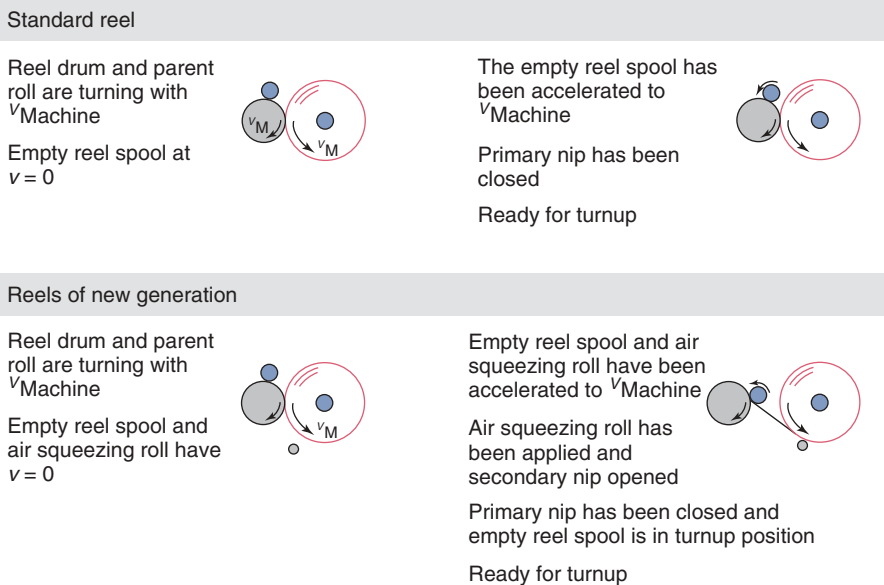


Figure 19.8 Turnup preparation for two kinds of reel types. (Source: Voith.)

19.5.2

Nordic Turnup

The most simple and oldest system is the Nordic turnup. The parent roll opens the nip a little and then is decelerated. Thus, a web loop is formed between the reel spool/reel drum running at machine speed and the decelerated parent roll. Because of the vacuum between the outgoing web and the empty reel spool, the paper web starts to wrap the spool. When it reaches the nip, at low basis weights, the web will be cut by the suddenly induced acceleration. For high basis weights, the web will be cut by the high tear forces because the paper on the parent roll and on the new reel spool moves in different directions. For heavier paper grades, wrapping of the empty spool can be supported by an air stream from below. The disadvantages of this system are the high amount of top broke and the high load of all components, when the paper is torn in the nip, especially at higher basis weights.

19.5.3

Web-Wide Cutting Knife

With the winding concepts, where the nip between drum and finished roll is opened, the web can be cut with a web-wide knife operated in the open draw. As the new spool is already wrapped by the web, the system is self-threading. The system has a very high turnup efficiency and is mainly applied for lower and medium basis weights of up to about 120 g m^{-2} .

19.5.4

Air-Supported Turnup Systems (Gooseneck, Cobra)

The air-supported turnup systems have their main applications at basis weights of up to 100 g m^{-2} , or in special cases of up to 150 g m^{-2} . A blowpipe formed similar to a gooseneck gave the name to one of these turnup systems. A small cut of a few centimeters in the CD will be created, for example, with a needle, in the middle of the web before the drum. The thus weakened web can be blown by the gooseneck blowpipe to the empty reel spool. The tear in the cross-direction will be supported by two nozzles blowing from the middle to the edges between the primary and the secondary nips.

For very small paper machines, one or two blowpipes in the cross-direction, positioned at the edges after the primary nip, are sufficient. They cut the web from the edges and transfer it to the empty spool. The so-called Cobra system can also be used to support the gooseneck for large paper web widths.

The air-supported systems only need compressed air as a medium and have a quite simple design. As web cutting is not clearly defined, the turnup quality depends on the paper properties and the machine speed. As a further consequence, some bottom broke may occur.

19.5.5

Tape Turnup System

For higher basis weights and board and packaging grades, the tape turnup system is often used. Here, a tape of sufficient strength is placed before the drum, below the web, across the machine width. One end of the tape is provided with an adhesive, which will connect the tape to the edge of the empty spool as soon as it reaches the nip. A brake on the end of the tape builds up adequate strain in the tape, so that it can tear the web when it is wound as a spiral on the empty spool. This system can provide defined tear forces acting on the web at the tape edge. Although several tape types with different thicknesses are available, there are still bottom losses due to the marking of the tape.

19.5.6

Turnup with High-Pressure Water Jet

One of these kinds of turnup system has two high-pressure nozzles before the reel drum, which can be moved very quickly in the cross-direction. These nozzles start in the middle of the web at a distance of about 20–40 cm. The high-pressure water jet, thus, cuts a center strip, which is transferred to the empty reel spool after the primary nip. After its successful turnup, two high-pressure nozzles are moved at high velocity toward the edges of the paper web, which finishes the turnup of the full web width. The kind of center strip cutting and transfer to the empty spool is the main difference in the existing systems (Figure 19.9).

On a new generation reel, where the secondary nip is opened, the next step is to cut the center strip in the open draw after the primary nip with an air nozzle or a small knife. The stripe is then self-threading and the turnup can be finished as described previously.

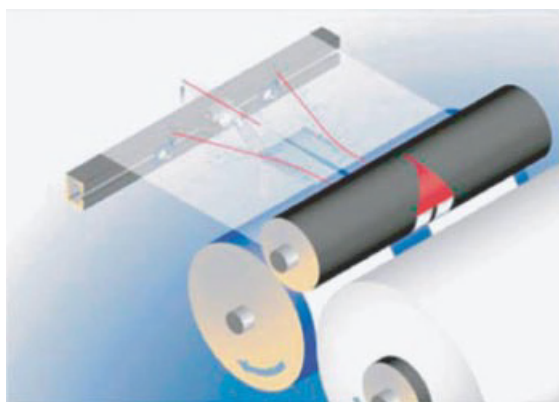


Figure 19.9 Turnup system with high-pressure water jet and cutting form sheet. (Source: Voith.)

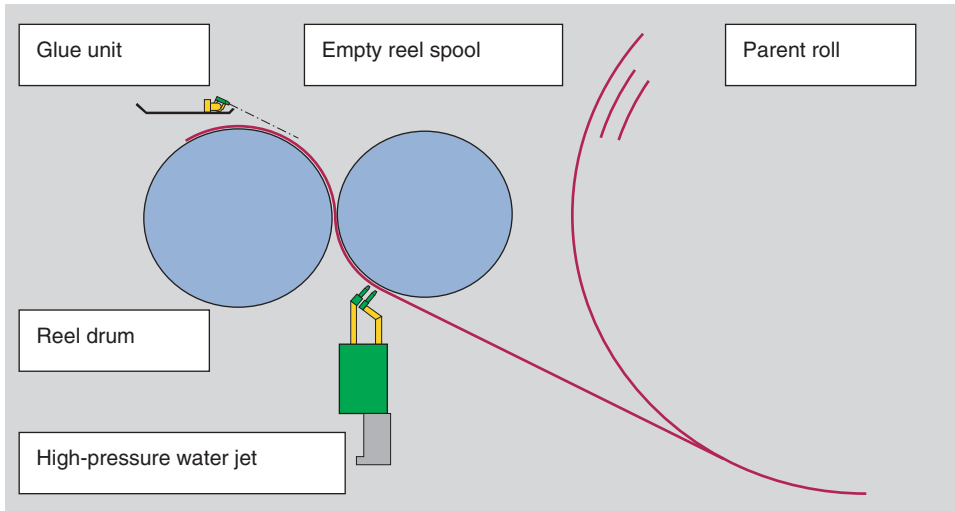


Figure 19.10 New type of turnup system cutting the web after the primary nip. (Source: Voith.)

Another high-pressure water jet system is similar to a gooseneck, which only turns up the center strip. This system can be used both with a closed and with an opened secondary nip. With these systems, the beginning of the center strip is not immediately fixed at the empty reel spool, which can lead to considerable bottom broke, especially, with the gooseneck-type system.

Figure 19.10 shows a newly developed system for the new generation reels. This turnup unit cuts the web after the primary nip on the new empty reel spool and fixes the beginning of the web with glue or water.

Turnup units, which weaken the web before the nip by needle or high-pressure cut, have the disadvantage that they could lead to a web break before the reel drum. With this new design, higher turnup efficiency is obtained than with previous systems.

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20

Paper, Packaging, and Carton Board Machines

Herbert Holik

Since the earliest times of industrial papermaking, Fourdrinier and mould formers have been used for the production of all kinds of paper and board. In the past century, the machines started to be more customized to the special requirements of the individual product grade, based on quality, economy, and operational requirements. When planning a new machine or a major rebuild today, requirements have to be defined and decisions made relating to, for example, capacity, furnish, essential product properties, frequency of production changes, multi-ply, multi-layer, or single-layer production, machine width and speed, machine equipment, and so on. The variety of machines and their layouts are mainly related to the five main classes of paper and board grades with their varying requirements and can be defined as

- Graphic paper machines
- Packaging paper machines
- Carton board machines
- Tissue machines
- Specialty paper machines.

20.1

Graphic Paper Machines

Johann Moser and Herbert Holik

The majority of paper machines worldwide produce graphic paper grades on Fourdrinier wire sections or hybrid formers. These kinds of conventional forming section usually satisfy the quality and capacity requirements. Their disadvantages are the limitation in machine speed of about 1200 m min^{-1} and, for some paper grades, the nonsymmetry in the web z -direction.

Modern paper machines for graphic paper production are – except machines for tissue grades – the fastest and widest paper machines. Current limits for wire width as key design parameter is $11\,700 \text{ mm}$ and for design speed 2200 m min^{-1} . A further increase in width and/or speed has many obstacles and is, therefore, not economic for the time being. Major obstacles are machine tool capacity, weaving

loom capacity (width) for machine clothing, shipping of parts (size and weight), and headbox pump size.

The principle design mostly comprises a gap former, a closed-draw press section, a single-tier or combined single-/double-tier dryer section, and in certain cases, a size press or a coating station. The technological progress as well as increased cost pressures have led to online multinip calendering positioned before the reel in supercalendered (SC) and lightweight coated (LWC) papermaking lines.

The paper machine layout and operating conditions differ according to the special requirements of the grades produced with regard to

- wood-containing paper such as newsprint and SC or LWC paper grades;
- woodfree paper such as copy paper or base paper for coated paper

with

- offline or online coating and
- offline or online calendering

Figure 20.1 shows an overview regarding paper grade and quality level. A less demanding grade such as newsprint results in a more simple machine layout, and concept, and woodfree coated (WFC) paper as the most demanding grade requires a more complicated and expensive machine layout.

20.1.1

Newsprint Paper Machines

Newsprint paper must be made with high efficiency and productivity. Demands regarding paper surface quality for printing and optical appearance are on the lower side. The preferred furnish at present is deinked pulp (DIP). Key properties for newsprint papers are strength, stiffness, roughness, brightness, opacity, formation, linting, and dusting.

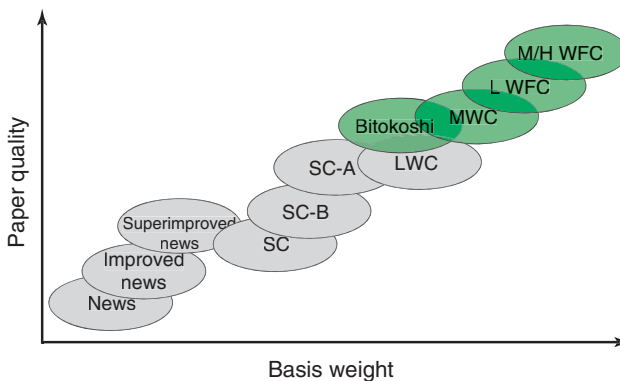


Figure 20.1 Overview of paper grade and quality level.

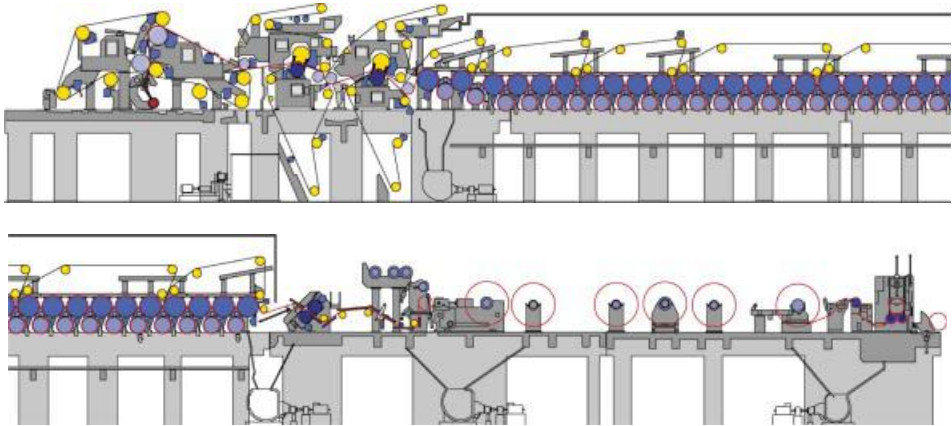


Figure 20.2 State-of-the-art newspaper paper machine.

Figure 20.2 shows a state-of-the-art newspaper paper machine. These machines are designed for an output of up to $400\,000\text{ t year}^{-1}$. With a main basis weight of 45 g m^{-2} , a trim at the paper machine reel of $10\,650\text{ mm}$, and a speed of 2200 m min^{-1} , a daily production of about 1500 t can be achieved. A special feature of such a machine is the fully supported web run up to the end of the dryer section reducing web breaks to a minimum. A headbox with dilution water system delivers the stock into the wedge of the forming zone. A roll/blade gap former provides enough dewatering capacity and loadable blades ensure good formation. With a tandem shoe press (two extended nips), dryness levels of more than 50% are achieved. A single-tier dryer section with web stabilizer boxes, a hard nip calender, and the reeler make up the rest of the machine.

For the production of improved newspaper, two soft nip calenders are installed instead of a hard nip calender in order to achieve the lower roughness target. In some markets such as Japan and in some other special cases, a further improved surface quality is demanded. In this case, a newspaper machine will be equipped with a surface sizing unit, that is a film size press, and an after-dryer section.

20.1.2

SC Paper Machines

SC paper grades are a cost-efficient choice for magazines. They are uncoated and made of wood-containing stock. The key properties of SC paper grades are roughness, gloss, porosity, formation, oil absorbency (Cobb-Unger), opacity, and optical appearance. The grade is used for offset or rotogravure printing and contains up to 33% filler to promote smoothness and gloss. Especially, rotogravure printing has very high demands on paper surface quality. According to the roughness level, different grade specifications do exist (SC A+, SC A, SC B, and SC C). Various furnish recipes as follows are used:

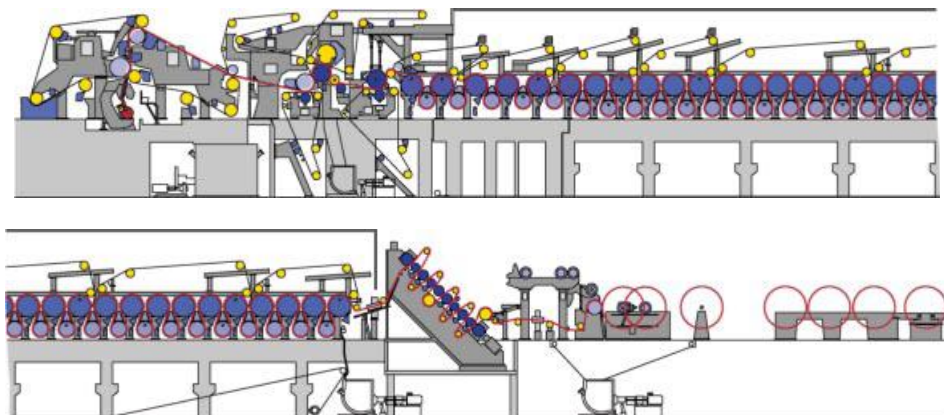


Figure 20.3 Modern SC paper machine.

- TMP plus chemical pulp
- Groundwood plus chemical pulp
- DIP with a high portion of recycled magazine paper.

A furnish of groundwood and chemical pulp has the best potential to make excellent paper quality, but it is also most expensive. The energy input is high and a high ratio of reinforcement pulp (chemical pulp) must be used.

Figure 20.3 shows a modern SC paper machine. Such a machine is designed for making up to 400 000 t year⁻¹ of SC paper. With a basis weight of 56 g m⁻², a trim at paper machine reel of 9070 mm and a speed of 1800 m min⁻¹, a daily production of more than 1200 t can be achieved. The machine comprises a dilution water headbox, a roll/blade gap former, a tri-nip press section plus straight-through press, a single-tier dryer section, a multinip calender, and the reeler.

As the stock shows a poor dewatering behavior, a high dewatering capacity on the forming roll is required. This means that the design dispose of a large forming roll wrap angle. A conventional press section (shoe press in third nip position) favors surface quality; however, it has a speed limit because of the open draws with unsupported web run. In such a press section, the bottom side faces twice a smooth surface and the top side just once. The intense contact of the paper surface with the smooth roll surfaces ensures the raw paper roughness to be on a low level, which does not need a too high compression of the web during calendering. This avoids or reduces blackening. The web enters the calender (at high speeds) with about 11% moisture content by targeting final moisture of 5.5% at the reel. Depending on the roughness requirements, the online multinip calender is equipped with 6, 8, or 10 rolls.

For SC A+ grades, two off-line calenders are a better solution operated at low speed in order to achieve the desired roughness levels of about 1.0 PPS. A less expensive machine design comprises a press section without a fourth press. Here, the trade-off is a higher two-sidedness of roughness or oil absorption.

20.1.3

LWC Paper Machines

For quality magazine printing, LWC papers are preferred. The key properties are very similar to SC paper. In the past, the preferred furnish was groundwood or TMP with reinforcement pulp. At present with state-of-the-art deinking technology, a DIP-based furnish is the first choice. For the best surface quality and optical properties, a coat is applied on the top and bottom sides of the web.

Figure 20.4 shows the design of a modern LWC machine. Recent machines are designed to make up to 300 000 t year⁻¹. With a main basis weight of 60 g m⁻², a trim at paper machine reel of 8020 mm, and a speed of 1700 m min⁻¹, a daily production of almost 1200 t can be achieved. A dilution water headbox, a roll/blade gap former, a tandem shoe press with transfer belt, and pre-dryer section are well suited for base paper production. Before coating with a film coater, a hard nip calender adjusts roughness, porosity, and CD caliper profile of the web on entering the coater. The film coater is followed by an air flotation dryer, an after-dryer section, a multinip soft calender, and a reeler. Older designs have two blade coater stations installed instead of a film coater unit. Blade coaters deliver superior surface properties; however, they may have lower efficiency as minor web defects result in web breaks, and the design requires a remarkable higher investment budget.

20.1.4

Machines for Woodfree Uncoated (WFU) Paper Production

Paper for office applications (digital printing: photo copy, inkjet, and laser), commercial printing (mostly offset printing), and writing purposes is produced on machines tailor-made for these grades. The key properties for the grades are formation, roughness, bulk (caliper), stiffness, two-sidedness, surface strength, and optical appearance.

Different from paper machines for commodity papers such as newsprint, SC, and LWC, these machines have to cover a wide basis weight range (60–300 g m⁻²). For

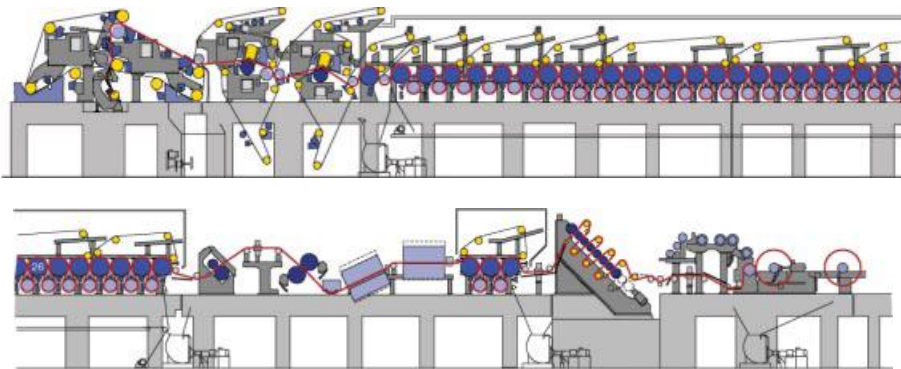


Figure 20.4 Example of a modern LWC paper machine.

good quality, the basis weight ratio (maximum/minimum) on one machine should not exceed 3 : 1 in order to maintain good paper quality and operating efficiency. Preferred furnish is chemical pulp, the majority of machines use eucalypt species. DIP based on recycled material from offices is also a well-suited furnish, but because of capacity constraints and massive price fluctuations, this furnish is not very common. Two categories of paper machines differing in their layout are found at present in the market, which concern large-scale or small- and medium-scale machines.

Large-scale machines are designed to produce up to 600 000 t year⁻¹. With a main basis weight of 80 g m⁻², a trim at paper machine reel of 10 500 mm, and a speed of 1600 m min⁻¹, a daily production of 2000 t can be achieved. A further speed increase would be possible applying higher press impulse (line load) but on the expense of bulk. Small-scale machines produce up to 180 000 t year⁻¹ based on a trim of 5280 mm and a maximum operating speed of 1200 m min⁻¹. Figure 20.5 shows a schematic drawing of a large-scale machine to produce WFU papers. Gap forming and two extended nips for wet pressing are first choice. The web is fully supported from forming to the end of the pre-dryer section. Surface sizing is provided with a film sizing unit for promoting surface strength. After the dryer section, a hard nip calender and a reeler make up the end of the machine.

A small-scale machine does not need gap forming. There is also no need to have a 100% single-tier dryer section because of lower maximum operating speed. A double-tier dryer section has the advantage of cutting down the machine length. For machines with a wide basis weight range and a wide quality window, two soft calenders (two independent nips) are the first choice for achieving roughness levels below 100 ml Bendsen. In this case, the single-nip calender (hard nip) is replaced by two soft nip calender stacks. In many cases, the machine layout already takes into account the space for such an extension. Cutting edge technology is single-nip shoe pressing. Instead of two shoe presses, the press section comprizes only one shoe press. Tailor-made felts and sophisticated felt conditioning ensure cost-effective production.

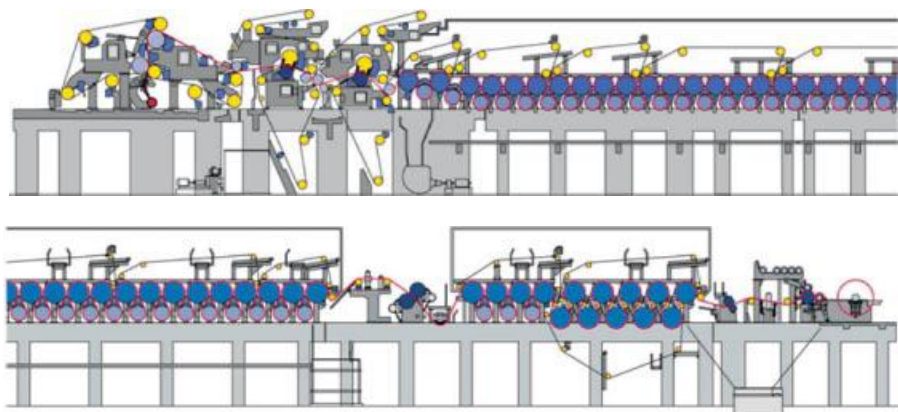


Figure 20.5 Principle design of a machine to produce WFU papers in large scale.

20.1.5

Machines for WFC Paper Production

In the past years, the size of machines for woodfree coated (WFC) paper production has changed dramatically. State-of-the-art machines produce more than 1 000 000 t year⁻¹. WFC papers are the most demanding grades regarding quality. The key properties are gloss, roughness, surface strength, brightness, whiteness, and two-sidedness.

Highest demands are given when these papers are used for prime printing products such as business reports, life style magazines with advertisements for luxury goods, or sales leaflets for expensive cars. The machines also cover a wide basis weight range from coated paper up to coated graphic board products (300 g m⁻²). Double-coated products are standard and more and more triple-coated products are printer's first choice. Again, these machines can be divided into two categories of layout, the large-scale and the small- or medium-scale machines.

Except calendering, all unit operations are online, which cuts down the investment costs. Large-scale machines are designed to make at least 700 000 t year⁻¹ and even more than 1 000 000 t year⁻¹. With a main basis weight of 128 g m⁻², a trim at paper machine reel of 9770 mm and a speed of 1800 m min⁻¹, a daily production of 3240 t can be achieved, which results in 950 000 t year⁻¹. Small-scale machines produce up to 200 000 t year⁻¹ based on a trim of 4810 mm and a maximum operating speed of 1100 m min⁻¹.

Figure 20.6 shows a schematic drawing of a large-scale machine for WFC paper production. Gap forming and two extended nips for wet pressing are first choice.

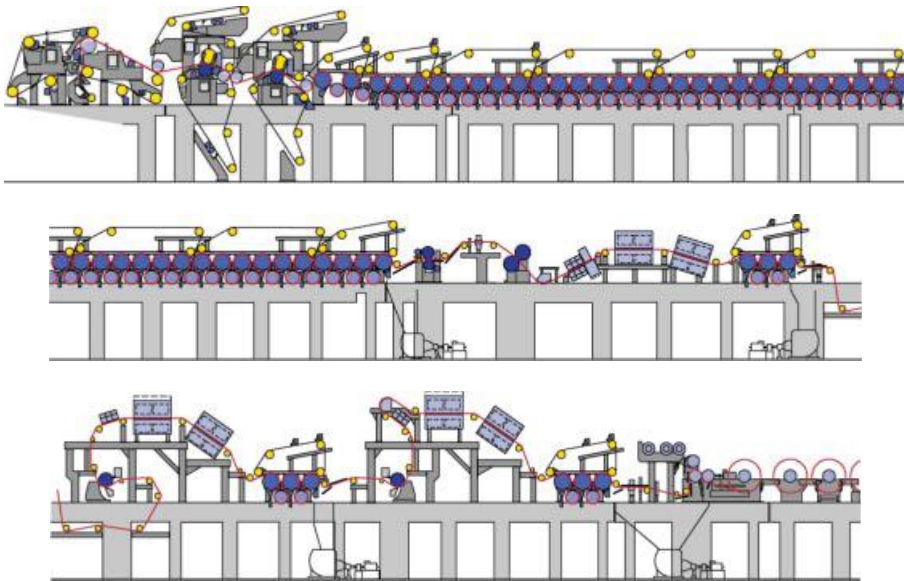


Figure 20.6 Modern design of a WFC paper machine.

The entire pre-dryer section is of single-tier design. The coating section consists of a film pre-coating unit and two blade coating units, all online. Before the web enters the coater units, it passes a hard nip calender for smoothness and caliper control. Three short, compact dryer sections (air flotation dryers, IR dryers, and cylinder dryers) evaporate the water after coating. Finally, the web is reeled on an advanced reeler. The large and heavy parent rolls (e.g., diameter 3.7 m and weight 125 t) are shipped to off-line calendering to promote smoothness and gloss.

For small-scale machines, sheet forming is done by a hybrid former instead of a gap former. Also, on small-scale machines, the entire web run from forming to the end of the pre-dryer section is fully supported by fabrics and rolls, which means no open draws.

20.2

Packaging Paper Machines

Herbert Holik and Stevan Lomic

The main products of packaging paper machines are the base for corrugated board, which shows a steady growth and has a high capacity on the market. Corrugated board consists of at least two outer layers (testliner (TL) or kraftliner), which are glued to a corrugated inner layer (corrugating medium (CM) or fluting) to obtain high bending stiffness. The bending stiffness of container board is 1000 times higher than that of carton board.

TL and CM are made from recycled fibers, whereas kraftliner and fluting from virgin fibers. Corrugated containers must safely transport the packed product, for example, from the origin to the supermarket. Here, they inform the customers and the staff about the content and its characteristics, and therefore should allow an appealing printed display on the surface. So, the main quality requirements are the box compression resistance (ability to pile the boxes) and good printability. As a result, the raw paper must show sufficient strength, measured as short span compression test (SCT) or ring crush test (RCT) for liner and Concora medium test (CMT) for CM or fluting.

The various applications require a wide basis weight range of about 70–450 g m⁻² to be run on one single machine. In Europe, emphasis is put on 70–130 g m⁻², whereby in future even lower basis weights should be available in the market. Here, the main furnish is recovered paper. By its adequate treatment in stock preparation and thorough cleaning of the fabrics and rolls in the paper machine, good paper quality as well as good machine runnability at high machine speeds are achieved. Machine speeds were 500–800 m min⁻¹ in the 1970s and 1980s. At present, the maximum operating speed is above 1500 m min⁻¹ with design speeds of up to 1800 m min⁻¹. The driving force for the speed increase is the emphasis on lowered basis weights and low specific investment cost.

Different trends in Europe and Asia can be observed. In Europe, new paper machines (Figure 20.7) are designed for 1500–1800 m min⁻¹ with one- or two-layer headboxes and gapformers with a width of 5.5 or 7.6 m (respectively 7.9 m

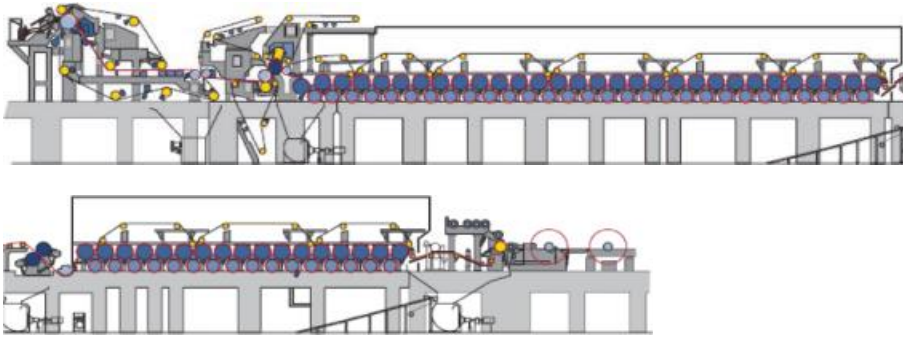


Figure 20.7 Paper machine producing corrugating medium and testliner (basis weight $75\text{--}145\text{ g m}^{-2}$, design speed 1800 m min^{-1} , wire width 8550 mm , and production $400\,000\text{ t year}^{-1}$).

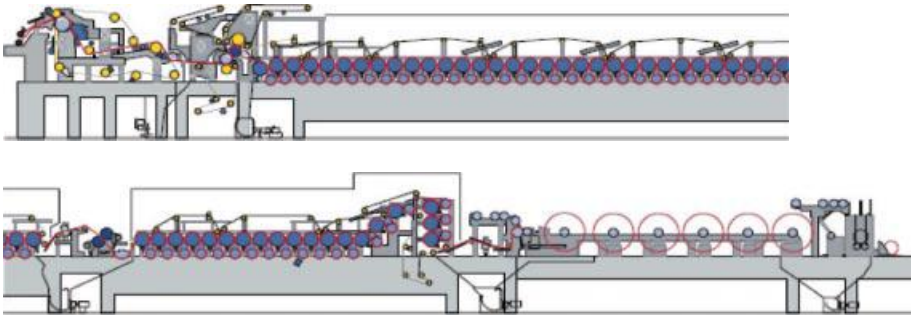


Figure 20.8 Paper machine producing testliner and fluting (basis weight $65\text{--}140\text{ g m}^{-2}$, design speed 1600 m min^{-1} , wire width 8750 mm , and production $455\,000\text{ t year}^{-1}$).

untrimmed width at the reel). In Asia, almost all new TL/CM paper machines are three-ply Fourdrinier paper machines with a width of 6.66 m (Figure 20.8). The paper machines in Asia, especially in China, are equipped with a stock preparation providing three types of recycled fibers (short, middle, and long), which determine the design of the wire section. Additionally, the Asian market requires high-performance TL unbleached kraftpulp in the top layer. In order to reduce the furnish costs for these machines, the top layer is designed for a minimal basis weight.

High machine speeds require a twin-wire gap former to ensure high uniformity of the product and sufficient dewatering capacity. Twin-wire gap formers are available in different configurations. One is shown in Figure 20.7, which depicts a state-of-the-art packaging paper machine with the headbox in upper position. Lamellas in the headbox nozzle help to optimize fiber distribution and control MD/CD ratio. A two-layer headbox with different fiber fractions in the two layers is an option to increase paper strength properties, respectively increase flexibility regarding furnish composition.

The press section with two (Figure 20.8) or three nips (Figure 20.7) ensures high dry content of the web on entering the dryer section. As the paper web is always supported during its transfer from the wire to the dryer section, without any free draw, machine runnability is high even at the elevated machine speeds and lowered basis weights. For runnability reasons, the pre-dryer section is single tier. Safe web run is supported by air flow-based stabilizers. For high machine speeds, a film press replaces the pond size press as the latter starts to encounter unacceptable pond turbulences at speeds above $800\text{--}1100\text{ m min}^{-1}$. Surface sizing increases the strength properties of the final sheet significantly. However, the web strength in the machine is reduced dramatically by rewetting during sizing. That is why for low basis weights, high moisture pick up at the size press, and high speed production, an air float dryer may be used after the film press, followed by single-tier and double-tier dryer groups.

In reeling, one important requirement is the large paper roll diameter for two main reasons: The first is to reduce paper loss. A certain loss at each reel is unavoidable; so, less reels with larger diameters for the same production reduce the overall loss. The second reason is to allow one single winder to cope with the paper machine output. This can be reached by reducing the nonproductive time for parent roll change in this noncontinuous process step. At present, Jumbo rolls with diameters of up to 4.5 m are produced.

There are other packaging products in the market, for example, white top liner and sack paper. White top liner has a white surface to cope with the high demands for an appealing display. For its production, two webs are formed in two separate forming units – one white and one brown layer and then couched together ahead of the press section. New paper machines (Figure 20.9) are equipped with a three-ply wire section to reduce furnish costs. To ensure best coverage and printability, the web is coated in an online curtain coater and at least one blade coater.

In the case of sack paper, high strength and sufficient elongation at rupture in both directions (MD and CD) as well as defined porosity of the paper are required. These special properties are important, for instance, during the filling of the sacks. Other applications are all kinds of wrapping. A sack paper machine (Figure 20.10) has a single Fourdrinier designed for very low consistencies in the headbox of about 0.1–0.3%. A single-shoe press ensures a high dry content after the press section

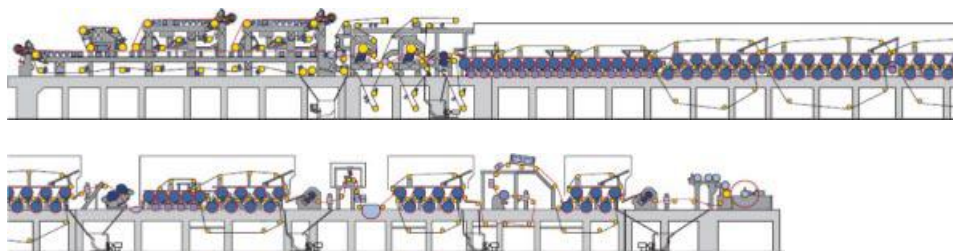


Figure 20.9 Paper machine producing coated white top testliner (basis weight $140\text{--}220\text{ g m}^{-2}$, design speed 1200 m min^{-1} , wire width 1.0410 mm , and production $850\,000\text{ t year}^{-1}$).

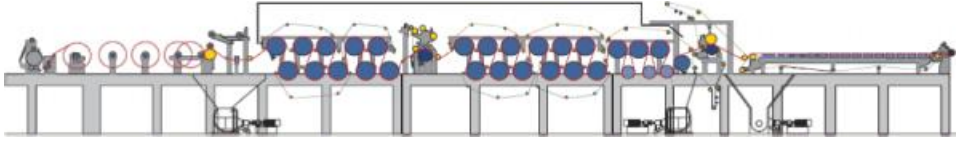


Figure 20.10 Paper machine producing sack paper (basis weight 70–120 g m⁻², design speed 800 m min⁻¹, wire width 4.000 mm, and production 75 000 t year⁻¹).

at the defined porosity of the final product. For the highest elongation of this kind of packaging material, the “Clupak process,” introduced in the 1960s, is applied. Here, the still wet web is pressed in a nip, where a compressible belt runs with the web. The belt deformation in the nip and the shape regain of the “extensible unit” after the press nip result in microcreping with up to about 8% elongation (MD) at rupture. Microcreping can also be obtained by passing the web through a nip with hard and soft covered rolls.

20.3

Carton Board Machines

Herbert Holik and Stevan Lomic

Carton board is a product with a wide range of basis weight of about 160 to more than 600 g m⁻². Carton board together with containerboard have the highest share, about 80%, of the total paperboard production. Carton board is mainly used for production of carton boxes to pack, for example, food, cigarettes, pharmaceuticals, or cosmetics. Additionally, a wide range of specialty boards exist such as artboard, gypsum board, playing card board, bookbinder board, and so on. As the requirements for these board grades vary a lot, the furnish and the board machine design may differ accordingly. Some of the basic required properties are:

- Mechanical properties such as bending stiffness (bulk and Young’s modulus) to protect the packed goods against damage.
- Flatness, plybond, creasability, and punching to ensure good runnability in converting and packaging lines.
- Resistance against moisture, gas, and flavor to protect the goods from quality changes.
- Freeness from impurities such as microorganisms, toxic or mutagenous substrates, and taint or odor to protect the goods against contamination.
- Brightness, gloss, roughness, and printability of the surface to ensure appealing information, identification, and promotion of the packed goods.

Paperboard mainly has a multi-ply structure to achieve the different product requirements in the most economical and environmental-friendly way, for example, by applying various furnishes in the different plies. The surface plies (top and back

plies) have to ensure the strength properties (bending stiffness) and, together with the coating, the required surface quality. With the inner plies (undertop and filler plies), the bulk is optimized (affecting bending stiffness). Most carton boards are on-machine coated and calendered to obtain appealing surface characteristics.

Depending on the product and the geographic location of the board producer, virgin or recycled fibers or both fiber types are used as raw material. In multi-ply production, the individual plies are formed on separate forming units and couched together in wet condition. Formation of two layers in one forming unit is also done. Different forming principles as described as follows have been applied either uniquely or in combination with others.

In the past 10 years, the speed of board machines was dramatically increased from 600 to above 900 m min⁻¹ and a few machines are operating even at higher speeds (1100–1200 m min⁻¹). The main reason for doubling the speed is specific investment cost as well as operating costs.

In suction formers, 3–11 cylinder formers in series with suction chambers produce webs of about 25–100 g m⁻² each which are couched on a transfer felt, thus building up the baseboard. The maximum speed increased to above 450 m min⁻¹, and the maximum width is about 5 m. Cylinder formers without vacuum application are limited to a maximum speed of about 150 m min⁻¹.

In Fourdriniers and hybrid formers, each ply is formed on a separate Fourdrinier wire. Hybrid formers are used, for example, to produce the filler ply with the widest basis weight range and highest basis weights, which require extended dewatering capacity. The headbox and wire section have to be adapted to the high throughput ratio and the high surface quality requirements for coating and printing. The maximum speed of a Fourdrinier and hybrid formers for carton board application is about 1000–1200 m min⁻¹.

In the past few years, a trend toward less plies in the wire section was determined by energy consumption and because of better coverage with curtain coaters. In this case, no undertop layer is needed to ensure good opacity and coverage. New board machines for standard folding boxboard (FBB) production (from virgin fibers) have only three plies; for white-lined chipboard (WLC), mainly made from recycled fibers, three or four plies.

As Fourdriniers in combination with hybrid formers have sufficient speed, potential gap formers are seldom used in carton board production. Besides the sufficient capacity, wire sections with Fourdriniers are achieving better quality levels. Nevertheless, gap former installations can be found for certain applications of specialty board such as gypsum board, where a higher MD/CD ratio is allowed, respectively, requested.

The press sections of modern machines for carton board are designed for high dewatering capacity, high bulk, smoothness, and good runnability. This leads to press designs with typically three press nips. At the beginning of the twenty-first century, the standard design for a carton board machine was a double-felted suction press in the first nip, followed by a double-felted shoe press nip and finally an unfelted smoothing press or a single-felted roll press to enhance surface smoothness. For board machines running at higher speed, a closed web run

ensures stable sheet transfer, whereby an open draw at lower machine speeds is accepted to avoid rewetting of the web. Rewetting occurs when top and bottom felts form a so-called sandwich with the paperboard web. In the past years, the design with a double-felted shoe press followed by a single- or double-felted shoe press became standard. At the end of the press section, an unfelted smoothing press or single-felted (at higher speeds) roll or shoe press can be found.

The dryer section consists of more than 100 drying cylinders (Figure 20.11) in the pre-dryer section and about 16–20 in the after-dryer section. One or two single-tier groups are followed by double-tier drying groups. With increasing machine speed, the number of single-tier groups has increased and even web-supporting equipment can be found in the first groups of the pre-dryer as well as after-dryer sections. For good flatness of the finished product, the top and the bottom cylinder rows are heated separately to control curl tendency.

Starch or size can be applied in a film press or a pond size press to enhance surface strength and bending stiffness. In this case, an after-dryer section is required for baseboard drying.

Before coating, the roughness of the baseboard has to be reduced by calendering. In modern board machines, this is done by a heated hard nip calender. As an alternative, soft nip calenders can be used for reduced densification. Shoe nip calenders or belt calenders are also used, which combine long dwell time, low specific pressure, and high roll surface temperature to achieve minimum roughness at the lowest densification. In Europe, for machines below about 650 m min^{-1} , the use of a machine-glazed (MG) cylinder is state of the art for high bulk, low roughness board production. As the entering web dryness (about 60–70%) and exiting (about 70–75%) web dry content are crucial for smoothness and bulk of the baseboard, the MG cylinder is often the bottle neck for machine speed increase. For the board machines operating at higher speeds, a hard nip calender with moisturizer is standard. It can be expected that in the next years, different concepts for calendering will be available in the market.

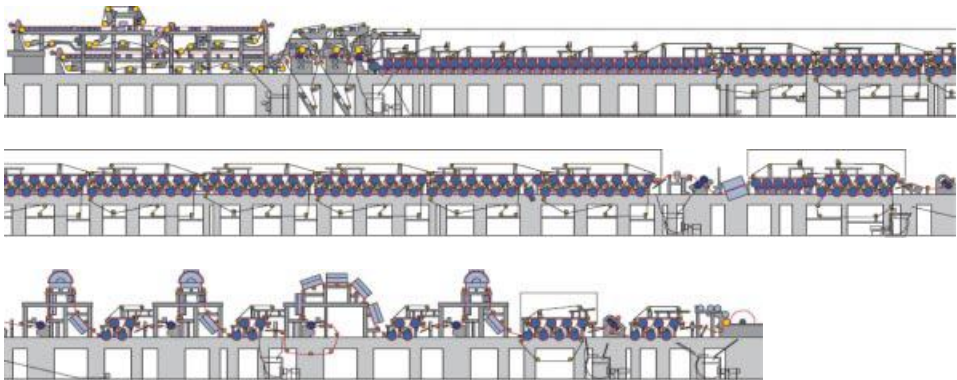


Figure 20.11 Board machine producing folding boxboard (basis weight $180\text{--}350 \text{ g m}^{-2}$, design speed 1400 m min^{-1} , wire width 8750 mm , and production $1\,200\,000 \text{ t year}^{-1}$).

Virgin fiber-based carton board is mainly double coated on the top side and uncoated or single coated on the back side. In Asia, where almost all of the new board machines are installed, triple coated is state-of-art (Figure 20.12). WLC made of recycled fibers is mainly triple coated on the top side and uncoated or single coated on the back side (Figure 20.13), each layer with special tasks and coating formulations. Coating is done by roll applicators or free jet applicators for highest surface requirements and machine speeds. A significant improvement was carried out in the past years in the area of coating drying regarding the web run as well as energy efficiency.

Final carton board post-calendering is mainly done with soft nip calenders. The Pope reeler can be used for reeling up to a diameter of 3.8 m; reelers with center torque are applied for diameters of up to 4.4 m. A state-of-the-art board machine (Figure 20.12) with online coating and final calendering has a length of

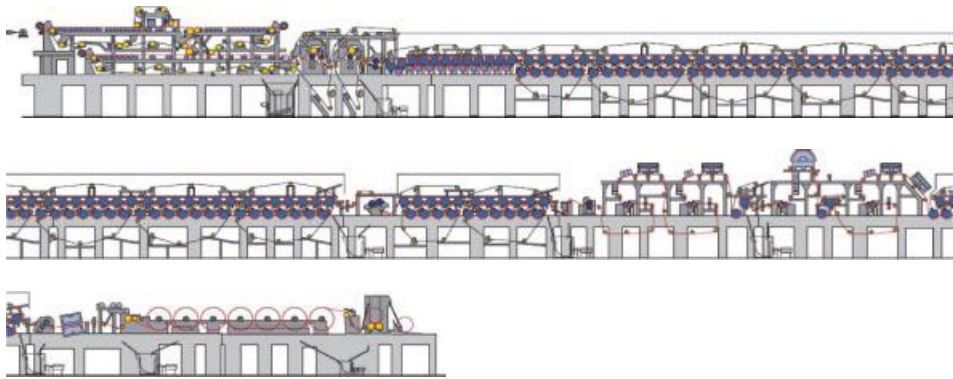


Figure 20.12 Board machine producing folding boxboard (basis weight 290–350 g m⁻², design speed 900 m min⁻¹, wire width 8750 mm, and production 1 000 000 t year⁻¹).

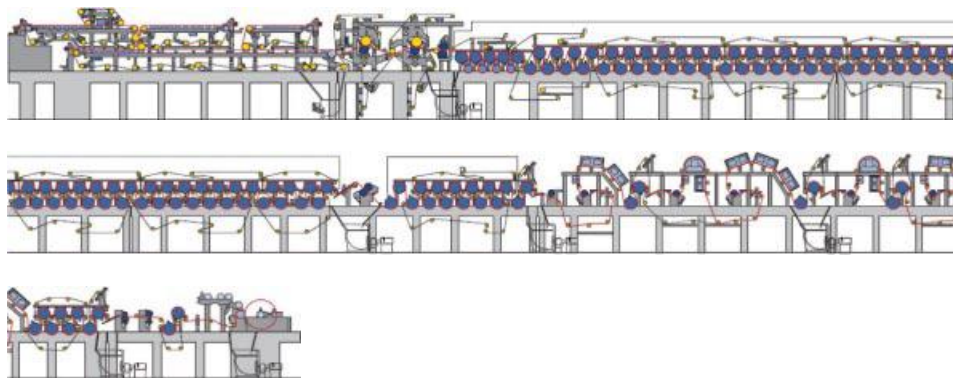


Figure 20.13 Board machine producing folding boxboard and white-lined chipboard (basis weight 200–400 g m⁻², design speed 900 m min⁻¹, wire width 7320 mm, and production 650 000 t year⁻¹).

approximately 400 m, and the worldwide fastest and widest board machine has a length of up to 500 m (Figure 20.11).

20.4

Tissue Machines

Herbert Holik, Rogério Berardi, and Thomas Scherb

20.4.1

Overview

Tissue machines produce tissue grades with basis weights of 10–45 g m⁻², which are the bases for the various hygienic products. Consumer demands drive the tissue industry to evermore softness and absorbency of the tissue grades used, for example, in the bathroom (toilet, facial) or the kitchen (towels). Softness can be increased by the proper selection of fiber furnish and chemical additives or the proper machine design and operation. On the other hand, sufficient paper strength and economy of production have to be regarded.

Compared to other paper machines, tissue machines are compact as regards their widths (maximum 8.0 m and most common from 2.8 to 5.6 m) and lengths, which are between 45 and 80 m. Tissue machines are the fastest paper machines with a maximum speed at present of about 2200 m min⁻¹ (in the forming section) and heading for even 2400 m min⁻¹. Recent maximum production capacity is about 100 000 tpa, most commonly from 35 000 to 70 000 tpa.

At present, there are three different types of tissue machines in the market: the conventional tissue machine, the through air dryer (TAD) tissue machine, and the advanced tissue moulding system (ATMOS) tissue machine. Their basic production principles are similar: web forming, dewatering, drying, and creping. But within these steps, they vary a lot. Table 20.1 gives an overview of the principle design and operating conditions of the three main types of tissue machines. Also, the resulting products differ a lot, as can be seen in the images in Figure 20.14.

20.4.2

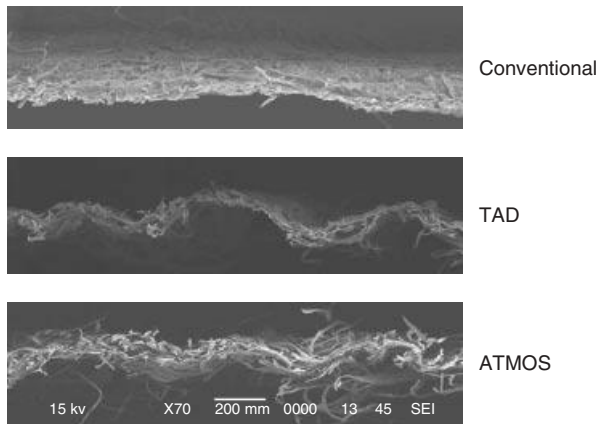
Unit Processes in Tissue Production

20.4.2.1 Web Forming

In the former times, tissue was made – and is still made in many places – on Fourdriniers, later followed by suction breast rolls (Chapter 14) and since the 1970s by gap formers. Since the 1990s, the so-called Crescent former is the most accepted system. Recent tissue forming section for conventional tissue machines is a roll former, where the headbox jet is deposited in the wedge between two converging fabrics. One-, two-, or even three-layer headboxes are used, the latter for stratification of the tissue web. The converging fabrics can be either two forming wires (twin wire) or a forming wire and a felt (Crescent former). In this case, the felt transfers the web directly to the dryer section. Web formation is completed

Table 20.1 Overview of design parameters and operating conditions of the three main types of tissue machines.

Type of tissue machine	Web forming	Dewatering	Drying	Wire width (mm)	Machine length (m)	Creping factor	Operating speed (m min ⁻¹)	Capacity (t year ⁻¹)
Conventional	Crescent C-wrap S-wrap (with felt)	Shoe press roll Suction press roll	Tissue cylinder Air impingement hood	<8000 (2800–5600)	45	10–25	2200	<70 000
TAD	Twin wire (Former with inner and outer wires)	Suction boxes and air caps	Air through dryer Tissue cylinder Air impingement hood	<8000 (2800–5600)	60–80	2–5	1500	<70 000
ATMOS	Crescent with moulding fabric	ATMOS module with suction roll and ATMOS press	Tissue cylinder Air impingement hood	<8000 (2800–5600)	50–60	5–15	1600	<70 000

**Figure 20.14** SEM pictures of cross-sections of tissue papers from conventional, TAD, and ATMOS tissue machines. (Source: Voith.)

during the contact of the wire(s) on the forming roll. The web dryness at the end is about 10–15% depending on the fiber furnish, as well as wire and felt design. The wire run in the forming section may be designed as a C-wrap or an S-wrap with the headbox placed at the top or bottom position in both cases. In Figure 20.15 a conventional tissue machine with a Crescent former as an example of a C-wrap design is shown.



Figure 20.15 View of a conventional tissue machine. (Source: Voith.)

20.4.2.2 Dewatering

The web is dewatered by vacuum and pressing with one or two rolls or shoe press against the Yankee cylinder. In case of two rolls, most commonly, one roll is a suction press roll, the other one has a plain shell. For a single nip, a suction press roll or a long nip press roll is applied. When using the shoe press as pressing device against the Yankee cylinder, a suction roll is installed before the nip to increase the web dewatering. At present, typically only one press nip or the shoe press is applied in order to avoid too much loss in volume. The dryness after the last press nip is about 38–42% with one suction press roll and from 42% to 46% with the shoe press.

20.4.2.3 Drying

The dryer section in tissue machines consists of one large-diameter tissue cylinder named Yankee dryer with an air impingement hood (Chapter 16). During its contact with the cylinder, the web is dried within less than half a second to a final dryness of 95–96%. As the drying capacity of the tissue cylinder is limited because of dimension and safety reasons, the air impingement hood has to provide more and more drying capacity with increasing production and at high machine speeds, it is more than 60%.

20.4.2.4 Creping

Creping of the web provides volume and softness of the tissue product. The creping factor is defined by the ratio of the speed difference of the web before creping and the speed at the reel related to the speed before creping. It is about 10–25% depending on the product. Important is the creping quality, that is, the web structure (“wave length”). This is strongly influenced by the dryness of the web and the doctor work, which in turn depends on the doctor geometry and the adhesion of the web to the

Yankee cylinder surface. Here, the coating chemicals are important, influencing the web adhesion to and release off the Yankee cylinder surface. The coat is built up by hemicelluloses of the web and by spray of adhesion and release aids.

20.4.3

Conventional Tissue Machines

For conventional tissue machines (Figure 20.15), recent maximum speed is about 2200 m min^{-1} ; typical widths are between 2.8 and 8.0 m and length about 45 m. Production capacity is up to 100 000 tpa.

In a state-of-the-art conventional tissue machine, the web is formed in a gap former (Crescent former with wire plus felt). It is transferred by the felt to the dryer section. Here, it is first vacuum dewatered and then 100% of the web is pressed and mechanically dewatered by a suction press roll or a shoe press acting against the Yankee cylinder. The web is dried, by intense contact and impingement heating, to about 95–96% dry content. The web is then creped by a creping doctor and wound up. The main parameters influencing bulk are indicated in Figure 20.16.

20.4.3.1 Wet Creped Tissue

There are also some machines where a Yankee cylinder with air impingement hood dries the web only up to about 70–80%. Then, the web is wet creped and finally dried to 95–96% in a conventional after-drying section and wound up.

20.4.4

TAD Tissue Machine

This machine type has been the standard for premium tissue production since long time. Current maximum operating speed is about $1400\text{--}1500 \text{ m min}^{-1}$, typical width from 2.8 to 5.6 m, and length about 60–80 m. Production capacity is up to 70 000 tpa.

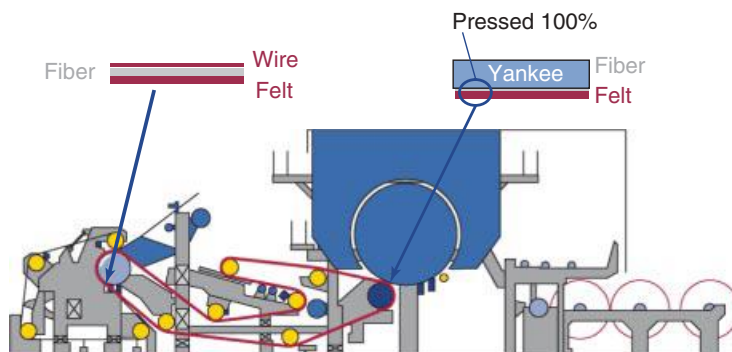


Figure 20.16 Principle of forming and dewatering in a conventional tissue machine. (Source: Voith.)

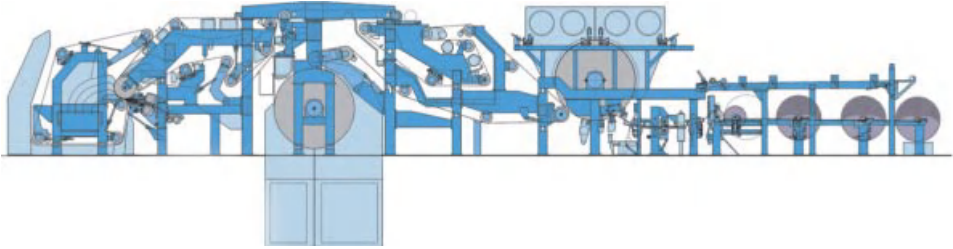


Figure 20.17 Tissue machine with through air dryer (TAD). (Source: Andritz.)

In a TAD tissue machine (Figure 20.17), the web is formed in a twin wire as described before. Then, it is vacuum dewatered and transferred to a structured fabric. The sheet then is sucked into the valleys of the structured fabric to ensure a three-dimensional pattern. After that it is pre-dried to about 70–85% dry content to ensure uniform through air drying and moisture profile in one or more TADs without mechanical pressing. Here, the through dryer replaces the press nip dewatering in order to preserve the bulk. On the other hand, this results in substantially higher thermal and electrical energy consumption for drying. The web is then transferred, only 20–25% of the sheet being pressed at the knuckles of the structured fabric and glued to the Yankee drying cylinder. About 75–80% of the web remains unpressed for quality reasons. Coating agent application ensures good sticking of the structured web to the Yankee cylinder surface to obtain the required characteristics at creping. Web length decrease by creping is only about 2–5% in this case. Between the Yankee cylinder and the reel, a gap calender is installed to calibrate caliper/bulk versus handfeel as described before, always with special attention to bulk preservation. Figure 20.18 shows the positions in forming and dewatering where and by which means the wet bulk is preserved.

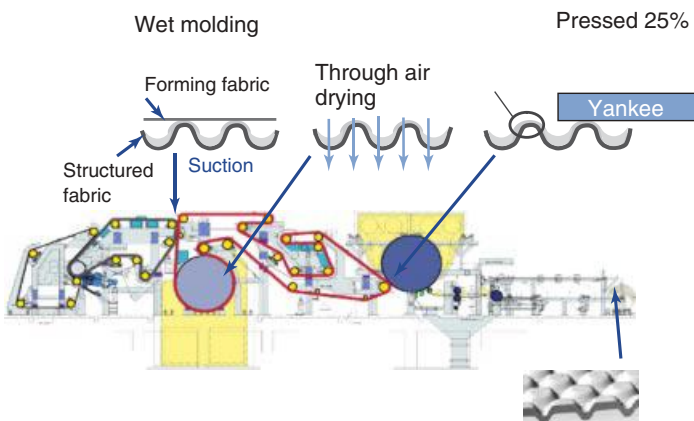


Figure 20.18 Principle of forming and dewatering in an TAD tissue machine for bulk preservation. (Source: Voith.)

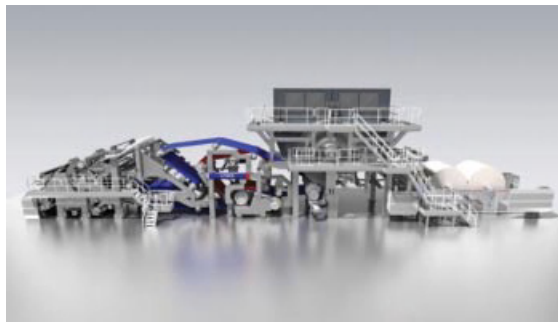


Figure 20.19 ATMOS tissue machine. (Source: Voith.)

20.4.5

Wet Moulding Tissue Machines – ATMOS

This machine type (Figure 20.19) has been developed for high-premium tissue quality production with special attention to bulk, softness, and absorbency as well as low energy consumption (up to 60% less usage of electrical and thermal energies). It came to the market in 2007. Current maximum operating speed is about 1600 m min^{-1} , typical widths 2.8 and 5.6 m, and length about 50–60 m. Current production capacity is up to 70 000 tpa.

Formation is done in the same way as with a conventional Crescent former. But in this case, the felt is replaced by a structured molding fabric. This ensures a three-dimensional web structure already during formation. After the actual web forming in the Crescent former, a wet-shaping box with vacuum continues to dewater and structure the web. The following vacuum roll is for maximum dewatering, mainly by air sucked through the web. Here, the web is in intense contact with the dewatering fabric and the permeable belt, the latter withstanding high tensile loading in a rather long nip and with hot air flow through the nip. A hood on top of the module provides hot air and steam for temperature increase (and thus viscosity decrease) of the water to be sucked out. Some kind of “press” follows builtup by a plain shell roll and a suction roll for gentle dewatering. Owing to the structured fabric, only 20–25% of the web is pressed at the knuckles of the fabric and further dewatered. This means that the structured fabric carries the web – with the fibers protected within the pockets of the fabric – through all the dewatering positions up to the Yankee cylinder. The parameters for bulk preservation are indicated in Figure 20.20.

The web is transferred to the Yankee cylinder by a press roll. Owing to the fabric structure, the web compression is minimized. Like on TAD, only 20–25% of the sheet is pressed against the Yankee and 75–80% of the fibers remain unpressed. Special coating chemicals ensure reliable sheet transfer and uniform adhesion to the Yankee cylinder. The latter is important for good creping results. Web length decrease in creping is about 5–15%. As on TAD machines, a gap calender is installed between the Yankee cylinder and the reel to calibrate web caliper/bulk

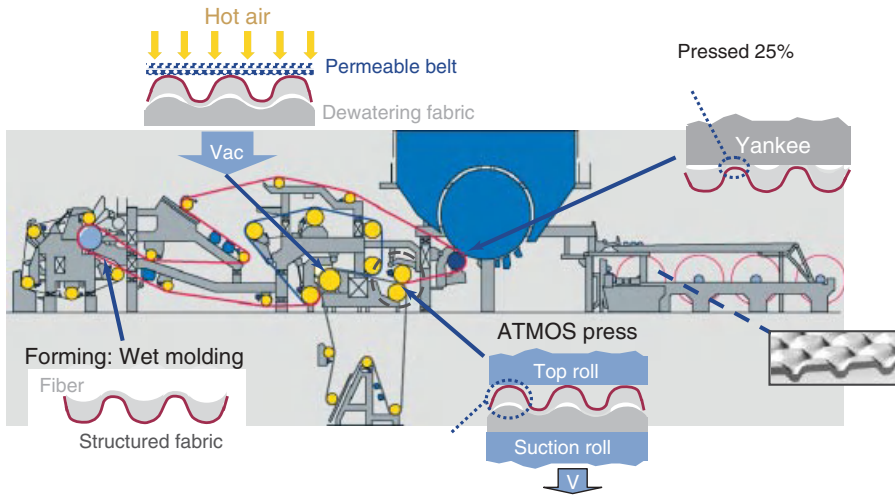


Figure 20.20 Principle of forming and dewatering in an ATMOS tissue machine for bulk preservation. (Source: Voith.)

versus handfeel always with special attention to bulk preservation. In the end, the structured web is wound up.

20.5

Specialty Paper Machines

Peter Mirsberger

The category of specialty papers defines a very wide range of different paper grades. Important segments are flexible packaging, printing, release liners, cigarette, filtration, security, and electrical papers. Within each segment, there is again a wide variety of specialized end uses and thus different and particular quality demands. These require special production technologies and specific know-how. Some of the required properties are very common and similar to commodity papers, but they are usually more distinct or with a closer tolerance. Such characteristics include profile quality, formation, smoothness, strength, caliper, porosity, and absorption. Some are very particular characteristics, such as wet strength, electrical conductivity, pore size distribution, resistance to certain chemicals, chemical reactivity, light proofness, heat resistance, and cleanliness.

Often specialty paper grades such as photo, cigarette, or label papers are cut into small formats. Here, the basis weight profile as well as the fiber orientation must be as uniform as possible across the width; so, dilution water technology in the headbox for CD profile control is standard on most paper machines for specialty paper grades. Other important quality characteristics of specialty papers are MD/CD tensile ratio and dimensional stability. Decor, inkjet, and label papers, for example, absorb a large amount of water during laminating, printing, or gluing.

Fibers, however, swell in width more than in length when wetted. To achieve the best dimensional stability, the fibers of the sheet should be randomly oriented to obtain a “square sheet,” that is, the lowest possible MD/CD tensile ratio is required over the full width.

Not only are the quality requirements various but also the production of specialty papers covers a wide range of speed and basis weights. The basis weights extend from 12 g m^{-2} for tea bag paper up to 300 g m^{-2} for specific photo base papers. The speed range extends from 40 m min^{-1} for banknote papers and up to 1600 m min^{-1} for thermal base paper. Accordingly, the production capacity of specialty paper machines covers a very wide range from less than 1 t h^{-1} to more than 35 t h^{-1} . Often, different grades are produced on the same paper machine. Further characteristics of specialty paper machines are small tonnages per grade, many grade changes, and a dynamic grade development, that is, new grades are developed, which can cope with new market demands; other grades disappear from the market because of lack of demand. So, flexibility is a keyword – not only for the production of these papers but also for the paper machine layout.

The base sheet forming principle for specialty papers is the Fourdrinier. It can be used for the whole basis weight range and machine speeds up to 1400 m min^{-1} . In order to achieve best results concerning formation and dimensional stability, Dandy rolls or hybrid formers and effective wire shaking units are frequently used. New machines for thermal or release base paper, however, can exceed the speed limitations of hybrid formers. Gap formers are used in case when the maximum operating speed exceeds approximately 1400 m min^{-1} .

The basic raw material for specialty papers is wood pulp. There are, however, grades such as tea bag, plug wrap, or filter paper, where the required porosity, absorbency, or bulk can only be achieved using special plant fibers such as abaca, sisal, or hemp or even synthetic fibers such as rayon. These fibers are much longer than wood pulp fibers. Owing to their length and the demand for best formation and uniformity, even at lowest machine speeds, the inclined wire sheet forming principle is used for these grades (Figure 20.21).

Extreme dilutions are necessary in order to avoid reflocculation of the fibers and headbox consistencies even below 0.01% are run. Overlay papers for high abrasion-resistant surfaces, such as flooring laminates, are produced with embedded fillers (up to 30% aluminum oxide) on a three-layer former (Figure 20.22).

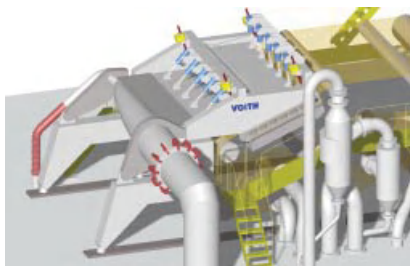


Figure 20.21 Inclined wire sheet forming principle. (Source: Voith.)

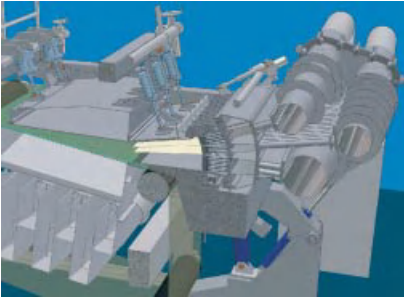


Figure 20.22 Inclined wire three-layer sheet forming with three separate headers, tube banks, and lamellas. (Source: Voith.)



Figure 20.23 Cylinder mold sheet forming principle for banknote paper production. (Source: Voith.)

Another “old-fashioned” well-proven sheet forming principle, which is found in specialty paper production only, is the cylinder mould former (Figure 20.23). It is still used for the production of cotton-based banknote paper and enables the application of three key security features:

- the use of cotton as raw material gives the paper a unique feel;
- the multitone watermark has a wide tonal range going from light through a number of shades to dark;
- the security thread can be fully embedded or windowed, that is, the thread appears at intervals in the surface of the banknote.

These security features together with more than a 200-year-old tradition and know-how make the cylinder mould former and cotton-based paper still the best choice for banknotes.

The press sections in specialty paper machines need to be highly flexible. For paper grades where only one smooth side is required, multiroll press concepts with two or three press nips and a closed sheet run can be used. For increased dryness and improved runnability, the press section can be equipped with a shoe press. For grades such as inkjet or bible paper, low roughness figures on both sides are required; so, a bottom-felted straight-through press is added in order to reduce the roughness on the top side and control the roughness two-sidedness.

Depending on the requirements, all available dryer section layouts are used for the production of specialty papers. Most common is the double-tier arrangement of the drying cylinders. At low production speeds, this proven and economic design allows high drying rates at acceptable runnability and machine efficiency. For improved runnability, fast machines are equipped with single-tier dryer groups, especially, in the first part of the dryer section.

One disadvantage of both the configurations is the required draw from press to dryer section – which limits runnability and achievable machine speed at low basis weights. The other one is the high shrinkage, especially, at the paper edges, which results in high web extension in cross-direction during rewetting in subsequent process steps.

In order to overcome these deficiencies, so-called MG machines are widely used for the production of specialty paper grades. The dryer section in MG machines is comparable to a tissue machine and consists of a large-diameter Yankee cylinder with a steam- or gas-heated impingement hood. The web is fully transferred and finally dried without any open draw. This allows the production of lightweight paper grades ($16\text{--}24\text{ g m}^{-2}$) – such as wrapping paper for flowers and gifts – at high speeds and excellent runnability. Owing to the restrained drying on the mirrorlike Yankee cylinder surface, the web does not shrink during drying and the paper shows a high single side smoothness and gloss. The resulting paper properties – the high dimensional stability as well as the excellent smoothness and gloss at high bulk (without calendering) – make the MG machine an interesting machine configuration for various specialty paper grades such as flexible packaging, release liner, and label paper.

Unfortunately, the production capacity of MG machines is limited by the evaporation capacity, that is, by the diameter of the Yankee cylinder. To overcome these limitations, MG machines can be equipped with a pre-dryer section or a shoe press for increased dryness in front of the Yankee cylinder. A most modern machine (Figure 20.24) for the production of flexible packaging grades (consumer bags, protective wrapping, medical papers, etc.) and release liner has a single-felted shoe press with transfer belt for dryness up to 50% and a large 6.4 m diameter Yankee cylinder with gas-fired impingement hood.

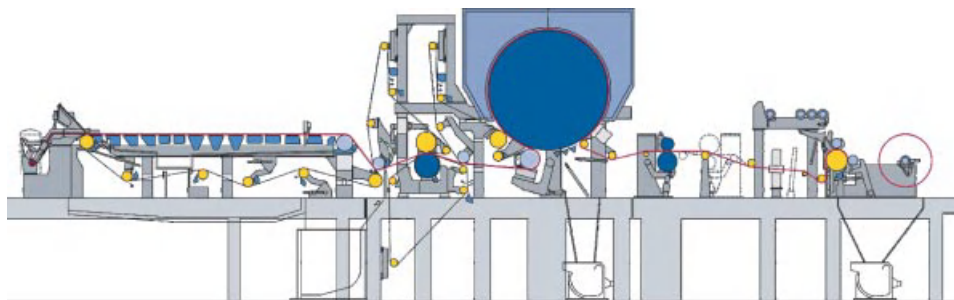


Figure 20.24 MG machine with shoe press and large-diameter Yankee cylinder for the production of flexible packaging and release base paper. (Source: Voith.)

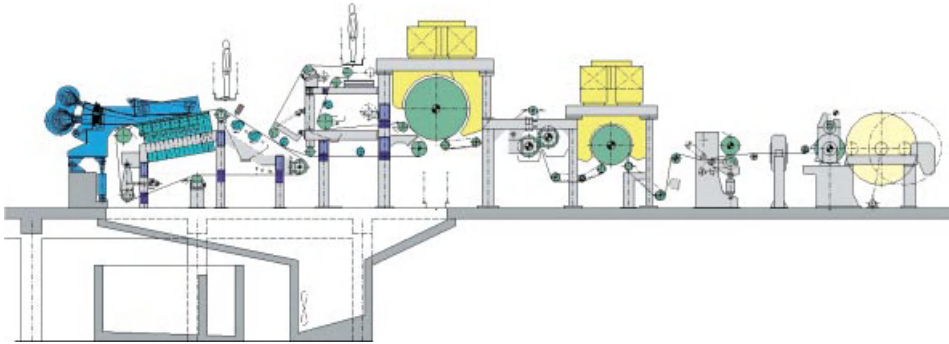


Figure 20.25 Machine with inclined wire former and through air dryer for tea bag paper production. (Source: Voith.)

If high bulk or high porosity is a must, as it is for filter or tea bag papers for example, densification by wet pressing should be avoided completely. In this case, the web is formed and dewatered on an inclined wire up to 28% dryness and finally dried on a TAD (Figure 20.25).

Specialty papers can be uncoated and coated. The uncoated grades are either machine finished like cigarette papers or base papers for subsequent value-adding off-machine process stages such as for photo base paper. Coated grades can be subdivided into two groups:

- 1) where the coat is needed for a certain special function, such as thermal or carbonless papers;
- 2) where the coat is needed for improved printability, such as label or cast coated papers.

In both cases, the base sheet is normally pre-coated on one or on both sides. By pre-coating, the functional coat weight can be minimized or the final surface quality can be improved. The most suitable and economical applicator for the pre-coat is the on-line film press. Both sides of the sheet can be coated simultaneously and different applications are possible.

The application of the functional coat is more demanding. For coated commodity grades, the quality generally increases with increasing coat weight. For coated specialty papers such as thermal or carbonless paper, however, the quality does not improve further once a certain coat weight for the functional coat is reached at any point. The optimum concerning uniform coverage and minimum coat weight is achieved with the curtain coater; a perfect layer of coating color is applied on the surface without any mechanical impact on the paper. Since the first commercial installation for specialty papers in the mid-1990s, the significant advantages of curtain coating have led to more than 30 units being installed for these grades. Owing to better flexibility and time efficiency, the functional top coat is applied off-line.

Most of the specialty paper grades are “single side” grades (one functional side only). Nevertheless, there is no typical or common calendering principle used for

specialty papers. Each of the different specialty paper grades has its own demands with regard to surface properties, smoothness, densification, caliper, porosity, transparency, and so on. Calendering of specialty papers, therefore, requires specific customized calender design.

Thermal base paper, carbonless, and label paper are pre-calendered usually with one soft or hard nip calender before applying the pre-coat online. While carbonless paper cannot be calendered any more once the pressure-sensitive functional coat is applied, the high one-side smoothness and gloss requirements of label papers are achieved by simultaneous back-to-back calendering of two paper rolls in a supercalender or multinip calender with polymer covered rolls at high loads and temperatures. For thermal paper on the other hand, high temperatures have to be avoided. At present, soft nips or shoe calenders are state of the art for these grades.

Decor paper is mostly printed on top side in rotogravure printing. The required single side smoothness of decor paper is achieved using calender design with two or four soft nips. Here, the printed side of the decor paper is in contact with the heated roll surface up to four times, supported by steam application as well.

For coated inkjet papers, two soft nips – one for each side – are necessary. Even more calendering is used for photo base paper. A combination of one hard nip for pre-calendering and a multi-hard nip calender stack for the final calendering is needed to achieve the high densification and high smoothness of these demanding grades.

Silicone base paper has by far the highest demands concerning calendering. In order to minimize silicon consumption, densification and smoothness should be

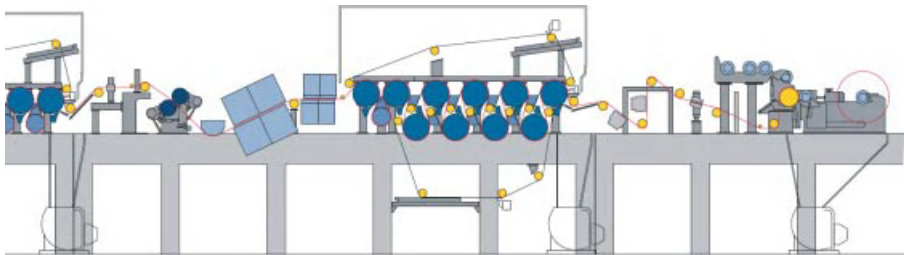


Figure 20.26 Dry end of a silicon base paper machine with film press for PVA application, after-dryer section, moisturizer and reel with center drive, and nip load system.

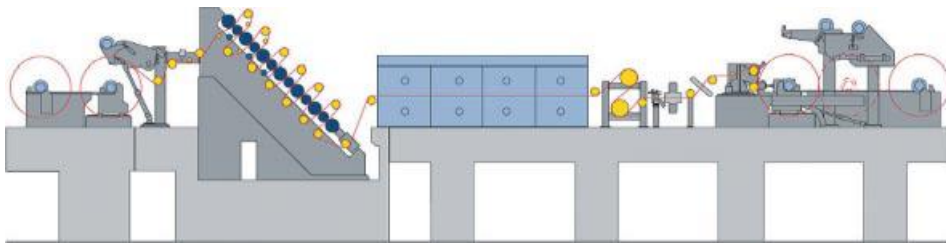


Figure 20.27 Off-line multinip calender for release paper.

as high as possible. For reduced porosity, polyvinylalcohol (PVA) is already applied in the film press. As effective final calendering requires a high moisture content, the web is rewetted again by a moisturizer in front of the reel (with center drive and nip load system) and wound up at 15–18% moisture (Figure 20.26).

After a sufficient homogenization time for the applied water, final calendering is done off-line (Figure 20.27). Up to 13 rolls (12 nips) of a modern multinip calender at maximum loads and temperatures (up to 400 N mm^{-1} and up to 180°C) are needed to achieve the required transparency, smoothness, and density.

21

Finishing

Rüdiger Feldmann

In a paper mill, the process steps followed by a paper machine can be summarized under the term *finishing*, that is, reel slitting and roll packaging, format cutting and packaging of the formatted sheets, and in a wider sense also off-line calendering, and sometimes off-line coating. Reel slitting converts the large parent reels from the paper machine into suitable size rolls to be delivered to the (external) customer after being adequately packed, or for further in-house processes such as sheet cutting. The input into the sheet cutter is precut reels of up to 2.5 m. The sheet cutter cuts the web into individual sheets, that is, cuts the web first in MD and then in CD. The individual sheets are piled automatically and packed. Reel slitting as well as roll wrapping and handling are described in the next two paragraphs.

21.1

Reel Slitting

21.1.1

Objective and General Description of Reel Slitting

The objective of reel slitting is to convert the large parent reels (machine reels, jumbo reels) from the paper machine into suitable size rolls which can be either sent directly to the end user, for example, a printer, or receive further mill internal treatment such as sheeting.

The machine on which reel slitting is done is commonly called a *winder*. Basically, winders consist of equipment for parent roll change, an unwind station for the parent rolls, a slitting station and a rewind station.

The rolls have to be free from defects (Figure 21.1) such as

- soft centers
- bursts
- corrugations/rope marks
- crepe wrinkles
- dishing

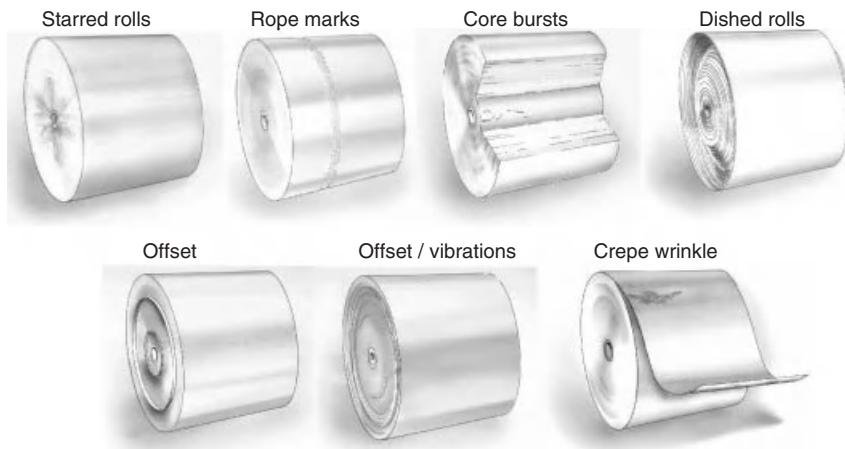


Figure 21.1 Various roll defects.

- dust
- concave or convex faces.

These kinds of defects may disturb the subsequent working steps in or outside the mill and might reduce the quality, for example, in printing or the productivity. The roll quality gives the mill the final reputation for their customers and therefore makes the winding process so important.

Winders have a series of basic operations in common, for example, unwinding, slitting, and reel and set-change. These operations are reviewed in the following. Later on, special attention will be paid to the various winder types and their suitability for the main paper grades to obtain optimum winding results.

Although various slitting techniques such as water jet slitting and laser slitting are available, most of the winders make use of the tangential shear slitting technique. With this method, the web is cut between two edge-contacting circular knives, the top slitter blade and the bottom slitter blade. In order to achieve optimum slitting results, the cut point should be located at the beginning of the wrap, that is, the area where the web contacts the bottom band. The depth with which the blade should incise into the web depends on the paper grade and ranges between 0.5 and 2.5 mm with 1.5 mm being a normal depth. The overlap of the top blade and the bottom blade should be between 0.5 and 2.5 mm, the exact amount depending again on the grade of the paper to be slit. Furthermore, it is recommendable that the top blade exerts a light side load in the range of 20–45 N onto the bottom blade. As the bottom bands wear, counter measures have to be taken in order to prevent the cutting nip to open up resulting in band wobble, so called slitter run out. The speed with which the bottom blade is driven is yet another decisive item. As a rule, this blade is driven at a speed that is somewhat higher (2–3%) than the running speed of the web.

With an improper setting of the blades, the slitter often generates dust. Yet, even under optimum conditions, slitter dust cannot always be avoided. Hence, suction devices are installed to remove the dust.

The pair of knives must be accurately positioned so as to precisely obtain the desired format for the sheets. Various solutions exist in this respect. Figure 21.2 shows one example: The apparatus for positioning has slides displaceable along guides and a belt with oppositely moving stretches as the belt is moved in a single sense. A coupling between the belt stretches and the slide can be actuated to press against one or the other stretch or pass of the belt to couple it with the slide. The coupling also has a cylinder-and-piston for clamping the slide against its guide to lock the slide when the proper position is reached. Positioning can be carried out manually, semiautomatically, or in a fully automated manner.

After slitting, the partial webs have to be separated. Any overlapping is unacceptable. The extent of separation should be 0.2–0.5 mm. In order to achieve proper separation, winders are featured with a spreader device consisting, as a rule, of two spreader rolls arranged parallel to each other (Figure 21.3).

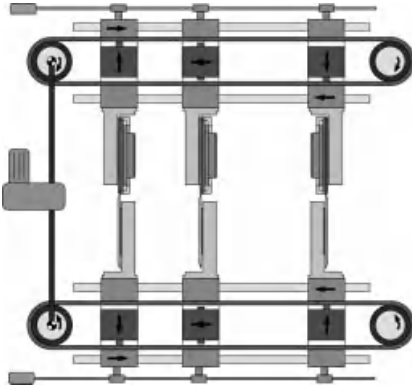


Figure 21.2 Positioning system for slitters.

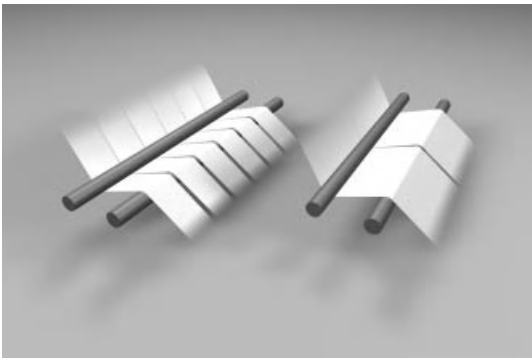


Figure 21.3 Web separation device.

The following provides an overview on the main technical data of current winders:

Parent rolls	
Maximum width	11.000 mm
Maximum diameter	4.500 mm
Maximum weight	135 to
Finished rolls	
Minimum width	150 mm
Maximum width	5.000 mm
Maximum diameter	1.800 mm – paper grades 2.500 mm – board grades
Maximum weight	10 to
Maximum working speed	3.000 m min ⁻¹
Maximum availability	99%

21.1.2

The Different Winder Types and Their Suitability for the Various Paper Grades

21.1.2.1 Classical Two-Drum Winders

The rewind station of a classical two-drum winder consists of a first and a second steel drum forming a winding bed wherein the set of rolls is wound side-by-side and a rider roll. The two-drum winder uses tension, nip load, and torque as winding parameters.

The first parameter “tension” is necessary for getting the single web-sheets spread and giving them a basic strain at the front drum. The amount of tension needs to be in a range of the elasticity of the web. A programmable tension curve is one basic instrument to influence the roll quality.

The second parameter, “torque,” is another tool for controlling the “wound-in-tension” or the density of the rolls. Increasing torque tightens the rolls. The torque is introduced by the second drum which is not wrapped by the paper. Therefore the second drum is torque controlled.

The first drum (wrapped drum) is a speed controlled drum.

The third parameter, “nip load in the winding bed,” results from the weight of the roll set and the rider roll load. At the beginning of the winding process, the weight of the rolls is not high enough to produce the required line load for introducing additional torque by the second drum. Hence it is the rider roll placed on top of the roll set which provides for the required nip load. As the diameter of the rolls grows, the pressure exerted by the rider roll is decreased. Finally, the rider roll serves only as means for keeping the set in the winding bed, for instance, in case of vibrations (Figure 21.4).

All of these parameters influence each other and have to be carefully adapted to the different paper grades.

Classical two-drum winders are used for winding:

- cigarette paper,

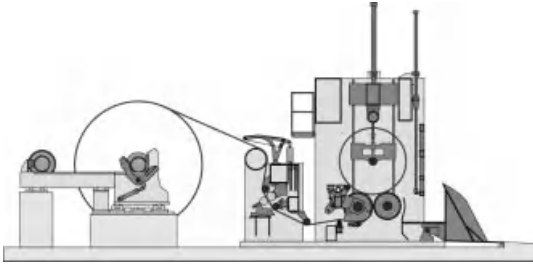


Figure 21.4 Two-drum winder with steel drums.

- corrugated medium,
- decor paper,
- filter paper,
- kraftliner,
- test liner,
- uncoated board.

21.1.2.2 Modified Two-Drum Winders

The two-drum winder is often called the *work-horse* among the winders on account of its easy setup combined with high productivity and efficiency and its initial investment cost being lower than with the single-drum winder. The classical two-drum winder is an economic solution. Yet, its technological limitations are the uncontrollable nip loads that necessarily occur when the roll diameters get above nip-load-critical limits thus risking roll defects. To overcome this drawback and to achieve low-intensity controlled nip pressures various modifications have been developed.

Modified two-drum winders are in use for the following grades:

- coated board
- directory paper
- envelope paper
- LWC paper
- newsprint paper (standard and improved grades)
- SC offset paper
- silicone base paper
- woodfree coated and uncoated paper.

21.1.2.3 Two-Drum Winders with Air Relief

The two-drum winder with air relief is equipped with a pressure box arranged beneath the winding bed and extending over its entire length. Compressed air fed through this box defines a compressed air cushion in the roller bed and counteracts the weight of the rolls. As the supporting area increases with increasing roll diameters (the supported roll surface gets bigger with growing roll diameter), a

rather low pressure (<10 kPa) is sufficient for effectively relieving the set of rolls (Figure 21.5).

21.1.2.4 Two-Drum Winders with Belt Support

This variant of the two-drum winder family consists of a drum and a belt bed to support the roll set. As the roll diameter exceeds a certain diameter, the weight of the roll set is partially transferred to the belt bed whereby the specific pressure in the nip is reduced (Figure 21.6).

21.1.2.5 Two-Drum Winders with Soft Covered Drums

The purpose of covering the drums with a soft material is to make the nips wider thus reducing the radial stress between the rolls and the drums to a level where even with heavy rolls no nip load-induced defects can occur.

The deformation of the covers in the nip especially at the first, that is, “wrapped drum,” avoids roll defects such as corrugations and rope marks and allows winding of defect-free rolls with a bigger diameter (Figure 21.7).

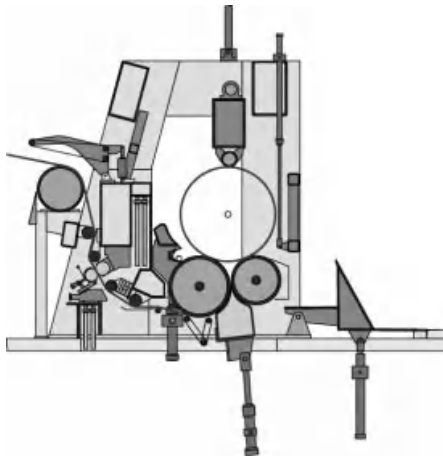


Figure 21.5 Two-drum winder with air relief.

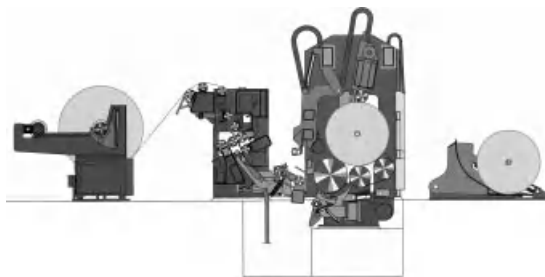


Figure 21.6 Two-drum winder with belt support.

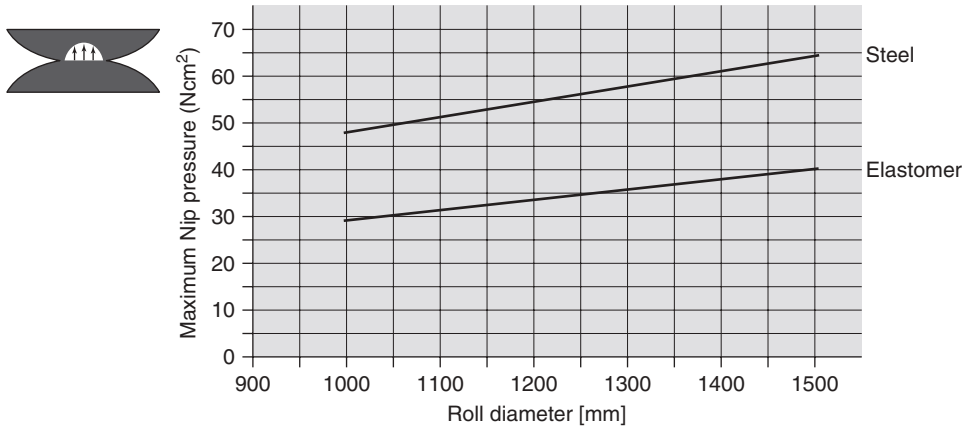


Figure 21.7 Comparison two-drum winder with soft covered drums versus two-drum winder with steel drums.

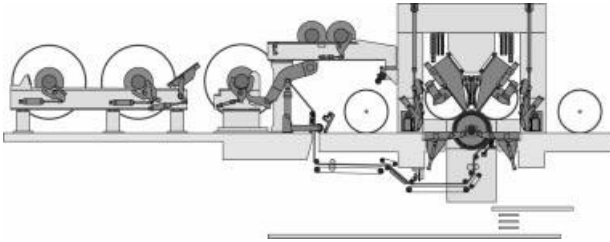


Figure 21.8 Single-drum winder – finished rolls in 11 and 1 o' clock position.

21.1.3

Single-Drum Winders

Single-drum winders – also called multi-station winders – are characterized in that each paper roll is supported on a common center drum, yet wound in a separate station. As the rolls are held by core chucks on both sides, they have to be arranged alternating on either side of the single-drum in ~11 and 1 o'clock positions (Figure 21.8). Consequently, because of the weight of the rolls that is partly supported by the center drum and partly by the core chucks the proportion can be freely selected. The 11 and 1 o'clock arrangement is used for winding wide rolls (actual tendency is width of 4.320 mm) of high density paper with a need for a very tight core winding to get the roll stiff enough for further production process, for example, printing. A tight core winding is reached by connecting the core chucks with an electrical motor that leads its torque via core chucks directly to the core of the wound roll.

In special cases, 9 and 3 o'clock positions are also met with (Figure 21.9). This arrangement is used for paper grades with paper surfaces very sensitive for high nip loads. Owing to the position of the rolls during the winding process the nip load

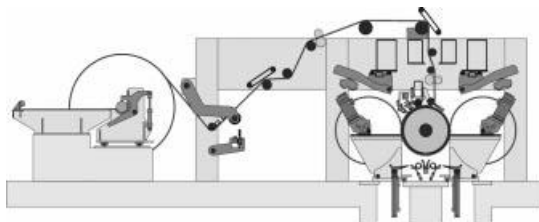


Figure 21.9 Single-drum winder – finished rolls in 9 and 3 o’ clock position.

theoretically can be reduced to zero. The necessary torque for tight core winding is created by the center torque motor.

Modern single-drum winders are core-, periphery-, and rider-roll supported winders. The main parameters influencing winding are web tension, nip load (by rider roll load or core-chuck carriage load), and torque. At the beginning of the winding process, rider rolls are placed against the cores so as to produce the required nip load or to avoid bending of wide cores because of web tension. When the diameter of the rolls has reached a certain diameter, the rider rolls are no longer necessary. The desired nip load is then obtained by the roll weight alone or by the relief pressure of the core-chuck carriages. Therefore, the rider rolls are disabled or pivoted downwards in order to support the wound rolls from below.

The grades to be wound on single-drum winders are

- carbon copy paper – winder designed as per Figure 21.9
- cast-coated paper – winder designed as per Figure 21.9
- LWC paper – winder designed as per Figure 21.8
- SC rotogravure paper – winder designed as per Figure 21.8
- silicone-treated paper – winder designed as per Figure 21.9
- thermal paper – winder designed as per Figure 21.9.

21.1.4

Automatic Functions

The productivity of a winder is a function of its speed, its acceleration rate, and its necessary stop times for set-change or reel-spool change. Especially the stop times can be reduced using automatic functions. To that end, equipment and controls have been developed which abridge the following functions:

- reel changing
- reel splicing
- web threading
- slitter positioning
- core inserting
- core gluing
- automatic set-change
- web cutting

- tail gluing
- roll ejecting
- automatic stop at windup and unwind diameter.

Furthermore, diagnostics functions are available that help the operator to quickly detect the cause of troubles on the winder and in the paper.

- Automatic stop at detected paper faults (holes, edge-cracks, etc.)
- Extended help messages if winding process discontinues
- Run time messages for preventive maintenance.

21.1.5

Automation/Operation

Modern winders are equipped with PC/PLC technologies. This allows high flexibility in adjusting the winding parameters as tension, torque, nip load to the specific requirements of the different paper grades. Furthermore, these technologies permit collecting all data of the winding process for advanced analysis of the production process.

21.2

Roll Handling

21.2.1

Objective and General Description of Roll Handling

The objective of roll handling is to prepare the finished paper rolls for shipment in such a way that they arrive at the end user in the best possible condition. The mill can contribute to this aim by two means, that is, by a most gentle internal transportation and by thoroughly wrapping the customer rolls so as to protect them from dangers to which they are exposed during external transportation on account of frequent loading and unloading actions, varying temperatures, and humidity changes.

21.2.2

Roll Wrapping

21.2.2.1 Wrapping Material

There are two different kinds of wrapping material, stretch film and packaging paper. Shrink film is hardly ever used for wrapping of paper rolls, as the creases formed on the faces of the wrapped rolls do not allow to store the rolls in a vertical position. Shrink wrap is only found with special applications, for example, for holding finished paper rolls on pallets.

Stretch wraps offer the advantages of uncomplicated wrapping machinery and low-cost material. The drawbacks are high UV sensitivity, slackening of the stretch wrap, and vulnerability to dirt. Furthermore, smooth plastic-wrapped rolls are more

likely to fall off the forklift trucks, particularly at low temperatures. And because of stretching, even slight tears caused by forklift handling can rapidly turn into serious damages. Some of the drawbacks can be avoided by wrapping plastic-covered rolls with paper as well. The simplest way to do this is with crepe-like packaging paper, using the same wrapping equipment as for stretch film.

Packaging paper is the classical and most commonly used wrapping material for paper rolls. It offers optimum protection for long transport distances and storage times. Packaging paper mainly comprises kraft or test liner sandwich papers with PE lining.

21.2.2.2 The Different Types of Wrapping Machines

21.2.2.2.1 Conventional Wrapping Machines Using Paper as Packaging Material

These machines basically consist of a two-drum winding cradle wherein the roll to be wrapped is rotated, a crimping device, a header press, and a number of unwind stations for packaging paper rolls (Figure 21.10). The wrapping method employed is the so-called “wide” method, that is, the width of the packaging paper is selected according to the width of the roll to be wrapped plus a crimp overhang. Depending on the width spectrum of the rolls to be wrapped, a series of unwind stations with packaging rolls having a different width is necessary.

The wrapping process is as follows: Before the packaging paper is applied, the roll is furnished with inner board header disks to protect the roll faces from possible glue and damages resulting from edge crimping. However, these inner header disks do also contribute to a face protection during later transportation. Then the packaging paper having a width which corresponds to the width of the paper roll (see above) is wrapped one to four times around the body of the roll. The wrapping can be further strengthened by gluing the outer layers of the packaging paper together, either with cold or hot glue. Thereafter the overlap is crimped. Finally, PE-coated test liner outer header disks are pressed on top of the inner header disks and the crimped overlaps. These outer header disks are normally fixed without any additional glue, just by pressing them against the inner header disks once the PE coating has been plasticized.



Figure 21.10 Conventional roll wrapping machine.

Conventional wrapping machines produce excellent wrapping. The only disadvantage of these traditional machines is that they require a lot of space for the multitude of unwind stations and that the mill has to store a lot of packaging paper rolls with different width. This disadvantage is eliminated with the wrapping machines described below.

21.2.2.2 Offset Wrapping Machines Using Paper as Packaging Material These machines are similar to the above-described conventional machines in so far, as the packaging paper is fed to the roll to be wrapped in a straightforward way. The main difference is that two or more packaging paper webs are combined into one broad sheet (Figure 21.11). Thus, rolls whose width exceeds the width of the available packaging rolls can be wrapped effectively with a reduced number of unwind stations.

21.2.2.3 Spiral Wrapping Machines Using Paper as Packaging Material The spiral wrapping machines employ a narrow standard width packaging paper strip (e.g., 500 mm) for wrapping. This strip is wound at a sharp angle around the roll body. The desired number of layers is automatically obtained by correctly selecting the angle or degree of strip overlap. The roll edges are additionally wrapped at right



Figure 21.11 Overlap wrapping machine.



Figure 21.12 Spiral wrapping machine.

angles with a constant overlap of ~ 150 mm (Figure 21.12). Spiral wrapping is suitable for all paper roll sizes and provides a wrapping that is even stronger than classical wrapping, as the glued spiral layers closely encircle the roll body and as the edge strips offer additional protection for the vulnerable edges of the paper roll. Spiral wrapping is not limited to any particular roll length. A comparison of Figures 21.13 and 21.14 shows that space required by a spiral wrapping machine is

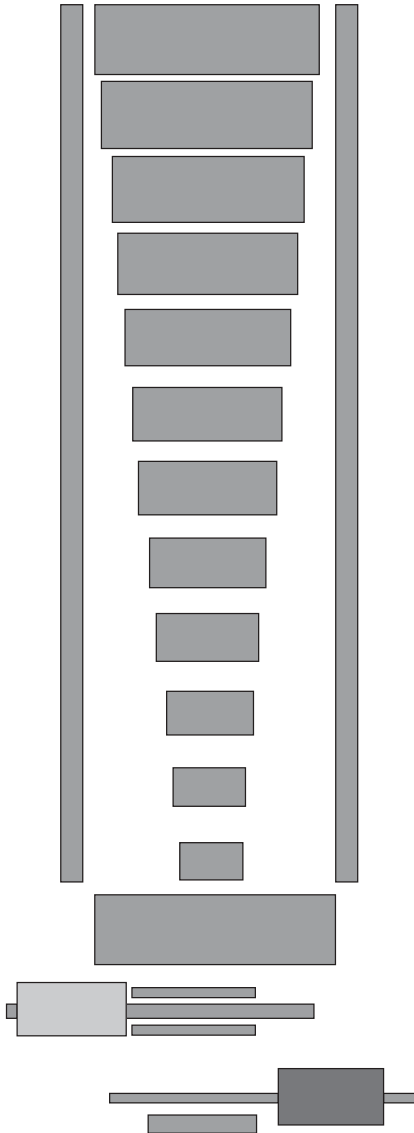


Figure 21.13 Top view conventional roll wrapping machine.

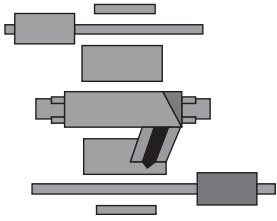


Figure 21.14 Top view spiral wrapping machine.

much lower (270 sq m vs 70 sq m, i.e., ~40%) than space needed for a traditional wrapping machine.

21.2.2.3 Wrapping Machines Using Stretch Film as Packaging Material

These machines consist of a stretch film dispenser and a two-drum cradle wherein the roll to be wrapped is rotated. The winding cradle can additionally be mounted on a turntable. Accordingly, there are two different wrapping methods: exclusively radial wrapping (Figure 21.15) or a combination of radial and axial wrapping (Figure 21.16).

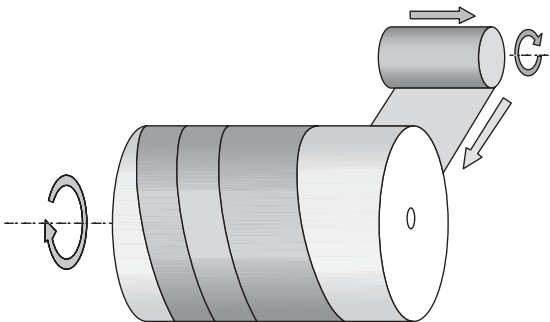


Figure 21.15 Radial stretch wrapping.

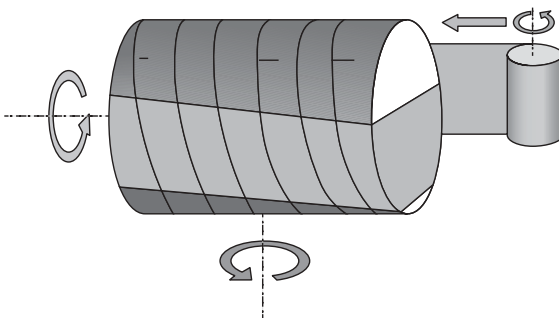


Figure 21.16 Radial and axial stretch wrapping.

For radially wrapping the rolls, the stretch film is guided into the nip between the rotating roll and the first carrying drum and is subsequently wrapped in a helical manner around the roll. If the two-drum cradle is mounted on a turntable, the roll can also be wrapped axially by rotating the turntable.

Rolls wrapped exclusively radially must be protected by header disks made of boxboard or corrugated board. These headers must be quite exactly the same diameter as the paper roll, as they are only held on by about 100 mm of stretch overlap around the roll edges. Such end covers enable trouble-free vertical stacking of the wrapped rolls.

Contrary to exclusively radial wrapping, axial wrapping delivers hermetically sealed rolls. Yet, as the face covers are rather irregular, axially wrapped rolls are inconvenient for upright storage.

21.2.3

Roll Conveying

Roll-conveying systems move the paper rolls from the winder discharge area via the wrapping machine to the roll up-ending device in the mill's warehouse. Naturally, layouts of the roll-conveying systems differ from mill to mill. Yet, the basic components are always the same. These are

- segmented cushion stop lines (Figure 21.17);
- belt conveyors (Figure 21.18) – meanwhile belt conveyors have been somewhat superseded by slat conveyors, as belt conveyors have a tendency to damage the paper roll on account of micro motions within the belt;
- slat conveyors (Figure 21.19);
- carousel conveyors (Figure 21.20);
- turntables (Figure 21.21);
- lifts (Figure 21.22);
- sorting decks (Figure 21.23); and
- up-enders (Figure 21.24).



Figure 21.17 Segmented cushion stop lines.

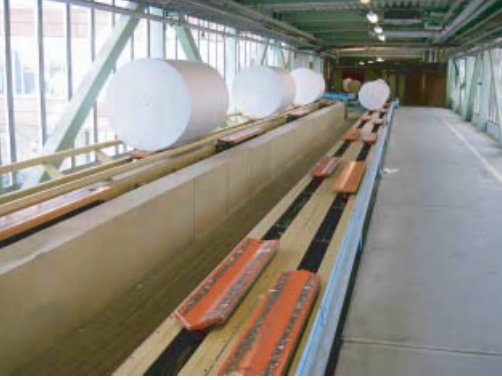


Figure 21.18 Belt conveyor.



Figure 21.19 Slat conveyor.



Figure 21.20 Carousel conveyor.



Figure 21.21 Turntable.



Figure 21.22 Lift.

21.2.4 Automation

The wrapping and conveying processes including roll identification, marking, weighing, and labeling as well as roll tracking are managed by automation systems based on computers and electronic devices. The majority of the functions



Figure 21.23 Sorting deck.



Figure 21.24 Up-ender.

are carried out automatically so that the operators only have to supervise the processes.

22

Control Systems for Paper Machines

Rudolf Münch

22.1

Objective and General Terms of PM Control Systems

22.1.1

Objective

A typical paper machine has a few thousand remote or automatically controlled functions such as positioning systems, drives, valves, and more than a thousand additional measurement devices to monitor the process and the condition of the machine. It is impossible for an operator to oversee all these devices without the help of modern automation systems. For example, he is guided through the process of starting the machine; many control sequences happen automatically after a “start” button is pressed, and he gets detailed diagnostics if something fails. Computers are also used to maintain the quality standards; however, the operator is still needed to handle the exceptions and to decide how to proceed when something fails.

22.1.2

Explanation of Terms

Control systems for paper machines can be categorized in different ways. The following terms are those most commonly used:

- **MCS, machine control system:**

- Discrete logic, safety interlocks, sequential controls

The MCS ensures that the machine attendant can safely operate the machine using control desks with pushbuttons, switches, status lamps, and so on. Many of these functions are usually also available on screen displays. Examples of MCS functions are movements of rolls, blades, or other machine parts with involvement of limit switches or other safety interlocks.

Machine control functions usually require fast reaction. For example, if a machine part reaches a limit switch during a controlled movement, it usually

has to be stopped by the MCS in less than 20 ms. The cycle time of an MCS is therefore in the 5–20 ms range.

- **DCS, distributed control system:**

- Analog process controls

Analog process controls are mainly simple standard controllers. Examples are level controllers in chests, pressure controllers in pipes, and so on. Most process controllers act much more slowly than the MCS controls. Actions happen in seconds to minutes. The cycle time of typical DCS functions is therefore in the 1–4 s range.

- Wet end controls

Some controls in the process are more complex than just standard proportional-integral-derivative (PID) control loops. One example is the wet end control, which ensures uniform process conditions in the approach flow of the paper machine and in the forming section by maintaining constant consistencies, gas content, charge, and other parameters. It involves, for example, special software tools (soft sensors) using wet end data instead of direct measurements to predict basis weight during the start-up of the machine, when the paper has not yet reached the reel or the quality measurements. Such wet end controls not only reduce the start-up time of the process but also minimize the consumption of chemicals, that is, only as much retention aid is used as is really needed to reach a required retention level in the forming section.

- **QCS, quality control system:**

- Paper quality measurement

The QCS has online sensors for basis weight, ash content, moisture content, gloss, and other paper quality parameters. The sensors are mounted on measurement frames, which allow the sensors to move (scan) within 20–40 s across the paper width. These sensors measure the paper quality parameters in cross machine direction (CD) and machine direction (MD). Each scan typically gives about 1000 measurement values (databoxes), equally spaced across the web width. An array of CD measurement values is also called a CD quality profile or CD profile.

The average measurement of each scan gives one MD quality value. A time series of MD measurement values is also called an MD quality profile or MD profile.

MD measurement values and CD profile measurements are available only every 20–30 s.

- Paper quality control in MD

The first target of quality control in MD is to keep the main quality parameters of the produced paper within the limits defined for the current production. As an example, basis weight control is achieved by continuously adjusting the stock valve, which feeds the blended stock to the machine.

The second target is to ensure fast grade changes, that is, to ensure a fast change of basis weight, moisture, and ash content, to meet the specification of the next produced grade with a short transition time.

The third target is to allow the operator to change machine settings without too large an impact on paper quality. The most important example is the coordinated speed change control. This is a tool to allow machine speed changes without disturbing paper quality during the transition period. The effect of a speed change is compensated by coordinated adjustments of stock valve, ash valve, and drying energy, based on a dynamic process model.

MD controls are slow but complex control loops. Only two to three measurements are available per minute. Using interpolation techniques or Kalman filters, control steps can be performed every 5–10 s. MD controls are complex because of the considerably large transport dead time between actuators (i.e., stock valve) and measurement (i.e., scanner at the reel), which is typically larger than 1 min.

In addition, the quality parameters have some influence on each other. Opening the ash valve increases not only the ash content, but also the basis weight and moisture. Increasing the basis weight leads to higher moisture content at the reel if the drying energy is not increased simultaneously. Thus, a decoupling controller with dead time compensation is required.

– Paper quality control in CD

Many paper properties can be controlled in small control zones across the machine, to ensure uniform quality in CD. Such actuators are located, for example, in the headbox to control basis weight, in the press and the dryer section to control moisture content, and in the calender section to control the caliper across the paper width.

CD controls act even more slowly than MD controls. The measurement noise on zonal measurements is much higher than the noise on MD measurements. The measurement time of one zonal measurement (databox) is around 20 ms, whereas MD measurements are averages of typically 1000 databoxes (1 scan). The special complexity of CD controls is the coupling of adjacent control zones. Each control zone affects the quality of some neighboring control zones. The controller needs to know exactly the spatial response of actuator movements in the CD. On the other hand, the exact location of the response of a CD actuator in the paper may change over time, for example, because of the changing shrinkage of the paper in the drying section or because of web wander to the left or right.

– Paper quality reports

The QCS not only controls quality but also documents the achieved quality, which is required according to ISO 9000 and other quality regulations.

The quality reports also serve internally within the paper mill as a means of supervising the efficiency of the production process, by reporting per week, per day, or per shift how much paper of which quality has been produced.

• **MCC, motor control center:**

- From these cabinets, hundreds of motors on the machine are controlled. These are motors for pumps, movements of machine parts, or others. The MCC is additionally used to control a few other consumers of electrical power, for example, heating devices for oil in calenders.

- The MCC is not responsible for the roll drives in the paper machine. The drive system is usually an independent package, which is delivered by the machine drive supplier, and which receives its setpoints from the DCS.
- **Monitoring systems:**
 - Bearing and vibration monitoring
Acceleration sensors are attached to bearings and close to roll shafts, to detect bearings at risk of failing and roll roundness abnormalities before they have a negative impact on the process. Thus, bearing and roll changes can be done during the next planned shutdown of the machine, and do not cause extra downtime.
 - Monitoring of periodic paper quality variations
Typically 30–100 process data are measured in parallel. The measured signals include important quality data, taken from the QCS sensors. The aim is to detect the occurrence and the reasons for periodic paper quality variations.
 - Web break monitoring
Web break monitoring is a camera-based tool to find the reason for paper breaks and, as a consequence, to improve efficiency of the production process.
 - Web inspection system
Web inspection systems are also camera based. Multiple cameras are mounted in CD. They check the produced paper in MD and CD for defects such as holes, dark spots, and white spots.
- **Information system:**

An information system mainly fulfills three tasks:

 - It collects online data of MCS, DCS, QCS, and the monitoring systems into a central data storage.
 - It provides a user interface to view the historical data of these systems, allowing one to compare and correlate the data from the various origins. The most convenient user interface is based on web browser technology, similar to the Internet. Some of the data are presented to the user as time trends and others as statistical reports over a defined production period.
 - It provides tools for data analysis. This usually includes the capability of showing the Fourier transform or the cross correlation of selected data. More sophisticated information systems contain expert systems or data mining tools to automatically detect relationships between data.
- **Automation system:**

All the systems above together form the complete automation system of a paper machine (Figure 22.1). The automation systems are grouped around a fiber optical data network, which has a ring topology for redundancy reasons. The connected systems are operating stations, engineering stations for configuration or maintenance work, DCS cabinets, and server computers and dedicated control computers for various monitoring and control purposes. The dashed lines indicate the different locations with automation equipment, such as control rooms for operators, electrical control rooms (rack rooms) with DCS or QCS computers or the paper machine.

To summarize, nowadays systems can be divided into the following categories:

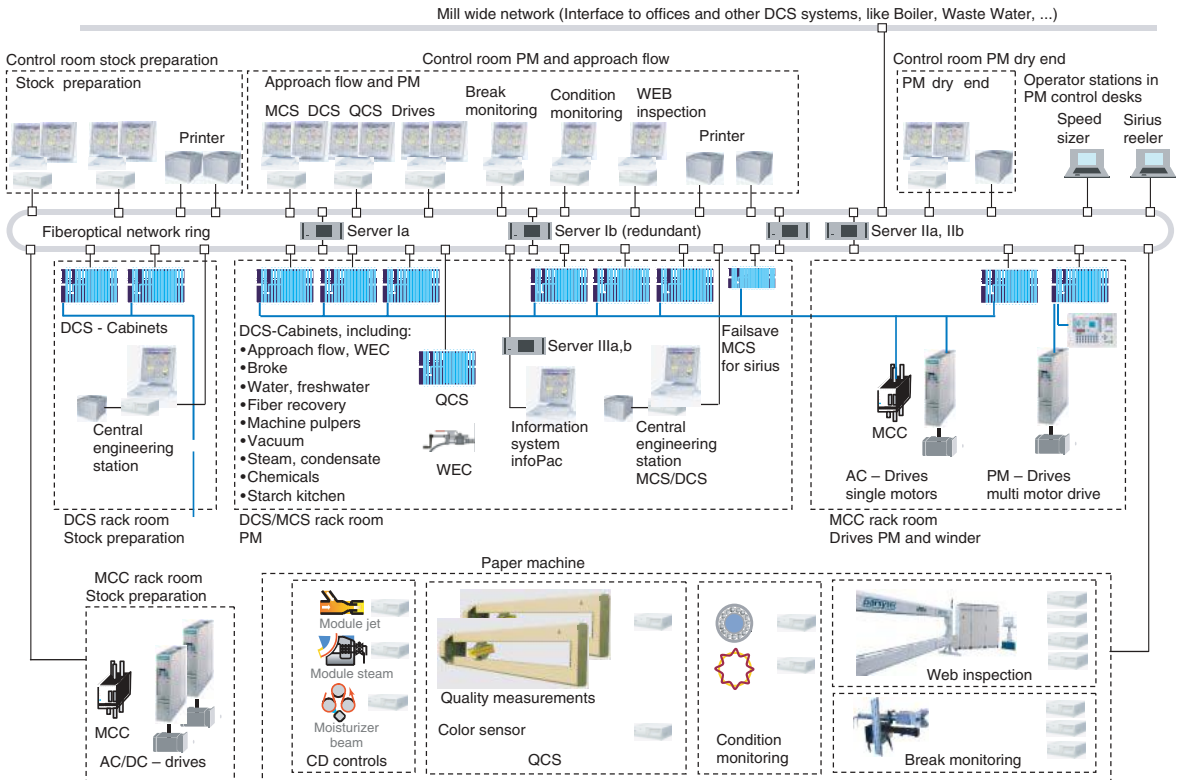


Figure 22.1 Example of an automation system – overview.

- DCS/MCS
 - Control systems for analog and digital controls
 - Capable of implementation of advanced model-based controls that are needed for, for example, soft sensor or QCS applications.
- QCS
 - Quality measurements for paper properties (direct measurements)
 - Measurements for felt and wire condition
 - Indirect measurements of paper properties, also called soft sensors
 - Quality controls (sometimes integrated into DCS systems).
- Monitoring systems
 - Bearing and vibration monitoring
 - Monitoring of periodic paper quality variations
 - Web break monitoring.
- Information system
 - Process history database
 - User interface
 - Diagnostic tools.
- Automation system
 - Includes all of the above systems.

In the following chapters, some elements of a paper machine automation system are discussed in more detail. The focus is on QCS and information systems, as they are mainly responsible for the ability of the mill to maximize quality tons on the reel.

22.2

Quality Control System (QCS)

22.2.1

Quality Measurements

22.2.1.1 Scanning Measurement

Most paper quality measurements in the paper machine are scanning measurements. In various locations, the so-called “scanners” with usually one upper and one lower measurement head are found (Figure 22.2). Both measurement heads move synchronously across the paper width. One scan takes about 20–30 s. The paper moves much faster than the scanning measurement. While the paper is moving, for example, 500 m, the scanner moves across the web only 7–10 m. Thus, the scanning sensors can be seen as a system that measures paper quality in MD and that is moved slowly across the web.

During each scan, hundreds of measurement values are collected. The resolution in CD is typically 10 mm. Each scan contains information of MD and CD variation of the measured paper quality. MD and CD information are used for different purposes and have to be separated from each other.

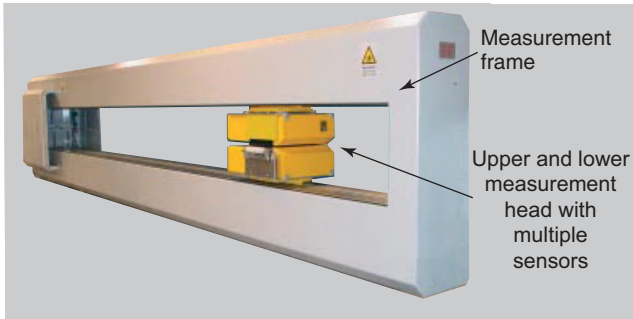


Figure 22.2 Quality measurement – scanner.

- The stable CD profile is given by a weighted average of multiple scans. Typically the displayed CD profiles on an operator screen correspond to an average of nine scans. Averaging is needed to suppress the MD variation and the residual variation of the process. Thus a CD profile contains the average of the last 3–5 min.
- The MD profile is the time series of average values of the individual scans. Advanced methods use, for example, Kalman filters to generate the best estimate of the current MD value every 5 s, by assuming that the CD profile has less dynamics than the MD profile.

22.2.1.2 Fixed Point Measurement

Besides scanning measurements, there are also a few fixed point measurements for paper properties, which are assumed to be constant across the web width. For example, color measurements are sometimes fixed point measurements, as color should not vary across the web width.

22.2.1.3 Basis Weight

Basis weight is measured in grams per square meter and it is the total mass of 1 m² of paper, including all components, such as fibers, fillers, and water. The sensors consist of a radioactive source and a radiation detector on the opposite side of the paper. The absorption of radioactive radiation is a measure of the total mass of the paper. Radioactive sources are usually promethium, krypton, or strontium. Promethium provides the signal with the highest sensitivity and can be used for basis weights up to 250 g m⁻². Strontium is used only in very heavy board applications.

Nowadays detectors are either ion chambers or solid-state detectors. Ion chambers are gas-filled tubes and require a high voltage to detect electrons. Solid-state detectors use the photovoltaic effect to detect electrons.

There are also other possible ways to measure basis weight, such as X-ray tubes to generate radiation or spectroscopic methods, but currently they cannot compete with the sensors based on radioactive radiation.

The accuracy of a basis weight measurement is typically 0.1 g m^{-2} . To get a better understanding of what this figure really means, it is good to know that the surface of the detector is smaller than 10 cm^2 . Thus, if a sample is fixed between the sensor heads with a size of 10 cm^2 , the weight of this sample is measured with a precision of 0.0001 g .

22.2.1.4 Moisture

Moisture is measured in percent of basis weight. The measurement is usually performed by analyzing the absorption of infrared light at three or four different wavelengths. Two of the wavelengths match the absorption peaks of water and the fiber. The other wavelengths are taken for reference purposes. Modern moisture measurements have four detectors internally to make sure that all wavelengths are measured simultaneously, whereas older measurements used only one detector and a spinning filter wheel.

For high weights above 300 g m^{-2} , infrared radiation can no longer pass the sheet. Therefore in this case, microwave radiation is used instead. The measured physical effect is that moisture slows down the speed of microwaves, which can be detected by, for example, evaluating the phase shift of the signal.

The best achievable accuracy of moisture sensors in a PM currently is 0.25% of the relative moisture content.

22.2.1.5 Fillers

Fillers or “ash” mean the amount of inorganic material within the paper. The measurement output is in either grams per square meter or percentage of basis weight. Typical inorganic components are

- clay
- calcium carbonate (CaCO_3)
- titanium dioxide (TiO_2).

Filler content is measured by absorption of radioactive radiation or by absorption of X-ray radiation. Thus the principle of filler measurement is similar to basis weight.

Radioactive radiation is monochromatic and stable. The radiation has one exactly defined wavelength. Clay, CaCO_3 , and TiO_2 have different absorption coefficients for radiation of the given wavelength. Thus,

- for measurement with radioactive radiation, the percentage of each filler component has to be known beforehand. With deinked pulp (DIP), an additional measurement of the ratio of the different components is required. This can be carried out by using XRF (X-ray fluorescence)
- for X-ray radiation, the spectrum of the radiation source has to be tuned by filters to compensate for the different absorption characteristics of the different fillers.

The accuracy of ash measurement today is typically 0.1 g m^{-2} , similar to basis weight.

22.2.1.6 Caliper

Caliper is measured in micrometers. There are three main ways to measure caliper:

- 1) **Contacting caliper measurement:** Two measurement fingers contact the paper from both sides. The distance between the fingers is measured using electromagnetic fields. This method is used when accuracy demands are high. For high-speed paper machines, the contacting measurement has many disadvantages:
 - a. At the contacting point, the paper becomes polished. A small glossy stripe may be visible on the paper surface.
 - b. If the stock is not of the best quality and if, for example, a small hard or sticky piece happens to be at the paper surface, the contacting sensor will tear it out. This may result in a hole in the paper or even in a web break.
 - c. The fingers are subject to wear as minerals in the paper grind the measurement fingers when passing by at high speed.

The accuracy of this method depends on the application and is between 1 and 0.5 μm . The relative accuracy, which is needed to measure the shape of a cross profile, can be better than 0.25 μm .

- 2) **Air bearing caliper measurement:** The sensors are mounted onto flat measurement plates with a diameter of roughly 60 mm. Those plates are drilled, with pressurized air coming out of the tiny holes. The plates are pressed toward the paper from both sides. The distance of the plates from the paper is controlled by the air flow. The distance between the plates is measured using an electromagnetic field.

The thickness of the paper is calculated by subtracting the thickness of the air bearings from the distance of the sensor plates. As the thickness of the air bearings is not known precisely, this method is mainly used as a relative measurement to detect MD and CD profile variations of very sensitive papers, where a contacting measurement is not applicable. However, the relative accuracy is much less than the accuracy of the contacting sensor.

- 3) **Optical caliper measurement:** Owing to the deficiencies of the air bearing sensor and the need for a precise noncontacting caliper measurement, most sensor manufacturers currently push the development of optical noncontacting measurement methods. They consist of three sensors:
 - a. An electromagnetic sensor, which measures the distance between the two sensor plates on opposite sides of the paper
 - b. Two optical sensors, which measure the distance between each sensor plate and the paper.

The difficulty here is that the paper surface is optically not well defined. The outer layer of the paper is less dense or may even be transparent. Thus optical measurements “see” the paper surface as being about 5 μm beneath the real physical surface. Therefore, it is still a challenge to reach the required measurement accuracy.

22.2.1.7 Coat Weight

Coat weight measurement usually requires two measurements, one before and one after the coater, which are subtracted from each other. These measurements can be basis weight measurements or ash measurements. Coat weight is measured in grams per square meter.

Nowadays in some cases, single-sided infrared coat weight measurements are used, as both sides of the paper are coated simultaneously, and the papermaker wants to know the amount of coat on each side. Such infrared coat weight measurements are hard to calibrate, as the infrared beam penetrates through the coating color into the paper, and the paper also contains minerals and pigments. Thus the accuracy of this kind of coat weight measurement varies a lot, depending on the application.

22.2.1.8 Color

Color measurement is a collection of optical measurements. The basic measurement is of color itself and is presented to the user in a color coordinate system. A common color coordinate system is, for example, CIELAB, where the parameters a^* and b^* define the color space and L^* defines the brightness.

Paper color is usually defined as the reflection of the surface of a pile of paper in defined light conditions, where all paper sheets in the pile have the same color. Thus the following difficulties arise in an online measurement:

- In a paper machine there is a running web, that is, one single layer of paper. The background of the paper is visible. Thus, the online measurement has to compensate for the opacity of the paper. This is performed by two measurements in sequence, one with a white background and one with a black background.
- Fluorescence transforms UV light into visible light. Thus the fluorescence effect changes the appearance of the paper, for example, in daylight. Fluorescence has to be measured separately when optical brighteners are added to the paper.

This explains why brightness and opacity measurements are usually part of a color measurement.

22.2.1.9 Gloss

Gloss is a measure of the reflectance of the paper at a given angle. The measurement is calibrated as follows:

- The appearance of black velvet corresponds to the measurement value, that is, a gloss value of 0.
- The appearance of black glass corresponds to the gloss measurement value of 100%.

22.2.1.10 Others

Other available sensors include the measurement of formation, roughness, and porosity.

Further sensors are still in the process of development and cannot be treated as standard sensors. These include sensors for fiber orientation, strength properties, and so on.

However, there still remain many important paper properties that are not yet measurable online, and where online measurements will probably not be available in the near future. Most important to note in this category is printability. A printability sensor, for example, would be able to predict “missing dots” in a real printing test.

Some of those properties will be measurable using the so-called “soft sensors.” For example, a soft sensor for porosity would “measure” porosity on the basis of a calibration of about 100 process data against corresponding laboratory measurements of porosity.

22.2.2

Quality Control

22.2.2.1 Machine Direction Control

MD control uses MD measurement values to control the downstream quality of the paper. Advanced MD controls are based on physical process models of the paper-making process. This means that mathematical models describe the physical process and are able to predict the effect of control actions on the process and on paper quality. Such model-based controls are especially essential to achieve the following:

- **Start-up control:** to control the paper quality as fast as possible during start-up of the machine. This is a topic for machines that restart quite often during the day, as, for example, off-machine coaters.
- **Coordinated speed change control:** to keep quality constant even during speed changes. This requires a coordinated change of at least stock, ash, drying capacity, and speed. For example, if the stock valve is turned, it takes a while until the consistency change arrives at the headbox. This is due to the transport delay time between the stock valve and the headbox, and also to the mixing time in the chests. The increase in machine speed should start when the consistency at the headbox changes (Figure 22.3). Control of ash content and the settings of the dryer section have to be done in a similar way.
- **Production maximization control:** to increase the machine speed when the process is not at the limit, for instance, when drying capacity is still left and machine speed is below a user-defined maximum speed. In fact, this involves a series of coordinated speed changes.
- **Grade change control:** to keep the time for a grade change as short as possible.

22.2.2.1.1 Basis Weight MD Control Basis weight controllers adjust the stock valve and adjust the amount of blended stock to achieve a constant basis weight at the reel. Basis weight is defined as the total weight per square meter.

The first difficulty when controlling basis weight is, that an adjustment of the stock valve has an effect on basis weight and moisture. Thus: a basis weight controller disturbs the control of moisture content.

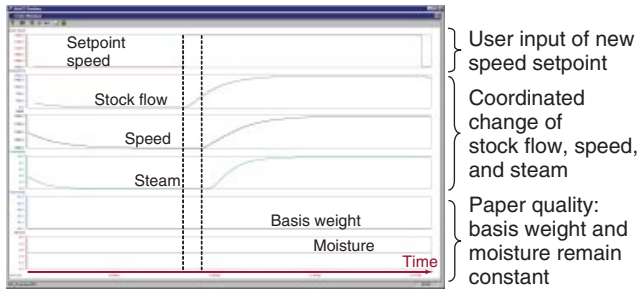


Figure 22.3 Coordinated machine speed change control.

The second difficulty is, that a moisture controller changes the basis weight of the paper, as adding or removing water means changing the total weight.

An additional difficulty arises when a filler control is present, as changing the filler content has an effect on basis weight and moisture.

Thus: There is a coupling between basis weight control, moisture control and filler control of the paper web, which needs to be managed.

Nowadays MD control systems use therefore strategies for decoupling the effects of these quality controls.

22.2.2.1.2 Moisture MD Control Moisture controllers usually adjust a heating device, such as

- steam pressure in drying cylinders
- infrared radiation devices
- valves to control the air flow in contactless air impingement drying hoods.

In some cases, moisture at the reel is controlled by adjusting rewetting devices having a series of spray nozzles across the web.

22.2.2.1.3 Filler MD Control The filler control adjusts an ash valve, to meter, that is, to add fillers within the approach flow of the paper machine. Filler control is needed because of filler variations in the blended stock, especially if DIP is used.

22.2.2.1.4 Wet End Control Wet end control is not a classical MD control, but it belongs nowadays to the category of MD quality controls, as it stabilizes the process in the MD direction.

In the past, quality was mainly assured by quality tests after the manufacturing process. That is, quality controls looked only at the outcoming paper at the end of the machine.

Nowadays the process itself is the target of improvement, assuming that a good and stable process ensures good quality production by itself. So intermediate controllers ensure process stability, and the traditional quality controllers achieve their target more easily.

Wet end control comprises the following parts:

- **Retention control:** In reality, this is a white water consistency control. The amount of retention aid is controlled to ensure that the white water consistency stays constant. This means that the percentage of fibers, fines, and fillers remaining on the wire after the filtration process in the former stays constant. Retention control is linked to filler control, as adding fillers means that more retention aid is needed to keep retention in the forming process constant.
- **Charge control:** Fixatives are added to the stock to keep the charge constant. This is important because charged particles influence the effectiveness of retention aids. Therefore, retention control and charge control are frequently used simultaneously (Figure 22.4).
- **Gas control:** Defoamers are added to keep the air content in the stock constant at a low level. Using gas control reduces the amount of defoamer needed. Air in the stock has many side effects, for example, it alters the calibration of consistency meters.
- **Consistency sensor calibration:** Measurement of fiber or filler consistency is one of the most demanding process measurements. Accuracy has to be very high for control purpose, but consistency meters are sensitive to a lot of process parameters such as gas content and flow rates. Therefore, wet end control comprises a means to improve the calibration of consistency meters by taking other process parameters into account. Thus the advanced consistency sensor calibration uses a soft sensor calibration technique.

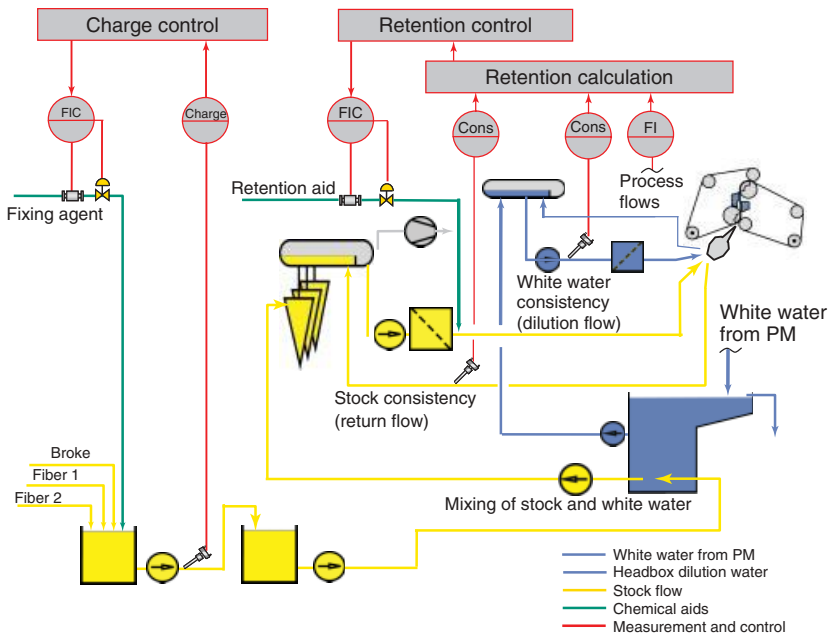


Figure 22.4 Retention and charge control.

- **Basis weight prediction:** When a paper machine starts up, it takes a while until the paper is fed through the machine and finally passes the scanning measurement device. After starting the scanner, it takes another 20–30 s to get the first measurements. To shorten the time until on-grade production is reached, basic controls such as basis weight have to start earlier. Therefore, basis weight is predicted based on wet end measurements. MD control can adjust basis weight even before the scanner starts measuring. This prediction is again realized using soft sensor technology.

22.2.2.2 Cross Direction Control

Cross direction control uses measured CD profiles to adjust actuators that are spaced across the machine width. The goal of CD controls is to ensure even quality in the CD. The challenges of CD control are as follows:

- The effect of an actuator adjustment can also be seen in adjacent zones. From a control point of view, the zones are coupled with their neighboring zones. A spatial decoupling controller is required for good CD control.
- Sometimes, more than one actuator controls the same quality profile. For example, both a steambox and a moisturizer control the CD moisture profile at the reel. The two actuators have to be coordinated in their actions.
- Sometimes, one actuator has an effect on more than one paper quality. For example, a headbox actuator has effect on the basis weight profile and, as a side effect, also on the moisture profile.

22.2.2.2.1 CD Basis Weight Control Actuators at the headbox are used to control the CD basis weight profile. Two principles are widely used:

- **Slice lip actuators:** Linear displacement actuators with a spacing of between 75 and 150 mm deflect the slice lip of the headbox nozzle.
- **Dilution actuators:** Motorized valves feed dilution water into the stock distributor, which is located upstream of the headbox nozzle. Typical spacing between actuators is 35–100 mm.

The advantage of dilution actuators is that the headbox nozzle is not changed mechanically. Local changes in the headbox nozzle result in a nonuniform jet velocity and jet direction. This leads to CD components in the jet flow, which widens up the response of an actuator movement and reduces the capability to control narrow streaks.

The uneven jet velocity also has negative side effects on other paper properties such as the fiber orientation profile.

22.2.2.2.2 CD Moisture Control For CD moisture control, different actuators can be used:

- **Steambox actuators:** A steambox in the press section is used to increase the temperature of the web and hence decrease the viscosity of the water in the web. Thus, zonal heating results in a zonal effect of improved press dewatering.

The dryness of the sheet entering the drying section should be as uniform as possible or the profile should have a certain shape. Deviations in CD dryness profiles before the dryer section result, for example, in uneven shrinkage, curl, overdried edges, edge cracks, paper web breaks, or poor moisture profile at the reel.

To ensure uniform dryness after the press, moisture profile measurement after the press is required to control the steambox CD actuator settings. For good CD profile control capability, steamboxes can have an actuator spacing down to 75 mm and quite small overlapping responses of neighboring actuators in the paper.

However, as steamboxes are often used to increase production, the mean value of all CD actuators should be as high as possible. The remaining potential to change the actuators is sometimes no longer sufficient for good high-resolution CD control performance. In these cases, the steambox may control only long wave profile deviations, whereas the correction of short wave deviations is left to the moisturizers. Thus, for steamboxes an actuator spacing of 150 mm or larger is in many cases completely sufficient, especially if moisturizers are also available in the machine.

- **Moisturizers:** Moisturizers with spray nozzles are used to rewet the paper to adjust the moisture CD profile. The spray nozzles can be controlled individually by a CD control computer. Rewetting for profiling purposes is usually kept as low as possible. Rewetting is, in fact, a waste of drying energy, if it is not needed for other reasons, such as curl control. Moisturizers usually have an actuator spacing of about 100 mm. A typical design is where each actuator consists of four pairs of valves and nozzles. Thus the amount of water added to a CD location is defined by which valves are opened. Thus, for the amount of water added in a given control zone, $2^4 = 64$ different combinations can be chosen.

To avoid streaks, the nozzles have a defined spray angle and a defined distance to the sheet. Spray angle and distance are chosen to ensure an overlapping spray pattern. Thus, each nozzle sprays 50% of the water into the neighboring control zones. This avoids moisture streaks in the rewetting process.

- **Air water moisturizers:** Air water moisturizers are used to control droplet size and droplet speed over a wide operating range. The droplets are much finer and faster than with pure hydraulic moisturizers. This allows one to apply more water. Air water moisturizers usually have only one nozzle per CD control zone, which is controlled continuously. This avoids the limitation to the 64 control steps of the moisturizer and gives better controllability. In addition, the CD spacing of the nozzles is much less. In some applications, more than 300 nozzles are controlled individually, having a CD distance of 25 mm.

Air water moisturizers are used

- in sensitive applications where too large droplets have a negative impact on paper quality, for example, on printability.
- in applications where paper is, for quality reasons, overdried in the drying section, and then rewetted, for example,
 - * to control curl
 - * to reduce mottling
 - * to reduce two-sidedness of roughness and gloss

* to achieve the best possible moisture CD profiles, down to a 2σ deviation of 0.1% relative moisture.

- **Infrared heating:** Zonal infrared heating corrects moisture profile deviations within the drying section and has the additional advantage of improving the drying capacity of the machine, instead of reducing it as do moisturizers. Infrared heaters use either gas or electric energy. Both are more expensive than drying by steam, which limits the number of applications in industry. The zone width of the infrared heating system is usually around 150 mm, but half this size is possible.

22.2.2.2.3 CD Caliper Control For CD caliper control in online calenders, off-line calenders, or supercalenders their nip pressure is zonal controlled through local change of the roll shell diameter or shape.

- **Zone-controlled calender rolls:** The roll shell is internally supported by an oil cushion or a series of oil hydraulic pistons, which can be controlled individually. The number of CD control zones per roll varies, usually between 8 and 60, depending on the construction. Limiting factors are, for example, the number of pipes inside the roll, which are needed to allow individual oil pressures in the various zones. In addition, counter zones are frequently used. They are on the opposite side of the nip. The purpose is to get more degrees of freedom in the zonal nip adjustment.

The mechanics of roll shell together with nip pressure zones and counter zones are quite complex. For example, if only an edge zone is loaded, the whole shell is affected. Therefore, the control is done in two steps:

- The CD control algorithm calculates the required line load profile in the nip.
- A simulation model of the roll is used to calculate the required zonal pressures to achieve the line load profile. This model of the roll is generated by the machine builder and also takes safety limits into account, to avoid roll damage by profile control actions.
- **Zonal heating of rolls using eddy current:** The principle is similar to eddy current breaks. A magnetic field generates current in the moving metal roll. The current heats the roll. With increased temperature the roll diameter increases as well. The advantages of using eddy current are as follows:
 - Energy efficiency is high.
 - Heating may have a positive side effect, if higher gloss is required at that position.
 - Zone spacing can be smaller than with calender rolls and is typically around 100–120 mm.
 The downsides are as follows:
 - A zone cannot actively decrease the roll diameter. This limits the ability to react on small streaks in the profile.
 - The heat flow in the roll does not allow short wave profile corrections. For example, if every second zone is heated, heat also flows to the nonheated zone

in between from both sides. In narrow spaced applications its temperature tends to be like that of its neighbors.

- **Zonal heating/cooling of rolls using hot/cold air:** This kind of equipment is usually applied at heated rolls, to control the surface temperature profile of the roll. The advantages are as follows:
 - Energy consumption and investment are less than for eddy current actuators.
 - Compared to the eddy current solution, short wave profile corrections are much easier to achieve, as between two heated zones the middle zone can be actively cooled. Only cold air can actively decrease roll diameter, that is, between two heated zones.
 - Smaller zone spacing can be achieved because of the active cooling principle. Usual applications have 75 mm zonal spacing; 38 mm spacing is possible if the demands on caliper profile are very high.
 - If the actuator is used together with a zone-controlled calender roll, it is beneficial if the smallest possible zone width is used. In this case, CD control activities are split: long wave corrections are done with the calender roll, whereas the hot/cold air device takes care of the short wave deviations, which cannot be handled by the calender roll itself.

22.2.2.2.4 CD Gloss Control CD gloss control uses actuators in online calenders, off-line calenders, or supercalenders. Gloss is affected by heat, line load, and surface moisture in the nip. As the CD line load and CD roll temperature also affect caliper, CD gloss control usually uses zone controllable steamboxes to change surface moisture. As steam affects the paper very locally, controllability of gloss profiles is very good. Zone spacing is not less than 150 mm, because of space restrictions in the calender, and each zone in the steambox requires its own steam chamber with a steam valve.

22.3 Information Systems

22.3.1 Importance of Information Systems

Information systems in the paper mill exist mainly at two different levels.

- 1) **Enterprise level:** To collect all information concerning the material flow in the paper mill, including, for example, quality parameters of the produced paper. The information is usually collected in a very rough timescale, that is, reel based. The purpose is to derive figures that are required for commercial control of the mill.
- 2) **Process level:** To collect quality and process data in quite high time resolution to be able to analyze and track process problems, to find the technical reasons

for poor/excellent production, or to summarize the data in reports as needed by the enterprise level systems.

While enterprise level systems deal mainly with production quantities (amount of good/bad production), process level systems include tools to analyze reasons for good/bad production.

Comprehensive collection of process data is more and more widely used but is still not available in many older mills. This is due to

- lack of communication standards in automation systems;
- strict border between QCS and DCS/MCS type of systems when those mills were built.

The earliest information systems were the following:

- **QCS quality reports:** summarizing production and quality over reel, shift, day, or grade
- **DCS process trending:** trend of important process variables.

Until recently, there was no simple means to show in a flexible way on one screen, for example, how press settings (DCS data) affect moisture profile quality (QCS data). One obvious reason is that DCS systems are (still) not built to handle “array based” information such as CD profiles. They can deal only with single values such as steam pressure. On the other hand, QCS systems are not built to handle thousands of process values, which require totally different engineering and configuration tools.

Modern information systems bridge the gap, by using history data bases that can deal with tens of thousands of tags (variables), with single values and with profile data as well. In addition, they provide simple access to the data via a web browser and also from the operating screens on the production floor.

Besides QCS and DCS, there exist more systems at a paper mill, which have the main task of collecting information for diagnostic purposes:

- **Machine condition monitoring system:** These systems collect information via vibration sensors to analyze bearings and drive components. Advanced systems include an expert system for quite detailed analysis of the drive component. A machine condition monitoring system can, for example, detect whether the outer ring or the inner ring of a bearing is damaged and is likely to fail within the next few weeks. On the basis of this information, the mill personnel can arrange countermeasures and exchange the bearing during the next planned shutdown. Typically a few hundred vibration sensors are connected to such a system. They are scanned one by one. Scanning occurs about every hour. The signal analysis uses known geometrical bearing and roll data and relates them to the actual measured signals to diagnose the condition of the bearings. The measurements have to be taken with a sampling rate of about 10 kHz to be able to diagnose bearings in detail and to give a prediction of the remaining lifetime of the bearing.
- **Process condition monitoring system (sometimes also called technological monitoring system):** These systems collect information from QCS sensors, vibration

sensors, pressure sensors, triggers at rolls and fabrics, and so on to analyze the reasons for periodic quality disturbances. All collected signals are taken simultaneously with sample rates from 100 Hz to 4 kHz, depending on sensor type and application. The required measurement frequency is given by the revolution time of the machine elements, which can cause quality variations, such as felts, rolls, and pumps.

The correlation results are calculated using time synchronous averaging. A process condition monitoring system can, for example, detect whether an applicator roll is responsible for periodic coat weight deviations or whether a moisture variation is correlated with the revolution time of a press felt.

- **Barring monitoring system:** This system identifies calender rolls that cause barring. Technically it works similarly to a process condition monitoring system.
- **Web inspection system:** A series of cameras arranged in the CD inspect 100% of the produced paper. Image analysis technologies are used to automatically classify the paper defects into different categories, such as bright spot, dark spot, wrinkle, and hole. The web inspection systems generate reports, independently from QCS. On the basis of the camera-based measurement and the image analysis, areas with serious defects can be marked online. A special winder control can stop the winder precisely at these positions, to cut off low-quality production.
- **Web break monitoring:** A couple of cameras are installed at the front side and drive side of the machine to supervise positions where the web is not guided by wires or felts, and where the paper risks breaking. Optical light barriers detect paper breaks. In the case of a paper break, the last minute of the camera readings are stored to a hard disk for later analysis by the production personnel. On the basis of the camera recordings it can be analyzed at which position of the machine, for example, an edge crack started to be seen, and how it evolved to a paper break, or it can be seen whether the paper clipped to a roll and caused a web break. This allows the mill personnel to analyze the reasons for breaks and to optimize the runnability of the machine.

22.3.2

Process Analysis Using Information Systems

Current development of information systems aims to automatically derive knowledge from historical data (Figure 22.5). When analyzing difficult technological problems such systems still need off-line analysis by technological experts to interpret the results. In a typical application, 6–12 months of recorded quality and process data are analyzed with respect to the given technological questions, such as “Most of the production in the last six months showed average printability but sometimes printability was excellent. Why? Which are the machine settings to achieve best quality?”

Such questions are difficult to answer, as several hundred machine settings and raw material parameters have to be taken into account as potential influencing factors. Data mining technologies based on neuronal networks, expert systems, or

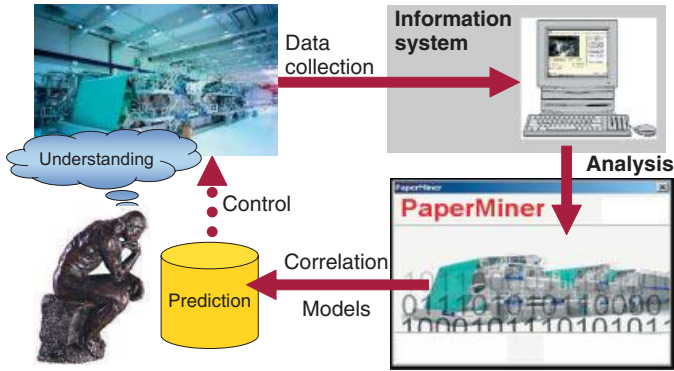


Figure 22.5 Data mining in the paper manufacturing process.

algebraic methods are used to find the requested answers. Algebraic methods are in many cases not sufficient, as these can deal only with numbers (process values), but not with cardinal data such as felt supplier and ash supplier which are also of high importance.

Simpler, but still difficult applications can run online and give information on the quality of a produced paper, which is not measurable online. Those applications are called *soft sensors*. The paper quality is estimated on the basis of historical data. For example, basis weight can be predicted quite well on the basis of some process parameters in the wet end section. Historical data can be used to “learn” the relation between the measured process parameters and the produced basis weight. The learning takes place iteratively to adapt to slowly changing production conditions. Such a prediction is useful during start-up of the machine, while the paper is still not through the drying section and still not measured by a quality scanner. Having a basis weight predictor, the user can still adjust basis weight and therefore, achieve good quality, even before the quality measurement starts scanning.

The challenge of soft sensors is to automatically reject data that are not adequate in order to learn the relationships between the quality parameter concerned and the process data; for example, because a sensor was wrong, the machine settings were just in the process of being changed, and the press felt was worn out just before replacement. This is especially challenging in applications where a 100 or more process data are required to really predict a given paper quality. An example is the prediction of strength parameters. Influences on strength are, for example, the furnish composition, the jet/wire ratio, retention, dryness after press section, tension in the draws, and calendering conditions.

23

Uniformity of Paper Web Properties

Herbert Holik and Johann Moser

23.1

Overview

The uniformity of the paper web is a property by its own as it affects both quality and economy of the product and of the production. It is even more important at present, for example, in view of the requirements of high efficiency and quality printing. Uniformity will be seen here as the uniformity in machine direction (MD), in cross machine direction (CD), and in *z*-direction; the latter is mainly considered as symmetry (anisotropy) of the web across its thickness.

Since the second half of the last century further improved knowledge about the causes of poor MD and CD properties' profiles has been built up and published, and online measuring equipment as well as actuators have been developed for many properties. But some properties can only be measured off-line in the laboratory. Soft sensors may "measure" those paper properties in future by logic combination of other parameters, which can be measured online. So a closed control loop can be set up for these properties as well. Closed control loops need actuators to improve the profiles, their effects and limitations will also be explained.

23.1.1

Defining Profile Deviations by Statistical Methods

Using standard statistical methods, the following characteristic values can be determined: total standard variation, standard variation in MD, standard variation in CD, and residual or random variations. The latter are deviations which cannot be associated with either the MD or CD variations. The residual variations inform about the stability or more precisely the instability of the system. Besides these four statistical numbers, the actual paper web profiles in both MD and CD are important for the papermaker. From these profiles, operators may be able to see in detail at which position the deviations occur, and how large they are.

23.1.2

Requirements and Some Interdependencies Regarding MD and CD Profiles

The given quality standards as regards, for example, basis weight, thickness, gloss, or smoothness have to be met over the whole area of the paper web in order to meet the requirements of the customer. Or the web strength (resulting from basis weight, moisture content, and stock characteristics) along its run through the paper or converting machines should always be above the minimum strength required in the production process to avoid web breaks. In this case, the deviations are only allowed in positive direction (to be safe), which usually means higher raw material input. Only a very uniform profile assures smooth machine run at lowest raw material costs.

Depending on the paper or board grade, different properties' profiles are important. Properties such as basis weight, moisture content, thickness (caliper) or smoothness, and gloss are basic requirements for most of the grades. It should be noted that a poor basis weight profile can be seen in the moisture profile, a poor moisture profile influences the profiles of caliper and smoothness or gloss, and also the temperature profile. The latter has a negative effect on caliper, smoothness, and gloss profiles. All this can be explained by well-known paper technological basics: for example, a higher basis weight results in a higher moisture content, which in turn means a lower compression resistance and thus more thickness reduction in calendaring. Temperature differences of the web may result in diameter variations of rolls showing up in poor caliper, smoothness, and gloss profiles.

In this chapter the causes for poor profiles are discussed. Tables will indicate the extent of the potential negative effect of the machine sections and machine elements on the different paper properties' profiles. They show the possible cause and occurrence, indicate the typical resulting profile shape, and estimate the probability of negative influence.

To assure uniform MD and CD profiles, one has to take into account all the direct and indirect influences coming from the stock, and the operating conditions in the different sections of the paper machine. A good advice is to run the machine long enough with the help of the control loop tools, but to investigate early enough the actual causes of the poor profiles and remedy the evil at the source. This avoids negative influence on other properties' profiles or damage of machine components, for example, felts or roll coatings.

23.1.3

Symmetry in z-Direction

Symmetry of the web in z-direction at many grades has a strong influence on the further use of the paper and board product, be it the fines and filler distribution in z-direction, the fiber orientation or the frozen tension in the web. Nonsymmetry may result in uneven printing results of the two sides or in deformation (curl) of the sheet under changes in temperature or moisture content. The causes for those nonsymmetries and their cure are given in the last paragraph.

Table 23.1 Overview of the potential negative influence of the different sections of the paper machine on the MD profile of some paper and board properties.

		Approach flow system	Headbox	Wire section	Press section	Predryer section	Size press	Coaters	After dryer section	Calender
MD profile of	Basis weight	■	○	○	-	-	○	○	-	-
	Moisture	○	-	○	○	-	○	○	-	-
	Caliper	○	-	-	○	-	○	○	-	■
	Smoothness/ gloss	-	-	○	-	-	-	○	-	■

Effect: ■ = significant; ○ = weak; - = negligible.

23.2 MD Profiles

Table 23.1 gives an overview to which extent the different sections of the paper machine may influence the MD profiles of basis weight, moisture content, caliper, and smoothness or gloss. In the following the origins of poor MD profiles of both basis weight and caliper are described in more detail and shown how to improve them.

23.2.1 MD Basis Weight Profile

Poor MD basis weight profiles may come from deviations in suspension consistency and flow rate supplied to the forming section, furthermore from deviations in the retention aid flow rate, vacuum variations in the former section or in mechanical conditions such as headbox tilting or wire drive.

23.2.1.1 Consistency

The origins of suspension consistency deviations can be variations in consistency or in flow rate of the thick stock or white water as well as in instable mixing of both components. So for both components measures have to be taken to assure constancy. As white water is a mixture of white waters of different consistencies all its components have to be kept constant in flow and consistency, and good mixing must be ensured. Suspension consistency deviations of, for example, 2% result in a basis weight variation of about the same amount. Short-term consistency deviations result in local MD profiles, which differ from position to position across machine width (and thus in an unstable CD profile). This can be explained as follows: the stock approaching from the drive side of the machine influences the MD profile here earlier than at the tender side. The time lag showing up in the MD profile between drive and tender side corresponds to the time taken by the fibers or

suspension to travel from the drive to the tender side. In Figure 23.1, the effect of a “bump” in consistency is shown. As the bump flows through the distributor the CD profiles will differ over time (t_1 up to t_6). Hence, the local MD profiles will vary over width as well. The headbox pump (mixing thick stock and white water) can only mix components locally but cannot reduce or eliminate consistency variations occurring over a period of time.

23.2.1.2 Retention

Retention aids have to be added at constant rate and should be well mixed with the suspension. The effect of any nonuniform flow rate is similar to a consistency deviation, but the influence is less, the amount depending on overall retention in the forming section and paper grade. Poor mixing may mostly result in unstable MD profiles such as for consistency variations, sometimes in local stable CD deviations.

23.2.1.3 Headbox Flow Rate

Flow rate variations come from pressure pulsations (high frequencies) or from control or in general from system instability (low frequencies). Pressure pulsations from pumps and screens show the frequency of the drive and its multiple depending on the number of rotor blades. Pressure pulsations of the headbox pump show higher amplitudes when this pump does not work in its optimum range. This means that pump size and type should be selected correctly. Hydraulic instabilities may originate from air cushions in the pipe, or by poor piping bending design or when inadequately uniting or dividing the flows. A pressure difference of 2% results in a deviation in the flow rate of about 1% and about the same amount (1%) in basis weight of the web. To get an idea of the effect of the deviations in the

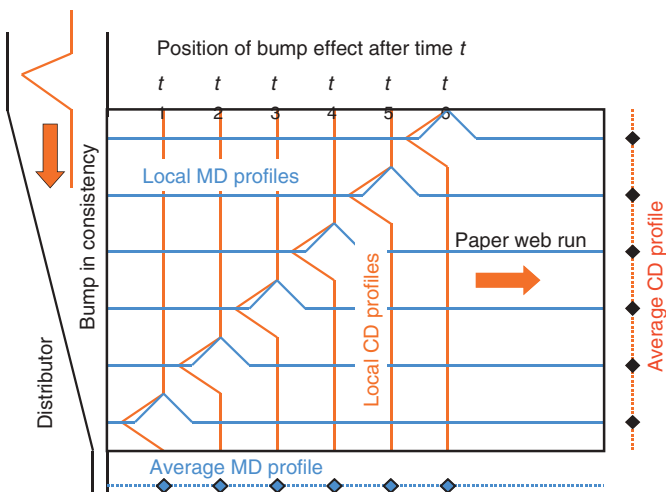


Figure 23.1 Impact of a bump of consistency variation out of the approach flow system on the local MD basis weight profile.

running web: 100 Hz, for instance, at 1800 m min^{-1} mean a wavelength of 30 cm in MD, which is the length of a DIN A4 sheet.

In a similar way as explained for consistency deviation, the local MD profiles are influenced by pressure pulsations as the pressure pulses propagate with the velocity of sound through the distributor. For reducing the amplitudes of disturbing pulsations, dampers can be installed ahead of the headbox which is usually done for Fourdrinier headboxes. A more detailed view on the effect of variations in the approach flow system on the MD and CD profiles and standard variations measured in the laboratory is given in Section 23.3. Figure 23.2 shows the typical frequency ranges of disturbances in the approach flow system and their origins.

Unstable wire drive has the effect that more (at the moment of lower wire speed) or less (at higher wire speed) suspension is delivered on the unit of wire length over the time (the supply from the headbox supposed to be stable). Furthermore, unstable drive of the felt(s) in the press section results in basis weight deviations as the web will be more or less elongated. So, stable drive conditions for the fabrics have to be assured in wire, press, and dryer sections.

Tilting of the headbox (in z -direction) is mainly excited by vibrations in MD, propagating through structures such as basement or wire section. The result of headbox tilting is that the distance varies where the jet impinges the wire. This supplies more or less suspension on to the unit of wire length over the time.

23.2.1.4 Vacuum Variation

Wet suction boxes and/or curved vacuum assisted forming shoes having vacuum variations (pulsations) can also create significant MD basis weight variations. A higher vacuum extracts more fibers, fines, and fillers from the web and the basis weight decreases. Poor drop leg run toward the seal tank is one of the major reasons

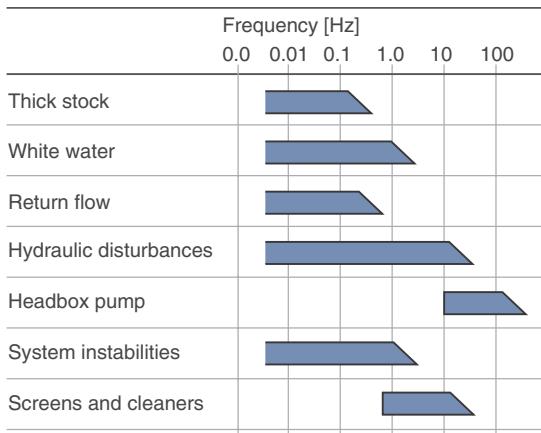


Figure 23.2 Typical frequency ranges of disturbances in the approach flow system and their origins.

Table 23.2 Overview of the potential origins of basis weight nonuniformities and their effect on standard variations.

			Effect on basis weight standard variation		
			MD	CD	Residual
Deviations in	Consistency	High frequency	○	○	■
		Low frequency	■	○	○
	Pressure	High frequency	○	○	■
		Low frequency	■	○	○

Effect: ■ = significant; ○ = weak.

for vacuum variations. The best tuned control loop cannot overcome the design flaw, so the pipe run must be modified.

Table 23.2 gives an overview of main potential origins of disturbances of basis weight and the effect on standard deviations.

23.2.2

MD Caliper Profile

As a special problem of MD caliper and smoothness or gloss profiles, calender barring is dealt with here. Barring in calenders is a problem in the industry since a very long time. It is not only a matter of paper quality and operating costs (because of damaging of the roll surfaces) but also of severe noise generation. Barring is usually caused by vibrations of the roll itself or of the framing. It mainly occurs at the natural frequencies of the roll. At its natural frequencies only low energy is

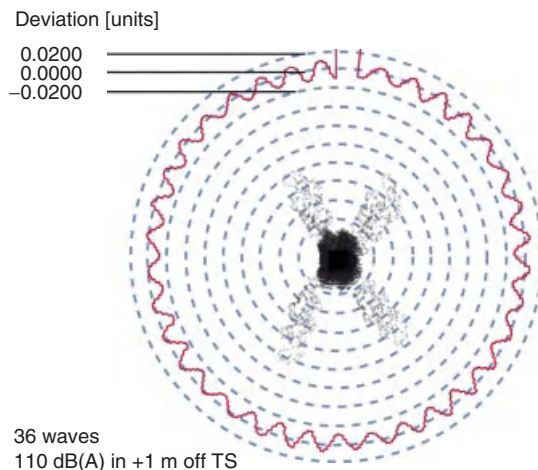


Figure 23.3 Measurement of the run out of a soft calender roll. (Source: Voith.)

required to excite roll vibration leading to roll cover deformation and wear. “Bars” of varying caliper, smoothness, and gloss appear in the web, and heavy noise occurs. So the roll has to be changed and reground after a short production time.

In Figure 23.3, an example of a wear measurement (run out) on the circumference of a soft calender roll working against a hard mating roll is shown. Exactly 36 waves on the surface have been measured. In this case, for a run out (double amplitude) of about $20\ \mu\text{m}$ a noise of 110 dB(A) has been measured at tender side about 1 m off the calender [1].

One system (Figure 23.4) to reduce the barring problem (introduced in 2007) is based on the known principle of interference, using a nip control roll with

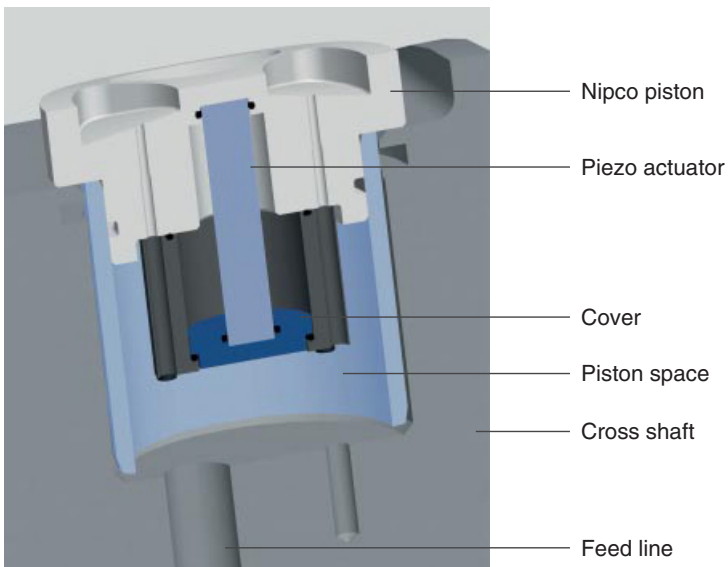


Figure 23.4 System to reduce barring by interference in a Nipco roll. (Source: Voith.)

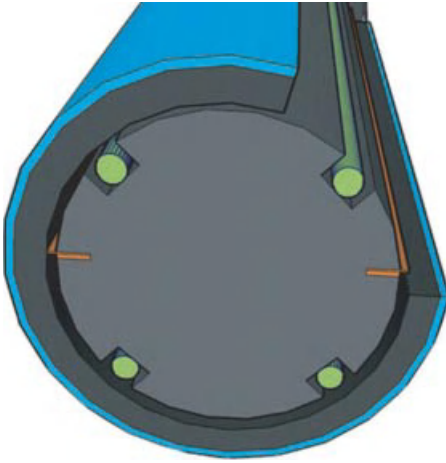


Figure 23.5 System for reducing barring by frequency shift in a Swimming roll. (Source: Andritz Kuesters.)

hydrostatic pistons. The barring movement is measured as regards acceleration and frequencies. Then pressure pulses are generated by piezo actuators with same frequencies and same amplitudes as measured but displaced by half a wavelength. Thus the barring amplitudes are extinguished or at least reduced [1].

Another principle is frequency shifting of the roll system. By inserting air-inflated hoses to the oil volume of a swimming roll, the total mass as well as the stiffness of the system is reduced (Figure 23.5). Thus the natural frequency is increased [2].

A further principle is described in [3]. Here, the central bores are filled with an antivibration compound consisting of an incompressible fluid and solid particles. Owing to inertia the solids try to not follow the movement, whereas the fluid has to flow through the package of the solid particles. By transferring kinetic energy of vibration into heat the amplitudes are reduced.

23.2.3

MD Coat Weight Profile

Sometimes coat weight varies in MD at high frequencies. This can be often triggered with the revolutions (rpm) of the backing roll. Its negative dynamic behavior may have different causes: shell and roll cover thickness varies, the shell is not exactly circular, the roll is not well balanced, bearing and framing transfer vibrations to the roll. Main actions are not only to remedy the above-mentioned faults but also changing the quality and elasticity of the cover may be helpful.

23.2.4

MD Irregularities in Tissue Making

Nonuniform shape in circumference direction of the dryer shell (run out) may be detected by noise variations at the creping doctor when creping conditions vary in the course of one revolution. Detrimental effects may be creping problems, uneven wear in MD, and machine vibration. One cause of the cylinder run out are the different local heat transfer conditions in MD inside the cylinder. Each condensate removal installation (usually a soda straw type) creates singularities around the circumference of the cylinder as the heat transfer rate in its neighborhood is different from the remaining shell area. As a result, local shell temperature and as consequence local radius deviations at those positions (some tenths of millimeters) may occur.

The run out can be decreased by smoothening the heat transfer inside the shell. This can be done by increasing the soda straw clearance to the shell. If a reduction of blow through steam is admissible this may also help. Spoiler bars do not only make the heat transfer much more uniform but also increase the overall drying capacity of the cylinder [4].

23.3

CD Profiles

Table 23.3 gives an overview on how far the different sections of the paper machine may influence the CD profiles of basis weight, moisture, caliper, and smoothness or gloss. In the following, the potential causes of poor CD profiles of these properties will be shown. It should also be cross-checked with off-line laboratory equipment whether the indicated profiles are a fact and not a fake [5].

It is also discussed how to rectify deviations. Generally speaking, when trying to rectify the CD profile of any paper property it should be done at the very origin of the disturbance. The use of control equipment may have an impact on other web properties and in certain cases can also damage machine components to some degree. So its use may be not advisable in every case and for a too long time.

23.3.1

CD Basis Weight Profile

Poor CD basis weight profiles can have their origins in the approach flow system, in the headbox, in the wire section, in the dryer section, in the coater section, and also in the control system. Table 23.4 summarizes the possible causes in the different sections and show how strong their effect can be, and how high their probability is. It also indicates whether the typical deviations are of short or long wavelength character.

Table 23.3 Influence of the sections of the paper machine on the CD profiles of o.d. basis weight, moisture, caliper, and smoothness or gloss.

		Approach flow system	Head box	Wire section	Press section	Predryer section	Size press	Coater	After dryer section	Calender
CD profile of	Basis weight	○	■	■	–	○	○	■	○	–
	Moisture	–	○	○	■	■	○	■	■	–
	Caliper	–	○	○	○	–	–	○	–	■
	Smoothness/ gloss	–	○	○	○	–	○	■	–	■

Effect: ■ = significant; ○ = weak; – = negligible.

Retention aids may produce short wavelength deviations in CD when they are not well mixed with the stock and stable streaks of them are passing the headbox. In general, the headbox is the main factor influencing the CD basis weight profile. Here the distributor (geometry, recirculation rate, and throughput), the distributor block uniformity, as well as nozzle and slice geometry are decisive. In the wire section, the uniformity of the forming wires as regards dewatering resistance (due to their manufacturing or cleanliness) and the equal dewatering function across width of open rolls, table rolls, and foils are required. In the dryer section, shrinkage at the web edges is higher than toward the center and varies when web draw or main fiber orientation (MFO) changes. Local size pick up in the size press, and thus variation in basis weight to some degree, depends on the CD profile of moisture content of the ingoing web.

For control of poor CD basis weight profiles, there are two possibilities: by slice bar adjustment or by dilution. For slice bar adjustment, usual standard is 75 or 100 mm (up to 200 mm in the past) distance between the spindles. Owing to fluid dynamic principles such a control also shows strong adverse influence on the basis weight in the neighborhood of the controlled area (about three to five times the spindle spacing). Furthermore it influences MFO. The amount of local CD basis weight control is also limited by the bending characteristics of the slice bar.

The other principle is control by local dilution. The standard spacing of these control modules at present is 50 mm (up to 150 mm in the past) down to a minimum of 35 mm for special applications. Recent response width is 1.5–2 times the control module width. For this principle, the control potential is only limited by the consistencies of the “thick” stock and white water for dilution. It has no impact on MFO.

Taking typical standard spacings of spindles or dilution modules the response width of CD basis weight control by spindles is about four times larger than with the dilution modules (Figure 23.6).

Table 23.4 Positions in paper production potentially causing poor CD basis weight profiles, potential causes, kind of deviations, and their potential effect.

Process or machine section	Potential cause of poor CD basis weight profiles	Potential effect	Typical wavelength CD	
			Short	Long
Approach flow system				
Retention aid addition	Streaks, poor mixing	○	▲	–
Headbox				
Geometry	Poor calculation, manufacturing	○	–	▲
Headbox surfaces (finishing)	Dirt deposition nozzle or turbulence generator	○	▲	▲
Flow	Out of design range	○	–	▲
Recirculation rate	Too high, too low	●	–	▲
Turbulence generator	Partly blocked	●	▲	–
Nozzle geometry	Inadequate	●	▲	–
Top wall design	Deflection	●	–	▲
Bottom wall (apron) design	Deflection	●	–	▲
Edge wall friction	Not taken into account	●	▲	–
Edge feed or bleed	Too high, too low	●	▲	–
Slice lip, mechanical condition	Deformed, worn	●	▲	–
Alignment of headbox	Wrong	●	▲	–
Dilution ratio	Too high, too low	●	▲	–
Jet impinging line on wire	Not straight, not uniform	●	▲	▲
Velocity difference jet–wire	Change in drag/rush over width	○	▲	▲
Bottom lip	Deformed, worn	●	▲	–
Deckle bars	Wrong position	●	▲	–
	Poor alignment	●	–	▲
Wire section				
Nonuniform forming fabric structure	Poor manufacturing	●	▲	–
Forming fabric CD waves	Wear of fabric	●	▲	–

(continued overleaf)

Table 23.4 (continued)

Process or machine section	Potential cause of poor CD basis weight profiles	Potential effect	Typical wavelength CD	
			Short	Long
	CD stability, poor fabric design	●	▲	–
	Roll deflection, wire tension too high	●	▲	–
	Local roll cover wear	●	▲	–
	Ceramics in poor condition	●	▲	–
Contaminated wires	Poor wire cleaning	●	▲	–
Dewatering elements				
Position not rectangular to MD	Poor mounting, displaced in operation	●	–	▲
Slots, perforation	Deposits, plugged	●	▲	–
Dryer section				
Shrinkage	Single-tier/double-tier design	●	–	▲
Variation in shrinkage	Web draws not constant (drives)	○	▲	▲
Control system				
Gauging device	Poor calibration	●	▲	▲
Software	Poor control algorithm	●	▲	▲

Effect: ● = significant; ○ = weak; – = negligible; ▲ = most likely type.

For wider range control, the recirculation valve at the distributor can be used, which has an impact on the profile mainly on the drive side (usual valve position whenever installed). As Figure 23.7 shows this kind of control has an impact on MFO as well and has a limited potential for CD profile control.

23.3.2

CD Main Fiber Orientation (MFO) Profile

A MFO angle (Chapter 13) different from 0 (0 means exactly MD) may cause problems in machine operation or in later use of the paper such as reduced paper strength in MD, diagonal curl, and diagonal elongation. Figure 23.6 shows the typical effect on the MFO profile when CD basis weight control is done locally either by locally dropping the slice bar or by adding dilution water. Local control with slice

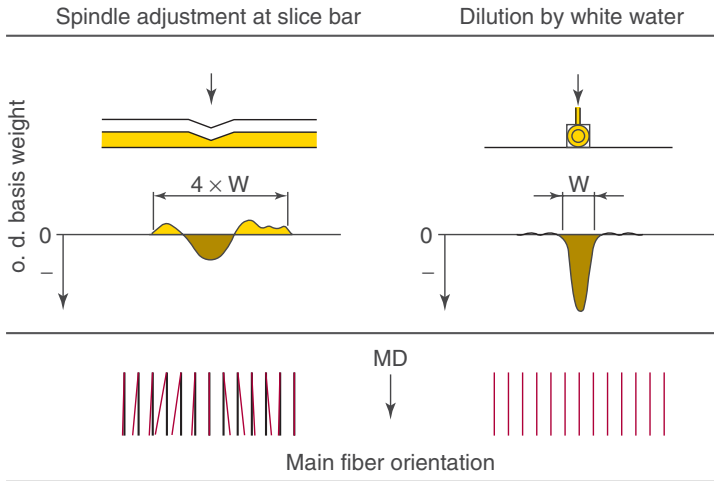


Figure 23.6 Comparison of slice bar and dilution control – width of influence on local CD basis weight and on main fiber orientation MFO.

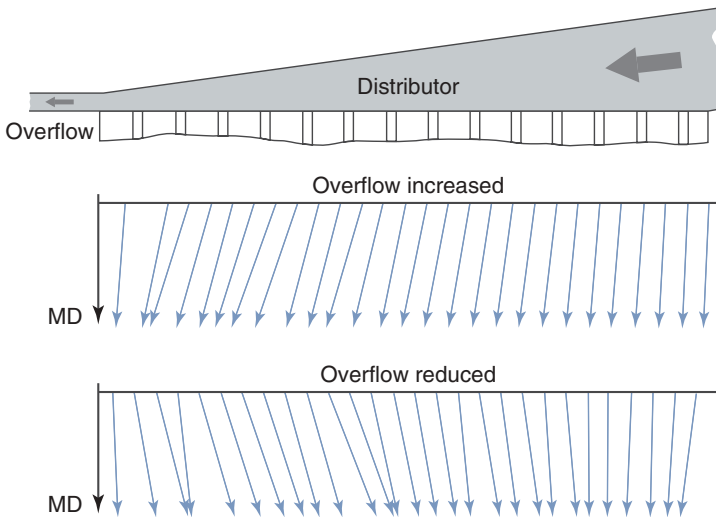


Figure 23.7 Measured effect of a change in recirculation flow rate of a distributor on the CD profiles of basis weight and main fiber orientation MFO.

bar influences the jet direction in its neighborhood, whereas with dilution control no effect can be observed.

Further negative influence may come from the distributor (geometry, throughput, and recirculation). In Figure 23.7, the effect of a change in the recirculation rate of the distributor on the MFO is shown [6]. Further effects come from the distributor

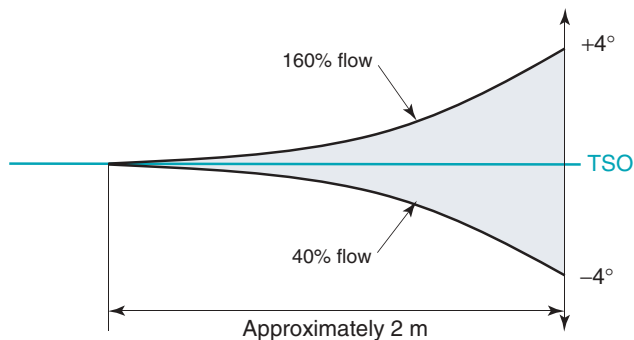


Figure 23.8 Effect of varying edge flow control on MFO at the paper edges.

block (cleanliness, geometrical uniformity), the geometry of the headbox nozzle, the slice bar geometry, the interaction of suspension jet and wire, the wire section (dewatering conditions), and the dryer section (shrinkage). Table 23.5 shows the positions in paper production potentially causing poor CD profiles of MFO, mentioning potential causes, the kind of deviations, and their probability. To improve CD MFO profiles, the above potential negative influences have to be checked and deviations reduced or abolished.

A different negative effect on MFO angle comes from the deckle boards of the headbox. At tender and drive side the suspension slows down because of friction on the wall surface inside the headbox nozzle, thus a velocity gradient is created, which results in fiber misalignment. With edge control flow on tender and drive side the problem can be eliminated. The width of impact is about 2.0 m from each side into the web. Figure 23.8 shows the effect on the MFO profile when the edge control flow is changed by $\pm 60\%$ compared to standard condition. The performance of the control is independent of the slice opening, which is important for machines making a wide basis weight range.

23.3.3

CD Moisture Profile

Table 23.6 gives an overview on the positions in paper production which may cause poor CD moisture profiles. It shows potential causes, the kind of deviations (wavelength), and their potential effect.

A poor CD moisture profile may affect product quality (smoothness and gloss, frozen tension in the paper) as well as economy (overdrying part of the web to obtain admissible maximum moisture or to assure minimum dryness deviations all over the web, web breaks are more likely). The possible causes of poor CD moisture profiles are manifold: a poor CD basis weight profile, nonuniform dewatering resulting in a not uniform web build up in the wire section, uneven dewatering conditions in the press section (felts and rolls), nonuniformity in the dryer section (cylinders, condensate removal, dryer fabric, air condition and air

Table 23.5 Positions in paper production potentially causing poor CD profiles of main fiber orientation MFO, potential causes, kind of deviations, and their potential effect.

Process or machine section	Potential cause of poor CD main fiber orientation (MFO)	Potential effect	Typical wavelength CD	
			Short	Long
Approach flow system				
Retention aid addition	Streaks, poor mixing	○	▲	–
Headbox				
Geometry	Poor calculation, manufacturing	○	–	▲
Surfaces (finishing)	Dirt deposition nozzle or turbulence generator	○	▲	▲
Flow	Out of design range	○	–	▲
Recirculation rate	Too high, too low	●	–	▲
Turbulence generator	Partly blocked	●	▲	–
Nozzle geometry	Inadequate	●	▲	–
Top wall design	Deflection	●	–	▲
Bottom wall (apron) design	Deflection	●	–	▲
Edge wall friction	Not taken into account	●	▲	–
Edge feed or bleed	Too high, too low	●	▲	–
Slice lip, mechanical condition	Deformed, worn	●	▲	–
Alignment of headbox	Wrong	●	▲	–
Dilution ratio	Too high, too low	●	▲	–
Jet impinging line on wire	Not straight, not uniform	○	▲	▲
Velocity difference jet–wire	Change in drag/rush over width	○	▲	▲
Bottom lip	Deformed, worn	●	▲	–
Deckle bars	Wrong position	○	▲	–
	Poor alignment	●	–	▲
Wire section				
Nonuniform forming fabric structure	Poor manufacturing	●	▲	–
Forming fabric CD waves	Wear of fabric	●	▲	–

(continued overleaf)

Table 23.5 (continued)

Process or machine section	Potential cause of poor CD main fiber orientation (MFO)	Potential effect	Typical wavelength CD	
			Short	Long
	CD stability, poor fabric design	●	▲	–
	Roll deflection, wire tension too high	●	▲	–
	Local roll cover wear	●	▲	–
	Ceramics in poor condition	●	▲	–
Contaminated wires	Poor wire cleaning	●	▲	–
Dewatering elements				
Position not rectangular to MD	Poor mounting, displaced in operation	○	–	▲
Slots, perforation	Deposits, plugged	●	▲	–

Effect: ● = significant; ○ = weak; – = negligible; ▲ = most likely type.

distribution in pocket ventilation, and fabric pressure for good contact to the cylinders).

A poor CD moisture profile in tissue production is negative as regards product properties as well as economy for it needs more drying energy to locally reach the minimum acceptable dryness, other sections are overdried. This may result in nonuniform coat build up on the cylinder surface and nonuniform creping. Same is true for the wear of the Yankee dryer across width. The causes may be poor CD uniformity of the felt (dewatering behavior) or suction press roll conditions (line load profile, cleanliness) or cylinder shape due to varying operating conditions of the Yankee dryer. The Yankee dryer and the press roll(s) have corresponding crownings to compensate for deflection under operating conditions in order to ensure a uniform line load distribution. These are exactly fitting for only one setting of these conditions. Influencing parameters for a given dryer (wall thickness, head design) are the steam pressure, temperature difference across the cylinder wall, circumferential speed (centrifugal force), and the line load of the pressure roll(s). Figure 23.9 gives an example of the effect of varying operating conditions – compared to design conditions – on the line load distribution over width in the nip formed by the Yankee dryer and the pressure rolls [4].

The type of CD moisture profile control tools depends on whether the deviations are constant or varying over time and which kind of dryer section is given. For multicylinder dryer sections, control tools such as fine tuning of spoiler bars (for constant deviations), or sectioned blow boxes and moisturizers (varying deviations) are used. An improved CD moisture profile entering the dryer section can be

Table 23.6 Positions in paper production potentially causing poor CD moisture profiles, potential causes, kind of deviations, and their potential effect.

Process or machine section	Potential cause of poor CD moisture profiles	Potential effect	Typical wavelength	
			Short	Long
CD basis weight profile	Table 23.4	○	▲	▲
Wire section				
Forming wire	Table 23.4	○	▲	▲
Dewatering elements		○	▲	▲
Press section				
Press nips	Roll crowning too high, too low	●	–	▲
	Nonsymmetrical external loading	●	–	▲
	Poor operation of nip control roll	●	▲	▲
	Local roll wear	●	▲	–
	Press roll void volume locally plugged	●	▲	–
Press felts	High pressure shower nozzles blocked	●	▲	–
	Felts contaminated	●	▲	–
	Poor felt conditioning	●	▲	–
	Nonuniform water content	●	▲	–
Steam blow box	Local plugging of zones (stock)	●	▲	–
	Steam valves blocked	●	▲	–
Dryer section				
Shrinkage	In general	○	▲	▲
Cylinder	Inside heat transfer (spoiler bars defect)	●	▲	–
	Cylinder face streaky (contaminated)	●	▲	–
Air supply	Rate/distribution air inlet/exhaust	●	▲	▲
Dryer fabrics	Contaminated, streaky	●	▲	–
Blow boxes	Holes blocked, adjustment poor	●	▲	–
Infrared drying	Elements defect	●	▲	–
Web moisturizing system	Rate/overlapping spray nozzles	●	▲	–
Control system				
Gauging head	Defect measuring instrument	●	▲	▲
Software	Poor control algorithm	●	▲	▲

Effect: ● = significant; ○ = weak; – = negligible; ▲ = most likely type.

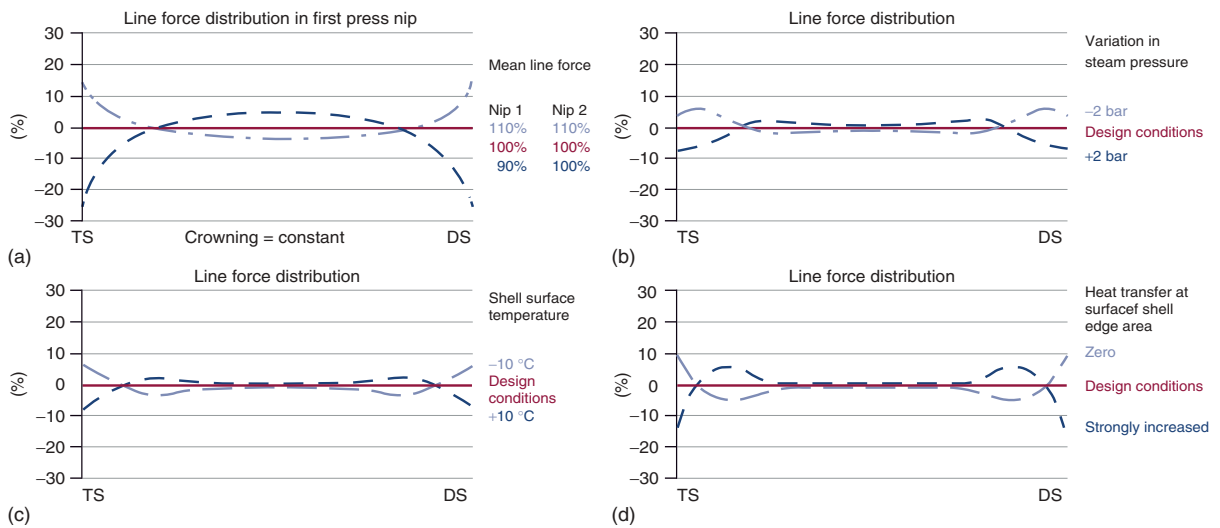


Figure 23.9 Calculated effect of varying operating conditions on the line load distribution over width of a Yankee dryer compared to design conditions [4]. (a) Effect of line load variation. (b) Effect of steam pressure variation. (c) Effect of surface temperature variation. (d) Effect of heat transfer variation at the cylinder shell edge area.

reached by a nip control roll in the press section. It should be borne in mind that excessive local pressing (to overcome a malfunction at another place) damages the felt and may negatively influence paper characteristics.

In tissue drying, spoiler bars can be placed inside the Yankee cylinder to control deviations constant over time. Recent standard is a drying hood sectioned over width. For more even dewatering at the press position a softer press roll cover or a special nip control roll may be used.

23.3.4

CD Caliper Profile

When reeling a paper web with a poor CD caliper profile the local caliper deviations are added up. This may lead to problems such as cracking of the paper in the reel. Poor caliper profiles may also lead to problems in converting or use.

Table 23.7 gives an overview on the positions in paper production potentially causing poor CD caliper profile, their potential causes, the kind of deviations, and their potential effect.

Causes of poor CD caliper profiles can be

- poor CD profiles of basis weight where higher basis weight usually results in higher caliper;
- poor CD profiles of moisture, as higher moisture content means higher compressibility;
- poor CD profiles of temperature where higher temperature leads to higher compressibility;
- poor CD calender nip profile because of grinding inaccuracy, wear, or local temperature differences.

It should be noted that a deviation of 5 μm in roll radius are 5% of the thickness of a 100 μm caliper paper which would be, for example, 10% when the paper is compressed to half of its thickness in the nip.

First approach should be – here again – to rectify uneven operating and machine conditions such as deviations of the paper web CD profiles of basis weight, moisture, and thickness, and to regrind the calender rolls when wear is uneven or the mainly applied line load has been changed.

Active control means for smaller deviations are air showers or induction shoes. In former times, wooden friction shoes were used as a remedy. For wider range deviations nip control rolls are best suited.

Figure 23.10 shows an example of the principle effect of an air shower nozzle creating a heat sink on the geometry of a calender roll, internally heated or not. It can be seen:

- The effect is better for a roll, which is not internally heated than for a heated one. Heating has a softening effect.
- The width of the effect on the roll surface temperature is much larger than the opening of the air jet nozzle. This is due to heat flux, which is not only radial through the shell wall but also transversal along its length.

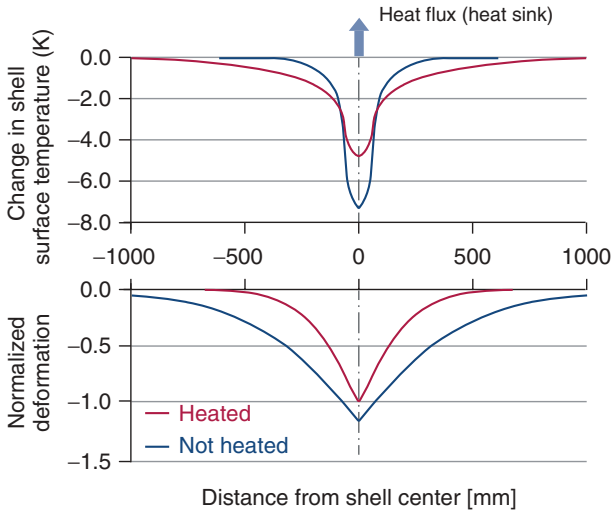


Figure 23.10 Calculated effect of an air shower nozzle on the geometry of a calender roll, internally heated or not [7].

- The radius change does not correspond to the actual temperature differences. This is due to the fact that the shell cannot locally shrink or expand freely. Local shrinkage or expansion is impeded by the neighboring material with a different temperature (and thus different shrinkage or expansion).

There is a long list of influencing factors on the resulting shell geometry [7]:

- **Roll dimension:** face length, diameter, and shell wall thickness (and cover material).
- **Shell material properties:** thermal conductivity, thermal expansion factor, and Young's modulus of the shell (or shell layers).
- **Heat transfer conditions:** local heat transfer coefficient, effective width of local heat transfer, temperature of local heat source, ambient heat transfer coefficient, ambient temperature, internal heat transfer, internal temperature, distance between individual heat sources or sinks.

The effect of these local variations of the shell diameter on the paper depends on the elastic behavior of the paper itself (Young's modulus, thickness) and especially on the elastic properties of the rolls building up the nip. Figure 23.11 shows the effect of a heat sink applied to the hard roll on its radial deformation, and on the resulting CD line force profiles in a hard and a soft nip. It should be noted that higher local pressure results in higher local smoothness and gloss. Same is true for higher temperature and usually for the moisture content of the web.

Table 23.7 Positions in paper production potentially causing poor CD caliper profile, potential causes, kind of deviations, their potential effect.

Process or machine section	Potential cause of poor CD caliper profiles	Potential effect	Typical wavelength	
			Short	Long
CD profiles	Basis weight Table 23.4	○	▲	▲
	Moisture Table 23.6	●	▲	▲
Press section				
Press nips	Roll crowning too high, too low	●	–	▲
	Nonsymmetrical external loading	●	–	▲
	Poor operation of nip control roll	●	▲	▲
	Local roll wear	●	▲	–
	Press roll void volume plugged	●	▲	–
Press felts	High pressure some shower, nozzles blocked	○	▲	–
	Felts contaminated	○	▲	–
	Poor felt conditioning	○	▲	–
	Nonuniform water content	○	▲	–
Steam blow box	Local plugging of zones (stock)	○	▲	–
	Steam valves blocked	○	▲	–
Dryer section				
Shrinkage	In general	○	▲	▲
Cylinder	Inside heat transfer (spoiler bars defect)	○	▲	–
	Cylinder face streaky (contaminated)	○	▲	–
Air supply	Rate/distribution air inlet/exhaust	–	–	–
Dryer fabrics	Contaminated, streaky	○	▲	–
Blow boxes	Holes blocked, adjustment poor	○	▲	–
Infrared drying	Elements defect	○	▲	–
Web moisture control system	Rate/overlapping spray nozzles	●	▲	–
Calender				
Rolls	Roll crowning too high, too low	●	▲	▲
	Nonsymmetrical press force	●	▲	–
	Poor zone distribution of nip control roll	●	▲	–
	Local roll wear	●	▲	–
	Nonuniform internal heating	●	▲	–
Air showers	Blocked nozzles	●	▲	–
Induction shoes	Dead elements	●	▲	–
Control system				
Gauging head	Defect measuring instrument	●	▲	▲
Software	Poor control algorithm	●	▲	▲

Effect: ● = significant; ○ = weak; – = negligible; ▲ = most likely type.

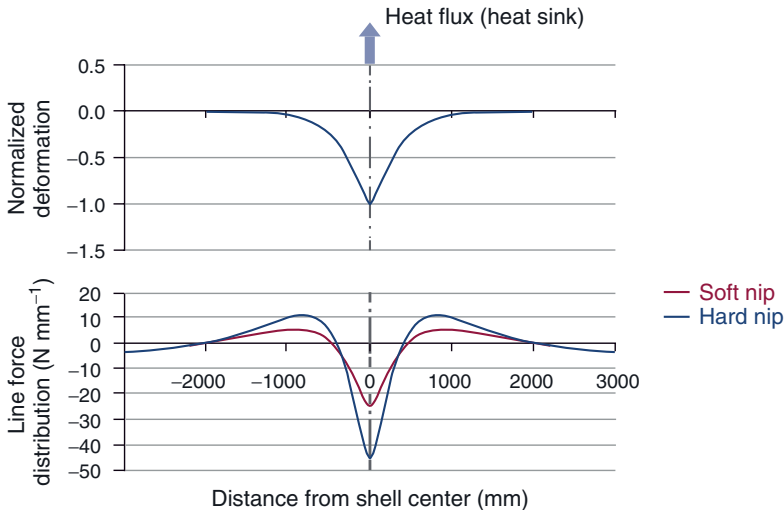


Figure 23.11 Calculated effect of a heat sink applied to the hard roll on its radial deformation, and on the resulting CD line force profiles in a hard and a soft nip [7].

23.3.5

CD Smoothness and Gloss Profiles

Control of CD caliper profiles has an impact on the CD profiles of smoothness and gloss, as the usual technical means to influence these properties are the same. So these properties are interconnected to a high degree. One exception is local steam application to the web surface whereby smoothness and gloss can be influenced in some extent independently from caliper.

23.4

Some Aspects of MD and CD Basis Weight Profile Tests in the Laboratory

In the paper industry, profile tests are often done in the laboratory as a separate check independent from the QCS (quality control system). Hereby, a number of $n = 10\text{--}30$ equidistant paper stripes are cut out of the parent roll over the whole width. The distance d between the individual stripes usually is $d = \pi \times D$, with D as the diameter of the parent roll to be tested. Each stripe is then measured in full length or cut into numerous samples, each of them being weighted. This delivers basis weight profiles of each stripe. The mean CD basis weight profile is calculated as the average of the n profiles. The MD profile is calculated from the mean values of the CD profiles [8].

The limitations of this method are discussed using the example of a paper machine with reel speed $v_{\text{reel}} = 2000 \text{ m min}^{-1}$, parent roll diameter $D = 4 \text{ m}$, number of stripes $n = 10$, machine width (pond width) of $w = 10 \text{ m}$.

Deviations in the approach flow (pressure, consistency) run through the headbox distributor at a velocity v_{distr} . This takes a certain time t_{distr} , which can be calculated as

$$t_{\text{distr}} = w/v_{\text{distr}}$$

Pressure variations propagate in the suspension with the speed of sound which depends on the properties of the medium. Generally, the velocity of sound in fluids is

$$c_{\text{fluid}} = (K/\rho)^{1/2}$$

with K as the bulk modulus and ρ the density. For standard conditions, the speed of sound in water is $c_{\text{water}} = 1484 \text{ m s}^{-1}$ and in air is $c_{\text{air}} = 346 \text{ m s}^{-1}$. As fiber suspensions contain a varying amount of air, the velocity of sound usually lies in between these values and may vary over time.

Consistency variations run through the distributor at a varying velocity depending on operating conditions. Here the range is about $2 \text{ m s}^{-1} < v_{\text{distr}} < 5 \text{ m s}^{-1}$. During the propagation time, the paper machine has produced a web length of $L = v \times t$.

The actual profile (i.e., consistency) downstream the distributor is found in the web under a certain angle α against CD (Figure 23.12). The slope SL of the profile axis can be defined as

$$\text{SL} = v_{\text{wire}}/v_{\text{distr}}$$

v_{distr} may be the suspension velocity in the distributor or the sound propagation velocity.

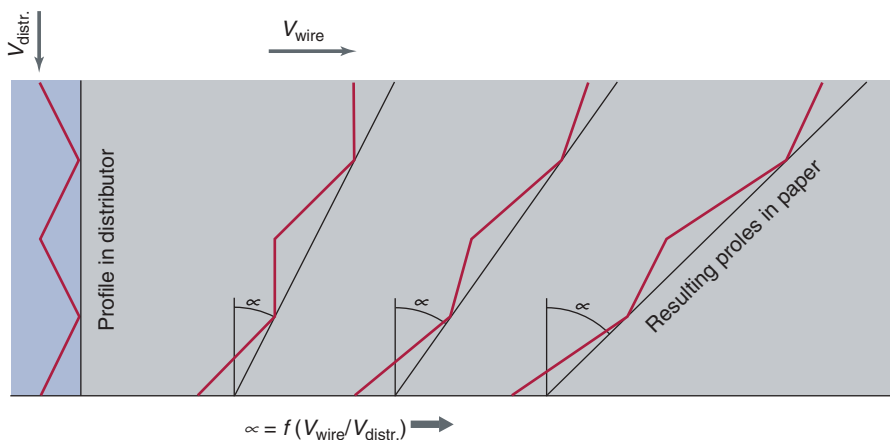


Figure 23.12 Effect of reel speed v_{reel} and the velocity of the disturbances in the distributor v_{distr} on the slope of the resulting profile in the paper web.

23.4.1

Test Samples Gained from a Limited Production Time

n profiles of a reel with a diameter of D_r , from a paper machine with a speed at the reel of v_{reel} cover a test time of

$$t_{\text{reel}} = n \times \pi \times D_r / v_{\text{reel}}$$

where, with the above numbers $t_{\text{reel}} = 3.6$ s. This means that all deviations in the paper web that occur over a longer time span than 3.6 s can only be partly found in these test samples.

23.4.2

Synchronized and Unsynchronized CD Profiles

Both consistency and pressure deviations are defined by their frequency and amplitude. The frequency for the stripe sampling is

$$f_s = v_{\text{reel}} / (\pi \times D_r)$$

given by the machine speed v_{reel} and the reel diameter D_r from which the samples are taken. Theoretical investigations have been made to show the evidence of this kind of statistical evaluation [8].

Identical CD profiles at the reel will be found for deviation frequencies of

$$f_{d1} = k \times v_{\text{reel}} / (\pi \times D_r)$$

with k as an integer number (synchronized CD profiles). The actual amplitudes of the deviations are then represented to full extent in the average CD profile. The residual variations are 0 as shown in Figure 23.13 for a wavelength λ (or $k \times \lambda$) corresponding to the paper web width w (or an integer manifold k). When measuring only every second sample the mean CD profile will show no deviations. Taking every second sample corresponds to a deviation frequency of

$$f_{d2} = 0.5 \times k \times v_{\text{reel}} / (\pi \times D_r)$$

Here all deviations show up as residual variations.

This kind of allocation of the given basis weight deviations to MD, CD, and residual variation values is unique for f_{d1} and f_{d2} . In between f_{d1} and f_{d2} (unsynchronized CD profiles), the amplitudes in the average CD profile are reduced and a large part of the deviations are found in the residual variations. MD variations are measured as 0. For larger ratios ($\lambda/w > 1$) as found with consistency deviations, the result shows increasing MD, decreasing residual and low to negligible CD deviations. High-frequency deviations ($\lambda/w < 1$) as often found as pressure pulsations result in high residual, low CD, and negligible MD variations.

As the frequencies of both pressure and consistency variations as well as machine speed may vary over time the distribution of the deviations on the CD, MD, and random variations will be different over time.

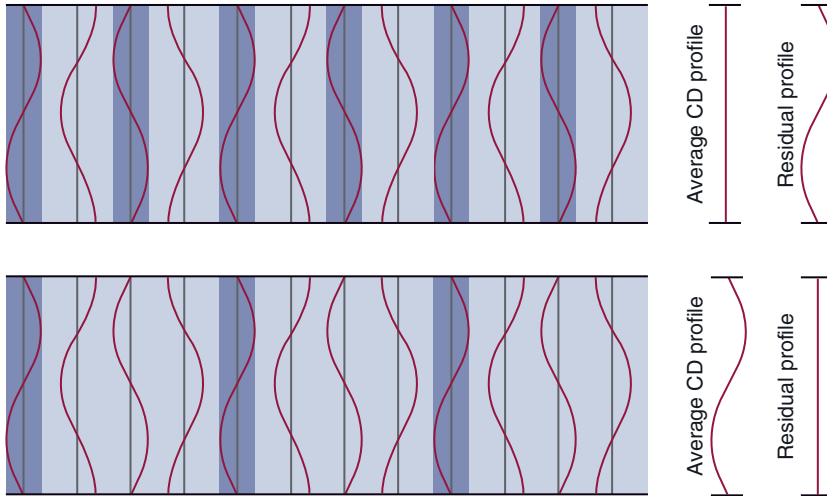


Figure 23.13 Effect of synchronized profile stripes and unsynchronized profile stripes on the average MD and CD profiles and random variation with a deviation wavelength equal to machine width.

Best information about the stability of the approach flow system as regards the influence on basis weight constancy is to measure consistency and pressure directly. The MD basis weight profile can usually be measured online with a basis weight sensor at a defined static position over width.

23.5 Symmetry in z-Direction

Good symmetry of the paper sheet in z-direction results in good behavior in converting and use at for many grades. In the following, the surface characteristics, for example, the fines and filler distribution or smoothness as well as the (non) symmetry in sheet structure such as fiber orientation and frozen stress are discussed.

23.5.1 Surface Characteristics

23.5.1.1 Fines and Filler Distribution

For good printing results on both sides of the sheet several requirements have to be fulfilled, for example, a symmetrical fines and filler distribution. The distribution is mainly determined in the wire section by the ratio of the amount of dewatering to the top and bottom side and how far fines and fillers have been washed out. A distinct nonsymmetry is given in the one-sided dewatering on the Fourdrinier,

whereas with a modern gap former a good control of the two-sidedness is provided. Outdated gap formers show also shortcomings in control.

23.5.1.2 Surface Smoothness

In the wire section, the topography of the wire surface is projected as the negative on the paper web surface. The smoother the wire surface design (finer wire threads and kind of weaving technique) and the lower the dewatering forces the less visible these wire marks will be.

In the press section, the felt surface contacts the web under high pressure. Here again marks on the web can be found which stem from felt structure and surface bat. In case of single-sided dewatering, one web side is pressed against a smooth roll surface, which generates a difference of smoothness between both web sides or equals out differences.

In a multicylinder dryer section, the contact with the drying cylinder surface has a minimal calendering effect even with only single-tier cylinder configuration. The situation on a MG cylinder is totally different as the paper web faces permanent contact with the smooth surface of the drying cylinder until the final target moisture level has been achieved. This results in a significant smoothness increase. Hence, here the contact of the web with the cylinder surface has to be very uniform.

Calendering can be done in hard nips where the calendering effect is similar for both sides. When heating one roll in a two-roll calender stack, the calendering effect is different for the two sides and can be adjusted by controlling the roll surface temperature. In a calender with hot and soft cover rolls the two-sidedness control is even more flexible. With an installation of two of such two-roll calender stacks with alternated arrangement symmetrical results can be expected. It also can at least partly even out smoothness nonsymmetry generated in the preceding sections.

23.5.1.3 Surface Densification

In the press section, the side of the paper web facing the felt gets more densified as the structural pressure in the paper at the felt side is always higher. A tri-nip press (second and third nip single felted) creates a significant two-sidedness as the top side faces three times a felt, whereas the bottom side only once. The top side is significantly more densified than the bottom side, which can be revealed in the Cobb Unger oil test. A coating base paper produced with such a press has an unequal coating color pickup (top vs bottom side).

23.5.2

Curl

23.5.2.1 Definition of Curl

Curl is defined as the tendency of a sheet of paper or board to bend around an axis which can be in MD, in CD, or in any “diagonal” direction (Figure 23.14). Curl usually starts when the originally flat sheet undergoes a change in moisture or temperature conditions. Curl is a matter of dimensional (non)symmetry of the

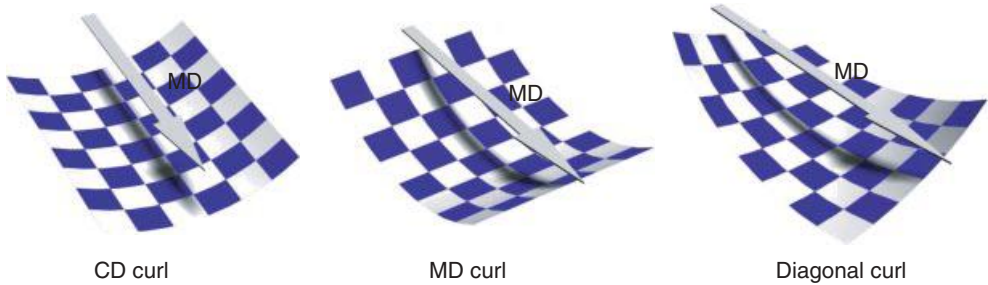


Figure 23.14 Definition of curl.

two sheet sides. Curl is found, for example, in copy paper, newsprint, or packaging paper and board and can be very harmful depending on the use. Curl can be observed in a sheet directly taken from the paper machine or later in use.

23.5.2.2 Mechanism of Curl

Shrinkage occurs when a paper is dried, based on change of fiber dimensions. The main shrinkage of fibers is in thickness, much less in length. For a random oriented sheet such as a laboratory hand sheet shrinkage is the same in all directions. A paper machine sheet shows a certain amount of fiber orientation (usually) in MD, which defines the shrinkage in MD (less) and CD (more). When the dried sheet undergoes changes in temperature or moisture it will expand, amount and main direction of expansion depending on degree and direction of fiber orientation. When top and bottom of the sheet differ in this respect the expansion differs between top and bottom and curl can occur.

During drying the paper shrinks. At symmetrical drying in z-direction both sides have the same “shrinkage history.” Nonsymmetrical drying results in frozen tension of one side. When ambient conditions (temperature, humidity) change, the relaxation of top and bottom side is different and curl occurs as well.

23.5.2.3 Causes and Cure of Curl

Curl is provoked by the difference in hygroexpansivity across the sheet thickness. This can be caused by the difference in sheet structure across thickness as regards fiber orientation (amount and main direction) or fines and fillers distribution. A second factor is stress two-sidedness which dates back mainly to nonsymmetrical drying.

In the headbox, a certain preorientation of the fibers takes place because of viscosity forces, for example, by friction or acceleration. For a symmetrical preorientation, symmetrical flow conditions in the headbox nozzle are required. The velocity difference between jet and wire $v_{\text{jet}} - v_{\text{wire}}$ results in a certain fiber orientation. In a modern twin wire former both wires have almost exactly the

same speed, which results at any jet/wire difference at the same degree of fiber orientation on both paper sides.

Stress two-sidedness is a frozen tension originating from the dryer section. With nonsymmetrical drying one side of the web is always a bit dryer than the other one, which means it would like to shrink more. As shrinkage at this side is restrained, frozen tension in this side of the sheet will be generated.

An air dry paper web leaving a single-tier dryer section has always a z-direction moisture gradient and faces moisture losses along the unsupported web run further down the machine. On the nonsupported run (free draw) both paper sides lose moisture; however, the moisture loss is not uniform. The side with higher moisture will face more water evaporation. This results later on in curl because of different shrinkage top/bottom side. The web always curls to the side with higher moisture losses [9–11].

23.5.3

Cockling

Cockling can be regarded as nonflatness of a paper sheet such as curl but in a small scale. It is mainly found in lightweight papers. The randomly distributed out-of-plane distortions can be differentiated as “bumps” (irregular cockles) or as troughs (waviness). Bumps are 5–15 mm in diameter, up to 1 mm out of plain, (mainly) oval in MD, and randomly distributed. Troughs are 15–30 mm wide, randomly distributed with orientation in or close to MD and are often found as a chain of cockles. In Figure 23.15, a typical example of cockling is shown as it can be found on a reel. In Figure 23.16, the result of an evaluation with the Cockling tester [8] and image analysis software is presented. At left the overall appearance is shown. Low pass filtering separates bumps from troughs. The two structures are evaluated separately showing their magnitude and share on cockling.

The main reason for cockling is a local nonuniformity in hygroexpansivity in the sheet in small scale distribution. It can be provoked by local differences in the sheet



Figure 23.15 Typical appearance of cockling on a reel.

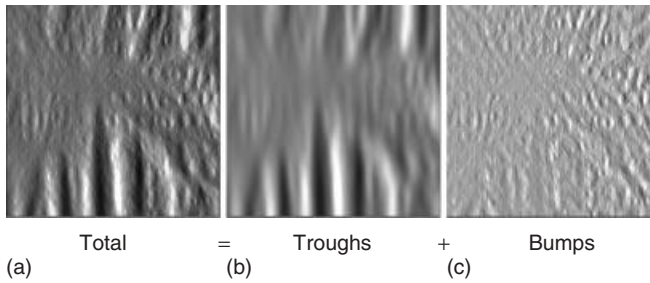


Figure 23.16 Result of an evaluation with the Cockling tester separating the overall cockling appearance (a) into troughs (b) and bumps (c).

structure, fines, and fillers content or by local differences in drying conditions. Cockling is more often found at high CD shrinkage, for example, at the web edges. High bending stiffness (high caliper, high Young's module) counteracts cockling tendencies. Therefore, cockling is less often found at higher basis weights [9].

When a sheet of nonuniform structure is dried under uniform drying conditions, the local dry content varies and local differences in frozen stress will be built up. In a uniform sheet dried under local nonuniform conditions (air permeability or tension of the dryer fabrics, dirt on the cylinder surfaces) the local frozen stress will differ within small distances, too. A change in ambient conditions (temperature, moisture) releases the tension and cockling occurs. So, uniform build up of the sheet in small scale in web forming, as well as uniform pressing and uniform drying are essential to avoid cockling. Cooling down the web matching the ambient conditions before reeling also reduces the cockling noticeably.

23.6 Formation

Formation defines the kind of fiber distribution in the sheet. Stochastic mass deviations (wavelength below about 100 mm) result in a visual contrast when regarding the sheet against a light source ("look through"). This visual impression is influenced not only by local mass distribution but also by density, light scattering, web thickness, color, and opacity. The impression of formation quality can be cloudy, grainy, streaky, or milk glass like, the latter is usually desired (Figure 23.17). Formation is not only an esthetical impression but also influences other main requirements such as sufficient strength at minimum basis weight, good printability, or low porosity.

Formation is first of all a nonhomogeneity in mass distribution, which can be measured by formation testers based on β -radiography or by formation testers, which include the light scattering influence. Only the optical measurements come close to the visual impression.

The formation quality is influenced by

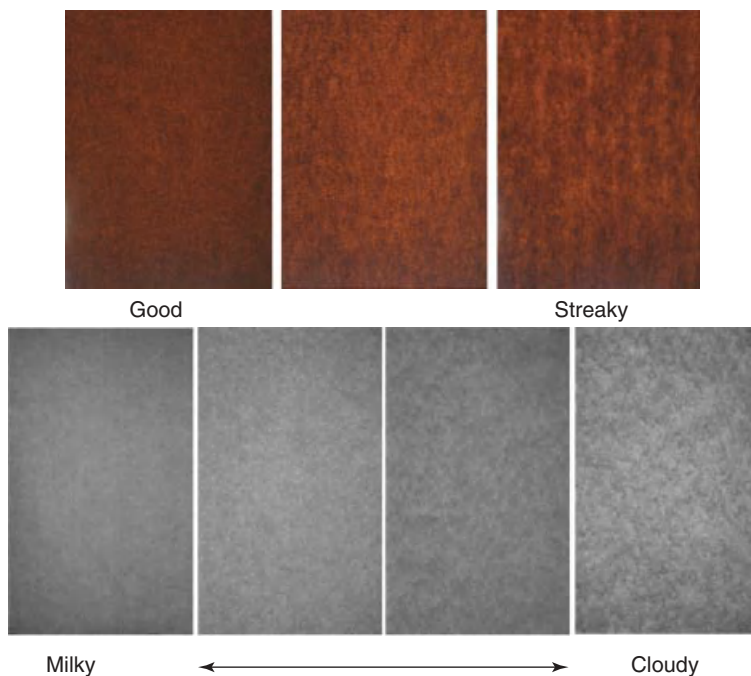


Figure 23.17 Examples of cloudy, grainy, and streaky and milk glass formation.

- Furnish:
 - **Length or thickness of the fibers:** the shorter the fibers the better formation
 - **Refining of the fibers:** cutting improves formation, fibrillating results in more cloudy formation
 - **Surface charge of the fibers:** for example, retention aids reduce formation quality
 - **Fillers:** higher amount of fillers at low retention improves formation.
- Operating conditions:
 - **Consistency:** higher consistency reduces formation quality
 - **Kind and degree of turbulence in the headbox:** too high and small scale turbulence may result in grainy formation
 - **Adequate velocity difference of jet and wire (not ratio as sometimes said in earlier times):** around zero difference formation is poorest, toward large differences formation quality decreases as well
 - **Jet impingement angle:** angle to be carefully adjusted
 - **Dewatering elements:** foil angle to be adjusted to machine speed and the actual consistency of the web, table rolls not to be used above 600 m min^{-1}
 - **Wire shaking:** frequency and stroke to be adjusted
 - **Dandy roll:** should be positioned at adequate distance ahead of the water line.
- Chemistry: retention level, retention aid system, and electric charge of the white water (or stock) to be adjusted.

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24 Paper and Board Converting and Printing

24.1 Converting Processes for Paper and Board

Renke Wilken

24.1.1 Overview

Paper converting technology covers all the necessary process steps to manufacture finished products from paper or board. Often nonpaper materials are combined with paper or board, in particular inks, lacquers, varnishes, and adhesives, as well as films and foils made from plastic materials or metals, textile materials, and others. Paper converting technology needs to deal with these materials as well and consider their special properties for proper design of the processes. Converting processes have to consider many more aspects, for example, general legal aspects or aspects resulting from the European Packaging Directive. For some industries, for example, food or pharmaceutical industry, there may exist several further special regulations. The special demand for recycling of used packages should be considered while packages are designed.

The diversity of paper converting products is tremendous. The main product groups are corrugated board and packages made from corrugated board, folding boxes, labels, and products for household and hygiene. In addition, production of books and brochures and learning and organization aids should be mentioned, as well as cashier rolls or greeting cards. An overview of the main groups of production in terms of euro values for Germany is shown in Figure 24.1.

Paper converting products include the very simple brown box made from corrugated board as well as the high-tech multi-laminated label for challenging technical purposes. So paper converting industry is not only based on paper and board but also on a broad variety of other raw materials. Particularly, plastic films are often used in combination with paper and board in order to fulfill special customer demands.

In spite of the variety of branches and products, the path from raw material to finished product is quite similar. Every converting process leading from raw material to finished product can be divided into a chain of subprocesses, each

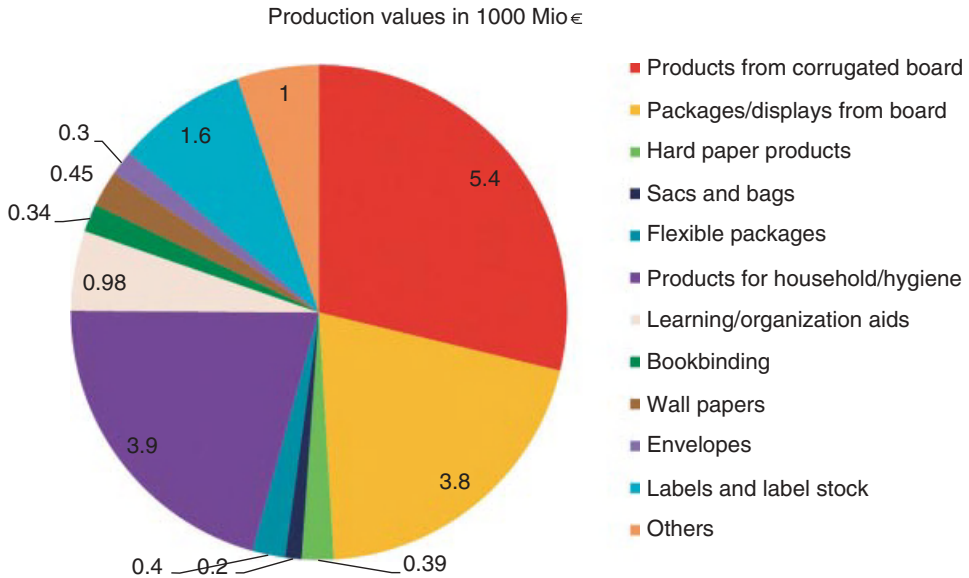


Figure 24.1 Main groups of paper converting products and production values (Germany, 2010).

providing a special kind of transformation or change in state. These subprocesses can be divided into six groups as shown in Table 24.1 (printing is dealt with in a separate chapter).

Usually, the final outcome of all subprocesses is the result of the action of a machine or of a part of a machine (tool, effector) and the reaction of the material to

Table 24.1 Subprocesses of paper converting.

Group	Name of subprocess	Aim of subprocess
1	Forming processes	Processes that change the shape or form of the material to be processed
2	Separating processes	Processes that locally destroy the structural cohesion of the material to be processed
3	Joining processes	Processes causing local structural cohesion within the material to be processed
4	Processes for combining materials	Processes designed to change the usage properties of the material to be processed
5	Transport processes	Processes taking place in, or using, machinery and which cause changes in location, amount, or position of the material to be processed
6	Printing processes	Processes transferring information onto the material to be processed

be processed by it. For an ideal result, it would need an ideal subprocess with ideally designed and constructed machine or tools and ideal properties of the material to be processed. As every subprocess demands a special set of ideal properties, it is not possible to design a material to be converted that ideally fits all subprocesses of a converting process at the same time. Thus the material properties have to be adjusted as best as possible to fit at least the most important subprocesses.

So the development of machines and tools with higher tolerances against nonideal materials is an important task and a future challenge for machine manufacturers. At the same time, the paper manufacturer should improve their products according to the demand of the subprocesses. The precondition is to understand the principle changes in state in each of the subprocesses that are described in the following chapters.

24.1.2

Forming

24.1.2.1 Introduction

The aim of the subprocess, forming, is to achieve a change in state without changing the mass or the dimensions of the material to be processed. Often it is a change from a virtually two-dimensional state to a three-dimensional state.

In accordance with DIN 8580, forming processes can be divided as follows:

- **Compressive forming:** forming of materials by single- or multiaxis compressive stresses.
- **Tensile/compressive forming:** forming of materials by combined tensile and compressive stresses.
- **Tensile forming:** forming of materials by single- or multiaxis tensile stresses.
- **Forming by bending:** forming of materials by bending stresses.
- **Shear forming:** forming of materials by single- or multiaxis shear stresses.

Only a few of the different forming processes are used in paper converting technology – mainly compressive forming (e.g., embossing), tensile/compressive forming (e.g., drawing), and particularly forming by bending (e.g., corrugating). A general map of forming processes is shown in Figure 24.2.

That paper can be formed is because of its elastic and plastic properties or, in general, because of its rheological properties. These properties are best understood by stress–strain curves, which typically look similar to the curve shown in Figure 24.3.

The slope of the first part of the curve is approximately linear and defines Young's modulus. If strain exceeds about 0.1% (yield point), elastic deformation changes to plastic deformation and the paper is elongated irreversibly. If stress results in strain of approximately 4%, the paper will break (tensile strength). The mechanical paper properties strongly depend on previous stress history (Figure 24.4) as well as on temperature and humidity conditions.

As elastic behavior is a result of simple deformation of the fiber network, plastic deformation occurs if single fiber–fiber bonds rupture under the action of tensile

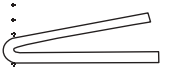

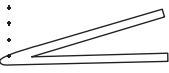
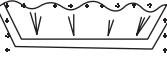



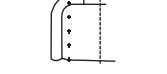





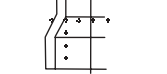
Process	Final form of processed good	Process	Final form of processed good
Folding		Embossing	
Folding with tool		Hollow embossing	
Pleating		Drawing	
Corrugating		Edge crimping	
Edge bending		Edge coiling	
Rounding		Beading	
Winding		Reducing	

Figure 24.2 Overview on forming processes according to [1].

stress. As a result, the smooth stress–strain curve is in reality a serrated curve with slight stress relaxation after every fiber–fiber bond rupture and deformation of the residual fiber network with increasing stress. Because of a weakening of the fiber–fiber bonds with increase in the moisture content of paper, the changeover from elastic to plastic deformation decreases and elongation at break increases; tensile strength also decreases with increasing moisture content. Much more difficult are the investigations regarding the behavior of paper during compression tests as regards important mechanical properties in the z -direction.

The stress–strain properties of paper are anisotropic and different in the three main directions. Mainly the properties in the xy -plane are focused on. Usually the elongation at break is much higher in CD than in MD, while it is the reverse for tensile strength. Forming processes can be performed much easier, when the paper is preconditioned by increased moisture content or temperature or by oil application.

24.1.2.2 Folding

Folding is a process of forming by bending. A material can be folded after a preparatory step to define the folding line (folding A). To prepare folding lines, it is usual to crease the material, which in turn locally decreases bending stiffness S . For single-layer flat material, S is given by Young's modulus E (material property)

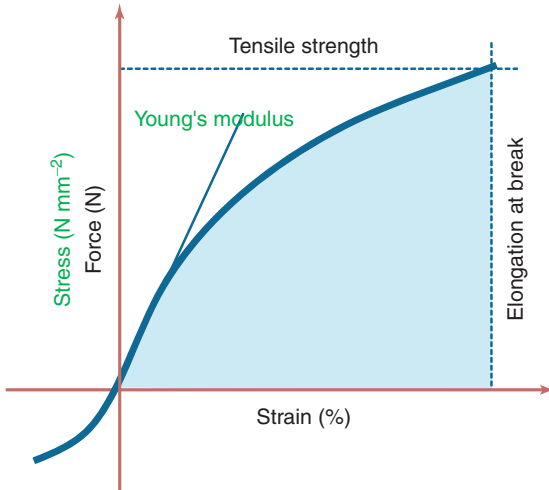


Figure 24.3 Typical stress–strain curve for paper obtained from a tensile strength test.

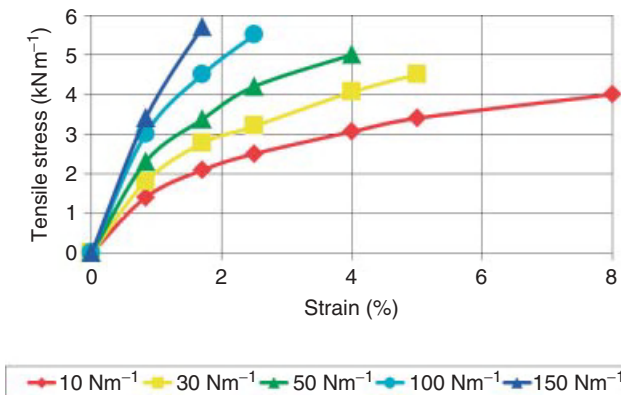


Figure 24.4 Tensile strength and elongation at break depend on web tension in the paper machine during drying.

and momentum of inertia I (with b representing the width and D the thickness of the sample) as

$$S = E \times I = E \times \frac{b \times D^3}{12}$$

As *bending stiffness* is defined as the product of the Young's modulus and the momentum of inertia, reduction can be achieved by reducing the thickness or by reducing the Young's modulus (Figure 24.5). The material can now be folded easily along the creasing lines by bending forces.

Folding (B) is a process without a preparatory step. To maintain a well-defined folding line, the material is first folded by bending forces. Then the folding line is

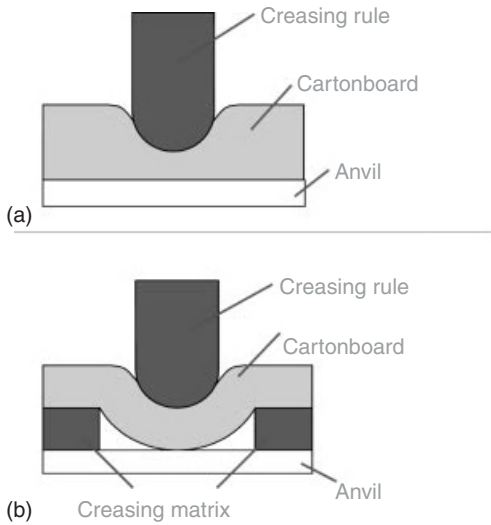


Figure 24.5 Creasing to prepare folding lines. (a) Creasing by compression – creasing rule to reduce thickness locally. (b) Creasing by reducing Young’s modulus – by pressing the material into the creasing matrix with the help of the creasing rule the bonding strength between layers is weakened.

pressed strongly. As a result, the fibrous structure of the material is weakened or partly destroyed within the folding line. So a sharp-edged folding line is formed.

24.1.2.3 Embossing

Embossing is an example of compressive forming and is often applied. The low-yield point of paper and board under compression is utilized. To change the shape of the material a certain forming resistance of the material has to be overcome. The necessary force F depends on the load A and the specific forming resistance σ_0 of the material (c as a correction factor):

$$F = c \cdot \sigma_0 \cdot A$$

The elastic part of the material deformation will be restituted after the load is relieved. Usually, paper and board can be compressed by approximately 50%. As a rule of thumb 20% are elastic deformation and will be restituted. Some forming processes are shown in Figure 24.6.

24.1.2.4 Winding

Winding of paper is a very common process to manufacture cores, tubes, and similar products. Three different basic forms of winding are found (Figure 24.7). Spiral winding is most often used to produce cores for textiles and paper as well as packaging materials such as drums and cans.

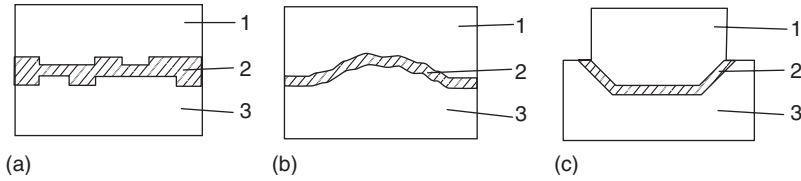


Figure 24.6 Forming by embossing. (1) Female part of embossing tool, (2) material, and (3) male part of embossing tool according to [1].

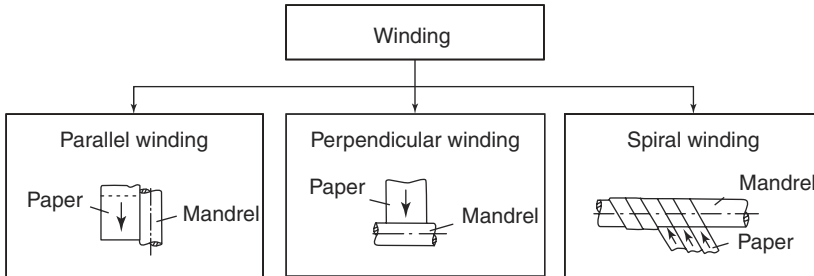


Figure 24.7 Basic winding processes according to [1].

24.1.2.5 Corrugating

Corrugation of the paper material is one of the basic processes in manufacturing corrugated board. Hereby, the plane paper has to be transformed into a sine-wave shape. The forming process results in a strong strain load on the paper. Depending on the geometry of the wave shape, the elongation can be up to 15%, much more than the typical elongation at rupture. Therefore, the process asks for special preconditioning of the paper by heating and moistening and the use of a tool that is heated up to approximately 180 °C. Under these conditions, the paper can withstand the high strain load.

Forming occurs between two rotating steam-heated rolls with mating parallel corrugations. These rolls form a press nip where the web is forced into a fluted shape. Owing to its associated frictional conditions, this arrangement needs a sophisticated feed geometry (Figure 24.8).

With F_1 as the web tension of the fed web, α_{tot} as the sum of all wrap angles, and μ as the friction coefficient, the web tension F_2 at the end of the corrugating

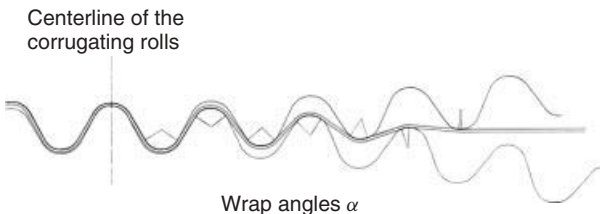


Figure 24.8 The press nip of mating corrugated rolls, centerline, and wrap angles α being marked.

process is given by

$$F_2 = F_1 \times e^{\mu \times \alpha_{\text{tot}}}$$

The equation shows that the friction between the paper and corrugated rolls should be as low as possible.

24.1.1.3

Separating

24.1.1.3.1 Introduction

Separating processes serve to destroy the structural cohesion of a material at predetermined locations. The term *structural cohesion* relates to both the cohesion of the elementary components of a material and the cohesion of the elements of a composite material to be processed.

According to DIN 8580, separating processes can be subdivided into the following categories:

- **Splitting:** mechanical separation of materials without forming the material into a certain shape (e.g., cutting off, tearing).
- **Machining:** mechanical separation of material particles (chips) by means of tools with geometrically determined cutting edges (e.g., milling, sawing, and drilling) or tools with geometrically undetermined cutting edges (e.g., grinding).
- **Ablating:** separation of materials by nonmechanical means (e.g., laser cutting).
- **Disassembling:** nondestructive separation of previously joined work-pieces (e.g., dismantling).
- **Cleaning:** removal of undesirable material from the surface of workpieces.
- **Evacuating:** removal of gas from hollow workpieces.

With the exception of evacuation, all the above separating processes are employed in paper converting. Of particular importance is separating by splitting, where special attention is paid to cutting in the following. Other separation processes are only mentioned in short.

24.1.1.3.2 Separating by Splitting

As shown in Figure 24.9, separating by splitting can be subdivided into cutting and tearing, while cutting itself can be subdivided into “pressure cutting” and “shear cutting.” In both cases, the variants are the shape of the cutting tools (knives) and their movement relative to the material to be processed (Figure 24.10).

Main requirements as regards the result of all cutting processes are as follows:

- **Dimensional accuracy:** the actual dimensions should accord as precisely as possible with nominal dimensions.
- **Quality of cutting edges:** they should be straight, clean, and free from dust.

Both parameters are influenced by the properties and the condition of the cutting tools (geometry, material, and surface condition), and also by the choice of the basic cutting principle and by the properties of the material to be cut, such as dimension, structure, or other characteristic values.

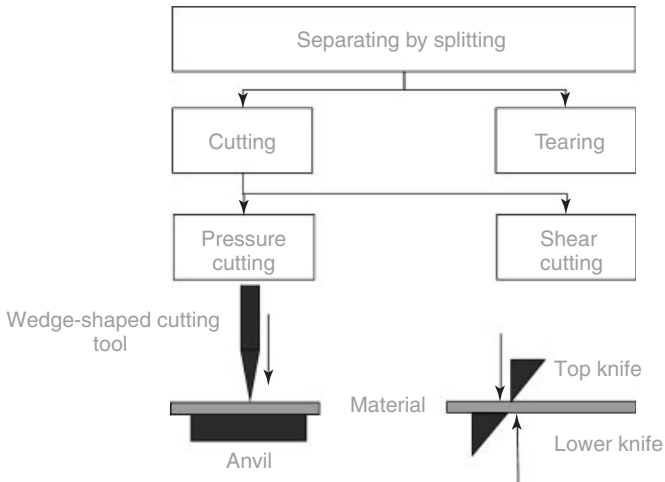


Figure 24.9 Schematics of cutting processes.

24.1.3.2.1 Pressure Cutting Pressure cutting involves the separation of the material to be cut using a mostly wedge-shaped straight or circular knife, working against a plane anvil perpendicular to it with or without a horizontal component of movement.

Paper or cartonboard is compressed by the knife (Figure 24.11) with the following effects:

- 1) elongation of top layers of the material
- 2) displacement of material by the flanks of the wedge-shaped knife
- 3) strong compression under the edge of the knife.

The result of the deformation is a strong elongation of the upper layers of the material. Geometrically, elongation at break occurs much before the material beneath the knife edge is compressed to a pore-free state. The top layer is further drawn into the cutting zone and breaks when elongation reaches critical values. This occurs beneath the knife edge because of stress concentration. The process is repeated layer by layer, until the last layers are reached, where the deformation is too low for critical values of elongation. Now the compression effect starts to be dominant and weakens the material until the pore-free status is reached and finally the bottom layer bursts, completing the cutting process.

To press the knife into the material, friction forces must be overcome as well as forces to displace material. It can be estimated that approximately half of the load is used for friction and displacement and not for cutting. It can be concluded that

- the quality of cuts is increased if the knife angle is low (on the other hand, wear of knife increases with decreasing angle);
- the necessary load is lowered, if
 - the friction between the knife and the material is low;
 - the knife angle is low (which reduces the displacement of material).

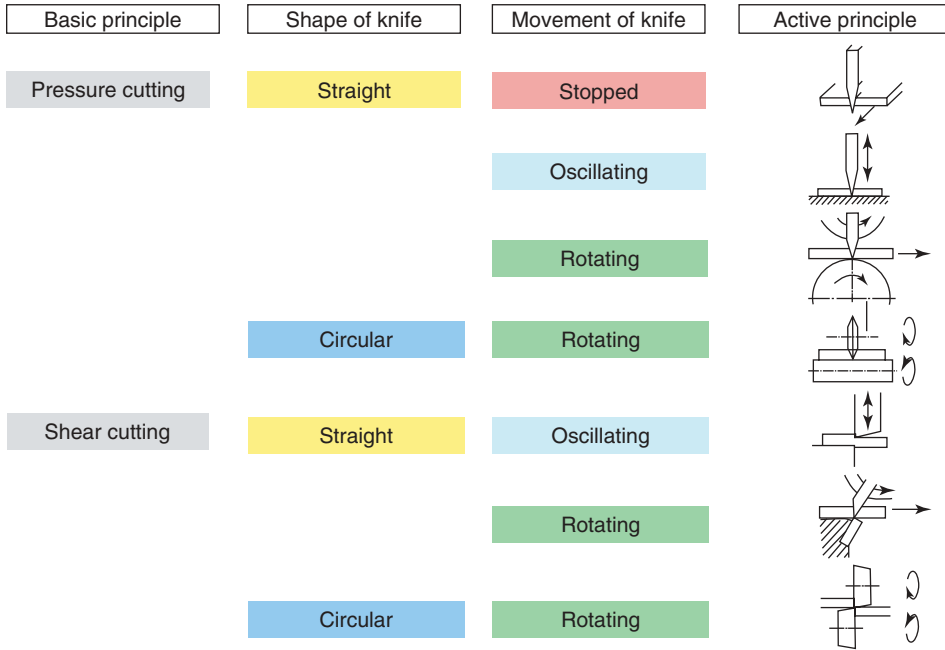


Figure 24.10 General map of cutting processes according to [1].

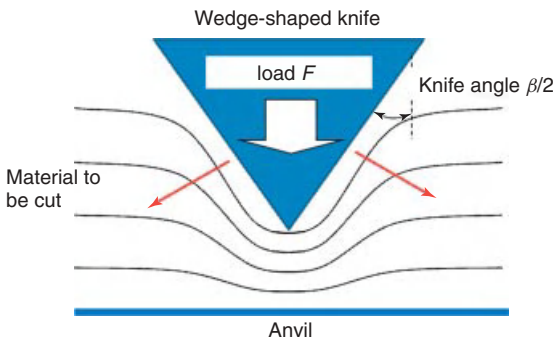


Figure 24.11 Principles of pressure cutting.

As mentioned, the load F depends on the properties of the material to be cut, expressed by the specific cutting resistance τ_0 . So the load F is

$$F = c \times \tau_0 \times l$$

where l is the active length of the knife, whereas c is a dimensionless number relating to the cutting device.

Typical specific cutting resistance values for sharp-edged cutting tools are

- 30 N mm^{-1} for folding box board

- 50 N mm^{-1} for gray board
- 70 N mm^{-1} for fiber board.

Machines for exact perpendicular movement of straight knives are flat-bed die-cutting systems as typically used for the production of folding boxes. Corresponding machines with circular knives are rotary die-cutting systems as typically used in the production of labels and boxes made from corrugated board. Another important family of machines are the cutters (sometimes also called guillotine-cutter or paper-cutter) mainly used in the graphic arts industry.

Depending on the details of the knife movement, different types of machines can be identified, as shown in Figure 24.12.

The reason for adding a horizontal or swinging movement component to the perpendicular movement is to reduce the load necessary for cutting because of a decrease of the apparent knife angle [2].

Assume a knife with a knife angle β . The blade edge of the knife is tilted against the material to be cut with angle ζ as shown in Figure 24.13. The knife moves in the direction indicated by the arrow. The movement direction is tilted against the material to be cut at angle θ . For an observer looking in the direction of movement, the knife angle seems to be $\alpha < \beta$. α is called the *apparent knife angle*. Between the angles exists a geometrical relationship:

$$\tan \alpha = \tan \beta \times \sin (\theta - \xi)$$

If $\zeta = \theta = 0$, the blade edge of the knife moves exactly parallel to the surface of the material to be cut. It can be seen from the equation that $\tan \alpha = 0$. This means that the apparent angle of the knife is 0 or that the knife appears to be infinitely sharp. This is called a *drawing cut*.

For cutters of type 1 the whole blade edge of the knife is in action at the same time. This is not true for cutters of type 2. Owing to the swinging movement the cutting process starts at the edge of the material to be cut. Owing to the knife angle

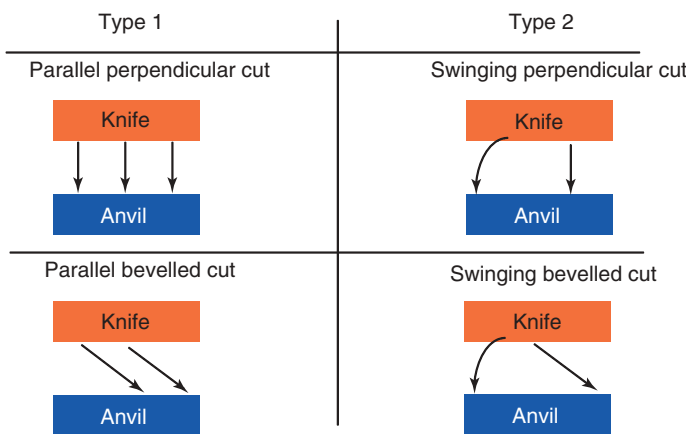


Figure 24.12 Movement of knife in different types of cutters (guillotine cutters).

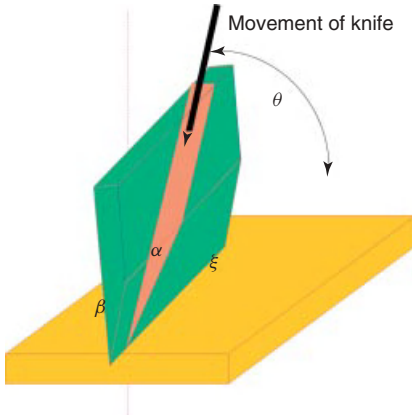


Figure 24.13 Explanation of angles (see text).

the material tends to be displaced before the knife reaches the other end of the material. The result is a torque, which may deform the material and reduce cut quality (Figure 24.14).

Quality losses are avoided by carefully pressing the material and fixing it by clamps.

There are some further reasons for cut quality losses. Typical characteristics of the cut materials may help identify the reasons and provide suggestions to avoid them (Figure 24.15).

24.1.3.2.2 Shear Cutting According to Figure 24.9, shear cutting involves the separation of the material to be processed through the action of two straight or circular tools working against each other. The geometry of cutting tools for pressure cutting and shear cutting are different, but the principles of the cutting process

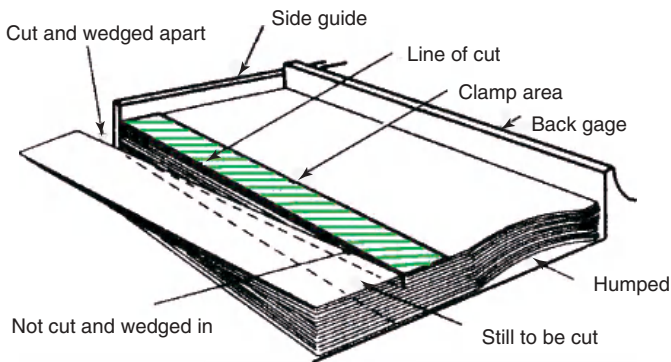


Figure 24.14 Deformation of material to be cut in cutters of type 2. (Courtesy of P. Veenstra.)

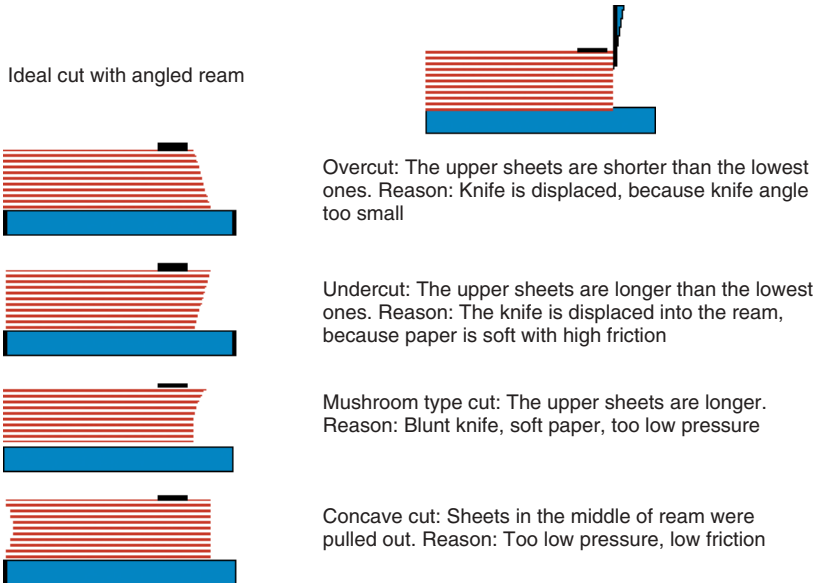


Figure 24.15 Representation of quality losses during the cutting of a paper ream with reasons.

are the same. This disregards additional torques resulting from the two knives in shear cutting instead of the one knife in pressure cutting.

In pressure cutting, the necessary knife load is proportional to the length of the knife in action. The corresponding factor in shear cutting is cut cross section A :

$$F = c \times \tau_0 \times A$$

Again, τ_0 is the specific cutting resistance of the material under specified cut conditions and c refers to the cutting device. The term *cut cross section* is explained in Figure 24.16.

The situation in Figure 24.16c shows the maximum extension of $A = A_{\max}$:

$$A_{\max} = \frac{D^2}{2 \times \tan \delta}$$

$\delta = 0$ results in the maximum value for F . With increasing δ , F decreases rapidly until $\delta \approx 6^\circ$. Higher values of δ do not change F significantly, but the risk of the material being displaced out of the cutting zone is increased.

An important family of machines using the shear cut principle is that of circular knives as commonly used in slitters. A slitter consists of two circular knives as shown in Figure 24.17.

The twist angle α is very small; for paper it is approximately 0.5° , for plastic or metallic films the angle is smaller, and for textiles or nonwovens slightly higher.

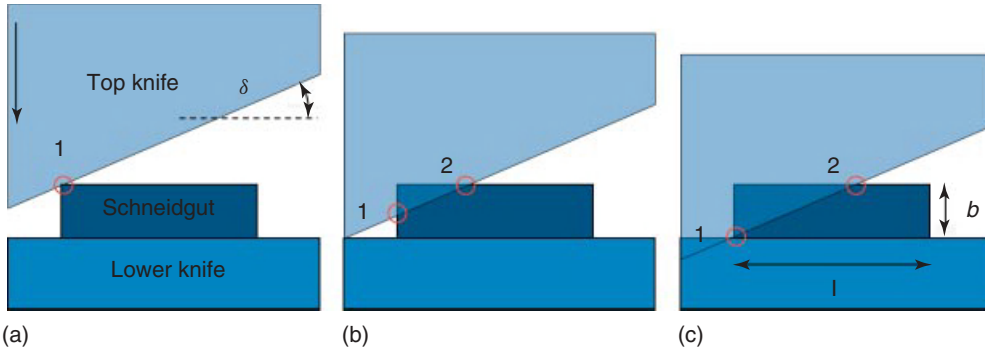


Figure 24.16 Shear cutting with a top knife having a tilted blade edge (angle δ). (a) The point where the knife touches the edge of the material is designated (1) and the cutting process begins. (b) The situation after the cutting process begins. The top knife covers a triangular shaped

area of the material. (c) Point (1) has reached the lower knife. The area of the triangle is at the maximum and stays constant until (2) has reached the right edge of the material. The triangular area covered by the top knife is called *cut cross section A*.

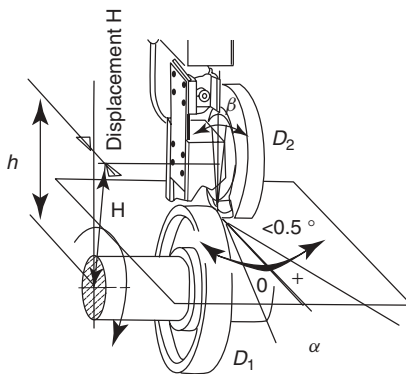


Figure 24.17 Principle of a slitting module consisting of two circular knives. D_1 , diameter of lower knife; D_2 , diameter of top knife; h , distance of knife axis ($h < D_1 + D_2$); and α , twist angle between top knife and lower knife.

The twist angle results in a one-point contact between the top knife and the lower knife, called the *cutting point*. The overlap of both knives should be approximately 1 mm.

Cutting results depend on the horizontal displacement of the axis of the two knives. For a displacement $H = 0$ (both axis are exactly matching vertically), the cutting point is lower than the zenith of the bottom knife. To avoid quality losses, the axis of knives must be displaced horizontally in order to shift the cutting point to the zenith of the bottom knife. The disadvantage of displacement is that the web already cut has contact with the twisted top knife, which results in friction and the risk of quality losses.

Slitters with two knives are not suitable for cutting thick materials such as solid fiber boards or corrugated board. Often slitters with only one very thin knife, which runs much faster than the web, are used for this purpose. The knife must be adjusted to minimize forces in the z -direction at the point of first contact between the knife and the material. Friction should be kept as low as possible, for example, through oil lubrication of the knife. Sometimes, additional supporting tools underneath the material are used to avoid bowing of the material under load.

While slitters are used to continuously cut the material in MD, cross-cutters are used for cuts in CD to produce sheets from a reel. Cross-cutters form an important machine family that uses the principles of shear cutting as well.

In the simplest case, it consists of a straight lower knife and a rotating top knife (Figure 24.18). The path of the blade edge is circular. The blade edge is slightly tilted against the axis of the knife-cylinder. As a result, the top knife and the bottom knife touch each other at only one point (cutting point). While the top knife rotates, the cutting point moves in a cross direction in the material.

During the movement of the cutting point in CD, the material is clamped in the cutting zone and piled up because of the rolls transporting the material into the cutting zone. Another disadvantage is often the beveled cut due to the path of the top knife.

A synchro-cross-cutter avoids these disadvantages. It has a rotating top knife and a rotating bottom knife. Both are mounted on the wall of cylinders and slightly tilted as described earlier. Again the result is a single point of contact (cutting point) running across the material during the cutting process.

The speed v of the cutting point can be very high, depending on web speed v_B and tilt angle δ of the knives:

$$v = v_B \times \cot \delta$$

For a tilt angle of $\delta = 1^\circ$ and a web speed of $v_B = 400 \text{ m min}^{-1}$, the speed of the cutting point is $v = 22.900 \text{ m min}^{-1} = 382 \text{ m s}^{-1}$.

In spite of the high velocity of the cutting point, the axis of the two knife-cylinders must be pivoted slightly in relation to the web in order to maintain exact rectangular cross cuts.

Figure 24.19 shows a cross section of a synchro-cross-cutter with a possible configuration of knives. A lot of factors influence the cut quality, for example,

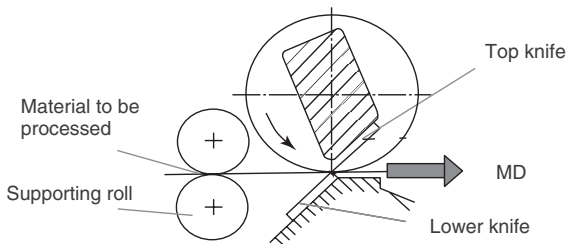


Figure 24.18 Principle of a cross-cutter with stationary lower knife and rotating top knife.

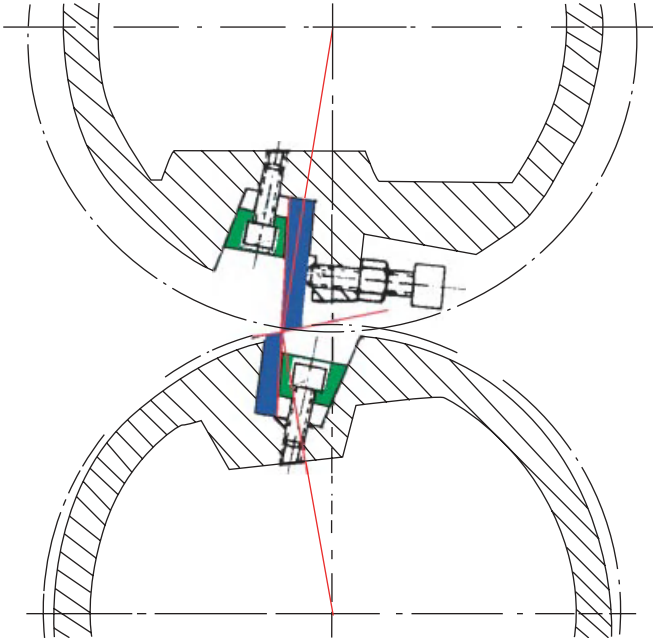


Figure 24.19 Schematic cross section of a synchro-cross-cutter. (Courtesy P. Veenstra.)

- diameter of the circular knife path
- distance of knife-cylinder axis (overlapping)
- position of top knife and lower knife
- geometry of knives.

Wrong adjustment of tools, worn tools, tools that are too weak, and tools without sufficient bending stiffness are often found to be the reason for poor cutting, leading to dusty and unclean material edges. A precondition to high-quality cuts is the careful supervising and adjustment of cutting tools as well as elements of the periphery of cutting machines.

Dimension accuracy of the cut sheets does not depend only on the cutting process itself but also on the hygroexpansivity of the materials. Particularly, in multilayer cutting processes all materials to be cut at the same time should be conditioned to the same equilibrium moisture content.

24.1.3.3 Ablating

Processes to separate by ablating are cutting with water jet and cutting with laser beam.

Water jet technology has not penetrated the paper converting industry in spite of providing the best cut quality even with thick materials such as corrugated board. The reasons are probably the cost of operation, caused beside others, by wear of the water nozzle. Nevertheless, water jet cutting systems still exist. Typical technical parameters of modern systems are

- water pressure up to 6200 bar
- pump power up to 100 kW
- water nozzle made from diamond or ruby with diameter less than 0.3 mm
- water consumption per nozzle about 500 ml min^{-1}
- water beam velocity more than 2500 m s^{-1} .

Laser cutting is a well-established technology, particularly in the production of pressure-sensitive labels as part of completely digital production lines including digital printing. For laser cutting systems, mainly CO_2 lasers are in use, radiating preferably with a wavelength of $\lambda = 10.6 \mu\text{m}$. Output power can be more than 1 kW. Depending on the properties of the material to be cut, a cut-speed of up to 500 m min^{-1} can be achieved if the cut is linear in MD. For cutting complex forms a beam guidance system consisting of two pivoting mirrors is used. Mass inertia of mirrors limits the pivoting speed and thus the cut-speed. An automatic control has to maintain constant energy density at any point of the cutting line. The laser beam is focused exactly into the plane of the material to be cut. The more precise the focusing of the beam is the larger the diameter of the mirrors. But with larger mirror diameter mass inertia increases, which results in lower cut-speed.

Owing to the high energy density during ablation evaporation occurs at the cut position, which may generate hazardous gases. So laser cutting units require closed working rooms and excellent exhaust gas treatment.

24.1.4

Joining

24.1.4.1 Introduction

The aim of joining processes is to cause structural cohesion in the material to be processed at well-defined areas. Joining processes can be subdivided into the principles shown in Figure 24.20.

The most important joining process within the paper converting industry is the use of the adhesive bond, which can be subdivided into

- gluing
- sealing

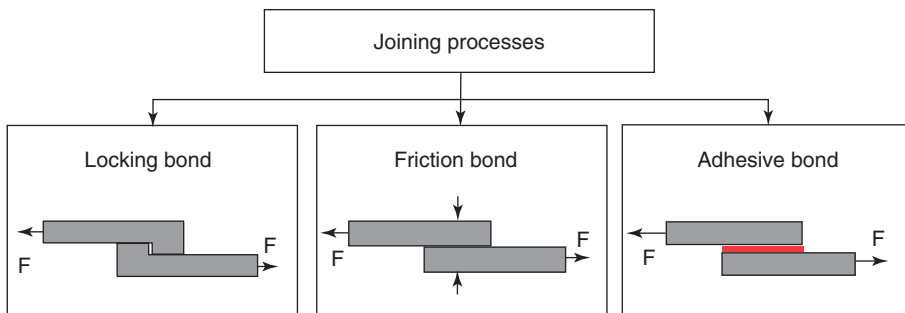


Figure 24.20 Joining processes.

with gluing being the most relevant one.

Examples of joining processes using locking bond and friction bond are sewing, riveting, and engrailing.

24.1.4.2 Gluing

Gluing is a joining process characterized by the use of an adhesive forming a layer between two adherents. An adhesive is a nonmetallic substance that joins adherents by adhesion and cohesion.

Cohesion takes place inside the adhesive layer. Cohesion increases with increasing molecular mass and better distribution of molecular masses.

Of the several theoretical approaches based on electrostatic attraction, chemical bonding, diffusion of molecules, and micropositive locking, adsorption of molecules on the adherent's surfaces seems to be the most successful approach. The basic requirements of an adhesive are as follows:

- 1) An adhesive must be applied to the adherents as a liquid.
- 2) An adhesive must be able to wet the adherent's surface or the adherents must be wettable. This means that its surface energy must be lower than the adherent's surface energy.
- 3) A liquid adhesive and the adhesive layer must be transformed to a solidified state, after application and after the development of adhesion between the adhesive layer and adherends, respectively, in order to develop cohesion. Transformation can take place, for example, by drying, by cooling down, or by chemical reaction.

Surface energy is a key parameter in adhesive technology with respect to adhesion. For liquids, it is measured easily by different types of tensiometers.

Technical liquids have surface energies between 23.5 mN m^{-1} (methyl-ethyl-ketone, 22°C) and 72.8 mN m^{-1} (water, 20°C). The surface energy of liquid adhesives ranges around 35 mN m^{-1} .

In contrast to liquids, the measurement of the surface energy of solids is much more difficult. One approach is to observe the behavior of a droplet of a liquid with known surface energy that is in contact with the surface of the solid under consideration. Surface energy tries to minimize the respective surface. As a result, equilibrium is established between surface energy σ_s of the solid, surface energy σ_l of the liquid, and interfacial energy γ in the contact zone as indicated in the Young's equation:

$$\sigma_s = \gamma + \sigma_l \times \cos \delta$$

δ is the contact angle. Figure 24.21 indicates special solutions of the Young's equation, showing that wetting can only be expected if the surface energy of adherents σ_s exceeds the surface energy of the liquid adhesive σ_l .

One sophisticated method is based on the measurement of contact angles of droplets present on the adherents. Test liquids with known surface energies and known polarities are used.

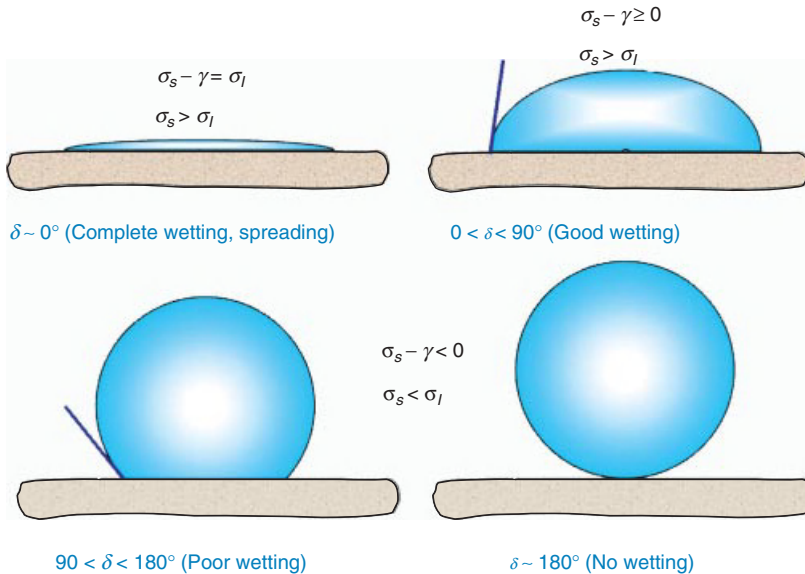


Figure 24.21 Special solutions of Young's equation. Contact angles for different surface energy combinations of liquid and adherent.

After developing adhesion the adhesive layer must be transformed to a solidified state in order to become cohesive and develop high bond strength. Depending on the adhesive's type, transformation can take place, for example, by drying, by cooling, or by chemical reaction. Changes in surface energy of the adhesive during transformation from the liquid to the solidified state cannot be ruled out.

Adhesives are polymeric systems of different types with different mechanisms of solidification. The latter can be used to define an adhesive classification as shown in Figure 24.22.

In paper converting, hot melts and emulsion adhesives are the most important, whereas in the corrugated board industry starch-based adhesives are mainly used.

Hot melts are made from thermoplastic resins completely free of solvents and water. They are liquefied by heating and applied in a hot state. Solidification takes place by cooling.

Emulsion adhesives are water-based systems produced by a special polymerization process. Solidification takes place by removing the water. The polymeric particles of the system coalesce and form a film.

Both systems differ in the time necessary to form bonds of high strength. The solidification process of hot melts is very fast, while the water removing process of emulsion adhesives is time consuming. The joining process has to take care of these differences.

Adhesive bonds are intended to withstand tear and shear forces. Peeling loads are dangerous and should be avoided as far as possible. Figure 24.23 shows the effects of pure tear load on an adhesive bond until failure.

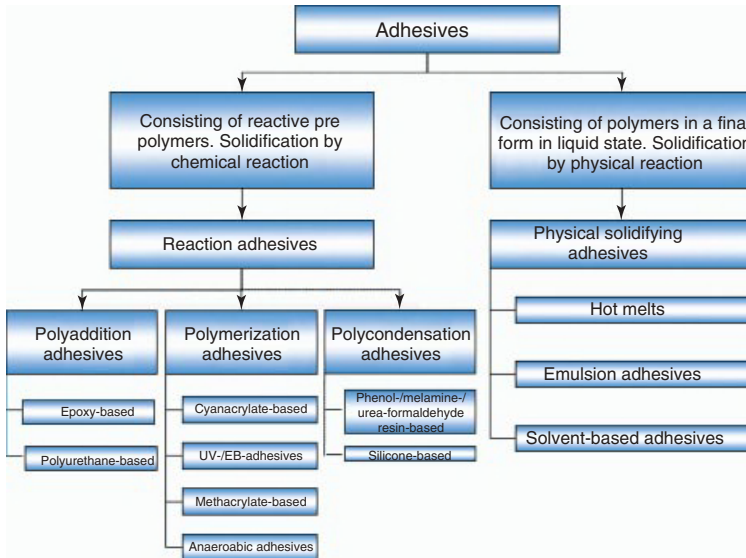


Figure 24.22 Classification of adhesives according to [3].

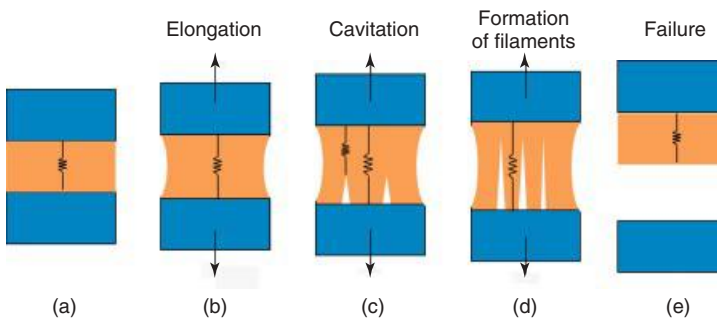


Figure 24.23 An adhesive bond under pure tear load. (a) unloaded bond; (b) under small load the adhesive layer is elongated (expressed by spring); (c) if load reaches critical values some base points of representing springs ruptured, and cavitation occurs; (d) continued cavitation leads to formation of filaments; and (e) if failure occurs the elongated filaments relax.

24.1.4.3 Sealing

Sealing, a further example of adhesive joints, cannot be applied to paper and board directly. It is necessary to coat them with a thermoplastic.

Sealing is similar to an adhesive bond using hot melt. To join the adherents, the thermoplastic material is liquefied or softened by heat. The adherents are bonded by maintaining pressure while solidification takes place during cooling.

A special process is sealing without heat, with only pressure. The film or paper to be sealed must be coated with cold sealable material forming nontacky films. The films are characterized by molecular constituents capable of migrating into

each other under pressure and forming a tight bond. Most cold sealable materials are formulated with natural rubber.

24.1.4.4 Frictional Connection and Positive Locking

Frictional connections are in use in paper converting as

- stapling and sewing
- screwing and riveting
- embossing.

Stapling is used in bookbinding and as an element of joining in the corrugated board industry. The strength of stapled connections depends on

- the strength of the material to be processed, particularly tear strength
- the strength of staples, particularly bending resistance
- the details of load impact and arrangement of staples with respect to direction of load impact (Figure 24.24).

Sewing is sometimes used to seal paper sacs filled with, for example, dry animal food, crops, or similar dry products. Single-needle seams are used as well as double-needle seams.

Screwing and riveting is seldom used in paper converting. Sometimes application to converted products is fixed by rivets. In paperboard containers where the top cover is hinged to the bottom part, rivets are used as hinges.

Embossing describes a special form of connection of two paper webs without adhesive, solely by the applying pressure. Examples are multilayer tissue paper products such as handkerchiefs, kitchen rolls, and toilet papers. Special design of embossing tools is used to produce paper filters for coffee and tea. The tool consists of two interlocked cog wheels. If the two layers of filter paper to be connected pass the nip of the tool it is corrugated and connected by high pressure particularly acting in the flanks of the cogs (Figure 24.25).

Finally, two examples of connections by positive locking should be mentioned:

- closure of envelopes by inserting flaps into slots;
- closure of folding boxes by inserting flaps.

24.1.5

Combining Different Materials

24.1.5.1 Introduction

A fiber-based material as paper consists of a porous structure. Packages for liquids or gaseous substances require barrier properties that cannot be provided by paper

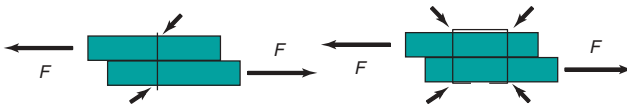


Figure 24.24 Connections with staples perpendicular (left) and parallel to the direction of load impact (right). Shear force F leads to torque within staples. From that, it can be expected that maximum load is higher if staples are parallel to the direction of load impact.

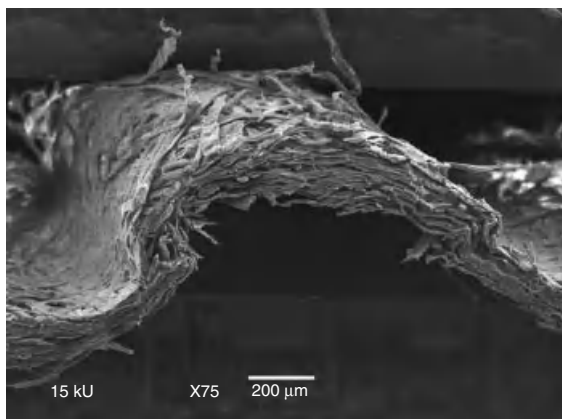


Figure 24.25 Cross section of the seam of a paper coffee filter.

alone because of its high permeability. Plastic films are a choice because of their low permeability and ease of handling in forming and sealing processes. The disadvantages of plastic films are the poor printability and low bending stiffness. Both printability and bending stiffness are the advantages of paper. As a result, a combination of paper and plastic film can avoid the specific disadvantages of each material, but provide the following benefits:

- impregnation (the thickness of the paper layer is not modified, but the free volume)
- coating (the free volume of the paper is not modified, no adhesive is used)
- lamination (the free volume of the paper is not modified, an adhesive is used).

As pigment coating of paper is part of the paper making process it will not be discussed here (Chapter 17).

The requirements for materials that paper should be combined with are determined by the transport mechanisms for gases and liquids.

A perfect barrier against gases cannot be provided by paper alone, but by a combination of paper with a pore-free material such as an aluminum foil. If only a low gas barrier is required, plastic films with suitable properties may be an alternative.

The two key factors that control the transport of liquids through a web are

- the wettability of the capillary walls
- the representative capillary radius.

Together with a pore-free material such as plastic one can produce materials with liquid barrier properties. For many applications it is sufficient to modify wettability of capillary walls.

24.1.5.2 Impregnation

The aim of impregnation is to modify the volume of the paper without changing its thickness. The process of modification can range from coating of capillary walls (fiber walls) to filling the porous structure completely.

Wettability of capillary walls can be reduced using proper impregnating agents. The liquid is impeded from penetrating because of capillary depression. To make papers greaseproof, for example, certain fluorine compounds are used as impregnating agents. Another example is the sizing of paper to maintain its writeability with aqueous inks (Chapter 17).

An example of nearly complete filling of the porous structure of paper with an impregnating agent is the treatment of decor papers with reactive resins.

Impregnating agents can be solutions or emulsions. In any case, the viscosity must be low in order to allow complete penetration in a short period of time.

24.1.5.3 Coating

Coating is the deposition of a material layer on the surface of paper without using an adhesive and without modifying the volume of paper. Coated paper is thicker than the raw paper.

To coat paper, different processes are known depending on the aggregate state of the coating compounds.

If compounds are gases, normally high vacuum evaporation equipment is necessary for coating. An example is the production of metallized paper. Often aluminum is the coating material, which must be evaporated and deposited on the paper under high vacuum.

For coating with thermoplastic polymeric materials, an extruder is the preferred applicator. The extruder feeds the material, de-aerates it, melts it, and delivers it as high viscose melt to the application tool, for example, an extended slot tool. It forms a film of melted material cooling down fast in contact with the paper. On the surface of the paper a firmly bonded polymeric film is formed.

Curtain coating is related to extrusion coating to some extent. Here, emulsions or solutions with lower viscosity are used. Depending on the design of the applicator, single-layer or multilayer films can be produced within one single coating process.

Other applicators are derived from printing technology using application rolls or anilox rolls precisely adapted to the properties of the coating compound.

24.1.5.4 Laminating

Laminating is a process of combining paper and another area-measured material with an adhesive. If the area-measured material is a plastic film normally the adhesive is applied to the film because of its better smoothness to minimize adhesive film thickness as far as possible. After application of the adhesive both materials are glued together in the laminator, and the laminated product is wound.

The condition of the adhesive in the laminator defines two different processes:

- **Dry lamination:** After application, the adhesive is dried and if necessary thermally reactivated by the laminator in order to provide sufficient tackiness. No permeability of the laminated materials is required.

- **Wet lamination:** After application of the adhesive and having passed the laminator, the laminated product is dried. Permeability of at least one of the laminated materials is a precondition.

Besides dry lamination and wet lamination, a lot of special processes are known.

An example of lamination in paper converting is the upgrading of high-quality sheet-fed offset prints on paper with high transparent plastic films made from polypropylene or polyesters. One- or two-component emulsion-based adhesives are preferably used. The printed sheets are glued to the film web. After finalizing the laminating process the plastic film is cross cut in order to separate the printed sheets.

24.1.6

Transport in Machines

24.1.6.1 Introduction

Machines in paper converting perform processes consisting of one or more basic subprocesses. In any case, there is an input of unprocessed material and an output of the processed material. The different input–output configurations are shown in Figure 24.26.

Examples of machines working from roll-to-roll are web-printing machines or web-slitting machines.

Examples of web-converting machines with cross-cutting unit are bag machines.

Examples of sheet-fed machines are sheet-fed offset printing machines.

In any case, the material to be processed must be positioned and fed precisely for the subprocesses performed within the machine.

24.1.6.2 Transport Roll-to-Roll

The main components of machines working from roll-to-roll are presented in Figure 24.27:

- unwinding and winding
- devices to guide the web (web edge guide and web tension control)
- drive mechanism including driving rolls.

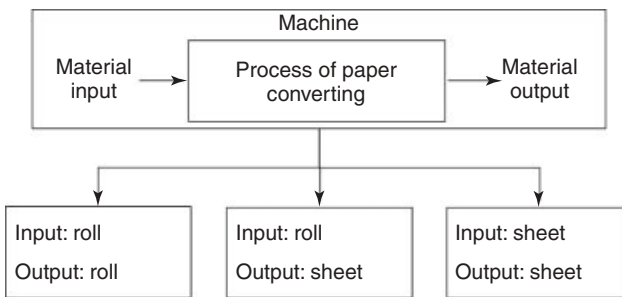


Figure 24.26 Input–output configurations for paper converting machines.

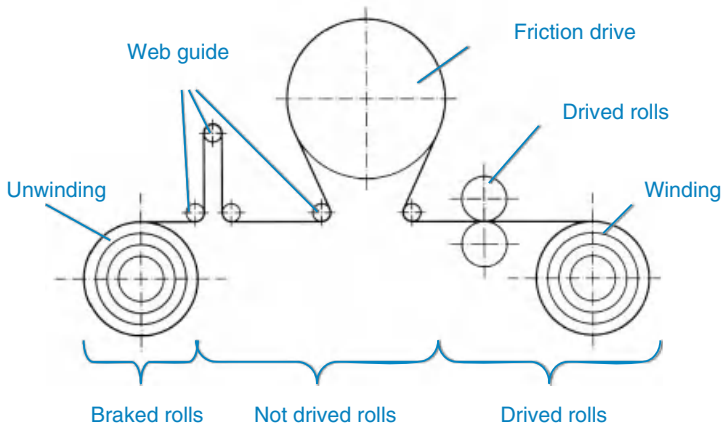


Figure 24.27 Components of a converting machine working from roll-to-roll.

The machine configuration must ensure that web speed and web tension are the same at any part of the process or subprocess.

To maintain web tension, the unwinding roll is braked. As a result, the drive must act against the brake momentum. As the brake moment depends on the radius of the unwinding roll it must track to provide a constant web tension.

For web alignment, the web edge must be detected. Optical or ultrasonic sensors are used. The signal of the sensors controls the correcting element, which can be a pivoting frame system.

Within this system, the web changes the direction four times, by 90° each time. The pivoting frame consists of two rolls. Correcting of alignment is performed by pivoting the frame around an imaginary pivoting point lying in the plane of the in-fed web. The pivoting angle is limited by the elastic properties of paper. A friction-locked contact between web and rolls without exceeding the limit of elasticity of the web is important.

For web tension control, dancer rolls are used. In a simple case, it consists of three rolls. Two rolls change the web by 90° each. Between the rolls is a movable roll changing the web by 180° . The web tension is controlled by maintaining a stable position of the middle roll.

Web drive is achieved by driving rolls wrapped by an angle α . As a result of drive momentum M_D the tension S_2 of the out-fed web is smaller than the tension S_1 of the in-fed web:

$$S_2 = S_1 - \frac{M_D}{B \times r}$$

where r is the radius of the driving roll and B is the width of the web.

Tied friction lock is achieved if the drive momentum does not exceed a maximum value given by

$$M_{D,\max} = r \times B \times S_1 \times \left(1 - \frac{1}{e^{\mu \alpha}}\right)$$

where α is the wrap angle and μ is the friction coefficient.

Not driven web guidance rolls must be driven by friction forces of the moving web without any slippage between rolls and web. The momentum needed ensures that the tension of the out-fed web is lower than the tension of the in-fed web. The momentum should not exceed certain maximum values in order to avoid slippage. The maximum value is given by

$$S_{2,\max} = S_1 \times e^{\mu\hat{\alpha}}$$

At the end of the process, the material to be processed has to be wound into a perfect reel.

Just as the unwinding roll needs a brake for due unwinding, a driving momentum is necessary for winding up, which depends on the radius of the reel as well.

The design of the winding machine and the strategy of tension control must meet the requirements of the material to be unwound and wound up, taking into account the extensibility and friction properties of the web. The aim is to achieve precisely wound reels with correct winding tightness, which are free of trapped air and wrinkles and have even distribution of tensile and compression stresses (Chapter 19).

24.1.6.3 Transport Sheet-to-Sheet

The main components of a machine working from sheet-to-sheet are shown in Figure 24.28. Decollation of sheets is normally done by vacuum suction devices pulling the top sheet in the vertical direction and then transporting the sheet in the horizontal direction by means of ribbons. The sheets are then transported to different converting units such as printing units and die-cutting units with transport processes between each.

The process is finalized by sheet deposition in order to form a stack of processed sheets.

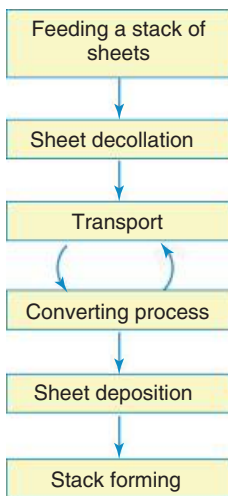


Figure 24.28 Basic process steps of sheet-fed machines.

For sheet decollation with vacuum suction devices, air permeability of the material to be processed is an important property. If air permeability is too high, double sheets can be fed. For horizontal transport with ribbons, friction properties of the paper/ribbon are the influencing factors in relation to the friction between adjacent sheets of paper.

The decollation system must transfer the sheets to a transport system consisting of grippers or clamps of a transport chain or similar devices to maintain exact sheet positions with well-defined distances between each other.

Sometimes, modern machines are able to correct sheet position immediately before feeding it to the converting unit. The edges of the sheets can be detected by means of optical methods or by printed marks.

To form an edged-stack at the end of the process the sheet can be guided as long as possible and released in due time. Other systems release the sheet with high horizontal velocity. The sheet must be slowed down in a short period of time. The stopping process demands for sufficient bending stiffness.

24.2 Testing of Converting Products

Irene Pollex

24.2.1 Testing in Paper Converting – General Remarks

Paper products are usually finished by several process steps, converted to new products, passed on or traded as intermediate or end products, and finally delivered to the end user. The main challenge of paper converting is to ensure the efficient, reliable, and high-quality processing of different materials to supply subsequent sectors or end users with high-quality products that are optimized in terms of cost, product, and process characteristics while meeting the respective requirements and needs.

Appropriate tests can ensure that the product meets all relevant quality demands and is manufactured by a trouble-free process based on efficient material and resource use. It is therefore common practice to use process-specific test procedures for quality assurance, which can be subdivided into the following main steps:

- **Incoming inspection:** testing of raw and process materials.
- **Process inspection:** tests and inspections carried out during manufacturing, covering all process stages.
- **Final inspection:** testing of products to determine compliance with specified quality and design parameters.

This multistage concept must be implemented by a systematic approach: test programs must also cover main aspects of the various converting processes and envisaged application.

An enormous range of paper converting products are available on the market for a multitude of applications: packages in the form of blanks, ready-made cartons, display stands, sacks or drums; accessories such as winding cores, cushioning materials, labels or pressure-sensitive tapes; commercial or end-use products such as magazines, writing pads, folders, books, lampshades, Easter eggs, carrier bags, paper napkins, and hankies.

Unlike the paper manufacturing sector, which has developed and used more and more specific test methods for process control, monitoring, and quality assurance in recent years, paper converters have largely limited their activities to laboratory testing here. Process measurements – for example, application weight and glue gap control, sheet counting and alignment checks, and moisture and temperature measurements – are mainly used for high-speed converting processes only. Online quality monitoring of parameters such as material composition, mass, and surface and strength properties has remained an exception so far. Daily practice has shown, however, that the use of suitable tests and data analyses in both laboratories and manufacturing systems enables targeted measures leading to better quality and process stability in subsequent converting operations.

Tests are usually based on the following *characteristics* classified by DIN 55350-12 [14]:

- **Quantitative characteristics:** measurable values assignable to a scale with predefined intervals (continuous or discrete characteristics), for example, thickness, bending stiffness.
- **Qualitative characteristics:** values assignable to a scale without graduation (no predefined intervals).

Besides using quantitative material characteristics such as stiffness or thickness, paper converters frequently rely on qualitative characteristics that are not further specified to describe properties such as the suitability for cutting or drawing and dust-free handling.

Quality tests based on measurable parameters are laid down in rules and standards for many converting products and product groups.

24.2.2

Converting-Specific Material Tests

Besides a number of basic, repeatedly used tests, there are many product-specific tests whose type, scope, and target values must be precisely agreed on between the customer and the manufacturer.

24.2.2.1 Overview of Test Methods for Paper, Paperboard, and Board

Many test methods are generally suitable for various tasks, paper grades, or products (Table 24.2). The majority of conventional methods are standardized and often provide the basis for specifications and target values.

Table 24.2 Overview of common test methods for paper, paperboard, and board (selection).

Property group	Frequently used test methods/parameters
Basic properties	Mass, thickness, moisture
Composition, structure	Qualitative and quantitative pulp composition, special cutting and preparation techniques for light microscopy and scanning electron microscopy (SEM), X-ray microanalysis (EDX), spectroscopic methods (FT-IR, NIR), differential scanning calorimetry (DSC) thermo gravimetric analysis (TGA), particle size measurement
Strength properties	Tensile strength, strain to rupture, elasticity, tensile stiffness, bursting strength, folding strength, bending stiffness, tearing and tear growth resistance, crush resistance (SCT, CMT, RCT, etc.), ply-bond strength, surface strength, abrasion behavior, surface elasticity
Surface properties	Smoothness/roughness (Bekk, Bendtsen, PPS, Sheffield), surface profile, contact area
Optical properties	Gloss, chromaticity coordinates, reflectance factor, opacity
Light fastness, heat and moisture resistance tests	Light fastness tests, Xenon test, climate tests (response to temperature and moisture variations), artificial aging, aging resistance, lifespan classes
Electrical properties	Surface resistance, volume resistance
Permeation properties	Air permeability (Bendtsen, Gurley, Bekk, Schopper, Sheffield, PPS), water vapor permeability, gas permeability, detection of PIN holes, mercury porosimetry, capillary flow porosimetry
Penetration and sorption properties	Water adsorption (Cobb), hygroexpansivity and wet expansion, wettability/penetration behavior, contact angle, surface tension, writability/sizing, grease proofness (Kit test), capillary rise (Klemm)
Printability properties	Determination of pick resistance, ink holdout, print penetration by laboratory test prints, print contrast/color density/print unevenness, abrasion resistance/ink rub-off
Converting properties	Creasing and folding properties, flatness, cutting/shearing resistance, heat sealing properties, adhesive strength, peel strength/delamination tests, fiber orientation
Chemical properties	pH, surface pH, Kappa number, alkali reserve, migration measurements, bleeding resistance detection of ingredients by capillary gas chromatography + mass spectrometry (GC-MS)
Biological properties	Bacterial count, antimicrobial agents biodegradability/compostability
Organoleptic properties	Panel tests for odor and flavor determination, analytical methods
Recyclability	Repulpability, deinkability

An increasing number of characterizations, however, are based on new and usually nonstandardized test methods. They are still rather uncommon in conventional paper testing, but can help clarify many issues.

In practice, often the tests suitable for the various materials of a product group are distinguished. Each material is preferably tested by certain test methods. Table 24.3 shows a selection of tests – excluding grammage, thickness, reel or sheet dimension tests – that are frequently used for specific materials. Most of these methods are standardized, and some of them can be found in product specifications.

Table 24.3 Important tests for quality specifications of paper, paperboard, and board (selection).

Group of Papers	Important tests
Graphic/printing paper/board	Optical properties, opacity, roughness/smoothness, gloss, pick resistance, tensile strength, tearing resistance, hygroexpansivity, moisture, oil absorption
Digital printing papers	Optical properties, opacity, roughness/smoothness, moisture, toner adhesion, running properties/frequency of paper jams, buckling, abrasion resistance, frictional behavior, electrical surface resistance
Packaging paper/board	Tensile strength, strain to rupture, tear growth resistance (Brecht-Imset), bursting strength, pH, ash, scratch resistance, ply-bond strength, water absorbency, wet expansion
Solid board	Bursting strength, puncturing energy, edge crush resistance, water repellence
Corrugated board paper	Bursting strength, short span compression strength, ring crush resistance, CMT, water absorbency
Sanitary papers	Sheet thickness (stack), tensile strength/strain to rupture, wet tensile strength, optical properties, water absorbency/water capacity, bursting strength (puncture tester), moisture content, wet expansion
Technical papers/paperboard/board for specialty applications	Vary greatly depending on application: usually strength parameters, density, and so on.
Cartonboard	Specific volume, bending stiffness, optical properties, pick resistance/delamination, creasability
Office board/office papers	Optical properties, writability, tensile strength
Envelope papers	Tensile strength index, bursting strength, writability, water absorption (Cobb), smoothness (Bekk), reflectance factor
Wallpaper base	Wet tensile strength, ply-bond strength, smoothness/roughness, wet expansion
Fancy board	Optical properties, surface properties

24.2.2.1.1 Selected Test Methods The following section describes a number of important test methods that are not included in Chapter 29 “Testing of Fibres, Suspensions and Paper and Board Grades” but are of interest to the various converting operations.

A key prerequisite for reproducible measurement of paper materials is that samples are adequately conditioned and tested in a standard atmosphere (EN 20 187).

24.2.2.1.2 Climate-Induced Dimensional Changes When talking about *flatness/dimensional stability*, we mainly refer to the response of paper and board materials to major changes in atmospheric conditions such as changes in ambient temperature and moisture, or one-sided exposure to heat or aqueous media such as ink or adhesives.

Dimensional changes can occur in the form of *elongations* (in MD, CD, and z-direction): *curl, diagonal curl, or long- and short-wave warpage*. *Climate-induced dimensional changes* can be measured by a number of different methods. Table 24.4 shows an overview of selected measurements.

24.2.2.1.3 TSI/TSO The elastic modulus is a material parameter that characterizes the behavior of paper under tensile load in the range where stress is proportional to deformation. It can be multiplied with thickness to obtain the tensile stiffness. TSO (tensile stiffness orientation in degrees) is a measure of the

Table 24.4 Overview of measurements for climate-induced dimensional changes.

Criterion	Method	Standard
Hygroexpansivity	Climate chamber	DIN 53130; ISO 8226-1; ISO 8226-1 and 8226-2
Wet expansion (hygroexpansivity over time)	Dimensional stability tester (DST 1200) – based on a climate chamber with optical analysis system	–
Curl	Various manual techniques	T 466 cm-82; ASTM 4825; Tappi um 427
	Deformation (curl height) measurement of board (SWU device)	–
Wet curl	Manual technique	Tappi um 428
Wet expansion/dry shrinkage	Fenchel	–
	Wet expansion (following immersion)	DIN 54517
	Wet stretch dynamics analyzer	Emtec or EMCO device
	Dry shrinkage (one-sided heat contact)	Emtec device

directionality of tensile stiffness indices (TSIs). TSI can be determined in a TSO tester, which uses the principle that the propagation speed of an ultrasonic pulse in the plane of the paper is proportional to the elasticity of the material (expressed as TSI) [4, 6]. TSO testers have several pairs of transmitters/receivers that are circularly arranged at regular angular distances to measure the propagation speed of a predefined ultrasonic pulse in the sheet plane.

TSI values and their angular distributions provide information about the deviation of fiber orientations from the machine direction about effects on other directional strength and elastic properties as well as about moisture-induced length changes or flatness deviations. The latter are of special interest to many converting operations because they can be used to identify the causes of undesired phenomena such as curl, diagonal curl, and stack lean.

24.2.2.1.4 Abrasion Resistance Paper products with highly abrasion-resistant surfaces are required for many converting operations and end uses. This makes it necessary to test the resistance of surfaces to mechanical stresses and loads. Commonly used test methods are

- pick test (picking resistance)
- Dennison wax test (T 459 om; Surface Strength of Paper (Wax Pick Test))
- abrasion determination by the abrasion wheel method according to DIN 53109.

24.2.2.1.5 Surface pH The surface pH of paper and coated and composite materials affects several converting properties. We must clearly differentiate between the pH values measured in aqueous extracts and the surface pH [7]. The pH is a measure of the acidity or alkalinity of aqueous solutions. It is the negative common logarithm of the hydrogen ion concentration and has no dimension [8]. The surface pH is measured by means of special spider or flat glass electrodes.

24.2.2.1.6 Water Vapor Permeability *Water vapor permeability* is one of the key quality parameters of coated papers. It is determined by the gravimetric method described in DIN 53122 Part 1. One side of the paper is exposed to a humid atmosphere, and the mass increase of an absorbent contained in an impermeable aluminum dish underneath the paper is measured by gravimetry.

24.2.2.1.7 Grease Proofness Another important aspect is the impermeability of paper and board materials to grease or other oil- or fat-containing substances. It can be quantified by several methods:

- grease permeability according to DIN 53116
- grease resistance test for paper, T 559 (*Kit Test*)
- turpentine tests for voids in glassine and greaseproof papers, T 454.

Some packing houses have developed their own test methods including different substances, and sometimes also higher temperature or moisture levels.

24.2.2.1.8 Liquid Penetration into Paper Surfaces The basic prerequisite for liquid penetration is an adequate *wettability* of the surface. Contact angle testers are used to determine the *contact angle and surface tension* of paper surfaces: a predefined volume of a special test liquid with known polar and disperse properties is applied on the paper surface, and the resulting interface phenomena are monitored, usually by means of a camera.

- Water absorbency according to DIN EN 20535 (Cobb method).
- Ultrasonic penetration test: The test measures the changes in ultrasound transmission in the paper structure resulting from wetting, penetration, and swelling processes. For this purpose, the sample is rapidly immersed in a liquid to measure the change in ultrasound intensity over time.
- Water repellency according to DIN 54515.
- Capillary rise (Klemm method) according to ISO 8787.
- Sizing degree determination.
- Writability with ink according to DIN 53 126.

24.2.2.1.9 Printability Properties Printing is one of the key processes in paper converting. *Printability* refers to the print result and its quality, the behavior of the material during printing, its initial properties, and suitability. Each of these properties can be described by several individual parameters and test methods. The test method used must be suitable for the printing process concerned because each combination of printing technique, machine, and ink makes specific requirements to the substrate, leading to different print results.

Laboratory test prints with predefined ink layer thickness are widely used to simulate print processes and perform comparative paper and ink assessments. The following parameters can be measured by means of weighed test prints:

- chromaticity coordinates
- ink consumption
- optical density
- gloss
- abrasion resistance
- ink layoff
- blocking
- light fastness
- resistance to chemicals
- organoleptic properties.

The suitability of paper or board for offset printing is usually determined by printability tests. Some of them are described in detail by standards or widely used testing instructions such as IGT-Tests:

- ink penetration test, ink setoff
- ink strike-through
- picking (wet, dry), delaminating (ISO 3783)

- varnishing properties/print penetration
- mottling tests (print, water, ink)
- yellowing by contact test, chemical ghosting
- blistering test
- ink trapping test.

No standard methods have been developed to date for determining the suitability of paper or board for flexographic printing.

24.2.2.1.10 Creasing and Folding Properties Creasing and folding are key processes for cartonboard converting. It is therefore advisable to test the *creasability* of cartonboard under appropriate conditions or determine suitable *creasability ranges* by laboratory tests. A number of different test setups are used in practice to produce predefined creases in the cartonboard surface. In most cases, the creasing quality is first assessed visually and by manual folding:

- laboratory creasing tests, DIN 55437–1
- determination of creasing range by visual assessment of creasings, DIN 55437–2
- creasings – determination of technical quality, DIN 55437–3 folding moment tests (Figure 24.29).

The creasing quality of blanks or cartonboard packages is mainly determined by the following methods:

- visual or, if applicable, microscopic assessment of creases and folds (optical quality)
- technical quality – measurement of the force required for folding the cartonboard along the creasing line
- crease angle measurement
- erecting force measurement.



Figure 24.29 Determination of technical quality of creasings using an equipment of the Company Lorentzen & Wettre.

24.2.2.1.11 Embossing Paper products can be provided with functional or decorative embossing. A frequent application is *Braille codes* on pharmaceutical packaging. Quality assessments of embossing usually include

- visual or automated assessments of the correctness and position of embossed characters, in comparison with models or originals;
- visual assessment of geometry or shape; embossing on decorative packages must be free from cracks and fissures;
- height measurement of embossed characters (optical, automated measurement).

24.2.2.1.12 Abrasion Resistance/Rub Resistance of Prints Prints, especially package prints, must be sufficiently resistant to abrasion stresses occurring during the transport of filled boxes, for example. The *abrasion resistance* of prints on paper substrates is tested by simulating these abrasion stresses under predefined conditions. The test instruments used in practice differ in the type and frequency of abrasive motions, weight of the abrasion body, and degree of automation. Abrasion effects are assessed on the print or counter print either visually or by measuring the color density or chromaticity coordinates by means of a densitometer or spectrophotometer (Figure 24.30).

24.2.2.1.13 Customary Abrasion Testers

- Ugra abrasion sled
- Quartant abrasion tester
- Sutherland rub tester
- Crockmeter
- Digital Ink Rub Tester
- ABREX Tester
- Hanatek abrasion tester
- Oser abrasion tester
- Taber abrasion tester (Figure 24.31).



Figure 24.30 Abrasion tests using a Quartant abrasion tester of the company Prüfbau.



Figure 24.31 Abrasion tests using a Taber equipment.

24.2.2.1.14 Light Fastness *Light fastness* describes the resistance of paper or prints to luminous radiation. To assess their light fastness, samples must be exposed to light under the specific conditions prevailing in each case. Because this would take a lot of time and effort, manufacturers have developed light fastness testers that obtain color changes in the surface after a relatively short period by illuminating the sample with xenon arc light largely similar to daylight conditions. Light fastness is expressed by numbers corresponding to the eight light fastness steps of standard depth dyed blue wool references. Step 1 indicates very low and step 8 indicates very high light fastness. Color changes can also be determined by optical methods, for example, by measuring the color difference (usually ΔE) between the initial and illuminated samples.

EN ISO 105-B02 Textiles – tests for color fastness; Part B02, color fastness to artificial light: xenon arc fading lamp test.

24.2.2.1.15 Quality of Cut Edges Apart from influencing the optical quality of the product, the *quality of cut edges* also has an effect on its dusting properties. Several methods are therefore used to assess the quality of cut edges, for example, microscopic edge quality determination according to DIN 12281 – requirements for copy paper. The standard classifies cut edges according to contour quality on a scale ranging from 1 (good) to 6 (poor). Other test methods use imaging techniques to determine the contour of cut edges.

24.2.2.1.16 Sealability Composite films or coated papers (e.g., PE-coated paper and board) are frequently used for packages that are to be closed by *heat sealing* or welding. They are tested directly in full-scale or in pilot units in most cases. *Heat sealing devices* of different designs are available for exploratory tests where temperature, pressure, and sealing time can be varied in the laboratory to obtain heat seals for subsequent visual assessment or tensile tests.

24.2.2.1.17 Glueability Besides measuring the properties of the components being joined, it is often necessary to test the interactions between them under

specified conditions. PTS Method PTS-PP 102/84 describes a useful test method for the application of dispersion adhesives: the adhesive is applied on the first adherend by a specially designed test unit, and the second adherend is joined to complete the bond under predefined conditions after a predefined open assembly time. After a preselected setting time has passed, the components are peeled off one another, measuring the peel resistance.

Hotmelt adhesive joints are produced in the laboratory by softening the adhesive in a predefined operating window with a temperature-controlled applicator. The quality of industrial or laboratory adhesive joints can be assessed by force measurements under varying load conditions in a tensile tester.

24.2.3

Testing of Converting Products

The wide variety of paper converting products, applications, and requirements has led to numerous product-group-specific quality standards, test standards, and testing programs. A selection of suitable and widely used test methods for important product groups is outlined in the following sections.

24.2.3.1 Corrugated Board

FEFCO, the umbrella organization of the European associations of corrugated board manufacturers, issued a number of its own test methods (Table 6.12) many years ago. Most of them correspond more or less to the international standards developed later on. Today, corrugated board products are preferably characterized by means of EN or ISO methods.

- Basic weight of corrugated board after separation, ISO 3039: determines the grammage of individual layers in joined corrugated board.
- Bursting strength, EN ISO 2759.
- Edge Crush Test, ECT, EN ISO 3037: in the ECT, a steadily increasing compression load is applied to a corrugated board sample of predefined dimensions in the direction of vertical flutes.
- Puncture Energy Test, PET, ISO 3036: the PET measures the work required for puncturing the corrugated board material by means of a predefined body (Figures 24.32 and 24.33).
- Flat Crush Test, FCT, DIN EN 23 035: the FCT measures the maximum force that a flat-lying sample can withstand before it collapses under a compression load applied vertically to the sample area.
- Bending stiffness, ISO 5628: four-point method, analyzes the resistance of a corrugated board sample of predefined dimensions to a constant bending moment in the elastic deformation range.
- Adhesive joint strength, Pin Adhesion Test (PAT) (FEFCO 11): describes the maximum axial force that must be applied to break a predefined number of adhesive joints between the flat and corrugated webs.
- Water resistance of adhesive joints in corrugated board, DIN 53133: tested by storing one adhesive joint at a time in water.

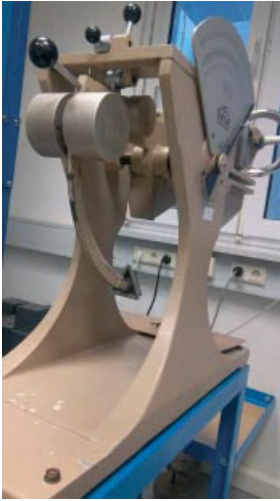


Figure 24.32 Puncture energy test for corrugated board using an equipment of the Frank Company. (view to the complete test equipment.)



Figure 24.33 Overhead view of puncture energy test for corrugated board using an equipment of the Frank Company. (view to the clamped tested sample.)

24.2.3.2 Packages

Some of the most Figure important package (box) tests are discussed below:

Pretreatment of samples

- EN ISO 2233, Packaging: complete, filled transport packages, and unit loads; conditioning for testing.
DIN 55446, Packaging: packaging materials, packages, and complete, filled transport packages; conditioning for testing.
- **Compression and stacking tests using a compression tester in accordance with EN ISO 12048**
Compression tests of packages and boxes simulate a compression load. The box compression resistance or *BCT value* (BCT: box compression test) determined by

these tests is one of the key performance parameters of packages and a measure of the maximum compression load the package can withstand.

- **Stacking test using a static load, EN ISO 2234**

The method describes three different ways of testing the stacking strength of filled packages or transport units under static conditions. Test weights must be chosen in accordance with the load conditions prevailing in each case. The test assesses whether the package can withstand the stacking load for 24 h or longer, or when it will collapse.

- **Strength of adhesive joints**

A key quality characteristic of both corrugated board boxes and folding cartons is the strength of the manufacturer's joint, which is a dispersion adhesive joint in most cases. The adhesive joint strength can only be quantified by means of tensile or peel tests; practitioners often resort to manual/visual assessments only.

- **Drop test**

The *drop test* is probably the most important strength test for sacks: a sack is filled with the original bulk material or a comparable material of the same density, mass, and surface geometry, closed and dropped from a predefined height in a drop tester whose opening mechanism does not affect the motion of the falling sack. The criterion is that the packaging material be in a sound condition after it was dropped. As a rule, any leakage of bulk material indicates failure. The drop test is also used for boxes and other packages.

24.2.3.3 Cores

A series of specific test standards is available for cores (winding tubes). They are listed in Table 24.5.

24.2.3.4 Labels

Nonadhesive labels are tested for

- resistance to penetration of alkaline solutions, DIN 16524-6
- resistance to alkaline solutions, DIN 16 524-7
- resistance of prints to water – water fastness, resistance to solvents
- resistance of prints to other chemicals – alkali resistance, fastness to soap, stability against detergents
- resistance to ice water and condensation water
- crease and wrinkle-free labeling
- resistance to wet and dry abrasion
- curl.

24.2.3.4.1 Self-Adhesive Products FINAT, the international organization of self-adhesive labeling producers (www.finat.com), has developed a number of specific test methods for self-adhesive products (Table 24.6 and Figure 24.34).

24.2.3.5 Tissue Paper and Tissue Products

Some of the most important test methods for tissue paper and tissue products are listed in Table 24.7.

Table 24.5 Testing of cores (winding tubes).

No	Testing of cores
ISO 11093-1	Part 1: sampling (ISO 11093-1:1994)
ISO 11093-2	Part 2: conditioning of test samples (ISO 11093-2:1994)
ISO 11093-3	Part 3: determination of moisture content using the oven-dry method (ISO 11093-3:1994)
ISO 11093-4	Part 4: measurement of dimensions (ISO 11093-4:1997)
ISO 11093-5	Part 5: determination of characteristics of concentric rotation – Technical Corrigendum
ISO 11093-6	Part 6: determination of bending strength by the three-point method (ISO 11093-6:2005)
ISO 11093-7	Part 7: determination of flexural modulus by the three-point method (ISO 11093-7:1997)
ISO 11093-8	Part 8: determination of natural frequency and flexural modulus by experimental modal analysis (ISO 11093-8:1997)
ISO 11093-9	Part 9: determination of flat crush resistance (ISO 11093-9:2006)
ISO 13542	Paper and board – specification for internal diameters of cores for reels (ISO 13542:2006)

**Figure 24.34** Peel adhesion using an equipment of the Thwing-Albert Instrument Company.

24.2.3.6 Bookbinding Products (Adhesive Binding)

24.2.3.6.1 Visual Assessment of Block and Adhesive Binding Quality To assure the quality of adhesive bindings, converters usually assess the quality of cut edges and sheet edges after three-sided trimming, and, if applicable, measure the notch depth, distance between notches, and adhesive film thickness.

24.2.3.6.2 Pull Test (Tear Out Test) The pull test evaluates the adhesion of sheet edges in the adhesive joint under predefined conditions. The test measures the force

Table 24.6 FINAT test methods for self-adhesive products.

FTM 1	Peel adhesion (180°) at 300 mm min ⁻¹ (Figure 24.34)
FTM 2	Peel adhesion (90°) at 300 mm min ⁻¹
FTM 3	Low speed release force
FTM 4	High-speed release force (10–300 m min ⁻¹)
FTM 5	Resistance to elevated temperatures
FTM 6	Resistance to ultraviolet light
FTM 7	Silicone coat weight
FTM 8	Resistance to shear from a standard surface
FTM 9	Loop tack measurement
FTM 10	Quality of silicone-coated substrates for self-adhesive laminates: release force
FTM 11	Quality of silicone-coated substrates for self-adhesive laminates: subsequent adhesion
FTM 12	Adhesive coat weight
FTM 13	Low temperature adhesion
FTM 14	Dimensional stability
FTM 15	Surface tension of plastic films
FTM 16	Chemical resistance – spot method
FTM 17	Chemical resistance – immersion method
FTM 18	Dynamic shear
FTM 19	Recycling compatibility of self-adhesive labels
FTM 20	Fluorescence and whiteness
FTM 21	Ink adhesion (basic)
FTM 22	Ink adhesion (advanced)
FTM 23	Die strike ((i) paper and (ii) filmic paper)
FTM 24	Mandrel hold
FTM 25	Evaluation of silicone coverage of coated papers
FTM 26	Wash-off paper and film labels
FTM 27	Ink rub test for UV printed labels' ink surface against substrate or ink surface

that must be applied to vertically tear out a single sheet from the adhesive-bound book spine.

Further tests for bookbinding products are

- angular tensile test (tear out test)
- flex test (sheet turning test).

24.2.3.6.3 Compression Resistance Test The strength of adhesive bindings can also be tested in the following way: the product is opened and placed on a flat surface, and pressure is applied to its spine region after a setting time of 6 h (hot melt adhesive) or 24 h (PUR adhesive).

24.2.4

Transportation Tests

Nearly every product – including converting products – must be packed for shipment in such a way that it reaches the customer in sound condition and without

Table 24.7 The most important test methods for tissue paper and tissue products.

No	Tissue paper and tissue products
ISO 12625-1	Part 1: general guidance on terms (ISO 12625-1:2011)
ISO 12625-3	Part 3: determination of thickness, bulking thickness, and apparent bulk density (ISO 12625-3:2005)
ISO 12625-4	Part 4: determination of tensile strength, stretch at break, and tensile energy absorption (ISO 12625-4:2005)
ISO 12625-5	Part 5: determination of wet tensile strength (ISO 12625-5:2005)
ISO 12625-6	Part 6: determination of grammage (ISO 12625-6:2005)
ISO 12625-7	Part 7: determination of optical properties – measurement of brightness and color (ISO/DIS 12625-7: 2010)
ISO 12625-8	Part 8: water-absorption time and water-absorption capacity, basket-immersion test method (ISO 12625-8:2010)
ISO 12625-9	Part 9: determination of ball burst strength (ISO 12625-9:2005)
ISO 12625-11	Part 11: determination of wet ball burst strength (ISO/DIS 12625-11:2011)
ISO 12625-12	Part 12: determination of tensile strength of perforated lines – calculation of perforation efficiency (ISO 12625-12:2010)

quality loss. This is ensured by packaging materials of various designs and combinations. The suitability of transport packages and unit loads for the envisaged transport application is determined by testing them under practical conditions, that is, exposing them to the stresses and loads typical of the respective transport chain. Stresses and loads are usually documented by observers and suitable instruments, to be able to assess their relevance later on. Another option is simulating the stresses and loads that can possibly occur during transport in the laboratory, using standardized test conditions that are based on the real transport chain.

The following methods are used to test the resistance of complete, filled transport packages and unit loads either individually or within test series or test programs [9]:

- Vibration tests
 - vibration tests at fixed low frequency, EN ISO 2247
 - random vibration test, EN ISO 13355
 - vibration tests using variable sinusoidal excitation
 - determination of resonance vibrations.
- Vertical drop tests
 - vertical impact test by dropping, EN ISO 2248
 - impact test by rotational drop, EN 14149
 - toppling test, EN 28768.
- Horizontal impact tests
 - inclined plane, EN ISO 2244
 - horizontal impact test, EN ISO 2244.

- Compression tests
 - quasi-static compression test, EN ISO 12048
 - stacking test, EN ISO 2234.
- Climate tests, EN ISO 2233 (temperature and moisture variation, also in combination with stresses and loads, for example, compression tests).

24.3

Printing Technologies

Simon Stahl and Edgar Dörsam

24.3.1

Introduction

Since the invention of movable-type printing by Gutenberg in the fifteenth century, many different printing methods have come into being. Today, the most important processes for printing on paper are the conventional technologies of offset (planographic), flexographic (relief), and rotogravure printing. In addition, digital printing processes that have been widely used in the Soho (Small office home office) field for years, such as inkjet printing and xerography (in laser printers and copiers), are increasingly finding their way into industrial applications. Digital printing enables cost-effective production of short runs and individualization of print products. Challenges remain, however, in particular for transferring the large data volumes required for imaging. Conventional printing methods are also increasingly being digitized. For example, plates are now laser-imaged using what is known as computer-to-plate (CtP) technology for nearly all processes.

The purpose of printing is to reproduce texts and color pictures using cyan, magenta, yellow, and black (or key) inks (referred to by the letters CMYK). To achieve this, full-color originals are electronically broken down, or separated, into C, M, Y, and K components. Printing units or heads then apply tiny dots of these inks (known as *halftone dots*) to the substrate in a pattern created by screening (Figure 24.35). Typically, a separate printing unit is used for each color. But a press can have considerably more than four printing units. Print products are often additionally enhanced by applying coatings (to achieve greater gloss and abrasion resistance) and/or gold or silver foil to them. Many presses are equipped to do this inline. In addition to graphic printing, there is also what is known as *functional printing*. This involves applying new kinds of materials instead of ink to give the product functional attributes. Devices such as organic light-emitting diodes, electrical circuits, or sensors can be created in this way. This poses different challenges, calling for the use of modified printing processes. Above all, homogeneous films with thicknesses in the nanometer range and very fine lateral structures are required.

Printing is a complex process. Printing inks, which are translucent, have to be applied in thin films only about 1 μm thick. Any deviations from this are easily spotted with the naked eye. This calls for a high level of print quality, and the presses

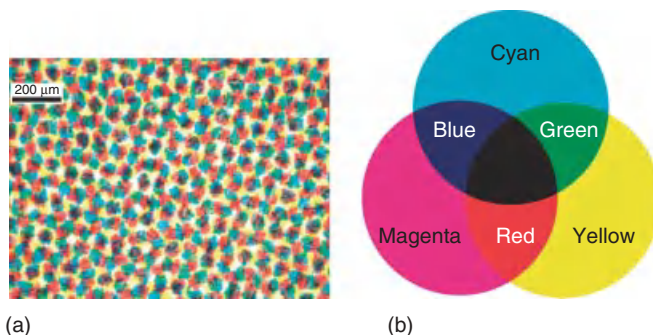


Figure 24.35 (a) Four-color halftone printing (microscope image). (b) Creating different colors by varying the relative amounts of cyan, magenta, and yellow ink and the whiteness of the paper. The halftone dots can also have different sizes and shapes. (Source: IDD, TU Darmstadt.)

and substrates used must also meet very demanding requirements. Each printed color separation consists of halftone dots and combinations of the translucent inks result in different color hues.

In order to produce high-quality print products, the paper, inks, and print process must be carefully harmonized with one another. The following sections present the most important printing processes and their major parameters.

24.3.2

Gravure Printing

24.3.2.1 General Description

Gravure printing technology is suitable for high-speed, high-quality applications. The basic principle is very simple. Normally, only two cylinders are involved. The gravure cylinder is engraved with tiny recessed cells in a mirror image of what will be printed. The cells are filled with ink from a fountain. Excess ink is removed using a doctor blade, so that only the cells contain ink and the intervening surfaces are nearly clean. At the nip (the point of contact between the two cylinders), the ink is transferred to the substrate. The impression roller has a flexible rubber or blanket surface that presses the substrate against the gravure cylinder.

Most gravure presses are high-speed, web-fed systems designed for long print runs of several million copies. Typical products are high-profile items such as magazines, mail order catalogs, high-quality packaging, banknotes, and securities. Gravure printing is also suitable for achieving outstanding quality, so it is used for offline refinement too. Some sheet-fed gravure presses for packaging exist.

Gravure printing methods can be assigned to one of two types: direct and indirect. Direct gravure printing includes rotogravure and intaglio gravure. Rotogravure is the most common approach, involving cylindrical printing forms (Figure 24.36). Intaglio printing is used for securities, banknotes, and postage stamps. Unlike rotogravure, the image is engraved into the cylinder without screening it into dots. Intricate images can be printed very well; high line pressure can create relief-like

embossing. Subtypes of indirect gravure are pad printing, intaglio offset, and gravure offset. In intaglio and gravure offset printing, an additional application roller with a compressible blanket is used to transfer the ink from the gravure cylinder to the substrate. Pad printing is commonly used to print on curved three-dimensional objects such as crown caps or bottles. In the following, the most common type of gravure printing – rotogravure – is described in detail.

24.3.2.2 Process

24.3.2.2.1 Ink Acquisition The gravure cylinder is partially immersed in an ink fountain. As it rotates, its surface and recessed cells are covered with ink. Under certain conditions, not every cell may be filled properly. These cells show up in the printed image as visible defects called *pinholes*. They can be caused by the drying of ink or entrapped air in the cells.

24.3.2.2.2 Metering of the Ink One of the most important parts of the gravure process is the doctor blade, which acts similar to a squeegee to scrape the cylinder before it makes contact with the paper. It removes excess ink from the nonprinting (nonrecessed) areas while leaving the right amount of ink in the cells. A microscopically thin layer remains on the nonprinting areas for lubrication. The blade is angled between 55 and 70°, which is crucial in order for its tip to optimally contact the surface of the cylinder. Usually, the blade also oscillates from side to side to ensure uniform abrasion.

24.3.2.2.3 Ink Transfer to the Substrate The ink is then transferred to the substrate, which is sandwiched between the gravure and impression cylinders at their point of contact, which is called the *nip*. For graphic products, dot splitting is necessary in order for every single cell to leave a distinct, well-defined dot. In solid-color areas, the individual drops coalesce on the substrate to create a uniform, continuous film. To improve ink transfer, an electrostatic charge can be applied to the impression roller or the web (called *electrostatic assist* or *ESA*). Instabilities during film creation can result in isotropic structures called *viscous fingering*.

24.3.2.2.4 Fluid Dynamics on the Substrate and Solidification After ink transfer to the substrate, the surface of the film can change dramatically. The wetting properties of the materials involved can smooth inconsistencies and create a

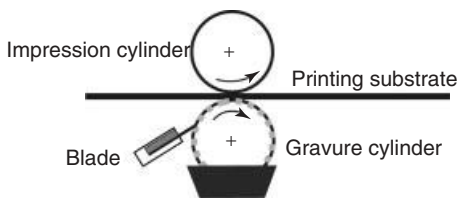


Figure 24.36 Rotogravure. (Source: IDD, TU Darmstadt.)

uniform film. Hot air is used for drying. As the ink dries, its changing solid content can result in surface tension gradients and even cause a smooth film to re-separate into individual droplets.

24.3.2.3 Inks and Process Properties

The inks normally used in rotogravure printing are low-viscosity solutions or dispersions. Their viscosities can range from a few millipascal-seconds to about 50 mPa·s at 20 °C and high shear rates. Some inks exhibit strong shear rate dependencies. This is an important aspect because the applied shear rates can vary from 100 s⁻¹ during ink acquisition to up to 10⁶ s⁻¹ when the cylinder is being scraped by the doctor blade. The ink largely consists of flammable solvents (toluene or ethanol), which cause complex explosion prevention. Water-based inks are also available for food-packaging applications.

24.3.2.4 Gravure Presses

Most gravure presses sold are large-surface, web-fed presses. They can be up to 4 m wide and run as fast as 15 m s⁻¹. To compensate for web stretching, the printing units have gravure cylinders of different diameters. For banknotes, securities, finishing and packaging applications, smaller presses less than a meter wide are available.

24.3.3

Flexographic Printing

24.3.3.1 General Description

Flexographic printing was invented for printing on board, paper, and foil for packaging applications. Its most characteristic feature is a flexible relief image plate. Only the raised printing areas carry ink; the rest of the plate must remain clean. Flexographic printing plates are made of photopolymer or rubber materials. Inking of the plate is done by an anilox roller, which is a cylinder with engraved cells on its surface. In contrast to gravure printing, the anilox roller is completely covered with cells. A metal cylinder (impression roller) applies the pressure needed to transfer the ink to the substrate (Figure 24.37).

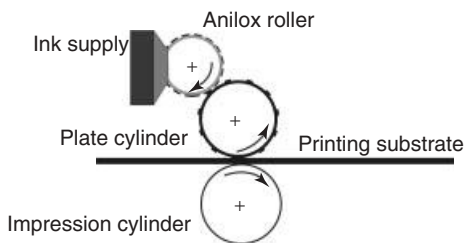


Figure 24.37 Flexographic printing. (Source: IDD, TU Darmstadt.)

Flexographic printing (often abbreviated to flexo) is primarily used in the packaging industry. Its market share has grown constantly over the years, driven mainly by improvements to print quality. Better anilox rollers and new technologies for imaging the plates have significantly improved the process. However, there is still a lack of standardization like that in offset printing.

Flexography is a relief printing method. Another method belonging to this group is letterpress (or letterset) printing, which was the first printing method ever used. Its name describes the principle quite well: letters covered with pasty inks are pressed onto paper. Quite unlike flexography, letterpress plates are hard and expensive. Today the traditional letterpress process has very little commercial importance.

24.3.3.2 Process

24.3.3.2.1 Ink Acquisition A chambered doctor blade is used normally to ink the anilox roller. It is a closed system in which ink circulates through a chamber. Two doctor blades seal the chamber and scrape excess ink off the roller. When using a chambered doctor blade, foaming can be a major obstacle to high print quality. The air, which is transported inside the chamber, and the foam generated by stirring combine to form air bubbles that interfere with filling of the cells on the surface of the anilox roller, resulting in printing defects. The tendency to foam depends mainly on the viscosity and formulation of the ink.

24.3.3.2.2 Metering of the Ink The engraved cells of the anilox roller are filled with ink in the chambered doctor blade. Excess ink on the cell walls is removed by the blade. Unlike gravure printing, the blade is usually at a negative angle (Figure 24.38).

Because of the negative angle, the blade only needs to apply slight pressure to scrape off the excess ink and convey it back into the chamber. In the contact zone between the anilox roller and the flexographic plate, the ink in the cells is transferred to the raised (printing) areas. This forms a homogenous layer on its surface. The homogeneity and thickness of this ink film depends on various

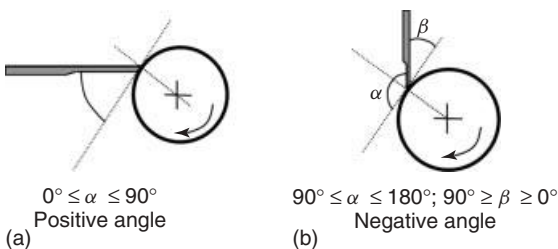


Figure 24.38 Different positions of the doctor blade. (a) A positive angle, which is normally used in gravure printing and (b) a negative angle as used in flexographic printing. (Source: IDD, TU Darmstadt.)

parameters: the geometry and screening of the cells, and also material properties such as the wettability of the plate and ink viscosity.

24.3.3.2.3 Ink Transfer to the Substrate Transfer of the ink from the plate to the substrate relies on the difference in surface tension between the two. In order for this to be possible, the wettability of the substrate must be greater than that of the plate.

Because the plate is flexible, the pressure between the plate cylinder and the substrate can be very low – an advantage when printing on fragile materials such as glass or silicone. Splitting of the film, especially in solid areas, can cause instabilities that result in surface defects such as *viscous fingering*.

24.3.3.2.4 Fluid Dynamics on the Substrate and Solidification The inks used in flexo resemble gravure inks, so the fluid dynamics in the printed film are also similar. During drying, concentration gradients can also cause defects in the printed film. Drying is accelerated by blowing hot air onto the substrate or exposing it to UV light in the case of UV-curing inks.

24.3.3.3 Inks and Process Properties

The viscosities of conventional flexo inks range from 20 to 300 mPa·s at 20 °C and high shear rates. Besides particle-based solutions and dispersions (normally in water or ethanol), more viscous UV-curing inks can also be used. These inks contain polymers that polymerize when exposed to high-energy UV light. Because they contain no dilutants, they are much more stable than conventional inks and deliver more consistent colors.

The amount of ink transferred depends mainly on the choice of anilox roller. This can be covered with cells of different sizes and depths, which determine its volume (expressed as $\text{cm}^3 \text{m}^{-2}$). Going beyond conventional electromechanical engraving, laser engraving allows “open” patterns such as hash marks (line engraving).

Flexographic plates are usually between 1.14 and 2 mm thick. These consist of a light-sensitive photopolymer and are imaged at a resolution of up to 8000 dpi (dots per inch). Direct laser engraving is usually used on rubber plates. An important role is also played by the tape used to attach the plate to the cylinder. “Sleeves” are now most commonly used; in these, the plate proper is permanently attached to a thin tube. Once an anilox roller has been chosen, there are only limited possibilities for varying the amount of ink that is transferred. One way to do it is by changing the ink viscosity. This parameter is measured inline; it can be modified by adding a solvent or by adjusting the temperature. Because the color of flexographic inks is less intense than in offset printing, up to eight printing units may be required for high-quality CMYK printing.

24.3.3.4 Flexographic Presses

Flexographic presses are usually web-fed. For packaging and label printing, in particular, presses with web widths between 0.3 and 2 m are used. A central impression cylinder (Figure 24.39), a stacked or an inline-frame design is used.



Figure 24.39 Flexographic printing press with central impression cylinder. (Source: Windmüller & Hölscher.)

24.3.4

Offset Printing

24.3.4.1 General Description

Offset printing is the most popular printing method used today, despite involving a very complex arrangement of the printing units. Offset involves a flat (planographic) image carrier; in other words, the printing and nonprinting areas of the plate are all on one level. Different surface properties are used to distinguish them: the material of the ink-accepting areas is oleophilic, while the nonprinting areas are hydrophilic. These are wetted with a thin film of dampening solution. The ink is only applied at the oleophilic areas. The image to be printed is then transferred to a so-called blanket cylinder and from there to the substrate (Figure 24.40). The advantages of offset printing include straightforward platemaking and a standardized process.

Apart from the plates, the inking unit is also fundamentally different from the other printing methods already described. It contains a large number of rotating

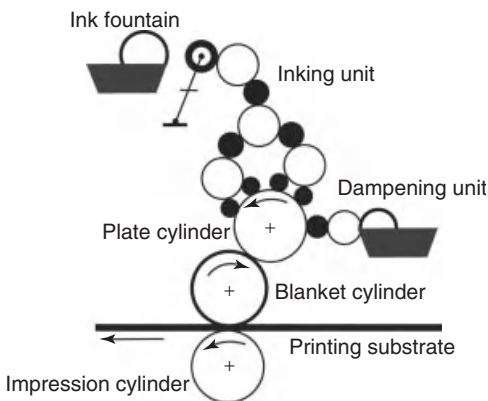


Figure 24.40 Offset printing. (Source: IDD, TU Darmstadt.)

rollers (typically between 10 and 20) that apply shear forces to liquefy the ink. This system also ensures flexible ink feed rates as required and makes it possible to print multiple colors without intermediate drying.

Offset printing is suitable for nearly all products produced by the graphic arts industry, but it is most often used for commercial work such as advertising, leaflets, and brochures, and for newspapers. The spectrum of usable substrates stretches from thin newsprint all the way to boards and plastic sheets.

A modern enhancement of the process is waterless offset, which dispenses with the dampening solution. The nonprinting areas of the plate are coated with ink-repelling silicone instead. This permits even finer screens and greater color saturation. However, it has not caught on widely owing to the greater costs involved.

In both conventional and waterless offset, a short inking unit can also be used. The ink is metered by an anilox roller, similarly to flexographic printing. The temperature of the anilox roller is changed to alter the viscosity of the ink and control the ink flow in this way.

24.3.4.2 Process

24.3.4.2.1 Ink Acquisition In sheet-fed offset, an ink fountain supplies the ink. A fountain roller rotates in the ink, acquiring a film whose thickness is individually set across a number of zones using keys. This permits the ink feed rate to be precisely adjusted to the printed image. A ductor roller oscillates between the fountain roller and the rest of the inking unit. In web-fed offset presses, which print faster, film inking units are used.

24.3.4.2.2 Metering of the Ink Preliminary metering of the ink is accomplished by the inking keys, each of which controls a zone about 30 mm wide. The rotational speed of the fountain roller and the frequency with which the ductor roller oscillates provide additional opportunities to regulate the ink flow. The ink is then conveyed from roller to roller through the inking unit toward the form rollers. On the way, the pasty ink is liquefied by strong shear forces. The many inking rollers ensure uniform ink feed and compensate for the discontinuous transfer of ink onto the plate. The ink form rollers, finally, transfer the ink to the plate. There it adheres only to the printing areas because it is repelled by the dampening solution covering the rest.

24.3.4.2.3 Ink Transfer to the Substrate The inked plate now transfers the ink to a cylinder covered with a rubberized blanket – the blanket cylinder – which in turn transfers it to the substrate. While this happens, part of the dampening solution is also conveyed to the substrate while the rest emulsifies with the ink. This process gets going during the makeready phase, which is why a certain number of unusable waste sheets have to be printed before the print process stabilizes.

24.3.4.2.4 Fluid Dynamics on the Substrate and Solidification After the ink has been applied to the substrate, its viscosity immediately increases, owing to the

fact that it is no longer being worked by the rollers. This very quickly results in a solid layer that can be overprinted. However, the high viscosity also prevents the formation of a uniform layer with leveling of any defects. Drying takes place by means of absorption and evaporation into the ambient air (coldset), blowing of hot air (heatset), or exposure to UV radiation in the case of UV-curing inks. With conventional inks, absorption into the paper accounts for most of the drying effect.

24.3.4.3 Inks and Process Properties

On the way from the fountain to the substrate, the ink is split many times: between each successive pair of rollers, roughly half the ink passes to the next roller. Because of this ink-splitting phenomenon, offset printing is not completely free of reverse effects: the print image tends to be transferred from the plate not only to the blanket, but also back to the inking rollers. To compensate for this effect, there are also rollers that move from side to side, called *oscillator* or *distributor rollers*. The ink itself is pasty but highly thixotropic; in other words, its viscosity varies greatly in response to shear stresses and the passage of time. Depending on the shear rate, its viscosity can be between 1 and 200 Pa · s. Conventional inks are oil-based particle dispersions; UV-curing inks are also used. The ink-splitting process in the inking unit also generates heat. Cooling systems are therefore employed to optimize print quality.

24.3.4.4 Offset Presses

Most commercial printing is done on sheet-fed presses. In these presses, grippers hold each sheet in place on the impression cylinder. Because the grippers extend above the cylinder's surface, the blanket cylinder has a corresponding gap. Most sheet-fed offset presses have an open-unit or unitized configuration with two or more printing units arranged in a row (Figure 24.41). Each printing unit lays down ink of a different color. Web-fed presses are used for large editions (e.g., newspapers). Many of these presses are so large that they fill an entire hall, printing more than four colors in a single tower comprising multiple stacked printing units.



Figure 24.41 Sheet-fed offset press with open-unit design. (Source: Heidelberger Druckmaschinen AG.)

24.3.5

Inkjet Printing**24.3.5.1 General Description**

Inkjet printing is a digital printing process that does not involve a plate. Consequently, each printed page can be completely different from the previous one. The image is formed directly on the substrate, controlled by digital data. Ink passes from a reservoir to a print head, where a nozzle propels it onto the paper. There can be either a single traveling print head or large fixed nozzle arrays.

Various inkjet technologies have become established in the market. These can be assigned to two broad categories: drop-on-demand (DOD) and continuous inkjet. In DOD inkjet technologies, a heating element (thermal inkjet or bubble jet) or piezoelectric element (piezoelectric inkjet) creates a pressure change in the ink reservoir that causes a droplet to be expelled (Figure 24.42).

In continuous inkjet systems, a pump creates a continuous stream of ink that is broken into individual droplets by a piezoelectric crystal vibrating at a high frequency. The ink droplets are then subjected to an electrostatic field to be charged selectively, which controls their direction of travel. Either the charged droplets are collected in a gutter for reuse (binary deflection) (Figure 24.43) or directed to various points on the substrate (multiple deflection). These systems are mainly used in roll-to-roll printing presses.

Inkjet printers are available in sizes ranging from very small models for home and small business use (predominantly DOD systems with a small number of nozzles) all the way to high-speed, roll-to-roll rotary presses with large nozzle arrays. Small inkjet units are also integrated in conventional printing presses for custom and personalized imprinting (addresses, use-before dates, etc.).

24.3.5.2 Process

24.3.5.2.1 Ink Acquisition The ink is transported to the print head by a pump (in continuous inkjet) or simple capillary pressure (in DOD inkjet).

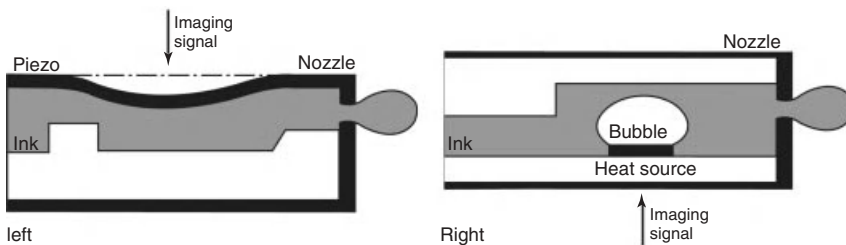


Figure 24.42 Different drop-on-demand (DOD) inkjet systems: (a) piezoelectric inkjet and (b) thermal inkjet. (Source: IDD, TU Darmstadt.)

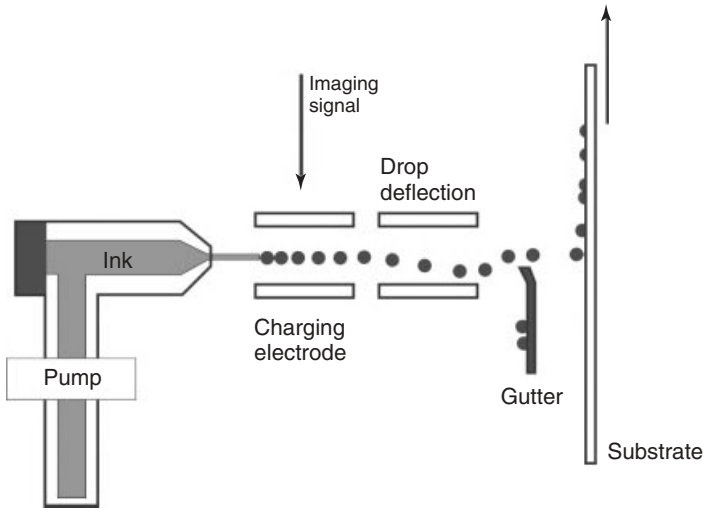


Figure 24.43 Continuous inkjet with binary deflection system. (Source: IDD, TU Darmstadt.)

24.3.5.2.2 Metering of the Ink In piezoelectric DOD inkjet systems, droplets are forced from the nozzle by pressure pulses created by a piezoelectric element that changes shape when a voltage is applied to it. Thermal DOD inkjet systems use a heating element that vaporizes the ink in a chamber. In each case, how the element is controlled determines how the droplets form and their size. The controlling signal therefore has to be adjusted to the ink and the print head. It is essential to prevent satellite (secondary) droplets from forming and air from passing through the nozzle.

24.3.5.2.3 Ink Transfer to the Substrate A droplet's velocity depends on the forces accelerating it and the resistance it encounters. These factors can be calculated and simulated to achieve optimal results. It is important to ensure a constant distance between the nozzle and the substrate, on the order of just a few millimeters.

24.3.5.2.4 Fluid Dynamics on the Substrate and Solidification When the droplets strike they can, depending on the substrate and the ink, bounce or splash. Spreading of the droplets on the substrate also plays an important role. While they dry, the droplets should merge and form continuous surfaces. Especially in thin lines, however, "periodic bulging" often occurs – the droplets only partially merge, and instead of a continuous line individual droplets are visible. At the edges of the printed dots or areas, there is also often waviness caused by the *coffee stain effect* (Figure 24.44). When the low-viscosity inks dry, gradients in the surface tension cause an accumulation of material at the edges while its concentration greatly decreases in the middle.

24.3.5.3 Inks and Process Parameters

The inks used in inkjet printing have a low viscosity between 1 and 50 mPa · s. They are typically water- or solvent based with low concentrations of solids. UV-curing inks are also used for industrial applications. The particles in dispersions should not be larger than a few microns across because most nozzles have a diameter of only 20–30 μm . High shear rates of up to 10^5 s^{-1} can occur within these fine capillaries. The inks therefore have to be specially designed for the print head; most printers require their own formulations.

24.3.5.4 Inkjet Printers

A large number of manufacturers offer printers for home and small business use. They are typically built for the A3 or A4 sheet format and print in color (CMYK). In most of them, the print head and ink reservoir form a single unit, so that the print head is always replaced along with the ink cartridge. This means that the print head only has a service life of a few hours. For industrial applications, there is a large range of versions for many different substrates and formats. There is a trend toward UV-curing systems, which are more reliable because the ink cannot dry inside the nozzles and clog them. In these systems, the print head and

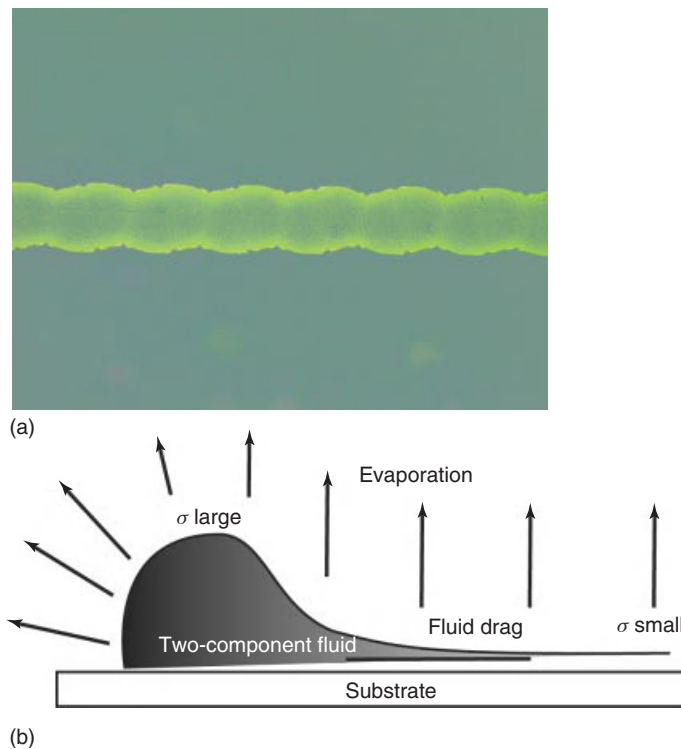


Figure 24.44 (a) Printed line with periodic bulging; (b) schematic diagram of the coffee stain effect. (Source: IDD, TU Darmstadt.)

ink reservoir are separate; the service life of a print head is 2000 h or more. For industrial roll-to-roll applications, mainly piezoelectric print heads are used. Inkjet is the printing technology with the greatest potential for further development. Print heads that expel droplets at a more constant rate and last longer can be expected, as well as page-width print heads with several thousand nozzles.

24.3.6

Electrophotography

Electrophotography (also known as xerography) has widespread applications; it is the technology used in most copiers and laser printers sold today. The heart of this process is a photoconductor drum that is uniformly charged before imaging. The image is projected onto the drum's surface by a controlled light source (laser or LED) that dissipates the charge in the nonprinting areas. Then, powdered (or, less commonly, liquid) toner is applied to the drum. The charged parts of the drum attract the toner and cause it to adhere. The resulting toner image is transferred to the paper by a combination of pressure and electrostatic attraction. Finally, the toner is fixed or fused by applying heat and pressure. To prepare the drum for the next cycle, it is completely discharged and cleaned of any remaining toner (Figure 24.45).

The printable substrates include, depending on the application, various kinds of paper, thin board, and foil. To enable color printing, either separate printing units are used, or else the same drum performs multiple imaging cycles. The printable formats and printing speeds vary greatly for different applications. Electrophotography is primarily used to print precut sheets, but some industrial systems print onto a paper web and then cut it into sheets inside the machine. There are innumerable vendors of xerographic devices for

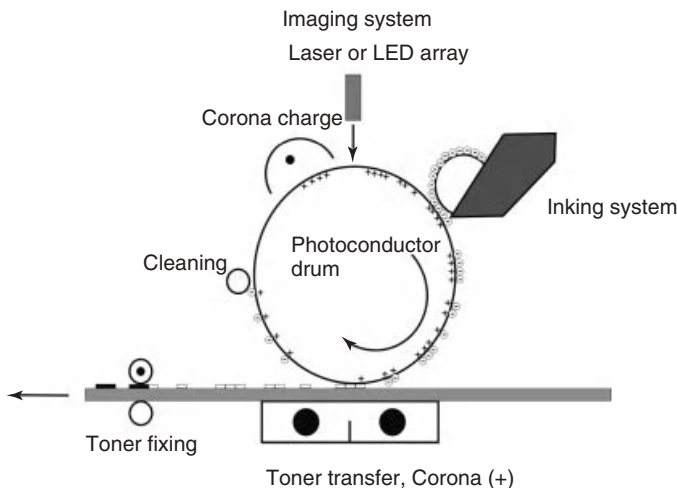


Figure 24.45 Electrophotography. (Source: IDD, TU Darmstadt.)

use in homes and small businesses. A few others offer machines for industrial applications, including systems with a liquid toner.

24.3.7

Process and Quality Parameters

Various criteria are used to evaluate the quality of print products. They include deviations from the original, fluctuations in color values, and so on, and also punctual delivery and cost. In order to measure various parameters determining the print quality, a color control strip is usually printed along with the image. In printing, a distinction is made between process and quality monitoring. Process monitoring is used to control the print process. In the conventional printing technologies, this is accomplished by measuring the color density. This procedure is standardized for each technology and each of the CMYK colors. Color density can be used as a measure of the thickness of a printed ink film. It is measured using an optical densitometer; the result also depends greatly on the paper used. Print quality is monitored with spectrophotometers. They measure the reflectance spectrum of inks (and paper) and use it to derive the standard color values X, Y, and Z. To assess quality, today the CIELAB color space with the coordinates L^* , a^* , and b^* is used. It is perceptually uniform, meaning that a given distance anywhere within the color space corresponds to a change in color of about the same visual importance. The difference between two colors (ΔE) can therefore be used as a measure of quality. In the printing industry, directional measurements are made using defined illumination and viewing angles of $45^\circ/0^\circ$ or $0^\circ/45^\circ$. Diffuse measurements using a sphere geometry are not as common. Unfortunately, it is impossible to convert measurements between the two systems.

24.4

Requirements on Paper

Rainer Klein and Martina Miletic

24.4.1

Where Do the Requirements on Paper for Print Products Come from?

The requirements on printing paper depend on a number of factors, the most important of which are cited in the following list.

- Use
 - application
 - * classical print products (newspapers, magazines, books, ...),
 - * packaging,
 - * printed products in the office and administration sector (laser, inkjet),
 - * special print products (decors, wallpaper, photographs),
 - surface

- * whiteness, luminosity, chromaticity coordinates,
- * gloss (glossy, semi-matte, matte),
- service life
 - * long,
 - * short,
- required quality level
 - * extremely high quality (HD printing, packaging),
 - * high quality (art calendars, illustrated books, packaging),
 - * medium quality (standard print products, packaging),
 - * low quality (e.g., newspaper printing, simple magazine inserts, packaging),
- economic aspects (basis weight of the print product → postage costs),
- functionality
 - * information,
 - * protection.
- Printing method (suitability criteria: quality, print run, other)
 - gravure printing,
 - offset printing (coldset, heatset, sheet-fed offset),
 - flexography,
 - digital printing (laser, inkjet, other),
 - artistic printing processes such as engraving shall not be discussed here.
- Printing process (runnability – efficiency),
- Print results (printability – print quality).

The factors listed above cannot always be clearly distinguished from one another and are frequently mutually dependent, in some cases to a great extent.

In the narrower sense, the requirements on the printing paper are derived from the selected printing process, the printing method, and the desired print results. The quality of a print product arises from the interplay of numerous, often interacting parameters due to the paper and printing process used. Figure 24.46 depicts important aspects of the printing process and print result. The printing process focuses primarily on productivity and any factors that might limit it such as web breaks and excessively slow setting (ink penetration). It must be mentioned in this context that performance characteristics of the printing process also have an impact on print quality.

The quality of the print result is frequently subsumed under the term *printability*. On the one hand, there are fundamental metrological parameters that can be used to characterize print quality. On the other hand, there are also printing elements that can pinpoint errors made in printing and processing. In addition, printing phenomena can occur, such as mottling and ghosting, and are usually due to rather complex causes.

Nowadays, manufacturers characterize printing paper by a number of fundamental paper properties originally developed for product development, production control, and quality control in the paper mill. In the absence of other characteristic values or sufficiently clearly defined requirements on the part of the printing industry, the quality specifications commonly agreed on in delivery contracts with

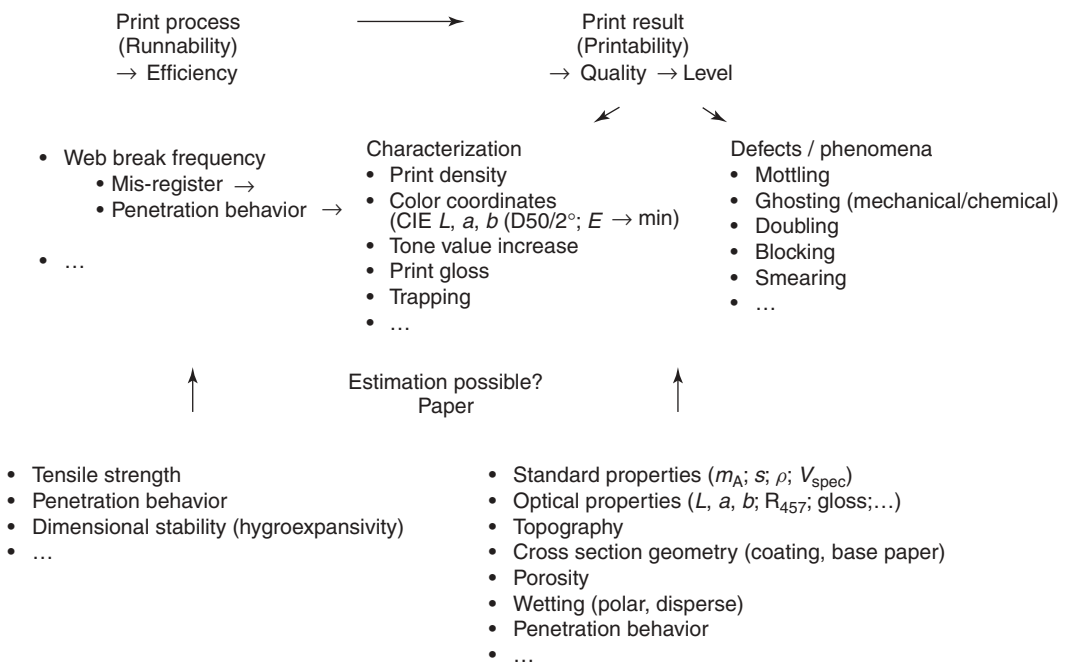


Figure 24.46 Paper – printing process – print results [10].

customers are usually based on a selection of these characteristics that are deemed relevant for the respective application.

The many attempts to determine correlations between these characteristic values and the paper characteristics that are in fact relevant in actual processing – hence, not only for printers – have up to now presented only mostly unsatisfactory results.

24.4.2

Standardization Aspects

24.4.2.1 The Paper Industry

A standard [11] exists for graphic paper in Germany that lays down the minimum requirements for some of the paper properties (Table 24.8).

The properties listed above are not adequate for the print-relevant characterization of paper. For this reason, an improvement of the same has been aspired to within the scope of the “Paper and Printing” Forum for the past few years in close cooperation with the paper and printing industries, the mechanical engineering sector, and the printing ink industry. Proposals for diverse characteristic paper values that the paper industry was supposed to recommend to the printing industry were discussed based on the results of the previous work conducted by the Forum [12] (Table 24.9).

The concrete characteristic values of graphic paper are normally published by the manufacturers on their respective Internet pages. In some cases, the paper characterization on the part of the manufacturers is more detailed than in Table 24.9. Mandatory minimum requirements or limits for the properties, however, have not yet been established.

Furthermore, there are standardization activities at the paper-print interface within the group of experts called *PAPERDAM* (Paper manufacturers meeting in Amsterdam) [13].

24.4.2.2 The Printing Industry

Standards relating to the prepress and printing processes exist in the printing industry. These standards occasionally place concrete requirements on the printing paper. These standards are

- ISO 12647 Parts 1–6 [14]
- MedienStandard Druck [15].

The MedienStandard Druck is published by Bundesverband Druck und Medien (bvdM) in Germany.

24.4.2.2.1 Gravure Printing In the section of the standard relating to gravure printing, a distinction is made between the different paper classes – coated paper, LWC paper, SC paper, and improved newsprint. Limits are also given for basis weight, gloss, roughness, and chromaticity coordinates.

Table 24.8 Technical delivery conditions for printed paper [11].

Feature	Offset printing DIN 19306-2				Gravure printing DIN 19306-3		Testing according to
	Uncoated		Coated		Uncoated	Coated	
	Reel	Format	Reel	Format	Reel	Reel	
Relative equilibrium moisture content(%)	$x \pm 6$	50 ± 6	$x \pm 6$	50 ± 6	35 ± 5	35 ± 5	DIN 53118
Color difference ΔE -wood-free	≤ 0.7	≤ 0.7	≤ 0.7	≤ 0.7	≤ 0.7	≤ 0.7	DIN 6174
RP-containing	≤ 1.0	≤ 1.0	≤ 1.0	≤ 1.0	≤ 1.0	≤ 1.0	–
100% RP	≤ 2.0	≤ 2.0	≤ 2.0	–	–	–	–
Bekk smoothness (s)	–	–	–	–	>1500	>1500	ISO 5627:1992
PPS roughness (μm)	–	–	–	–	<1.1 (SC)	<1.1	DIN ISO 8791-4
Glossy	–	–	<3.0	<3.0	–	–	–
Matte, not embossed	–	–	<5.0	<5.0	–	–	–
Opacity (%)	$\geq 100 \text{ g m}^{-2} : 90$				$\geq 55 \text{ g m}^{-2} : \geq 90$		ISO 2471:1998
	Opacity is dependent on the filler content, type of pigment, and paper luminosity. Values must be agreed upon accordingly for other basis weights.						
Oil absorption (g m^{-2})	–	–	–	–	<5	<5	DIN EN 20535
Residual folding strength (CD) (kN m^{-1})	>0.6	–	>0.6	–	–	–	Fogra method
Air permeance (ml min^{-1})	–	<2000	–	<2000	–	–	ISO 5636-3:1992
Width-related breaking strength (MD) (kN m^{-1})	>1.7	–	>1.7	–	>1.7	>1.7	DIN EN ISO 1924-2
Hygroexpansivity coefficient (CD) (%)	<0.15	<0.15	<0.15	<0.15	–	–	DIN ISO 8226-1
Deviation from the delivery (%)	<0.03	<0.03	<0.03	<0.03	–	–	–
Printability (Pick strength) (m s^{-1})	>1.5 No ink repulsion nor lifting of the paper coating must occur during the printing process					–	Zellcheming
Blistering resistance	160 °C in an oil bath					–	DIN 19306-2

ΔE – Color difference (heatset only).

RP, recovered paper; PPS, Parker print surf; SC, supercalendered; CD, cross direction; MD, machine direction.

Table 24.9 Recommended characteristic paper values – paper and print forum [12].

Feature	Gravure	Offset		Testing according to
		Reel	Sheet	
Basis weight	x	x	x	ISO 536
Thickness	–	x	x	ISO 534
Specific volume	x	x	–	ISO 534
Absolute moisture content	x	x	x	ISO 287
Rel. equilibrium moisture content	–	–	x	DIN 19306-2
	–	–	–	DIN 53118
Roughness/smoothness				
Parker print surf – S10	x	x	x	DIN ISO 8791-4
Bendtsen	–	x	x	DIN ISO 8791-2
Gloss				
TAPPI	x	x	x	ISO 8254-1
DIN	–	x	–	ISO 8254-2
Opacity	x	x	x	ISO 2471
L^* , a^* , b^*				
D65/10°	x	x	x	ISO/DIS 5631-2
D50/2°	–	–	x	ISO 13655
Luminosity	–	x	x	ISO 2470-2
Tensile strength, stretch at break	x	–	–	ISO 1924-2
Bending stiffness	–	–	x	DIN 53121

24.4.2.2.2 Offset Printing As laid down by the process standard offset, paper is broken down into five classes (Figure 24.47), and concrete property levels are defined for basis weight, chromaticity coordinates (L^* , a^* , b^*), gloss, and ISO brightness. The tone value increases and its tolerances that are permissible in printing are defined for these paper classes as well (A–F curves in Figure 24.47). Good print results should be achieved if the paper meets the property requirements and if it is within the tolerance range of the tone value increase.

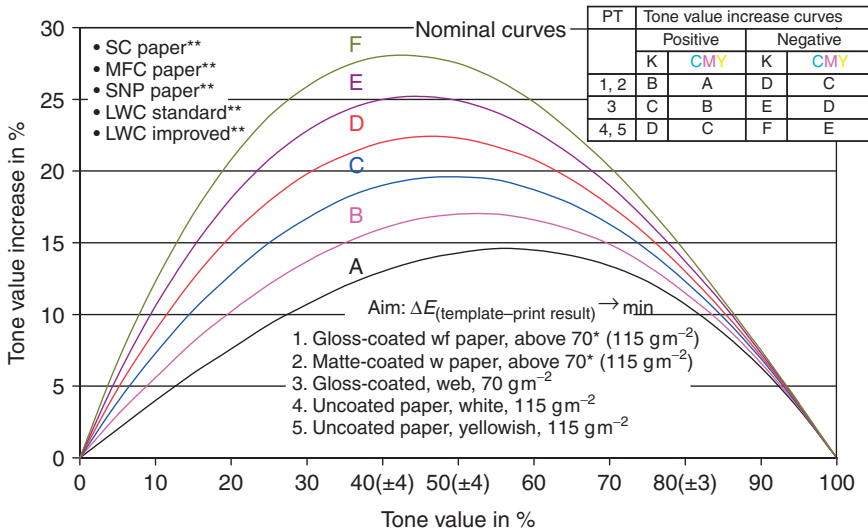
In view of the huge diversity of offset papers, it has been demonstrated that a classification with five paper classes is inadequate. The classification will be expanded for this reason by adding another four classes.

24.4.2.2.3 Flexographic Printing The printing stock for flexographic printing is broken down into

- corrugated board (coated or uncoated),
- coated paper,
- uncoated paper

- film,
- foil.

Concrete requirements on the chromaticity coordinates must be defined for the respective printing stock.



Values according to ISO 12647 - 2; *Median standard Duck 2010, bvdm; **These groups are not currently standard types according to ISO 12647-2. However, they are not to be incorporated into this standard in future; For the different paper types in ISO 12647 the *L*, *a*, *b* values, gloss, ISO brightness and grammage are listed; PT = Paper Type.

Figure 24.47 Tone value increase in offset printing according to the Process Standard Offset (PSO) ISO 12647-2 [14].

24.4.3

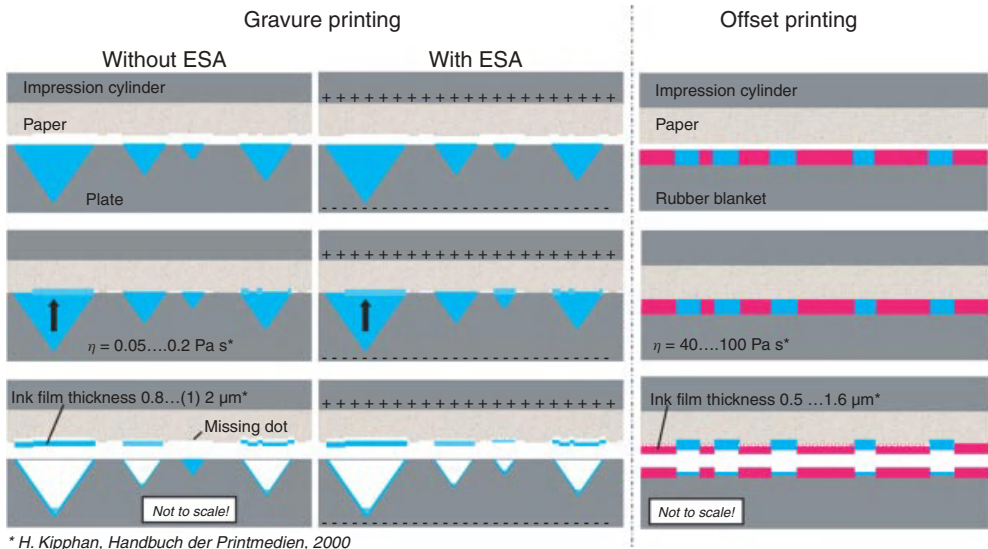
Requirements on Gravure Paper

Currently, gravure printing is carried out in two ways:

- toluene based: mass printing papers (magazines; catalogs, etc.),
- water based: package printing (suitability for contact with food), decor printing, etc.

Depending on the solvent used, slightly different requirements are placed on the printing paper, which is discussed in more detail below.

In gravure printing, the low-viscosity printing ink contained in area- and depth-variable cells must be transferred to the paper by contact between the paper and printing ink in the nip (Figure 24.48). The likelihood of ink transfer, especially from those areas of the printing plate with low print density, increases with rising smoothness (contact), absorbency (capillary action), and compressibility



* H. Kipphan, *Handbuch der Printmedien*, 2000

Figure 24.48 Schematic diagram of ink transfer in gravure and offset printing.

(contact) of the paper. This explains why corresponding requirements were placed on these paper properties in the past in an attempt to prevent missing dots.

The introduction of ESA a few years ago is conducive to ink transfer owing to an electric field that is formed. The requirements on gravure paper have declined in importance to some extent although they continue to be relevant.

In the past, the gravure process was generally used to print mass market products, which placed high demands on the print quality of SC paper and LWC/MWC paper (Figure 24.49a).

In addition to these print products, other products appeared on the market many years ago that placed less stringent demands on quality and thus on the printing paper itself (Figure 24.49b); improved newsprint [16] in most cases. Despite the use of ESA, missing dots continue to occur today, especially with the use of supercalendered paper. These missing dots can be traced back to extreme depressions (craters) stochastically distributed throughout the paper and are not necessarily reflected in the smoothness values of the paper [17, 18].

In addition to the remaining problem involving missing dots, optical homogeneity in printed areas of low print density continue to grow in importance in gravure products as well (inset of Figure 24.49a), that is, not only is the absolute value of a property relevant (e.g., smoothness, penetration behavior), but the temporal and spatial changes in the same are also of interest.

In the case of water-based gravure, the above-cited requirements are supplemented by the demand for a certain amount of water resistance so that the change in the dimensions of paper, which tends to be hydrophilic, remains within tolerable limits and does not negatively impact print quality.

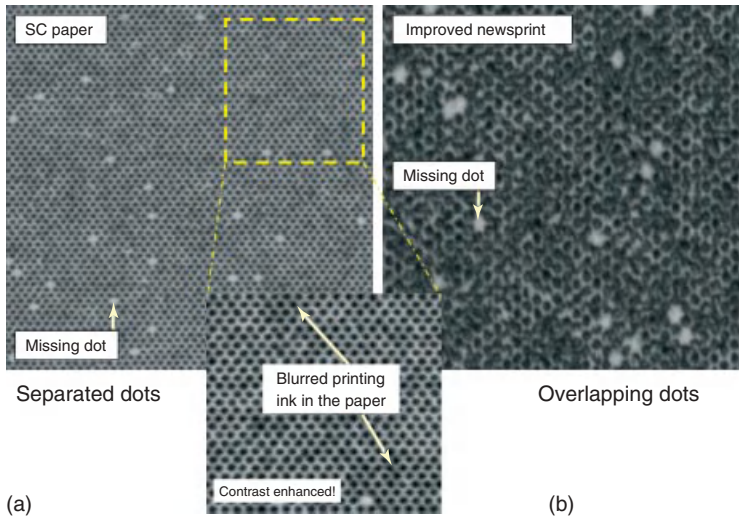


Figure 24.49 Gravure products with separated and blurred dots.

24.4.4

Requirements on Offset Paper

24.4.4.1 Cross-Procedural Issues

A distinction is made in offset printing processes between

- coldset printing
- heatset printing
- sheet-fed offset printing.

They dictate the requirements placed on the paper and in some cases additional underlying procedural requirements.

On the basis of the principle of ink transfer from the rubber blanket to the paper by ink splitting in a moist environment, the following basic requirements arise for offset paper in the light of this printing principle (Figure 24.48):

- adequate resistance to water → dimensional stability → register accuracy;
- adequate wettability and good sorption behavior (ink setting behavior) for fountain solutions and low-viscosity ink components (profitability);
- less stringent requirements on smoothness than in gravure printing, although not entirely irrelevant [19];
- adequate surface strength due to film splitting (dusting, coating ruptures) [20, 21];
- surface pH.

Sufficient water resistance is also necessary on the surface of uncoated paper in particular in order to prevent fiber rising (the water-induced erection of individual fibers not adequately anchored in the fiber network).

Satisfactory surface strength is also necessary to minimize buildup on the rubber blanket that closely relates to the profitability of the offset process (washing cycles) [22].

Beltz [23] compiled a list of print-related paper properties for offset paper. The following properties were regarded as being relevant: tensile stress, ink trapping, pressure and tension loads in the nip in the z -direction, setting behavior, moisture behavior (absorption, elongation, and shrinkage), and heat behavior (shrinkage, elongation, and hornification), as well as the uniformity of the paper in the same batch.

24.4.4.2 Paper for Coldset Printing

Mass market products (newspapers) with low quality requirements are generally printed on uncoated paper using the coldset process.

Both wood-containing virgin fiber paper and recovered fiber-based paper (recycling paper) are used in the basic pulp. The proportion of recovered fiber can amount to 100%. Requirements on the brightness values (luminosity), optical homogeneity (dirt specks), and chromaticity coordinates (a red cast in some cases due to the magenta ink) are placed on the recovered fiber-based paper. These requirements, however, result from the quality requirement on the printed product.

24.4.4.3 Paper for Heatset Printing

The heatset printed products are very versatile and this in turn results in a broad spectrum of applications for the resultant paper. Both uncoated and coated paper are used with basis weights ranging from 29 to 130 g m^{-2} . Papers with basis weights up to and exceeding 170 g m^{-2} are also used occasionally. In such cases, however, the setting in the rotary press (the blanket-blanket pressure) must be adjusted accordingly. At a given basis weight, the specific volume (thickness) plays an essential part in the runnability of the paper and also acts on the mechanical ghosting that can occur in particular in the case of high-quality heatset products. The ghosting effect is influenced not only by the dominant printing parameters but also by the paper itself. While ghosting tendency declines as the bending stiffness of the paper increases, it increases as roughness decreases [24].

The paper is exposed to extreme conditions in heatset printing. Water is absorbed in the printing units, thus increasing the absolute moisture from ~ 4.0 to 4.5% . The moisture is reduced to $0.5\text{--}1.0\%$ in the subsequent web dryer and then increases again to $\sim 2.0\text{--}3.0\%$ because of re-moisturizing. This moisture change occurs in the very short time of $\sim 2 \text{ s}$ at a machine speed of 15 m s^{-1} . The absorption of water causes the hygroscopic medium paper to change its dimensions (fan-out effect) that may also have consequences for print quality, as papers that undergo smaller dimensional changes usually produce better printing results.

The problems associated with the absorption and release of water can also have an impact on the converting of the print products. During papermaking, internal tension is created (frozen) in the paper during the drying process in the paper machine. This tension may be changed by the absorption and release of water and

is manifested in the form of waviness or unevenness in the print product (fluting, cockling) [25].

24.4.4.4 Paper for Sheet-Fed Offset Printing

The spectrum of printed papers is by far the largest in sheet-fed offset printing. Both uncoated and coated grades are used with basis weights in excess of 50 g m^{-2} . The bending stiffness of the paper is closely correlated with its basis weight (thickness). Adequate bending stiffness is required in particular for the trouble-free feeding of sheets into the printing press.

The paper should exhibit good ink setting behavior for economic reasons. This is important both for printing press performance and for the time that elapses between face printing and back-side printing. Furthermore, these papers should have a good dimensional stability and adequate resistance to water; otherwise, contact with the water from the fountain solution would lead to passer/register problems. Owing to the highly viscous ink used in all offset (lithographic) printing technologies and its transfer mechanism, a high surface strength for these papers is required. The topography of the surface in offset printing depends on the desired quality of the product and spreads from very smooth papers to those of relatively high roughness.

A compilation of measured paper properties for some common market papers is given in [26].

24.4.5

Requirements on Paper for Flexographic Printing

Flexographic printing is very adaptable regarding the printing substrates owing to the very flexible, raised printing plate made of polymer materials. Printable materials include elastic films, aluminum foil, paperboard, corrugated board, tissue products, pulps and nonwovens, and labels. In addition, flexo printing is also used to print wallpaper and laminating paper as well as a variety of coated papers. The percentage of flexo-printed newspapers is growing in some countries (England, Italy, and United States).

The diversity of printing substrates as well as the properties of the print products to be achieved requires a broad spectrum of printing inks (water based, solvent based, and UV- and electron beam curable). This in turn makes it difficult to define uniform requirements for the printing substrates. The choice of printing substrates and the necessary properties derived from such a choice therefore depend to a large extent on the product category and its quality requirements. Especially in the packaging sector, the choice of materials depends on the purpose of the packaging. Of great importance in this context is that the paper for food packaging must be suitable for contact with food, that is, there must be no or no appreciable health impairment of the food contained therein.

The low-viscosity printing ink is transferred under slight pressure (“kiss print”). The roughness of the printing substrate is only of secondary importance because of the flexibility of the plate. Nonetheless, partial ink transfer problems (UCA – *uncovered areas*) [27, 28] may occur in solid areas if there is not enough smoothness. The low viscosity of the printing ink causes “coffee stain effects” during drying, which can be reduced by the rapid setting behavior of the printing ink into the paper (Figure 24.50).

24.4.6

Requirements on Paper for Digital Printing

24.4.6.1 Electrophotographic Printing (Laser Printing)

The electrophotographic printing method is used both in offices and in administrative work, as well as for commercial print products with small to medium print runs.

Owing to the nature of the method, the paper must be capable of rapidly building up an adequate static charge to ensure good toner transfer. The charge should also dissipate quickly, however, so that the sheets do not stick together during transport or during converting (risk of jamming).

The toner is normally fixed at temperatures between 180 and 200 °C, that is, the paper is subjected to extreme stress just as in heatset printing. Problems with flatness and paper transport may arise as a result of shrinkage. Moreover, the paper must also exhibit sufficient surface tension amounting to $\geq 35 \text{ mN m}^{-1}$.

Depending on the purpose of the application, that is, authenticity of documents, a certification of printing papers [29] as well as prints [30] may be demanded. The

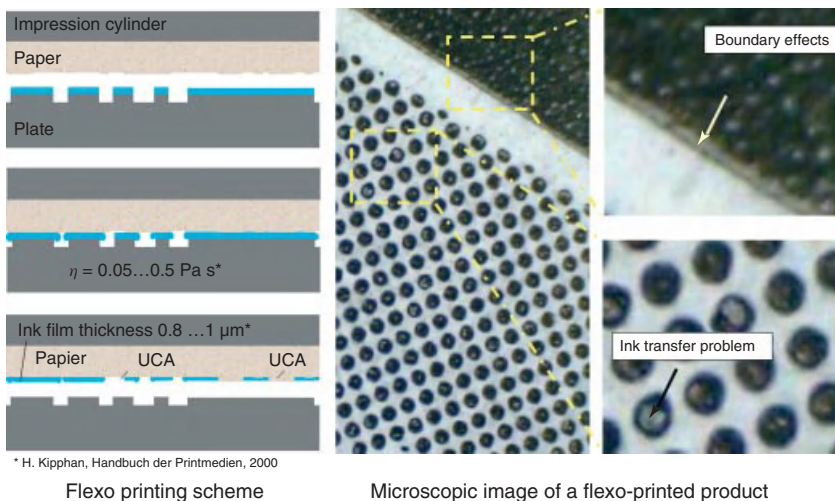


Figure 24.50 Schematic diagram of ink transfer in flexographic printing; flexographic patterns.

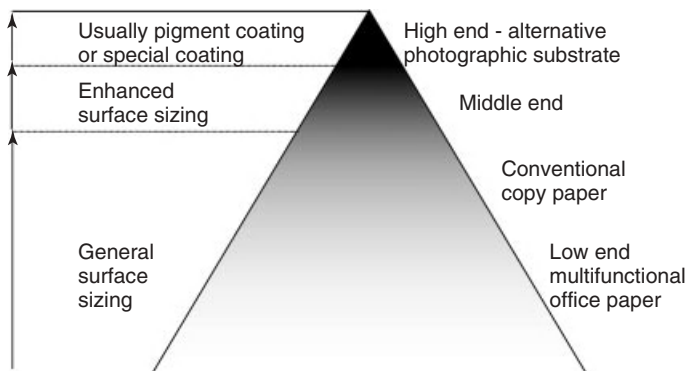


Figure 24.51 Segments of inkjet grades [31].

suitability of copy and print systems for authorized notary documents is defined in a special German regulative¹⁾.

24.4.6.2 Inkjet Printing

Nowadays, a variety of different paper qualities are being offered as inkjet paper, as the requirements for different user segments can vary considerably (Figure 24.51).

Multipurpose paper constitutes the lower market segment. It is normally used for all digital printing methods in office and communication settings and is usually uncoated, wood-free paper produced by neutral or alkaline papermaking processes [32, 33].

The paper in the medium-quality segment – multifunctional office paper – is, in most cases, surface sized with a specially adapted sizing agent and provides good print quality at acceptable prices [33]. These coatings are provided with a view to preventing or minimizing feathering and wicking as well as the coalescence of printing inks (Figure 24.52). In addition to these effects, the uniformity of the entire surface of a print is also of importance.

Professional end users in particular, who work as designers in graphic arts companies, for instance, or who make presentation materials, place very high demands on brilliance, optical color density, and dot sharpness. These papers that are currently being used to an ever greater extent for the production of photographs are at the top of the pyramid. Excellent inkjet suitability is achieved by using microporous aluminum oxide or silicon oxide coatings that are transparent because of the size of the pigment particles. These pigment layers are frequently applied to a PE layer so that the pore volume of the coating has to absorb all the transferred ink. As a consequence of the increasing printing speeds, the setting behavior of the printing ink must be constantly adjusted for such paper (this applies to dyes as well as pigmented inks). Ink setting behavior, however, competes with brilliance.

1) PTS-Prüfungszeugnisse über die Eignung von Kopier- und Drucksystemen für die Herstellung von Urschriften notarieller Urkunden gemäß § 29 der Dienstordnung für Notare (DONot).



Figure 24.52 Important effects in the assessment of the sharpness in print outlines in inkjet printing – feathering, wicking (according to [34]), and bleeding [35]

A number of requirements are placed on the quality of the inkjet print results across all products, the following list merely containing the most essential requirements: high print density, good color reproduction (chroma), gloss (for glossy paper), prominent dots, no wicking or feathering, no bleeding, no bronzing, no mottling, and no coalescence. The majority of these requirements are determined mainly by the ink setting behavior of the printing ink.

In addition to the requirements that stem from print quality, there are other requirements that are also of interest such as flatness and curl, which occur because of the sometimes rather large aqueous portions of the ink [36].

The quality of inkjet prints is defined in a DIN standard in Germany [37].

24.4.6.3 Cross-Technological Requirements on Paper

Now that specific aspects of the individual printing methods and the resultant requirements on the printing paper have been discussed, a few cross-procedural requirements will be considered below.

The runnability of the paper in the printing press is crucial for the productivity of the printing process. Good runnability assumes that the paper passes through the printing press without any web breaks (reel paper) or stoppers (sheet paper). This requires sufficient strength of the paper (tensile strength, tear resistance) and bending stiffness. The absolute strength values are of interest in this context, that is, the lower the paper basis weight, the lower will be the absolute strength values of the paper. In addition, it must be taken into consideration that paper strength is reduced by the transferred fountain solution in the case of water-based offset printing. The dry modulus of elasticity (E_D) and wet modulus of elasticity (E_W) are often used in this context to characterize the paper.

Water-induced changes in paper dimensions (dimensional stability, flatness, curl) are significant both for runnability and print quality in all printing methods that operate with water-based printing inks or in conjunction with water (fountain solutions). Paper that exhibits only minor changes has clear advantages.

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25

Health and Safety

25.1

Occupational Health and Safety

Winfried Harren

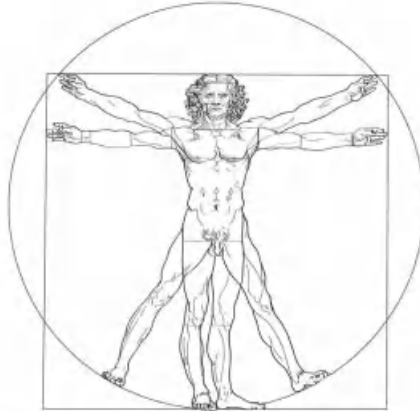
25.1.1

Introduction

Occupational health and safety is a generic term covering the fields of occupational safety and health protection. Improvements in health and safety at the workplace are a constant challenge. Future performance of a company depends on wise application of innovative technology, structures that are as lean and efficient as possible, and a qualified, motivated, and healthy workforce. Investments made in these three areas are deemed to improve the company's competitive position ("win-win situation"). Best performances seem to be realized by those companies, which internalize that the focus on wellbeing of their work force should be in the center of interest – a conviction which famous Leonardo da Vinci (1452–1519) has figured out in one of his drawings (Figure 25.1).

- **Health protection:** Where workers have to work under hazardous conditions, have no adequate qualification, or are not sufficiently supported by their colleagues, work can be hazardous to health. Analyzing the present state allows to detect the potential for improvements. The main analysis instruments are risk assessment, analysis of absenteeism, health circles, workshops, and employee interviews. Hazards to health at the workplace caused by damaging effects have a direct influence on occupational safety.
- **Occupational safety:** Improving occupational safety is focused on the technical and organizational aspects of health and safety. The main idea is to identify hazards that are defined as the coincidence of persons and danger (possible harm to persons) and to avoid them as far as possible.

By combining the various methods of analysis, it is possible to identify necessary actions and problem areas and determine local measures.



25.1.2

Health Protection

25.1.2.1 General Remarks

The aim of health protection is keeping the workforce in a healthy state and improving their health in the sense of a holistic approach (for example, enforced by the WHO). Most countries have statutory regulations obliging companies to take all measures required to prevent work accidents, professional diseases, and health risks at the workplace and to provide an effective first-aid system. Measures for preventing occupational health risks are determined by their long-term benefits and sustainability.

There are four organizational areas where such measures can be applied:

- design of the workplace,
- job organization,
- arrangement of physical factors, and
- consideration of psychological factors.

As an example, the main emphasis would consequently be on the following three areas:

- **Ergonomic aspects:** They deal with the aspects of physical and intellectual work. The aim is to adapt working conditions to the abilities and skills of human beings and to design work and workplaces accordingly.
- **Workplace health promotion:** It is not physical fitness alone which contributes to motivation, performance, and commitment of employees but also their psychosocial well-being.

Helpful measures are, for example,

- improving the organization and conditions of work
- encouraging active employee involvement
- strengthening individual competence.

- **Psychological stress:** It is the nature of work that it requires a certain amount of effort – physical and/or intellectual effort. In our world of quickly changing work environments, creating new methods of work and organization psychological stress is drawing more and more public attention. We are aware that psychological stress is inextricably linked to our lives. This does not only have negative effects but there can also be a number of positive aspects, for example, stress can be considered as the precondition for successful learning. But the results can be negative if a certain limit is exceeded.

Splitting up into separate main areas should not be understood as drawing a dividing line but is rather based on the multicausal perspective applied on the aspects of health and behavior.

25.1.2.2 Hazardous Substances

Hazardous substances are used among others in the production of paper, or they may be generated in the production process. Such substances are, for example, hydrogen peroxide, used as bleaching agent and for ink detachment, caustic soda for adjusting the pH value, and hydrogen sulfide which is created as an odorous by-product of biochemical sewage clarification.



In order to protect persons and the environment from substance-related damage, such hazardous substances must be handled with great care.

Hazardous substances in this sense are any substances, preparations, and products, which

- show one or more hazardous characteristics such as
 - harmful to health (caustic, irritating, toxic, and very toxic, carcinogenic)
 - endangering reproduction, mutagenic
 - explosive, oxidizing, flammable to highly flammable
 - sensitizing, for example, causing allergic reactions
 - dangerous to the environment
- generate or release dangerous substances during production or use,

- may transmit pathogenic agents, and
- may have been assigned a limit value for the amount and duration of exposure at the workplace.

In Germany, such limit values stand for that concentration of a substance where acute and chronic health damage is not to be expected. The necessary precautions when handling such products are described in technical rules for hazardous substances, safety data sheets, and technical instructions. They are the basis for instructions and documentation for the safety training of the workforce.

Until 2015, the classification, marking, and packaging of dangerous substances will be standardized internationally. There will be 28 hazardous classes, distinguished by:

- physical–chemical hazards
- harmful to health, and
- dangerous for the environment.

It goes without saying that there is a basic obligation for each employee to ensure to his best endeavors his own safety and health and to follow employer's instructions. This includes wearing personal protective equipment while and as long as a hazardous situation exists.

25.1.2.3 Noise

Noise is a negative sound event that is annoying and harassing for all living creatures and can be harmful to health.

The amount of noise is defined by the sound pressure level, a logarithmic measure expressed in decibel (dB). In order to take account of the characteristics of the human ear, frequency is usually weighted (generally by frequency filter A). Such weighting can be recognized from the value dB(A).



- The hearing threshold of healthy persons is about 0 dB(A), the pain threshold is 120 dB(A).
- Normal talking between two persons reaches 60 dB(A).

- Paper machines, refiners, and compressors generate about 90–100 dB(A).
- Cutting and hammering of metal sheet cause a level of about 100–115 dB(A).

Daily noise exposure levels (averaged sound pressure level for an 8 h shift) from 85 dB(A) onward can cause noise-induced hearing impairment. The hazardous level is reached even for relatively short exposure if the sound level is high, for example, already after 15 min for 100 dB(A). Risks to hearing caused by noise will even be doubled if the sound level is increased by 3 dB(A). The subjective perception of noise however is that a sound is sensed as twice as loud only if the noise level is increased by 10 dB(A).

Loss of hearing from noise is incurable!

That is why ear protection must be used from 85 dB(A) onward. In addition, employers are obliged to take technical and organizational measures for noise reduction (Section 25.2). In Germany, preventive medical checkups must be provided for employees exposed to noise at the workplace.

25.1.2.4 Hazards Caused by Electricity

Work on electrical equipment and devices must be carried out by qualified electricians only.

Contact with parts under voltage results in burning of skin and/or muscle spasms. The seriousness of harm depends on the voltage and/or the current flowing through the body. Hazardous electric arcs that cause burning can occur when switching high currents and in case of short circuits. High-voltage currents passing through the heart can even be fatal.



25.1.2.5 Intoxication

In case of intoxication by, for example, chemical substances, vapors, and gases, countermeasures must be taken immediately in order to save the injured person. Individuals that have been poisoned must be treated by a doctor without delay.

In Germany, countermeasures are specified in the safety data sheets.



25.1.2.6 Hazards Caused by Radiation

Injuries can be caused by heat (infrared), light (visible and UV light), laser, and ionizing radiation.

- High-intensity thermal radiation can cause burning of skin and in case of constant exposure acute and chronic inflammation. Permanent exposure can also be the cause of clouding of the eye lens (cataract).
- Light rays can cause blinding and UV rays can cause electro-ophthalmia, for example, during welding. Extensive exposure to UV radiation provokes skin blistering and cell deterioration. It is therefore essential for employees to use skin, face, and eye protection.
- Lasers (light amplification by stimulated emission of radiation) radiate light with an extremely high energy concentration. They are especially hazardous for the eyes. In Germany, laser areas must be provided with a laser warning sign and protective glasses be used. Medical monitoring of the staff is required.
- Ionizing radiation is generated by X-rays and by the decomposition rays produced by radioactive substances. Radiation is neither visible nor perceptible, but it damages the human organism and can provoke serious biological damage.
 - Alpha rays have a reach of about 4 cm and penetrate skin tissue to fractions of millimeters.
 - Beta rays have a reach of up to 8 m and can penetrate the human body up to 10 mm.
 - Gamma rays have a reach of several hundred meters. They are especially hazardous as they pass through the entire human body comparable to X-rays.

For all these rays, the inverse-square law applies according to which the intensity of radiation is inversely proportional to the square of the distance. All ionizing radiation sources must be effectively screened and clearly marked.

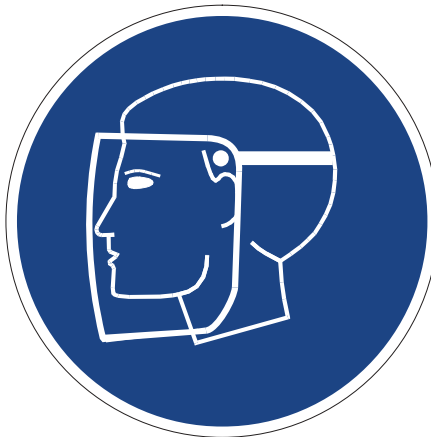
In Germany, a special permission is required for using radioactive substances.



25.1.2.7 Personal Protection

This denominates not only any equipment intended to protect the body from harmful influences (safety helmets, safety glasses, ear protection, gloves, special work clothes, and safety shoes) but also breathing protection and rope fastening systems to prevent falling from large heights.

Employees are required to use protective equipment as intended whenever hazards endangering persons cannot be avoided by technical or organizational protective measures. Examples are handling of hazardous substances and exposure to high levels of noise.



Employers are responsible for providing the required personal protection equipment, training employees, and ensuring that the equipment is used as intended.

25.1.2.8 Safety and Health Protection Signs

Signs are omnipresent in the working environment, whether they relate to prohibition or mandatory requirements, warnings, and emergency. Figure 25.1 shows a selection of internationally known prohibition and mandatory signs, warning and emergency signs, and their significance.


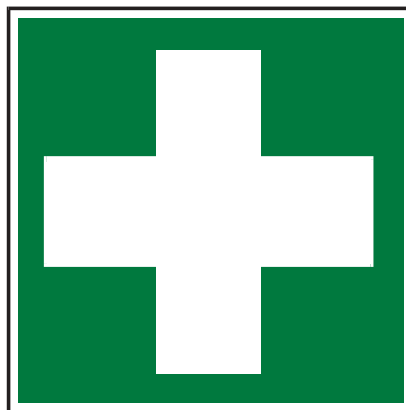
 No fire, naked flames, or smoking	 No pedestrian crossing	 Do not touch	 No unauthorized persons allowed
 Attention tripping	 Warning of automatic start	 Warning of industrial trucks	 Warning of toxic substances
 Use eye protection	 Wear safety helmet	 Use ear protection	 Use protective gloves
 Emergency exit	 First aid	 Eye rinsing equipment	 Automatic external defibrillator

Figure 25.1 Drawing by Leonardo da Vinci (1425–1519).

25.1.2.9 First Aid

In case of an accident, every person is obliged to immediately assist others to the best of his capabilities and with due care. Exceptions to this rule are cases where assistance is not reasonable, for example, if this would put the person himself at risk or other important responsibilities cannot be observed (for example, securing colleagues, but not protecting the workshop or the paper machine) or where qualified assistance is already being provided for, for example, by a medical doctor.



In general, companies already provide emergency services (first aid, in-house paramedics, occupational health services, and company doctors) and have emergency alarm systems. Every employee must make himself familiar with emergency plans in order to be able to take the right action in case of emergency.

Employees who are involved in an accident but are still capable of acting and persons who have knowledge of a nearby accident must for a start observe the following basic principles:

- keep calm and overcome the own shock
- think first, then act
- avoid additional damage
- protect the site of the accident
- get help or ask others to get help
- make an emergency call – take care of the basic elements of an emergency call
- do not leave injured persons alone, never give them anything to eat or to drink.

The basic elements of an emergency call are

- Where did it happen? Exact description of the location
- What happened? Short description of the sequence of events
- How many injured persons are there? Give number as exact as possible
- What are the types of injuries? Slight or life threatening injury
- Who is making this call? Give your own name.

Every employee can try to apply the basic elements of first aid. When an injured person is detected he/she would first of all control:

- **Consciousness:** response yes/no, unconscious?
- **Respiration:** breathing yes/no?
- **Circulation:** pulse yes/no?

Consciousness, respiration, and circulation are the basic functions of life. If one of these functions is disturbed, the situation may already be life threatening. Disturbances must be diagnosed and respective measures be initiated immediately.

As the extent of injuries cannot always be identified right from the start, it is important to check on the injured regularly. With all urgency, care, and concern, it should be clear that the safety of the helper must always be ensured.

25.1.3

Occupational Safety

25.1.3.1 Pressure Equipment

Vessels and other parts with equipment under pressure are called *pressure equipment*. According to 97/23/EC, they are

- steam boilers
- piping
- equipment under pressure, and
- equipment with safety function.



The stipulations laid down in Directive 97/23/EC apply to pressure vessels (pressure equipment) with an inner pressure of over 0.5 bar. Depending on the pressure level and the pressure content product ($p \times l =$ maximum overpressure in bar multiplied by content in liters), pressure vessels are categorized into four classes in Europe. Depending on the category of the equipment, tests must be carried out by qualified personnel or notified bodies before commissioning and then in regular intervals.

The general rule is that work on vessels and systems under pressure is prohibited.

25.1.3.2 Fire Protection

Fire protection comprises all measures and equipment required for preventing and fighting fires. Essential preconditions for the prevention of fires are, for example,

- correct installation of electrical equipment and cables,
- secured storage of combustible material,
- cautious handling of open flames (welding jobs, smoking, etc.), and
- tidiness and cleanliness.



Effective fire fighting requires

- exact description of organizational measures,
- keeping access and escape routes free,
- providing firewalls and doors and so on,
- ensuring that extinguishing systems and equipment are ready for use any time,
- regular checks of their deployment capability.

25.1.3.3 Industrial Trucks

Industrial trucks are in-plant vehicles used for transporting and lifting of loads, for example, fork trucks, electric carts, pedestrian operated trucks and storage, and retrieval equipment. They are generally powered by diesel fuel, batteries, and gas.



Most countries require

- that combustion engines are permitted in totally or partly enclosed spaces only if exhaust fume concentrations in the respiratory air are below the hazardous level.
- that fork trucks and industrial trucks with driver's cab or seat must be driven only by persons of minimum 18 years of age, which are physically capable and trained and engaged to do the job.

25.1.3.4 Load-Lifting Equipment in Hoisting Operation

Hoisting operation relates to load-lifting equipment on cranes, winches, lifting, and pulling devices that are intended for lifting and transporting of single loads. Load-lifting equipment is, for example,

- container harnesses, clamps, load-lifting magnets,
- crane hooks, permanently installed gripping units or pliers,
- hook chains and ropes, lifting belts, loop cords, and round lifting slings.



Load-lifting equipment must be checked for visible damage before first commissioning and at frequent intervals and must be replaced immediately if needed and be serviced by qualified personnel.

25.1.3.5 Falling Hazards on Papermaking Plants

Nowadays, machinery used in the production and finishing of paper is large plants with a width of more than 11 m and a length of over 500 m. Their height often ends up at 10 m above operating level. Workplaces on such machinery require platforms and catwalks (see EN 1034 Part 1, Machinery Directive 2006/42/EC) in order to ensure that workplaces can be accessed at all times. Access to such platforms and catwalks is generally provided by stairways and exceptionally free-standing or fixed ladders. According to ISO 14122 Part 3, standardized fall-off protection is required for fall-off heights of 0.6 m and above. Rare interventions such as felt changing can be done without fixed fall-off protection as the situation inside the machine does not allow permanently installed protection equipment. In such cases, safety is ensured by personal protective equipment, for example, safety harnesses, fall arresters, or direct roping up.



A special situation is protection required against falling into vessels with rotating components, for example, pulpers, that is, a railing with a standardized height of 1.2 m (EN 1034 Part 1). It must be ensured that such railing cannot be misused climbing through or stepping on.

25.2

Noise Abatement and Protection

Herbert Holik

25.2.1

Overview

Noise is present in daily life be it in private areas or at the workplace and also in paper mills. Here, high noise levels can be found at places such as the debarking drum or in the vicinity of refiners, calenders, or gears. Heavy vibrations of a machine or of machine parts may cause heavy noise – and may also rupture or reduce their functionality. Here, noise can be taken as indicator for malfunction.

Elevated sound levels may cause earnest health problems such as hearing impairment (noise deafness and tinnitus), annoyance, sleep disturbance, or heart problems. Less noise results in better concentration, and less mistakes are made. So noise abatement also contributes to accident prevention.

Paper mills are obliged to protect their personnel against noise and its negative effects on health, well-being, and effectiveness according to given standards. The supplier industry supports the mill with some low-noise machinery. On the other hand, in some process steps, noise generation is inevitable today, so noise dampening solutions must be installed or the personnel has to be protected by special means.

25.2.2

Some Basics on Acoustics

Sounds are pressure fluctuations propagating in a fluid such as air or water. They occur with a certain number of cycles per second (frequency). The whole frequency range of sound can be divided into three sections:

- The infrasonic range that lies below 20 Hz and is used, for example, to study geological phenomena such as earth quake.
- The audio range (20–20 000 Hz), which is audible by human ears and used for acoustic communication such as speech or music.
- The ultrasonic range (above 20 000 Hz), which is applied, for example, in medicine by ultrasonography.

Sound waves propagate in air (or water, etc.) with the speed of sound depending on the fluid and its physical conditions. The speed of sound is about 3.5 times

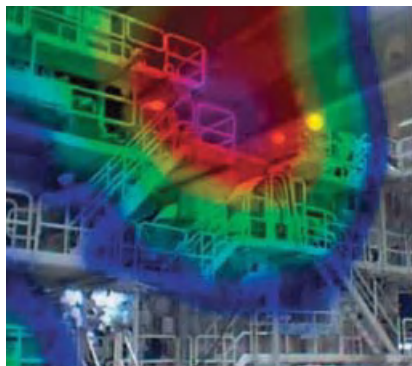


Figure 25.2 Acoustic image of a suction couch roll. (Source: Voith.)

higher in water (1450 m s^{-1} at 20°C) than in air (about 344 m s^{-1} at 20°C). In steel, it is circa 5050 m s^{-1} . With raising temperature and humidity, the speed of sound in air increases. The speed of sound in water largely depends on air content (the higher the air content, the lower the speed of sound) and increases with temperature.

The sound pressure level (loudness) is measured in natural logarithmic scale in decibels. This means that an increase of loudness by 3 dB is doubling the sound pressure level. Thus an addition of a noise source to a second one of the same loudness increases the total pressure level by 3 dB(A). The loudness propagating from a sound source is reduced in intensity with distance whereby low frequencies carry over longer distances.

For understanding and analyzing noise phenomena, acoustic time signals are sampled. The results can be presented, for example, as octave bands or as a spectrogram that displays pressure level and frequency profile over time. Acoustic images (Figure 25.2) inform about “hot spots” (similar to thermographical measurements) of noise for a fast overview and analysis.

25.2.3

Sound, Noise, and Men

The sensitivity to sound is individual, subjective, depending on whether the sound is wanted and well accepted or felt as annoying noise. Visitors of a disco endure very high loudness and have fun, whereas a starting jet or traffic noise may impair their comfort. The smallest sound pressure level that a human ears can hear is the “threshold of hearing” and has been defined as 0 dB. An increase of 10 dB(A) is felt by men as doubling of loudness. 120 dB(A) is defined as the pain threshold.

Sensitivity to noise is different for each person, only measurement can give objective data. The perception of the human ear for loudness (dB) is different for different frequencies. A noise of around 2000 Hz is felt to be more annoying than higher or lower frequencies of the same decibel value. As measuring results should also be representative for human hearing sensation, filters are used for different

applications (dB(A), dB(B), and dB(C) filters or the new ITU-R 468 noise weighting filter).

25.2.4

Noise, Noise Abatement, and Noise Protection in the Paper Industry

Noise may be generated directly in the air, for example, by the siren effect of suction rolls or by the kinetics of a free air jet exiting from an orifice (exhaust noise). When throttling an airflow, speed of sound is attained at a pressure ratio of about 1 : 2, generating heavy noise. Throttling water or suspension flow may generate cavitation when the local pressure close to the smallest flow cross section is reduced down to equilibrium steam pressure (depending on temperature).

Numerous examples for indirect noise generation by mechanical vibrations are found in a paper mill but also turbulences in thin wall pipes of large diameters may contribute to a high noise level.

There are primary and secondary measures to reduce noise. Primary measures aim to reduce noise generation at the source or completely avoid it. Secondary measures try to interrupt the noise path from the source to people and to the environment.

25.2.4.1 Primary Measures

For primary measures, the most radical solution is to abolish the noise-generating machine or machine part. Unfortunately, this is possible only in very few cases. One example is the noise of gears. A lot of them are installed, for example, in the dryer section. By using speed control motors – instead of gears – directly flanged to cylinders (or other rolls in other sections), the overall noise level is reduced.

In case of noise generation by piping, vibrations-improved support reduces noise – and additionally avoids defects at armatures and fittings. Noise generated by cavitation can be avoided when installing a second throttling valve in series. When the high pressure is only needed in certain operating conditions, a speed-controlled motor for pumps – or blowers – can be helpful and saves energy as well.

For lower noise generation, the cutting angle (angle between the bars of the rotor and stator) of the refiner fillings (Figure 25.3) should be large as, for example, required for fibrillating refining, on the other hand, it should be small for fiber cutting.

Suction rolls in the forming and press sections are the dominating noise generators in the paper machine. These rolls consist of a perforated roll shell and have an evacuated suction chamber at the inside (Figure 25.4). During operation, the small holes in the shell are once evacuated in the suction zone and then suddenly refilled with air when having passed the sealing. This induces a high-frequency noise (suction roll whistling) of each hole, the roll thus acting like a plenty of sirens. The loudness increases – or may even decrease for a certain speed range! – with increasing machine speed. For today's fast-running paper machines, the loudness is 95–105 dB(A) at a broad frequency spectrum. To reduce noise generation of the suction rolls,



Figure 25.3 Pattern of a refiner filling showing the bars. (Source: Voith.)

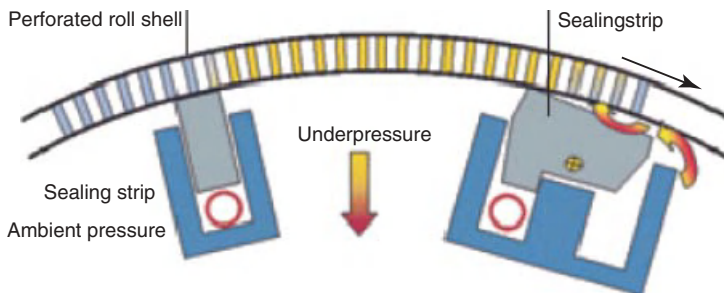


Figure 25.4 Suction roll principle. (Source: Voith.)

- the drilling pattern is optimized in a way that the holes are not aligned in axial direction in order to avoid simultaneous refilling of the holes (in suction press roll applications, shell strength may limit some drilling pattern);
- the shape of the sealing lip is designed in a way, which allows a nonabrupt, “soft” refilling of the shell voids with air [1].

Calender stack barring generates heavy noise like hammering. The reason is a regular waviness of the roll surface that increases with operation time of the roll. In Figure 25.5, the measured waviness of the circumference of a calender roll is shown. A high noise level of about 110 dB(A) in the vicinity of the calender stack was measured excited by these nonuniformities of the roll surface. Barring reduces regrinding intervals and lifetime of the roll cover. The negative technological results are regularly occurring bars in CD of low thickness and high gloss. Prolonged lifetime of the roll cover and lower noise level can be expected with rolls providing a passive or active dampening effect (Chapter 23).

25.2.4.2 Secondary Measures

Secondary measures include noise reduction effect by

- insulation of the noise source by noise barriers
- noise absorption
- protection of personnel against noise.

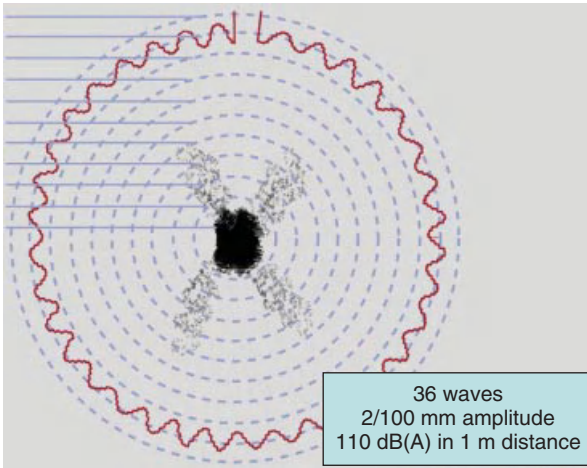


Figure 25.5 Measured waviness of a soft covered calender roll generating heavy noise. (Source: Voith.)

25.2.4.2.1 Insulation of the Noise Source by Noise Barriers For example, refiners are often installed in a separate room with good noise insulation as these machines are very loud. Single refiners or other single loud machines can also be covered by an insulating hood, consisting of noise dampening and absorbing material. But the access to the covered machines for service and repair is more time consuming. Good insulation also comprises avoidance of vibration propagation through pipings and foundations.

25.2.4.2.2 Noise Absorption Sound is reflected in the machine room at walls and the ceiling. Reflection can be reduced by absorbing material. Sound absorbing tiles are applied for the walls since longer times in paper mills. Noise absorbing plates can also be used fixed at walls and the ceiling (Figure 25.6). In Figure 25.7, the noise level is plotted, which had been measured along a paper machine. The measurements had been taken at a defined distance. The diagrams show the noise before and after the absorbers had been installed at walls and the ceiling [2].

25.2.4.2.3 Silent Areas Primary and secondary measures are not sufficient to reduce the noise level to an acceptable level in many places in a paper mill, for example, in the machine hall. Therefore, silence cabins, for example, at certain positions along the paper machine, are installed. The main control panels where people usually work are also noise protected to a high degree.

25.2.4.2.4 Personal Protection against Noise Health-related noise level limits have been established worldwide, which may still differ from country to country. In Europe, the prevailing standard is that for a certain average exposure hearing protection must be available (>80 dB(A)) or worn (>85 dB(A)). The exposure time

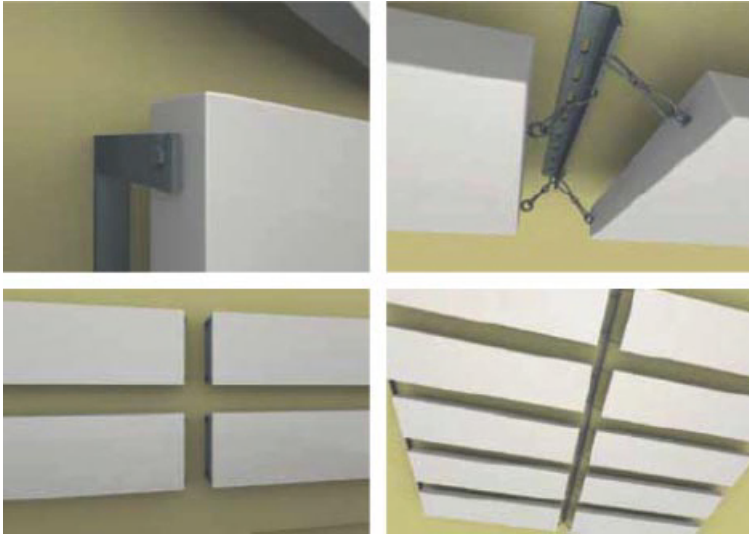


Figure 25.6 Noise absorbers for walls and ceiling. (Source: Voith.)

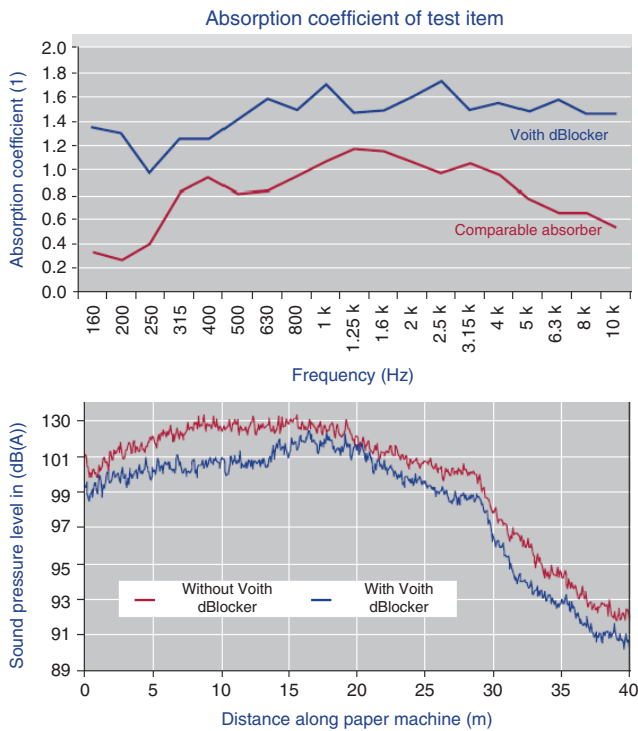


Figure 25.7 Noise level along the paper machine with and without noise absorbers. (Source: Voith.)

Table 25.1 Noise generation, abatement, and protection of personnel and environment in the paper industry.

Noise abatement and protection				
Principle solution	Avoid noise generation	Reduce noise generation	Reduce noise propagation	
		In paper mill	In neighborhood	
Examples	Delete noise generator <ul style="list-style-type: none"> - rpm controlled motors (direct coupled) instead of gears Subcritical pressure reduction <ul style="list-style-type: none"> - water (cavitation) - air (sound velocity) by - 2nd valve - rpm controlled pump motor Fix vibrating pipings	Refiner fillings <ul style="list-style-type: none"> - bar angle Suction roll <ul style="list-style-type: none"> - drilling pattern - sealing lip Calender rolls <ul style="list-style-type: none"> - surface grinding - passive damper - active damper Pumps in optimum operating range	Noise insulating machine housing Separate room for noisy machines Insulate <ul style="list-style-type: none"> - pipes - foundation Reduce noise reflection <ul style="list-style-type: none"> - wall structure (tiles) - absorbing elements 	Insulated control panel Silence cabins Ear plugs Limited exposure time Low air exhaust velocity Few and small openings in building Short opening times

of personnel to heavy noise is limited depending on the average noise level (Section 25.1). Usual personal protection means are ear plugs.

25.2.4.3 Noise Protection of the Neighborhood of Paper Mills

Special attention is paid to noise pollution that may annoy people in the neighborhood of a paper mill. Paper mills work day and night, whereas noise level limitations are different for day and night. So, for most noise sources, the night limit has to be followed.

The moisture of the air, the wind direction and air turbulences as well as the noise frequency determine how the noise level is reduced over distance and how annoying it is. Higher frequencies are damped better than lower ones. Noise dampening by distance is better with low air moisture. Exhaust air velocity should be low as noise energy of an air jet is dissipated not only by internal (within the jet) but also by external (boundary layer of the jet) friction [3]. Low exit velocities and small openings are favorable. Noise dampers at the outlet should be used.

Openings (e.g., doors) from the machine hall to the outside should be a minimum in size and number, and the openings in normal situations should be kept closed. Here, also organizational measures may reduce annoying noise at night time.

In Table 25.1, the principle solutions for noise abatement and protection are summarized showing typical examples.

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2. Graf-Müller, H. (2010) Voith dBlocker Effectively Reduces Noise. together, vol. 31, p. 45.
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26 Plant Engineering and Energy

26.1 Plant Engineering

Thomas Mack

26.1.1 Scope and Task of Plant Engineering

Paper mills are built up of different plant sections, which in turn are divided into different subsystems. These sections are

- Power plant/boiler house
- Fresh water treatment
- Raw material storage
- Stock preparation
- Paper production line
- Finishing
- Finished goods storage
- Effluent plant
- Infrastructure (workshops, roads, etc.).



Figure 26.1 Principle sketch of a paper mill.

Figure 26.1 shows a principle sketch of a paper mill.

The task of plant engineering is to combine the different plant sections with their individual subsystems to an economical and ecological paper mill. This is usually done in three steps:

- Basic engineering
- Detail engineering, and
- Procurement engineering.

Plant engineering also has to take into account the requirements for later service requirements, such as maintenance ore field studies.

With plant engineering, the total costs both for investment of a project and later on for the mill in operation (energy, raw material, and water) are significantly influenced. Therefore, focus has to be put on

- No overengineering (e.g., pump capacities, tank volumes, etc.)
- Optimized layout (building size, piping, etc.)
- Suitable subsystems (energy and flexibility)
- Intelligent interaction of the single plant sections or subsystems (e.g., combined heat recovery)
- Coordination between all involved parties
- Control of all activities to minimize the project time from contract date to take over.

To fulfill all these requirements, a pre-engineering is usually needed, with the following minimum scope:

- Balance of Plant (BoP)
- General process flow sheet
- Definition of main machinery
- Mill or process line layout.

26.1.2

Principle Methods of Plant Engineering

Plant engineering is an iterative process and covers the interfaces between design of the machinery, automation, and civil engineering as well (Figure 26.2).

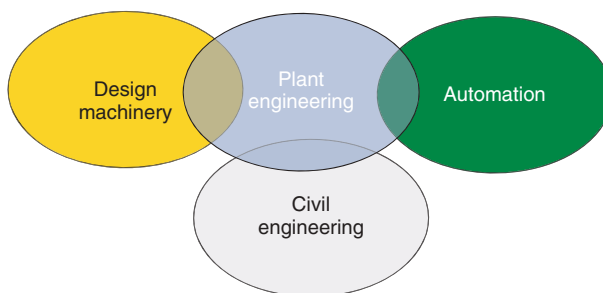


Figure 26.2 Relevant interfaces in plant engineering.

The involved parties have to share information according to a specified exact time schedule to ensure the shortest possible project period of time. Intelligent systems and combined databases are used to fulfill these demands.

The principle process is shown in Figure 26.3. A more detailed description of the three steps in plant engineering is given in the following chapters.

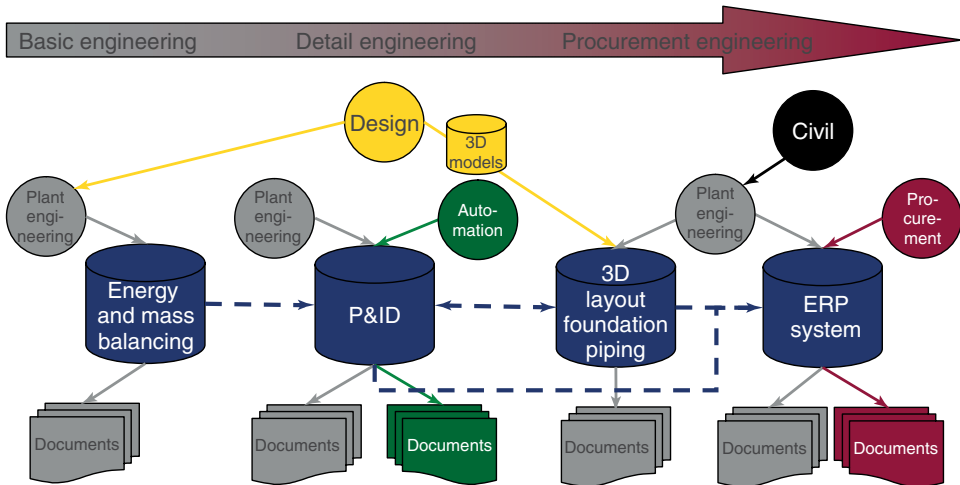


Figure 26.3 Principle process and activities in plant engineering.

26.1.3

Basic Engineering

Both the manufacturers of the individual machines and the process engineers for the different processes are responsible for the basic engineering. Ideally, the plant engineering department has the competence to handle the basic engineering for the main machinery as well as the core processes, which eases the integration of the subprocesses.

The result of basic engineering is documents, which contain all necessary information to integrate the machinery into the paper mill. The provided documents are

- Consumption data
- Mass and energy balances
- Process and instrumentation diagrams (P&IDs)
- Lists and specifications
- Layout and load drawings
- Position drawings
- Individual foundation plans.

The block diagram in Figure 26.4 shows the relationship between the different sections in a paper mill.

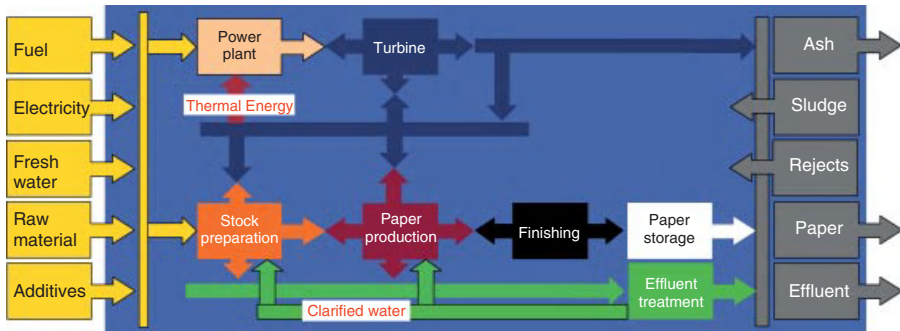


Figure 26.4 Relationship between the different sections in a paper mill.

26.1.3.1 Balancing

The complex interactions of all individual systems of a paper mill affect the investment and operating costs. To determine the optimal integrated solution, an overall mill balance is required, including electrical and thermal energy, raw material, water, and effluent. In Figure 26.5, a principle sketch of the BoP is shown with the

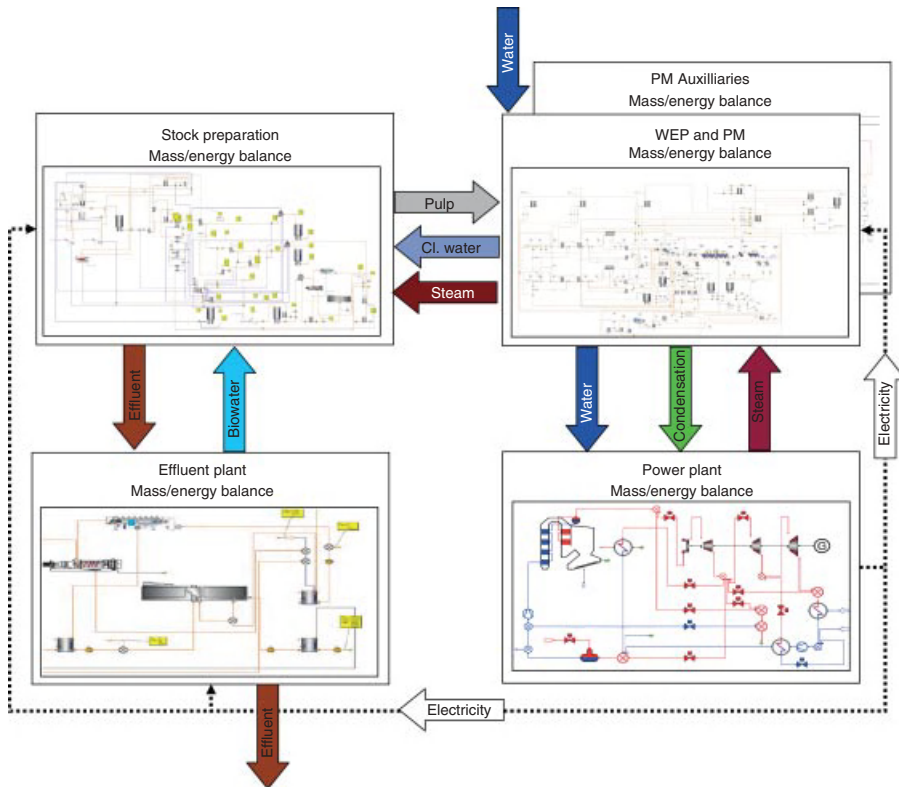


Figure 26.5 Principle sketch of a "Balance of Plant" (BoP).

interconnections between stock preparation, wet-end process (WEP) and the paper machine, the paper machine auxiliaries, the effluent plant, and the power plant.

These mass and energy balances are required for each section to define the individual machines and plant equipment for the different sections. The interfaces have to be defined to find the optimum connections between the different plant sections for the best BoP.

26.1.3.2 Process and Instrumentation Diagrams

There is a strong interconnection between process engineering and automation engineering. Both involved parties are handling partly the same equipment (e.g., motors, field devices, etc.). So, engineering and automation departments should use the same database with different templates for automation and engineering for the required documents (Figure 26.6). The benefits are

- One single database for one project
- All data input is done only once
- Excellent data quality
- Reduced number of defects
- Reduced engineering period
- Reduced total expenditure.

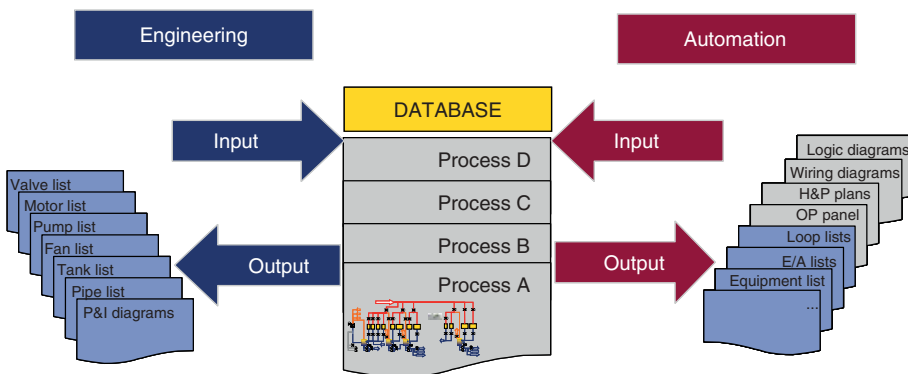


Figure 26.6 Collaboration between engineering and automation on the same database.

26.1.3.3 Layout and Load Plans

The layout is the base for all following engineering steps. The following items have to be considered when developing an optimal plant or process line layout:

- Space availability at mill side
- Installed equipment
- Optimized flow of materials
- Access for maintenance
- Minimum of piping and ducting
- Optimized building size.

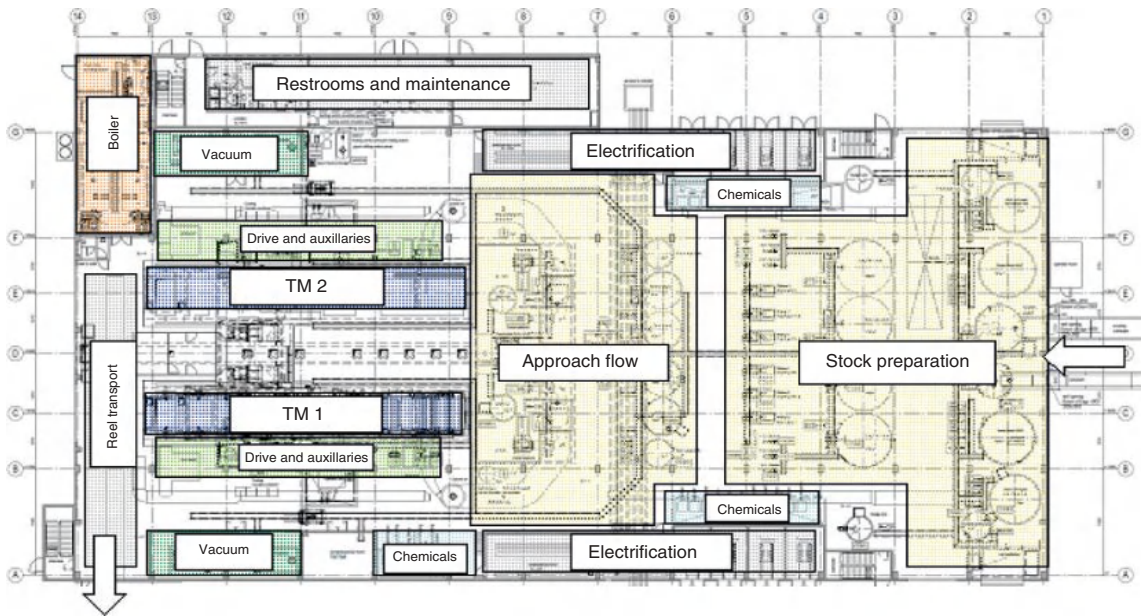


Figure 26.7 Example of the layout of a tissue mill with two 2 lines in one common building.

The load plans are the basic documents for civil engineering to execute the static and dynamic calculations of the building and the machine track. To cover all the required information of the civil engineering, the following data have to be indicated:

- Static and dynamic loads of equipment
- Static load of pipe systems
- Static and dynamic loads of the paper machine
- Earthquake factors
- Main openings.

Figure 26.7 shows an example of the layout of a tissue mill with two 2 lines in one common building.

26.1.4

Detail Engineering

To fulfill the requirements regarding procurement engineering and erection schedule, a 3D plant model is state of the art. It comprises the complete machinery, the complete piping, and ducting as well as the steel work and the main cable trays (Figure 26.8).

Figure 26.9 shows such a 3D model of tissue-producing plant with two machines. The design models of the machinery are integrated in the plant model with the help of an interface.

To shorten the engineering period, all involved plant engineering disciplines are working in one common plant model from the beginning of the project. The required documents for third parties, such as civil, will be generated as an extract of this model.

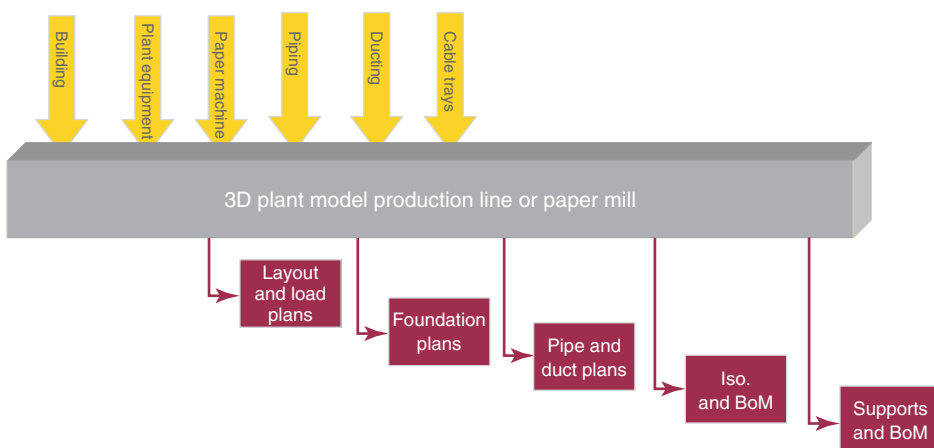


Figure 26.8 Input to establish a 3D plant model and resulting plans.



Figure 26.9 3D model of a plant with two 2 lines in one common building.

26.1.4.1 Foundation Plans

For civil detail engineering, plant foundation plans with the following content have to be supplied:

- the building constructions according to the civil plans;
- location of machines and equipment with dimensioned foundation bases including recesses for anchor bolts;
- location and size of the required embedded plates;
- drive foundations;
- openings in the floors, walls, and roofs;
- walkways and platforms;
- floor drainage.

26.1.4.2 Outline or Manufacturing Drawings

To be able to purchase the plant equipment such as tanks, chests, and steel components, for example, platforms for maintenance, outline or manufacturing

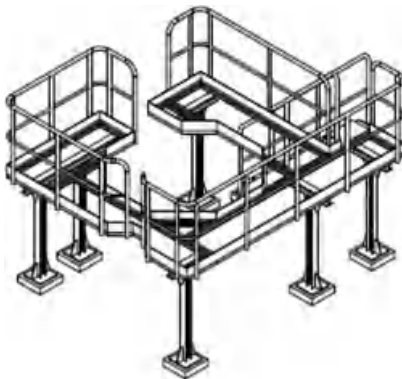


Figure 26.10 Outline drawing of a service platform screen.

drawings are required. Which kind of drawing is required depends on the capability of the sub-suppliers as regards own detail engineering.

Figure 26.10 shows an example of the outline drawing of a service platform of a screen, and Figure 26.11 shows an example of the outline drawing of a white water II tank.

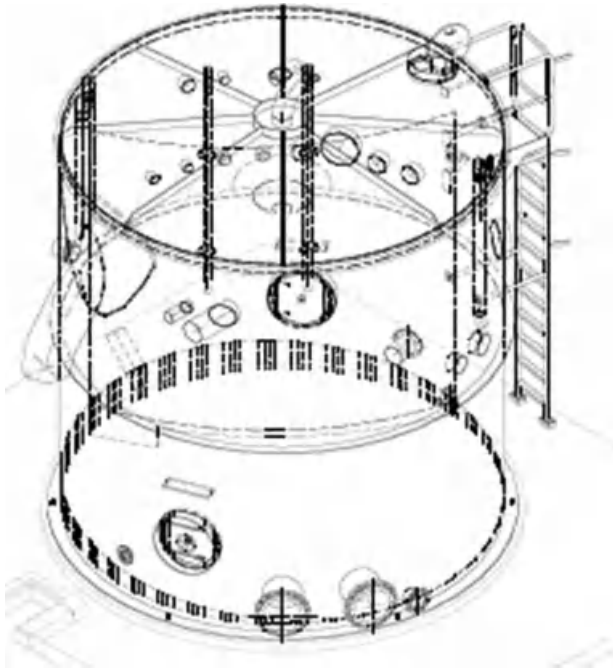


Figure 26.11 Example of the outline drawing of a white water II tank.

26.1.4.3 Piping

The machine equipment of each system in a paper mill has to be connected with pipe systems. Hereby, the different local regulations, such as the Pressure Equipment Directive, as well as mill standards have to be considered. For special pipes, for example, steam pipes, stress calculations have to be executed to fulfill the regulations of the authorities.

The output of piping engineering is isometric drawings (ISO), bill of materials, and the drawings for piping supports (Figure 26.12). The total number of single pipelines can lie between about 200 for a tissue line and up to about 8000 for a newsprint mill with deinked pulp (DIP).

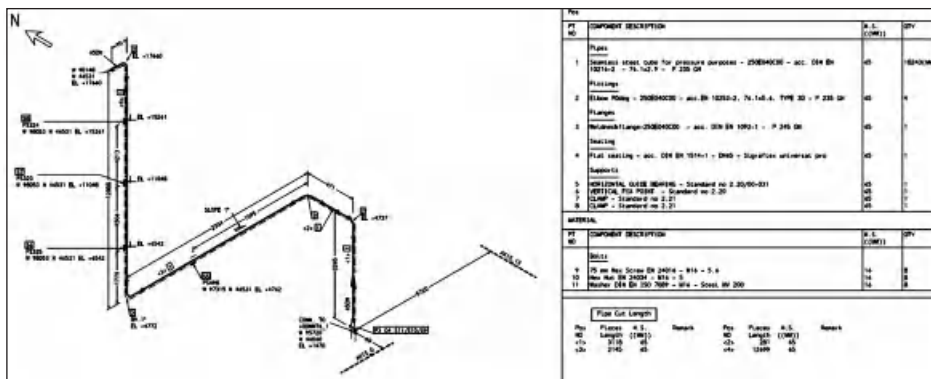


Figure 26.12 Example of an isometric piping plan (Manufacturing ISO) with Bill of Material (BoM).

26.1.5

Procurement Engineering

The complete engineered equipment has to be purchased. In the case of a tissue process line, equipments as listed in Table 26.1 are needed.

The activities of procurement engineering are

- Creation of tender documents
- Technical comparison
- Support purchasing department
- Order processing.

The procurement engineering has to further consider

- Delivery time
- Influence on engineering under consideration of the time schedule
- Erection schedule.

Table 26.1 Examples for the list of equipments to be purchased for a tissue mill.

Basis scope process supplier	Auxiliary systems	General plant equipment
Stock preparation	Boiler house	Pumps
Tissue machines	Hall cranes	Agitators
Approach flow	Vacuum system	Manual valves
Broke system	Compressor station	Control valves
Fiber recovery	Shaft puller and reel handling	Tanks and chests
Mechanical drive	Chemical systems	Piping and ducting
Mechanical drive	Chemical systems	Piping and ducting
Steam & condensate system		
Lubrication and hydraulic	Building ventilation	Steel components
Machine ventilation	Electrification	Insulation
Quality Control System (QCS)	Distributed Control System (DCS)	

So, the procurement engineering has to start early in the project because there is a strong interaction between procurement, basic, and detail engineering. Figure 26.13 shows the impact of the selection of a certain vacuum generation system on the engineering process.

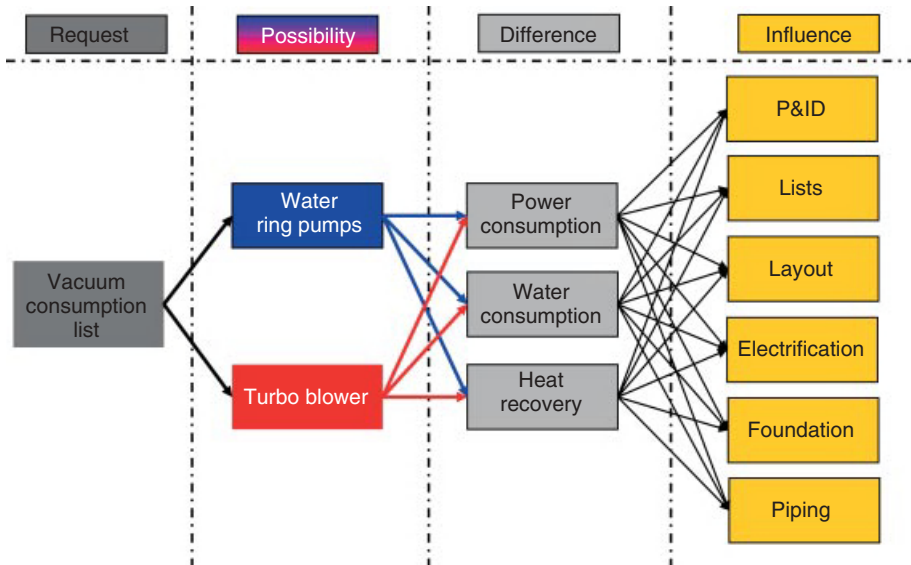


Figure 26.13 Impact of the selection of a machine for vacuum generation.

26.2 Energy

Hermann-Josef Post

26.2.1

Significance of Energy

Paper production demands a lot of energy. Its amount depends on the paper grade as well as the type of raw material for the paper produced. Benchmark figures are commonly expressed as energy intake per mass unit of paper and range from 1200 kWh t^{-1} for newsprint or packaging grades to above 6000 kWh t^{-1} for high-quality tissue grades. Two-thirds of the total energy is required as thermal heat, mainly for drying, and one-third as electricity to operate the numerous drives. The expenses for energy represent a significant part of the total production costs. In Figure 26.14, typical ratios of expenditures for pulp, chemical additives, energy, staff, and materials are given for the production of main paper and board grades.

For uncoated grades, energy costs are the second biggest ones and they are in the same range as labor costs. Only for coated grades, the expenses for chemical additives usually outperform the energy outlays. But it should be noted that the

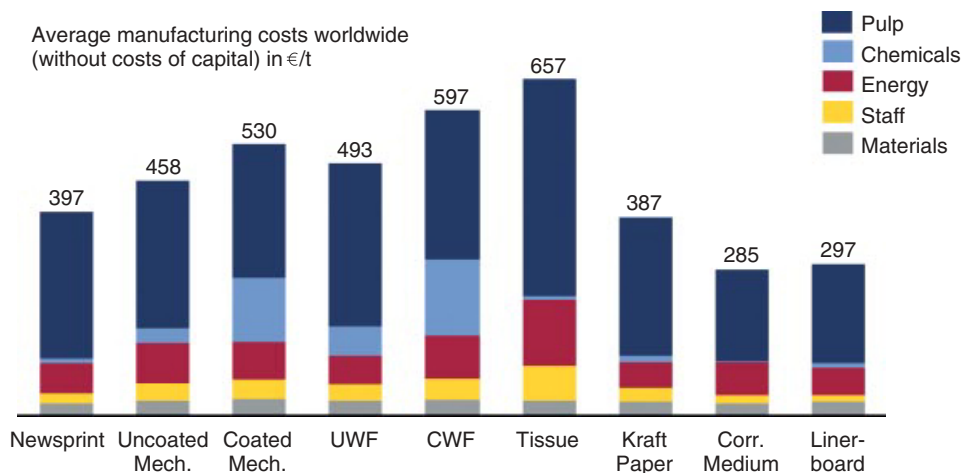


Figure 26.14 Average costs (without capital costs) of paper and board manufacturing (2010).

production of these additives and the preparation of the fiber raw material are also very energy intensive and thus these positions include additional indirect energy-related costs.

In future, expenses for energy will increase faster than other costs. The reasons are that fuel resources are limited, and on the other hand, the energy demand per human individual will dramatically increase with the increasing average standard of living worldwide.

Furthermore, public authorities push alternative fuels and put penalties on carbon dioxide emissions to reduce global warming. Unfortunately, these alternative fuels in certain cases may require more efforts for handling and processing. On the other hand, natural gas, for instance, is easily available via pipeline and burns nearly residual free. Thus, it can be used, for example, for direct heating in Yankee hoods or air flotation dryers for coat drying.

In consequence, choosing the right energy concept together with an efficient utilization of fuel resources are decisive factors for paper mills to stay competitive in future.

26.2.2

Energy Efficiency Assessment

The first step before making decisions on energy measures is to evaluate the current status quo. A straightforward approach is to break down the energy figures from top to bottom (Figure 26.15).

On the upper level, the entire mill is regarded as a big black box. In-going fuel streams and electric energy are related to the mass of the paper leaving the mill. Resulting specific consumption figures give a first idea of the energy efficiency of the overall paper production process. Such figures are often used,

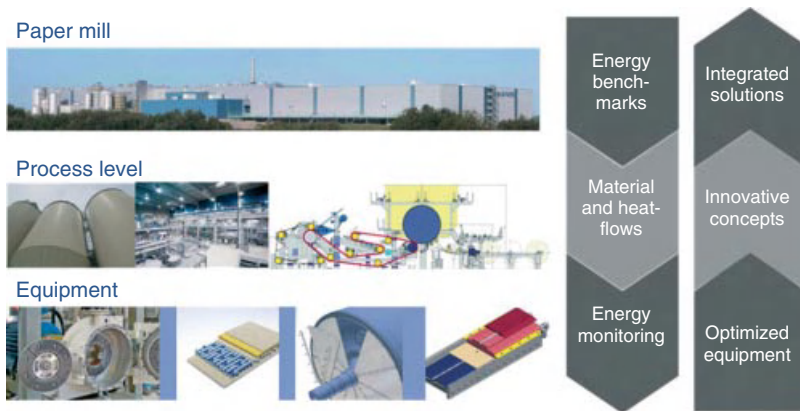


Figure 26.15 Analysis levels for acquiring energy-relevant data.

for example, to compare different production sites within one company. But the comparability of these kinds of values is limited as these statistics do not reflect neither different environmental conditions such as ambient air temperatures nor extra consumptions originating from the need to fulfill certain quality criteria. For instance, when specific tensile strength values have to be fulfilled, the papermaker might have to apply more refining energy than a competitor that has not to guarantee similar specifications. Or a mill located in Finland will certainly spend more heat for heating purposes than a mill in Spain.

Furthermore, such a simple benchmark is not able to reveal the reason for an unusual high or low energy consumption. A poor figure might arise from outdated and not well-maintained equipment or inefficient process design. Also, inadequate operation procedures and improper process controls can waste a lot of energy.

A second-level analysis will lead to a diagram illustrating all heat flows between major process units. The so-called Sankey diagram (Figure 26.16) depicts process units such as the stock preparation for each pulp grade used, the WEP, the vacuum system or the drying hood as blocks, and energy streams as colored lines, which are connecting the individual units. Thereby, the colors indicate the type of energy and the line thickness represent its amount.

A process flow diagram of a production line gives a good overview about the extent of heat recovery. It shows, for instance, what portion of waste heat from the drying section is recovered within the production process. Connections with the water supply facilities are common to provide process water with heat that otherwise would be released to the atmosphere.

Sophisticated energy-monitoring systems enable the most detailed analysis (third level). Nowadays, systems are based on software databases. Individual consumption figures are stored frequently, typically one data point per minute. Each energy consumer such as pumps, drives, dryer section groups, or gas burners is assigned to several categories. One attribute, for instance, distinguishes the type of the consumed energy, for example, gas, steam, or electricity. Another property

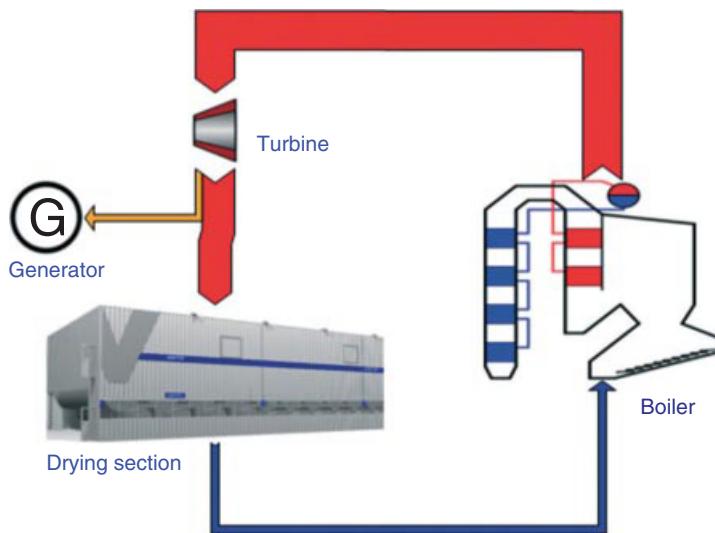


Figure 26.16 Example of a Sankey diagram depicting the steam flow from boiler to hood and hot condensate return.

characterizes the position within the production process in a hierarchical order: a pump belongs, for instance, to paper machine number 2, which is located in the WEP and is a part of the top layer line. This data structure enables users to get immediate access to information such as the current electricity intake of the WEP or the steam consumption of the dryer section. Features to prepare trends with historical data and generate automatic reports are also standard.

26.2.3

Energy Optimization

As soon as the most significant energy consumers have been detected, there are various approaches to optimize the energy efficiency. The most attractive solutions are those which can be implemented without any investment. They are often related to control optimization issues. This is demonstrated by some examples as follows.

During the daily operation, for example, only less attention is paid to the machine-related air system and hall ventilation because an inefficient heat recovery does not directly impact process stability and endproduct quality. Waste heat from the drying section exhaust can be transferred to the hall heating by a water-glycol system. In addition, the circuit includes also a steam-heated exchanger to supply extra heat in case if the heat recovery is not able to cover the entire demand. When the temperature set point is too high, the system will consume more steam than necessary and because of the higher temperature of the heat transfer, medium less energy is recovered from the paper machine exhaust.

Another example is the vacuum system. Vacuum is used for multiple purposes within the papermaking process: in the forming section, vacuum induces and

accelerates the dewatering process. Furthermore, it is used for holding and guiding the wet paper sheet. Also in the wet end, it can be used for deaeration.

Operators sometimes stick to the opinion that the more vacuum the better. But this is not always the case. Too fast early dewatering will form a dense layer on the wire that builds up a high flow resistance for the further watering. This sheet sealing effect can result in 10% higher vacuum consumption.

Unnecessary vacuum consumes not only electricity for being generated, but also has an negative impact on other consumers. Suction elements retard the movement of the wires and felts. Vacuum optimization measures have shown that it was possible to reduce the energy supply to drive the system by more than 5% while maintaining the production output.

26.2.4

Investment in More Energy-Efficient Equipment

The idea is not to change the process configuration as such or change the raw material composition but replace existing equipment with more energy-efficient ones. A very simple example from day-to-day's life is the replacement of conventional light bulbs by energy-saving lamps.

Accordingly, machinery suppliers for the paper industry have designed a lot of energy-efficient equipment during the past years. The development has been boosted by new design tools such as computational fluid dynamics (CFD) or finite element method (FEM). The CFD software utilities, for example, have helped to optimize the hydrodynamics within pulp-handling devices. Flow-optimized pulpers disintegrate the same amount of raw fiber material within a shorter time period and thus consume less energy. Another example are rotors for pressure screens. New designs enable the same function with less rotation speed and again less energy.

Hydraulically optimized headboxes place less pressure resistance to an equivalent flow rate than old-fashioned designs. This can save 8% of fan pump energy for fast running paper machines. Newer developments also allow stable production of high-quality paper grades without recirculation flow. This reduces the amount of flow that has to be supplied from the approach flow. The savings of power spent for pumping, screening, cleaning, and all other unit operations within WEP may add up to about 7% of the fan pump drive energy.

26.2.5

Process Modifications to Bring Down the Energy Intake

In the past, the plant design did not care much about energy efficiency. The focus has been to bring down investment costs or boost production output. In times of raising energy costs, it is advisable to review these process layouts with focus on energy efficiency as demonstrated by some examples.

The couch broke pulper has two major load cases. Under normal operation conditions, only the edge trim has to be handled. In the case of a web break, the unit has to cope with the entire production rate. The design of the main broke

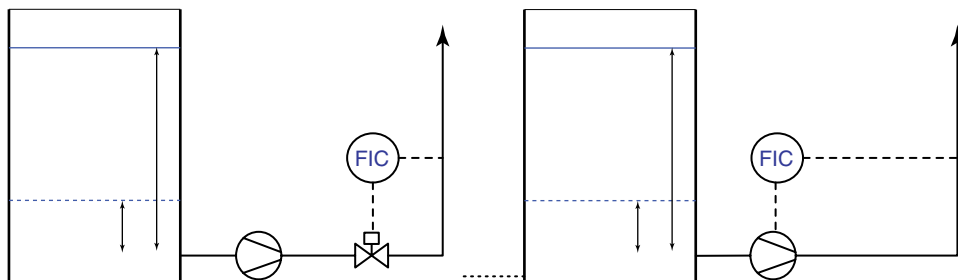


Figure 26.17 Introduction of flow control with frequency converters instead of throttle valves.

pump has to be done accordingly. As web breaks should only rarely occur, a small second pump could cover the edge trim, whereas the main pump is reserved for the occasion of a web break.

In recent years, control technology has made tremendous advances. In the past, control valves were used to regulate basis weight, and level boxes were used to adjust constant pressure. Nowadays, all this can be realized by frequency-controlled pumps. An example where the outflow of a storage tank was controlled by a pump followed by a control valve could demonstrate a potential to bring down the energy intake of this certain pump by up to 50% (Figure 26.17). The pump has to be designed, so that it can cope with a low inlet pressure resulting from a low head pressure in case the tank is nearly empty. In fact, the storage chest is almost filled and produces a high upstream pressure, which will be further increased by the pump before being destroyed at the valve.

Improved controls and advances in hydrodynamics have helped to enable paper production with smaller volumes. For example, machine and mixing chests in present wet-end designs are unified into just one chest, and the homogenization of the pulp flow is done by a pipe segment with baffles. This saves investment costs and energy consumed by one pump and one agitator, which would amount up to 50 kW for a larger paper production. On the other hand, constant dosing of the stock components is even more challenging.

Optimized equipment also allows operation with higher consistencies. This means that same amount of fiber material is diluted in less water and hence less volume flow has to be treated and pumped in the wet processes. An increase in concentration by 50% will result in a flow reduction of 33%.

26.2.6

An Optimal Energy Layout for the Entire Paper Mill

The closer integration of paper production, waste treatment, and powerhouse will lead to further improvements (Chapter 9).

A proper water management reduces the specific water intake per ton of paper. As effluent temperatures are usually higher than the values for ingoing fresh water,

the heat balance will also benefit from water saving. A total of 1 t h^{-1} effluent water saving means about 35 kW less thermal energy loss.

When the waste water is treated in an anaerobic bioreactor, the pollutants are converted into organic gases. Special engines that are adapted for the utilization of biogas may produce electricity and hot exhaust that can be further exploited for heating purposes.

Also, the rejects from stock preparation can be burned as secondary fuels. So, the energy concept of a paper mill is very individual and depends on a lot of boundary conditions.

One strategy is to use high-quality fuels and increase the utilization rate as much as possible (Figure 26.18). Natural gas can be burned in gas turbines, which have an electric efficiency above 30%. The hot exhaust can be used for steam generation in a waste heat boiler. The steam can be further used in a steam turbine for additional electricity production in a combined cycle power plant. Electrical efficiency values above 50% are feasible with such configurations. The energy required to evaporate the steam in the boiler for the steam turbine can be recovered when the steam is condensed in the dryer section of a paper machine. The combined generation of electric power and the use of the waste heat boost the total utilization rate to values above 90%. The drawback of the aforementioned approach is that the resources of these versatile fuels such as oil and gas are rare and the growing demand will raise the prices. Furthermore, oil and gas are traded on open markets via energy exchange what leads to tremendous price fluctuations and uncertainties.

Another strategy relies on local resources. Coal is available in many countries and stock lasts for a long time. Coal dust has a high energy content and is relatively easy to handle. But smaller coal-fueled power plants often do not have as high electric efficiencies as large-scale coal-fired power plants above 700 MW. Technologies such as fluidized bed boilers, supercritical steam conditions, and intermediate superheating are very cost-intensive technologies. Large coal-fired power plants at present achieve electric power yields above 50%, whereas smaller installations with back pressure steam turbines are generating only around 15% electricity. Nevertheless, good carbon dioxide emission rates could be achieved

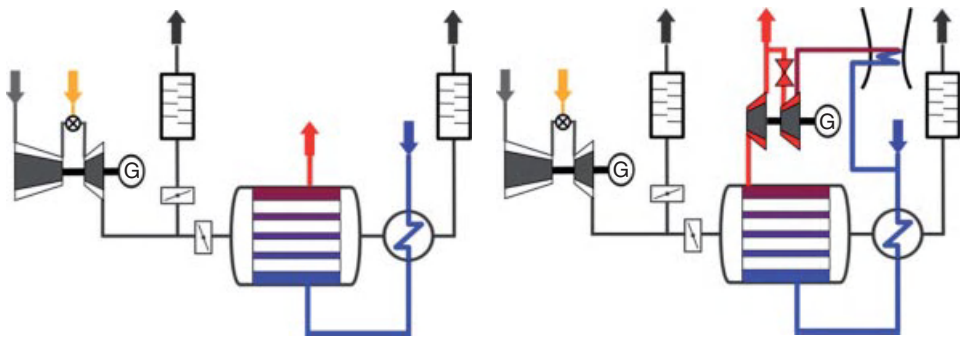


Figure 26.18 Schematic of a gas turbine power plant with and without combined steam turbine cycle to increase electric energy output.

when accomplishing an almost complete utilization of the waste heat in a combined heat and power process.

The public acceptance of biofuels is growing rapidly as the consequences of global warming have become more evident. Public authorities often promote the use of fuels with a better carbon footprint. Despite the handling of alternative fuels is often more challenging compared to fossil energy, the paper industry should have the expertise and infrastructure to overcome these hurdles and take this interesting alternative into consideration as well.

27

Environmentally Friendly Paper and Board Production

Günter Müller and Ingrid Demel

27.1

Background

The responsible and economical use of natural resources as well as the assessment of the impacts of products and their production processes on the environment and consumers are becoming increasingly important. Products with high environmental performance are of great interest. This specific feature significantly affects demand and buying decisions throughout the value-added chain as well as that of end consumers, thus supporting companies in their environmental efforts [1].

The principal reasons for this ongoing progress are cross-sectoral challenges such as

- Global warming
- Environmental pollution
- Shortage of resources caused by competing uses
- Cost effects on the raw material and product influencing profitability
- Emissions and pollution of air, water, and soil
- Social challenges and demographic developments
- Increased ecological sensitization of society.

Therefore, the proper position in this interplay of different factors is becoming more and more important for companies in virtually all sectors. This holds especially true for the paper industry as a resource- and energy-intensive branch.

27.2

Environmental Relevance along the Value Chain of Paper and Board Production

Paper products can be broken down into packaging grades, graphic paper grades, and tissue paper [2]. Furthermore, speciality papers such as overlay paper, battery pasting paper, decor paper, tea bag paper, or paper for coffee filters and coffee pads

are produced, for example, for the wood-based panel, textile, food, or automotive industries.

The basic raw material for paper and board manufacturing is fiber pulps obtained from renewable resources. They are recyclable, biodegradable, and combustible. Compared to other materials, these features bestow an environmental advantage on paper-based solutions [3]. Especially in packaging applications, however, paper and board are nearly always used in combination with nonrenewable materials, for example, barrier materials derived from fossil-based plastics or aluminum. This is due to the specific requirements placed on the final product that is used, for instance, in the food, pet food, laundering, and dry-cleaning agents industries.

Figure 27.1 gives an example of a typical value chain of paper and board production with renewable and nonrenewable inputs. Furthermore, possible specific requirements on the final product are highlighted.

Obviously there are many other sectors involved in the value chain, for example, the plastics sector, food and beverages, chemical and additives industry, energy and transport sectors, converters, and retailers. Each sector is affecting the environmental impact of the final product in its own specific way. This shows the trans-sectoral importance of considering environmental issues throughout the entire value-added chain of paper and board production.

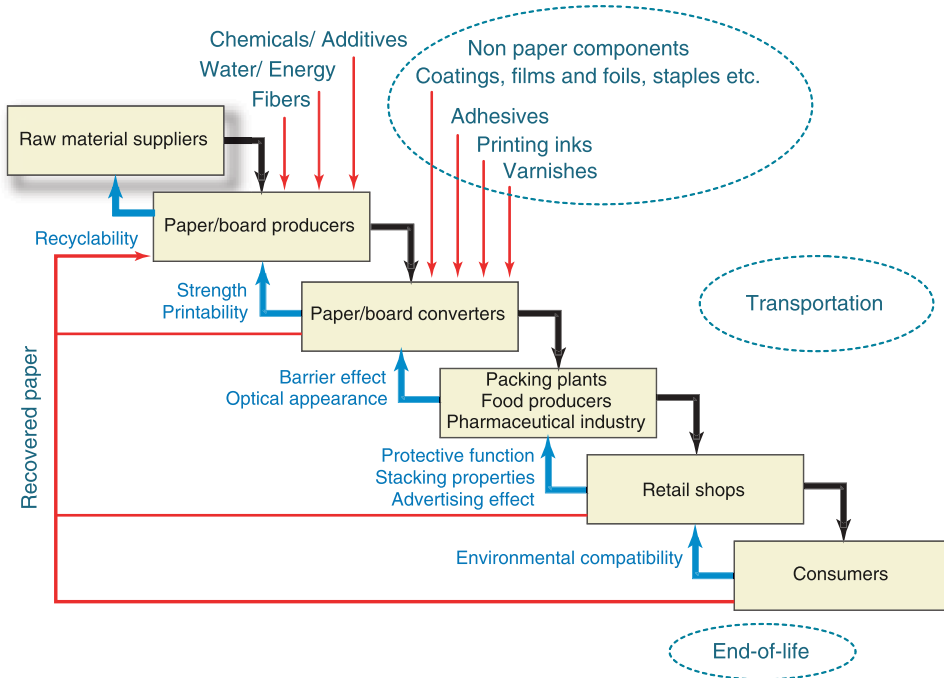


Figure 27.1 Example of a typical value chain of paper and board production.

27.3

Sustainability

27.3.1

Worldwide and European Efforts

For more than two decades, sustainability and sustainable development have been major elements of international politics. An important milestone can be seen in the publication of the Brundtland Report in the late 1980s. This holds true for the results of the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro in 1992 and the formation of the Commission on Sustainable Development (CSD), as well as in the follow-up conferences held since then [4].

Sustainability is also a central principle in European and German politics and is constantly evolving into a crucial strategic and operative management element of today's companies [5]. Germany, for example, defined 35 different sustainability indicators to evaluate its sustainability strategy, of which savings of resources, climate protection, raising the share of renewable energies, land use management, and innovation power, for example, are certainly of great interest to industry [1]. The "Europe 2020 Strategy" provides for a reduction in greenhouse gas (GHG) emissions by 20% compared to 1990 (and 80–95% by 2050 [6]), an increase in the share of regenerative energy sources in the EU energy mix to 20% as well as an improvement in energy efficiency by 20% [7].

27.3.2

Sustainability in Paper and Board Production

Sustainability aspects are taken into consideration as a result of customer requirements, economic calculations, and as a cross-sector competitive factor [5]. By now, many companies consistently consider sustainability aspects, based on what is known as the *three pillar model of sustainability* [8], thus incorporating not only economical but also ecological and social aspects in their decisions and processes. Paper and board products with good environmental performance are of great interest and are thus becoming an evermore decisive criterion for market success.

Several sustainability indicators can be derived for the paper industry based on the three pillar model. Some of them are shown in Figure 27.2.

27.4

Resource Utilization in Paper and Board Production

Global economic growth, particularly in China and India, compounded by the accompanying increase in the world population is causing a continuous shortage of natural resources. Thus, raw material prices are constantly rising that in many cases cannot be made up for in product prices. Among other things, this requires resource

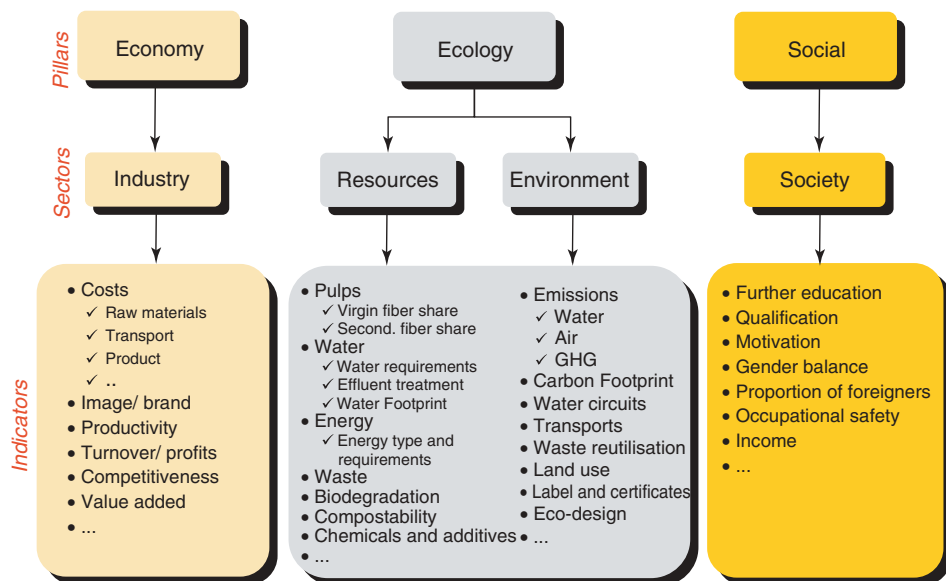


Figure 27.2 Sustainability indicators in the paper industry.

utilization that is designed to be as efficient, sustainable, and environmentally friendly as possible. The entire product life cycle from acquisition to transport, product manufacture, use and eventual disposal, or recycling has to be considered. In the paper added value chain, this principle applies in particular to virgin and secondary pulps, energy (the use of renewable energy), and water (in closed circuits, if possible). Further important issues are the use of chemicals, minerals, and other additives during product manufacture as well as the transportation of goods (Figure 27.1).

27.4.1

Virgin Pulps

The industrial importance of pulps is rising steadily [9]. The causes can be traced back to comparatively inexpensive production, weight reduction, and the specific properties for a wide variety of applications. Generally speaking, the natural fibers that are used include, in particular, wood fibers and especially cultivated fiber plants with high fiber content. Both types consist predominantly of cellulose, although they differ in their specific physical and chemical properties. For paper production, the virgin fibers used are especially fibers obtained from wood.

Global forest areas are declining continuously as a consequence of the constant increase in wood consumption. Problem regions include developing countries such as Africa, South America, and Asia. Of the globally harvested timber, more than 50% is used in industry and, of that figure, approximately 40% in the pulp and paper industry [10, 11]. Most of that wood comes from commercial thinnings,

sawmill by-products, leftovers from other industries, and small logs [12]. In this context, the certification of forests is increasingly being used to prove that the wood for the European paper industry comes from sustainably managed forests and responsible resources. The percentage of certified raw material used by industry is 55%. Sixty percentage of Europe's forests are currently certified. Eighty percentage of the industry's fiber supply comes from Europe itself [2, 12].

Nonetheless, wood supply is limited for further growth in traditional and new applications. The use of wood from sustainably managed short-turnover plantations is becoming even more important. Moreover, attempts have been made to replace wood with alternative fibers from annual plants from agriculture. However, they are not available in the necessary quantities for paper consumption and their use is also less environmental friendly [12].

27.4.2

Secondary Pulps

Recovered paper is a very important source of fiber raw material for the paper and board industry [2, 3, 13]. Recycling is considered the highest and best use of paper and paper-based packaging [3]. Therefore, packaging and paper production is based on the mixtures of virgin and recycled fibers, in which recycled fibers vary from 0 to 100% as a function of the packaging paper grade [3].

The share of recovered paper in the world's papermaking fiber furnish is currently 50% of the total, and it is expected to grow to 56% by 2020 [3]. In CEPI countries, recovered paper accounted for 51.4% of total fiber raw material used in 2010 [10]. The use of recovered paper in paper production in the CEPI countries varies greatly according to the grade of recovered paper. In 2010, the consumption of recovered paper in all CEPI countries was as follows: 43.6% corrugated and Kraft, 26.3% newspapers and magazines, 18.7% mixed grades, and 11.4% high grades. The corrugated and Kraft and mixed grades (92.7% by weight) are used primarily in the production of packaging papers and board. An amount of 31 226 000 t (63.8%) from a total of 48 972 000 t of recovered paper was used in the production of packaging paper and board [3, 10]. The utilization rate (use of recovered paper in a sector as a percentage of the total paper production in that sector, see Section 2.4) in packaging papers production was 75.3%, while as per the total industry, the utilization rate was 50.6% [10]. This proves that recycling is the most beneficial end-of-life option.

The German paper industry is the largest user of recovered paper within the European Union; about 70% of the raw material for papermaking is based on recovered paper [14]. This is mainly due to the high-quality recovered paper source separation system that is practised in Germany.

As the recycling is dependent on virgin material, the recycling loop operates with a continuous input of high-quality virgin fiber [15]. Recently, the two main certification systems operating in Europe, the "Forest Stewardship Council" (FSC) and "The Programme for the Endorsement of Forest Certification" (PEFC), have included recycled content in their certification policy [2].

27.4.3

Energy

The consumption of electricity and all primary energy in the European paper industry fell by 14% during the 1990s [2]. This was achieved, thanks to the use of more efficient processes. The specific energy consumption was reduced continuously as well. At present, it averages 3066 k Wh t^{-1} . This represents a reduction by more than 60% compared to 1955 when it amounted to 8200 k Wh t^{-1} [14].

The paper industry is already the largest user and producer of renewable energy in Europe. Fifty-four percentage of the energy used in paper mills comes from renewable sources. Ninety-six percentage of on-site electricity is produced by combined heat and power (CHP) [12]. Nonetheless, considerable amounts of energy are still required for production. The paper industry ranks third after the metalworking and chemical industries [14]. The GHG emissions associated with production are correspondingly high.

27.4.4

Water

A more efficient use of water, water recycling, and water loop closures have resulted in a significant savings of water over the past few decades. In addition, much funding has been invested in effluent treatment technology. Ninety-four percentage of the water used in pulp and paper production is returned cleaned to its source [2]. Specific water consumption currently averages $5\text{--}10 \text{ l kg}^{-1}$ of paper product. In 1955, it amounted to more than 170 l kg^{-1} [14].

To conclude, paper and board are an environmentally friendly and sustainable choice. This becomes evident from the use of regenerative raw materials and very high recycling rates. Optimized process solutions and innovative technologies in the past few decades have significantly reduced the consumption of water and energy as well as the amount of emissions in air/water/soil, thus also curbing the ecological impacts in the production of paper and board products.

27.5

Evaluation and Communication of Environmental Impacts

27.5.1

Demand for Products with High Environmental Performance

The evaluation and communication of the impacts of products and processes on the environment and consumers are becoming evermore important for companies and users. This holds especially true when new products and processes are to be developed or existing ones improved further. Great sensitivity is dedicated to an environmentally compatible and sustainable product design [16].

The increasing interest in environmental performance is reflected by the growing demand for tools such as certificates, labels, footprints, or the eco-design of products. This significantly influences corporate environmental behavior throughout the paper value chain, leading to new and/or optimized products and process solutions.

During the course of the past few decades, the paper industry has undertaken enormous efforts to reduce the impacts of their processes and products on the environment and to sustainably enhance environmental performance [2]. The reduction of atmospheric emissions, effluent load, carbon footprint, water intake, and energy use should be mentioned here [2, 14].

However, owing to increased environmental awareness on the part of society, it is expected that there will be further demands made on the paper sector, for example, concerning sustainable sourcing of raw materials, resource efficiency (reduce, reuse, and recycle), improved energy efficiency, further reduction in emissions, food safety, and the development of new applications based on pulp and paper.

27.5.2

Complexity of Available Tools

Various approaches exist when searching for evidence of the quality of products with respect to their environmental friendliness and harmlessness to health. There is a huge variety of available tools that are designed to assess and compare the environmental performance of products. Depending on the particular tool, parameters such as a sustainable forestry management, the share of recycled pulp, CO₂ emissions, waste management, or impact on water circuits are evaluated and/or demonstrated. Companies can decide to measure, improve, and communicate their performance based on tools such as

- standards (ISO 14001, EMAS, ISO 16001, ISO 14025, ISO 14040/14044, etc.);
- labels and certification systems (Blue Angel, Eco-Flower, FSC, PEFC, etc.);
- environmental data sheets (paper or carbon profile);
- guidelines (Global Reporting Initiative, UNEP/SETAC-Guidelines, CEPI's 10 toes, etc.).

The environmental impacts of products are assessable, for example, by using evaluation tools such as Product Carbon Footprint (PCF), Water Footprint (WF), Eco-Efficiency Analyses (EEAs), or Life Cycle Assessments (LCAs).

An LCA in line with ISO 14040/14044 evaluates all the stages of a product's life cycle from the cradle to the grave, thus from the raw material to the end-of-life of that particular product, for example, recycling [17]. The PCF, on the other hand, allows companies to make their specific contribution to CO₂ reduction measurable. It serves to communicate to the general public and to consumers in addition to its in-house use and to establish a general understanding of paper and environment.

Furthermore, the "Cradle to Cradle" concept approaches have to be mentioned. Starting point of "Cradle to Cradle" (from cradle to cradle) is the fact that nature

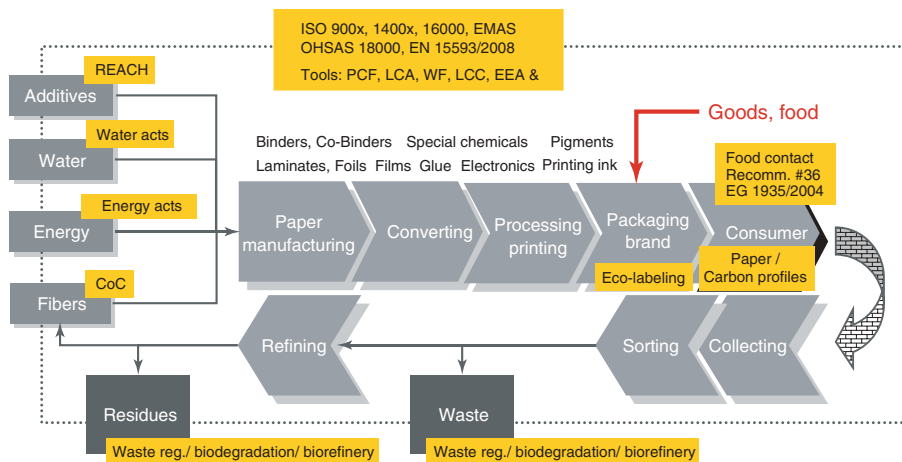


Figure 27.3 Standards and evaluation/communication possibilities in papermaking.

itself produces no waste because any waste or residue created by one living organism serves as nutrient or raw material for another one. What is important here is the eco-effective products that will re-enter the biological cycle as biological nutrients or circulate within closed loop industrial cycles as “technical nutrients” [18].

In addition, a large number of tools provide simplified evaluation of environmental impacts or partial LCA for specific products or product groups (e.g., “Check your Paper” by WWF [19]). Figure 27.3 shows examples of different evaluation and communication possibilities as well as how and where they can be used in paper and board production. It again becomes clear that this theme has trans-sectoral importance and affects the entire value chain as well as neighboring sectors.

Politics, Non-Governmental Organizations (NGOs), legislation, and industry are continuously adjusting limit values of already existing standards, labels, and guidelines as well as continuously developing new ones (e.g., ISO 14067, ISO 16759, Product Footprint Category Rules (PFCR) by CEPI in collaboration with the European Commission).

The enormous variety and complexity of these tools are highlighted in Table 27.1, comparing the use of environmental tools and aspects as a function of company size. Table 27.1 is based on a literature study conducted by the Papiertechnische Stiftung (PTS) focusing in particular on the evaluation of environmental and sustainability reports from more than 100 companies [20].

It is getting obvious that larger companies usually consider a broad range of different aspects for their products and processes and communicate them to customers and politics. They cover as many needs of their customers as possible.

Small- and medium-sized enterprises (SMEs) by contrast often have to focus on a distinct selection of evaluation and communication tools, especially owing to monetary and capacity aspects. Hence, they are often forced to publish trimmed-down versions of environmental/sustainability reports or do not even publish reports at all.

Table 27.1 Results of a literature study of PTS with regard to sustainability aspects.

Companies with >500 employees		Companies with <500 employees	
33 Companies	Frequency (%)	73 Companies	Frequency (%)
ISO 9001	97	ISO 9001	86
FSC	91	FSC	58
ISO 14001	91	ISO 14001	56
PEFC	76	PEFC	19
OHSAS 18001	76	OHSAS 18001	15
Social projects	67	Social projects	10
Continuing education	64	Continuing education	11
Promoting safety at work	58	Promoting safety at work	12
Carbon Footprint	56	Carbon Footprint	10
EMAS	49	EMAS	8
Paper profile	36	–	–
REACH	33	REACH	8
Water Footprint	30	Water Footprint	1
Blue Angel	24	Blue Angel	14
Renewable energy	21	Renewable energy	4
EU flower	12	EU flower	3
Nordic swan	12	Nordic swan	3

27.5.3

Eco-Label – a Possibility for Communicating Product Eco-Friendliness to the Consumer

Eco-labels mark products that have individual features that are more eco-friendly than others. They can serve as an important tool for end users. This type of labeling is an instrument of voluntary market information, thereby allowing prospective buyers to take environmental aspects into consideration. Generally speaking, a distinction is made between two groups, both of which are more or less directly associated with the paper industry.

Group 1 (raw material labels/certification systems) includes labels that refer especially to the wood as the original raw material for paper and board production and is intended to guarantee sustainable forestry management. The certification of all owners within the product chain (Chain of Custody, CoC) guarantees the consumer that the labeled products come from a certified and responsibly managed forestry operation. This means that not only the forest owner and the paper or board manufacturer but also the printer or packaging manufacturer must be certified as well. In Central Europe, the FSC and PEFC are the most important environmental labels or certification systems in this respect. Worldwide, besides FSC and PEFC, the Canadian Standard Association (CSA), the Sustainable Forest Initiative (SFI), and the American Tree Farm System (ATFS) should be mentioned.

Group 2 eco-labels (product labels) confirm that a product bearing this label complies with defined ecological requirements. This may include the use of especially eco-compatible raw materials as well as a number of other aspects, for example, the omission of certain chemicals or reduced energy and water consumption during production. The most well-known representatives are the Blue Angel and the EU Eco-label.

It is becoming more and more difficult for consumers to keep track of developments owing to the constantly growing number of different labels ranging from self-created manufacturer labels to independent and monitored quality labels.

The matrix shown in Figure 27.4 compares the most important raw materials and product labels based on selected criteria [21].

The importance of the raw material labels for papermaking and converting operations arises in particular from product chain certification. In view of the total global forest area of 3 900 000 000 ha, this certification is still suffering from teething troubles, as it amounts to only 308 000 000 ha (of which 204 000 000 ha are certified according to PEFC and 104 000 000 ha according to FSC criteria) or a total of 8% [22]. Furthermore, the actual problem regions (tropical deforestation) in Africa, South America, and Asia have hardly been mapped. Fifty-eight percentage of the certified forests are located in North America and 29% in Western Europe. The most productive forests are certified in accordance with the economic interests of the timber industry [22].






Criteria					
Minimization of emissions (air, water, soil)	0	0	++	+++	+++
Minimization of energy consumption during processing	0	0	++	+++	+++
Gentle treatment of resources	++	+	+++	++	+++
Consideration of aspects concerning human health	0	0	+++	+	++
Use of chemicals/pesticides/ fertilizer	++	+	+++	+++	+++
Responsible treatment of forests	+++	++	++	+	++
Consideration of sustainability aspects	+++	++	+++	++	+++
Use of recycled material	++	+	+++	+	++
Accessibility of award criteria and procedures	+++	+++	+++	+++	+++
Importance for German paper industry	++	++	+++	+	+
Reliability/Impartiality	+++	++	+++	+++	+++
Consideration of land use (resource m ⁻²)	0	0	0	0	0
Holistic view	+	+	++	++	++

Figure 27.4 Overview matrix with important raw material and product labels for papermaking and converting.

Product labels can be an important marketing instrument. However, they are restricted in some cases to certain countries (Blue Angel) or product groups (EU Eco-label).

27.6

Practical Implementation of Environmental Issues

As has been demonstrated, there are a number of different approaches to viewing environmental aspects and the environmental friendliness of paper and board products. Companies have to deal with all these tools, depending on their particular approach [23]. They use a

- Single issue approach
 - by external stakeholders (e.g., when NGOs manage to position themselves as opinion leaders dictating the agenda)
 - by themselves for specific marketing reasons.

The term *single issue approach* is understood to mean themes used especially in marketing, for example, labels or certificates.

- Life cycle approach
 - in order to create common sense on an excellent environmental profile of paper and its converted products
 - covering all relevant topic areas.

“Life cycle approach” in this context means the broadest possible consideration of all environmental aspects (inputs and outputs) of a product. This holds true especially for the production processes in the corresponding value-added stages and supply chains (resource use, raw material and energy efficiency, use of chemical additives, emissions, recyclability, etc.).

- Footprint approach
 - to cover at least the most relevant parts of a product’s life cycle.

“Footprints” are interposed between the aspects mentioned earlier. They each consider a thematic area in the life cycle of a product that is regarded as being relevant such as the Water- and Carbon Footprint. This, however, completely obscures other aspects that are certainly just as relevant. Table 27.2 shows by way of example and inspired by Demharter [23] the areas that should be considered and complied with when taking the environmentally friendly design of paper and board products into account. It can be expanded at will.

A high environmental performance of paper and board products and especially an effective contribution to better integrated resources goes hand in hand with a savings of fibers and an increase in the share of certified fibers. The carbon and WF have to be minimized. Especially, energy consumption has to be reduced significantly and continuously, going along with improved energy efficiency, the use of bioenergy and new technologies such as CHP. There is a need for the

Table 27.2 Areas, principles, and targets in environmentally responsible production.

Area	Principle	Goal
Forest	Sustainable forest management	Maximize share of certified fiber
Climate	Carbon footprint	Improve energy efficiency Maximize use of carbon neutral energy Increase bio-based energy
Water	Sustainable use of water resources	Water Footprint and effluent quality Net water consumption
Waste	Minimal waste	Minimize solid waste to landfill Reuse waste
Products	Sustainable products over their whole life cycle	Renewable raw materials Recyclable or biodegradable products High share of certified products Environmental eco-labels Life cycle assessment

loss-free reuse of consumed materials at the highest level of both product quality and technology and clean paper circuits.

An environmentally responsible production means that the impacts of paper and board products have to be minimized throughout the entire life cycle.

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28

Paper and Board Grades and Their Properties

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28.1

The Material Paper: A Survey

28.1.1

Introduction

The term *paper* refers to sheet material that is made essentially from fibers of plant origin. The characteristic feature of this inhomogeneous material is its fiber network, which is usually arranged in layers containing pores of varying size. The properties of paper differ substantially from those of the fiber resources. These differences are illustrated in Table 28.1, which shows some selected material properties of wood, the most important fiber source, as compared with paper. As a result of the physical and chemical properties and the highly ordered state of wood fibers, wood is unsuitable for direct production of sheet material, which could serve for writing purpose. The production of paper, that is, sheet material with properties that are optimal for writing, printing, or packaging, is possible only after the breakdown of wood into its elemental fiber building blocks, their modification in the pulping process, and their controlled bonding in the papermaking process. Paper can be made with an extremely wide range of properties by varying the production parameters: type of wood, pulping process, stock preparation, and papermaking process. This is illustrated in Table 28.2. The wide range of paper and board properties that result from the production parameters mentioned earlier can be enhanced further by the use of additives such as mineral and chemical aids. For instance, the smoothness and brightness of printing paper can be increased by the addition of inorganic pigments (fillers) [1]. Many special demands made on paper can be met by using suitable chemical additives, for example, wet strength by using wet-strength additives or printability by using sizing agents [2]. However, paper produced with all these aids will never meet all conceivable requirements at a time. In each case, only a few paper properties that are particularly important for the intended purpose can be optimized; concessions must be made with regard to the other properties.

* Contributed to the First Edition.

Table 28.1 Comparison of selected properties of wood and paper.

Property	Wood	Paper
Density (g cm^{-3})	0.3–0.5	0.5–1.5
Young's modulus (GPa)	1.3	1.8–4.3
Tensile strength (MPa)	90–200	20–200
Breaking length (km)	7–30	1–8
Strain to rupture (%)	0.6–0.8	0.8–4
Fiber alignment	Ordered	Random

28.1.2

Material Properties

The specific characteristics of paper vary widely, depending on the type of paper. Nevertheless, there are a number of properties that are characteristic of all papers. These are the degree of homogeneity, porosity, hygroscopicity, orthotropy/anisotropy, and viscoelasticity and are discussed below:

- Paper is an inhomogeneous material made from different elements: fibers, fillers, and air-filled pores. A sheet of paper exhibits inhomogeneities, which can have characteristic dimensions of a few millimeters or centimeters. These are known as *cloudiness* and result from undesired fiber flocculation in the sheet-forming process [3]. In this way, variations in caliper and density develop, and this leads to corresponding variations in transparency, the “clouds.” Finally, the production process can also give rise to inhomogeneities, for example, due to stock pulsations in the headbox and in the sheet-forming section [4]. Only betaradiographic measurements can give the exact information about local mass differences. The existence of inhomogeneities must be taken into account in paper testing, for example, by choosing the appropriate size of the sample.
- Air-filled pores in a paper sheet, the lumen of the fibers, and the inhomogeneity of the filler and fines distribution characterize the porosity of a paper and lead to an apparent density. This is why all attempts to describe paper as a continuous material have failed so far. Therefore, many of the parameters well known from other materials, that is, Young's modulus, may only serve as an auxiliary means.
- An important characteristic of paper is its hygroscopicity, that is, its ability to absorb or release moisture, depending on the ambient climate, until an equilibrium is reached. It is significant whether the state of equilibrium is established by absorption or desorption of water [5]. The equilibrium moisture contents of some types of paper at various levels of relative humidity are listed in Table 28.3.

As a result of the hygroscopicity of paper, physical paper properties, such as sheet dimensions, basis weight, tensile strength, strain to rupture, folding strength, bending stiffness, and so on, are dependent on the ambient conditions [6]. With a change in the ambient climate, the attainment of a new equilibrium

Table 28.2 Selected properties of some grades of paper and board.

Selected properties of some grades of paper and board	Property ^a	LWC, mechanical paper	Newsprint	Wood-free offset printing paper	Bag paper	SC-A, supercalendered mechanical uncoated magazine paper	Box board
Basis weight (g m ⁻²) ^b	–	54–55	45–49	81.4	69.7	45–60	286
Caliper (μm) ^c	–	45–46	62–80	110	106	39–54	453
Density (g cm ⁻³) ^c	–	1.25–1.3	0.61–0.74	0.74	0.66	1.15–1.23	0.63
Specific volume (cm ³ g ⁻¹) ^c	–	0.78–0.9	1.35–1.64	1.35	1.52	0.8–0.9	1.59
Tensile strength (N) ^d	MD	36–40.9	26.5–30	64.5	78.5	36–42	245.5
	CD	14.6	12.6	25.1	53.5	–	80.5
Elongation (%) ^d	MD	1.0–1.2	0.8–0.9	1.6	2.8	1.2–1.3	2.0
	CD	1.6	1.8	3.0	6.2	–	3.2
Breaking length (km)	MD	4.5–4.95	3.30	5.25	7.50	–	5.75
	CD	1.75	1.55	2.05	5.15	–	1.85
Tear growth resistance (mNm m ⁻¹) ^e	MD	180	120	340	640	–	1200
	CD	250	170	410	630	200–230	2440
Bursting strength (Mullen) (kPa) ^f	–	100	50	150	350	–	550
Smoothness (Bekk) ^g	fs	633–2460	71.4	18.2	6.1	–	22.9
	ws	600–2430	63.4	8.6	4.4	–	2.9
Smoothness Parker print surf testing equipment (PPS) ^h (1 MPa) (μm) ⁱ	–	0.7–0.8	–	–	–	1.0–1.2	–
Roughness (Bendtsen) (ml min ⁻¹) ^j	fs	22	90	273	702	–	113
	ws	20	114	469	838	–	>500
Specific bending stiffness (N·mm) ^k	MD	0.06	0.12	0.37	0.39	–	37.8
	CD	0.03	0.04	0.19	0.18	–	13.1
Brightness (%) ^l	fs	73.1 (76) ^m	55.9	84.6	–	66–67	81.5
	ws	72.3 (76) ^m	56.3	84.6	–	–	–
Opacity (%) ⁿ	–	92–92.7	96.5	90.5	–	88–93	88–93

^aMD, machine direction; CD, cross machine direction; fs, felt side; ws, wire side.

^bISO 536.

^cISO 543.

^dISO 1924.

^eDIN EN 21974, SCAN/P11:96.

^fISO 5758-01.

^gDIN 53 107-00.

^hPPS=Parker print surf testing equipment.

ⁱISO 8791.

^j8791/2-90.

^k5629.

^l2470.

^mBrightness D65 R457 (UV).

ⁿISO 2471.

Table 28.3 Moisture content of selected types of paper in equilibrium with various levels of humidity at 23°C.

Type of paper	Basis weight g m ⁻²	Relative humidity (%)		
		20	50	75
Newsprint	50	6.5	8.5	10.0
Gravure printing	65	6.0	8.0	9.2
Offset, mechanical	80	5.2	6.4	7.9
Offset, wood-free	80	5.0	6.3	7.5
Art paper, mechanical	120	4.1	5.7	6.9
Art paper, wood-free	120	3.8	5.3	6.5

moisture content of paper is a process that takes several hours. However, the change in physical properties of the paper starts almost without delay, occurring very quickly at the beginning and slowing down later. For this reason, paper should be processed in rooms in which climatic conditions are favorable for the particular property required. The paper must be in equilibrium with the climate in the room, and the climatic conditions must be kept largely constant. The testing of paper requires the establishment of testing climatic conditions (standard climate: 23°C, 50% relative humidity; cf. Section 28.2.1.1).

- Paper may be considered as an orthotropic material with regard to many physical properties. This orthotropy is due to the anisotropic properties of the individual fibers, which result from the fibrillated microstructure of the fiber rather than from the fiber shape [7]. As a result of the fibrillated structure, the fiber can accept, for example, high tensile forces in the direction of the fiber axis with low elongation; however, even small tensile forces acting perpendicular to the fiber axis cause high elongations. During sheet forming on a rotating wire most fibers are orientated in the moving direction of the sieve, the “machine direction.” Therefore, the machine direction must be considered and marked when taking samples for testing properties related to the direction, such as strength.
- Together with an orientation of the fibers mainly in the machine direction during the sheet-forming process on the wire (because of the jet–wire ratio), this leads to different material parameters in different angles. However, the behavior may be considered orthotropic.
- During drying, the fiber shrinks in the axial direction by only about 1–2%. In comparison, shrinkage in the direction perpendicular to the fiber axis (radial direction) reaches about 30%. If the fibers in a paper sheet were completely randomly oriented, sheet shrinkage in all directions would be equal and mainly governed by the low longitudinal fiber shrinkage. The more the fibers in a sheet are oriented in one direction the higher will be the sheet shrinkage in the direction perpendicular to the main fiber orientation. This is due to the increased influence of the larger radial fiber shrinkage. The fibers in a paper produced on a paper machine are not aligned randomly; the machine direction is usually preferred.

However, owing to fluid dynamics, the main angle of the fiber orientation may be inclined with a measurable effect on orientated properties.

- Furthermore, the fiber mat is passed through the paper machine under tension, which prevents free shrinkage of the fibers during drying, mainly in the machine direction. Restraining forces in the cross machine direction are lower and nonuniform across the width, being smaller at the edges. This results in a nonuniform cross machine profile of shrinkage.
- Both fiber alignment and shrinkage restraints are responsible for the orthotropy of the moisture expansion of finished paper in a large scale, which is generally far lower in the machine direction than in the cross machine direction, the latter being nonuniform across the width. Both these factors also affect the load-deformation properties (strain-to-stress) of paper, which are, therefore, orthotropic (cf. Table 28.2).
- On a small scale, porosity, filler and fiber distribution, and the degree of relative bonded area lead to an anisotropic state. This may be observed as cockling or as a high variance of different paper properties.
- Many papers exhibit anisotropy with respect to their composition in the normal direction (z-direction). The process technology of production on the Fourdrinier wire is responsible for this phenomenon. On the wire side, substances (fillers and fines) that can pass through the wire are washed out, while on the other side, they are retained by the fiber mat. This results in different smoothness properties on the two sides of the paper, known as the *two-sidedness of paper*. The two-sidedness of paper can be minimized by twin wire formers. A further anisotropy in the z-direction results from frozen stresses during unsymmetrical drying of the web at the top and the bottom sides. The two-sidedness is important in the testing of printability, for example. Therefore, the top and the bottom sides have to be marked.
- Finally, paper has viscoelastic properties [8, 9], that is, it can be elastic, similar to a solid, or viscous, similar to a thick liquid. The viscoelasticity is also a result of the superimposition of the properties of the individual fibers and those of the fiber network. The viscous flow of the individual fibers is caused by the sliding of fibrils at high tensile loads. The individual fibers exhibit elastic behavior at low tensile loads. In the fiber structure of paper, the sliding of fibers at fiber intersections results in a flow effect and the paper undergoes plastic deformation. A characteristic feature of viscoelasticity is the dependence of the onset of flow on the loading rate. Small loads acting over long periods of time result in flow, whereas large intermittently acting loads cause only elastic deformation. Therefore, in the determination of the tensile strength of paper, the time within which the tensile stress applied causes the paper to break is fixed.

28.1.3

Summary

Paper has essentially five characteristic features: inhomogeneity, porosity, hygroscopicity, orthotropy/anisotropy, and viscoelasticity. These features must be taken

Table 28.4 Characteristic material properties and their effect on testing conditions.

Property	Effect
Inhomogeneity	Sample dimensions, number of measurements
Porosity	Pressure during test
Anisotropy/orthotropy	Testing direction
Two-sidedness	Tested side
Hygroscopicity	Relative humidity, temperature
Viscoelasticity	Duration of test

into consideration in the testing of paper (Table 28.4). The magnitude of these features depends on the type of fiber, the fiber raw material, the pulping process, and the process techniques used in stock preparation and papermaking. Consequently, there are a large number of variables in papermaking, and many degrees of freedom are involved in the adjustment of the desired paper properties. Therefore, several different paths can usually be followed to obtain papers with comparable technical properties. This is of importance in the standardization of paper properties. Only the technical characteristics may be stipulated in each case, but not the process used to realize these characteristics; otherwise, there would be the danger of excluding new technologies and impeding technical progress.

28.2

Types of Paper, Board, and Cardboard

Paper and board are planar products made essentially from fibers that are mostly of plant origin, and from different portions of fillers [10]. Fillers are mainly inorganic substances, and their content in the product may vary from 0 to about 40%. Paper and board are formed by draining a fiber suspension through a sieve. The resulting fiber web is subsequently compacted and dried.

There are approximately 3000 kinds of paper and board products [11]. Most products with a basis weight up to 225 g m² are defined as paper. Above 225 g m², these products are usually called *board*, but the naming overlaps. Depending on their use, the paper and board grades can be divided into four main groups:

- graphic papers
- packaging paper and board grades
- hygienic papers
- specialty paper and board grades.

This classification has also been largely adopted by the Statistisches Bundesamt (Federal Statistical Office) of Germany in chapter 48 of the *Commodity index for foreign trade statistics* [12]. The basis of this systematology is a “harmonized system for the marking and coding of merchandise” of the “council for tariff cooperation.”

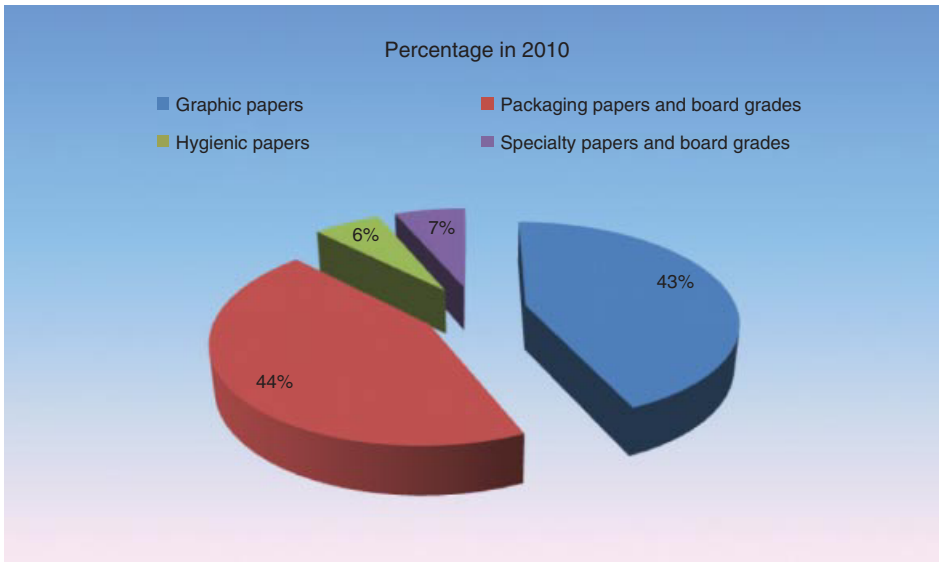


Figure 28.1 Percentage of produced paper grades by Germany in 2010. (Source: vdp report 2010 [13].)

The annual statistics of the association of the German paper industry (vdp) show the percentage of each group in 2010 [13] (Figure 28.1).

Another classification of paper and board is based on the raw material used during manufacturing. Paper and board may be made from recycled fibers or virgin fibers, and may be wood-containing or wood-free. Wood free means that a paper is produced from chemical pulp with less than 5% mechanical pulp. Hence, a wood-containing paper exceeds more than 5% content of mechanical pulp.

An overview of different terms related to paper grades or naming the grades may be found in DIN 6730 [14].

28.2.1

Graphic Papers

The term *graphic papers* refers to a large range of different papers that are suitable for printing and writing and are made from virgin or recycled fibers or mixtures of them.

28.2.1.1 Printing and Press Papers

Printing and press papers are divided into the following four subgroups [15]:

- 1) newsprint
- 2) wood-containing natural printing papers
- 3) wood-free natural printing papers
- 4) coated printing papers (wood-containing and wood-free).

28.2.1.1.1 Newsprint Newsprint represents an important subgroup. It consists primarily of a mixture of primary and secondary fibers (0–100%). The primary fibers include groundwood or TMP (thermomechanical pulp) and small amounts of chemical pulp, which are used to increase strength. The main field of application is newspaper production. Other uses are, for example, paperbacks, calculating machine rolls, and interleaving paper. The following are the two types of newsprint used:

- *Newsprint* has a basis weight of 40–49 g m⁻² (in certain cases up to 54 g m⁻²). It is machine-finished or supercalendered (SC). Standard newsprint should have an ISO brightness of 57–60%.
- *Improved newsprint* has a high filler content and is calendered to obtain a more closed surface. It is used, for example, in book and offset printing. The ISO brightness is about 10 units higher than the mean brightness of standard newsprint [16].

28.2.1.1.2 Wood-Containing Natural Printing Papers The term *wood-containing* indicates that these printing papers consist mainly of mechanical pulp along with chemical pulp, while *natural* indicates that they are not coated. Mechanical pulp may consist of groundwood, TMP, in some cases, refiner-mechanical pulp (RMP), or chemothermomechanical pulp (CTMP). All these pulps contain a substantial amount of lignin, whereas chemical pulps do not contain any lignin (if bleached) or very little (if unbleached). Fillers, for example, china clay or calcium carbonate, are used to produce high smoothness and good opacity. This important group of printing and press papers includes rotogravure printing paper, also called SC paper (supercalendered). Here, SC-A+, SC-A, SC-B, and SC-C are the subgrades (with decreasing quality demands). The following are the different types of printing papers:

- *Natural magazine papers* have high lignin content, and are filled and highly supercalendered. Their main use is in the production of magazines and catalogs.
- *Rotogravure papers (SC-A, SC-A+)* have the same properties as natural magazine paper, and are specially suited to rotogravure printing. ISO brightness is >67%.
- *Improved newsprint (SC-B, SC-C)*, improved for rotogravure printing containing up to 25–30% recycled pulp, has the same properties as natural magazine paper; ISO brightness is <67%.
- *Supercalendered offset paper* has the same properties as natural magazine paper. The ISO brightness is >67%, and the surface strength is optimized for offset printing.
- *Wood-containing thin printing papers* have a basis weight of ≤45 g m⁻². They are used for telephone, railroad timetable, and address books.
- *Book papers* are used in the production of books. They have a mechanical pulp content of 5–20%. The filler content depends on the desired specific volume.
- *Voluminous book papers* are produced with a ≥1.4-fold specific volume compared with book papers.
- *Supercalendered writing papers* are wood-containing natural papers that are sized and supercalendered. They can also be made from recycled fibers.

- *Machine-finished offset papers* are supplied in sheets or rolls.
- *Wood-containing coating base papers and boards* are intended to be further processed into coated papers or boards.

28.2.1.1.3 Wood-Free Natural Printing Papers Wood-free natural printing papers consist almost exclusively of chemical pulp. The proportion of fibers from mechanical pulp should not exceed 5%. Wood-free printing papers do not yellow to any appreciable extent and have a high strength. This is the main difference between these papers and the wood-containing grades described earlier. The papers are uncoated and normally leave the paper machine in a machine-finished state. For certain printing processes, these papers can be machine-finished or further calendered on a supercalender. This group of papers includes the following:

- *Wood-free, machine-finished natural printing papers* with basis weights of $\leq 80 \text{ g m}^{-2}$ (Group 1), $81\text{--}149 \text{ g m}^{-2}$ (Group 2), and $\geq 150 \text{ g m}^{-2}$ (Group 3).
- *Wood-free, supercalendered natural printing papers* with basis weights as described for machine-finished papers.
- *Letterpress printing papers* are particularly suitable for books (specific volume is ≥ 1.4 -fold).
- *Wood-free bible, thin printing papers, and thin letter papers* can be rag-containing or rag-free. They are highly filled to give good opacity. The basis weight is in the range below 40 g m^{-2} .
- *Coating base papers for printing papers and boards* are intended to be further processed into coated papers or boards.

28.2.1.1.4 Coated Printing Papers These represent the largest group within the printing and press papers. Here, the base paper is finished by the application of one or more layers of color to both sides of the paper web, which imparts a closed surface to the printing papers (Chapter 17). Table 28.5 gives an overview of coated paper and board grades with regard to the main components of base paper, basis weight, coat weight, brightness, and their main usage. These papers are supercalendered and supplied with a dull or glossy surface. They are described as wood-containing or wood-free, depending on the raw materials used. The wood-containing coated printing papers represent the largest part, and the LWC papers (lightweight coated), in turn, make up the main part of this subgroup. Basis weight varies for LWC from 35 to 80 g m^{-2} , for MWC (medium weight coated) from 70 to 130 g m^{-2} , and for HWC (heavyweight coated) from 130 to 170 g m^{-2} (basis weight figures include base paper plus coating weights if not stated differently). Figure 28.2 illustrates the relative positions of coated, mechanical pulp dominating papers in basis weight and brightness. Examples include the following:

- *Wood-containing two-sided coated papers.* Typical coating application is $5\text{--}13 \text{ g m}^{-2}$ per side. Base paper basis weight is $29\text{--}36 \text{ g m}^{-2}$. The main areas of application are magazines, catalogs, and job printing, with total basis weight of 39 g m^{-2} (ULWC, ultra lightweight coated).

Table 28.5 Overview of coated paper and board grades and their most important characteristics.

Paper/board grades	Base paper main fiber furnish	Basis weight base paper (g m^{-2})	Coat weight per side (g m^{-2})	Number of coating layers	ISO brightness (%)	Main usages of paper/board grades
Printing papers (both sides coated)						
ULWC (ultra lightweight coated)	MP, DIP	25–35	5–7	Single	69–72	Catalogs, magazines
LWC (lightweight coated)	MP, DIP	35–45	6–12	Single	72–78 (84)	Magazines, inserts
MFC (machine-finished coated)	MP, DIP	35–60	5–15	Single, double	72–78	Magazines, catalogs
FCO (film coated offset)	MP, DIP	30–45	4–10	Single	72–78	Inserts, flyers, and advertising
MWC (medium weight coated)	MP, CP	45–65	12–25	Double	80–88	Special magazines, advertising
HWC (high weight coated)	MP, CP	65–100	25–35	Double, triple	82–90	Magazine covers, advertising
WFC (wood-free coated)	CP	60–120	25–35	Single, double, triple	88–98	Magazines, image brochures, labels
Art paper	CP	60–150	20–40	Triple	94–98	Illustrated books, calendars
Board grades (mainly top side coated)						
FBB (folding boxboard)	DIP, RP, MP, CP	135–425	12–35	Single, double, triple	72–86	Packaging of food, book covers
WLC (white line chipboard)	DIP, RP, MP, CP	170–425	10–30	Single, double	76–92	Shoe and wine boxes, protection packaging
SBS (solid bleached sulfate)	BHSP, BSSP	120–250	15–25	Double	84–98	Packaging of chocolate, cigarettes, cosmetics
LPB (liquid packaging board)	BSSP, UBSSP	280–330	10–15	Single	76–86	Milk and juice packaging

MP, mechanical pulp; DIP, deinked pulp; CP, chemical pulp; RP, recovered paper; BHSP, bleached hardwood sulfate pulp; BSSP, bleached softwood sulfate pulp; UBSSP, unbleached softwood sulfate pulp.

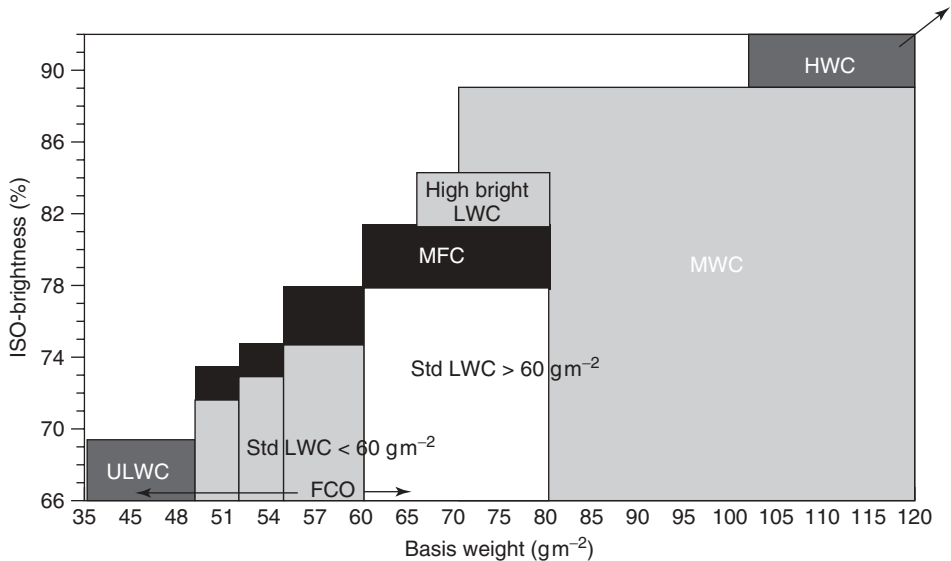


Figure 28.2 Classes of wood-containing coated printing papers and their positioning according to basis weight (base paper + coating layers) and brightness [10].

- *Wood-containing LWC paper* is coated on both sides; basis weight is $\leq 80 \text{ g m}^{-2}$. It is suitable for rotogravure printing and roller offset printing.
- *HWC papers* differ from other coated, mechanical pulp dominated paper grades in their higher coat weight. Traditionally, they are produced at a basis weight of $100\text{--}135 \text{ g m}^{-2}$. They compete with coated fine papers in such end use areas as high-quality magazines, catalogs, and magazine covers as well as in the area of direct advertising. HWC papers can be double or triple coated.
- *Wood-containing consumer papers*, coated on both sides, have a minimum mechanical pulp content of 50% and typical coat weight of $3\text{--}14 \text{ g m}^{-2}$.
- *Wood-free, two-sided coated papers* have a coating application of $3\text{--}14 \text{ g m}^{-2}$ per side, and the basis weights vary between 55 and 170 g m^{-2} . The fields of application are magazines, catalogs, books, direct mail, and labels.
- *Wood-free MWC* is coated on both sides and has a basis weight of $72\text{--}120 \text{ g m}^{-2}$ and typical coat weight of $12\text{--}25 \text{ g m}^{-2}$.
- *Art papers* represent one of the highest quality printing papers and are used for illustrated books, calendars, and brochures. The basis weight varies from 100 to 230 g m^{-2} . Art papers are produced with matt or glossy finish. The coat weight varies from 20 to $>40 \text{ g m}^{-2}$ per side. Art papers are almost exclusively available in sheets. They are triple coated, usually first with a precoater and thereafter with a double blade coater.
- *Pigmented papers, film coated offset (FCO)*, have a coat application of $5\text{--}10 \text{ g m}^{-2}$ per side and basis weights of $45\text{--}65 \text{ g m}^{-2}$. Wood-containing or wood-free coating base paper can be used for their manufacture.

28.2.1.2 Office and Administration Papers

These papers offer a wide spectrum for very different areas of use, for example, writing papers, papers for data printing, papers for forms, copy and duplicating papers, envelope paper, postcard board, self printing papers, refined papers for offset printing, blueprint papers, work drawing paper, bank notes, documents, and map paper. These printing and writing papers and the corresponding base papers are the papers that are used predominantly in offices, administration, and schools. The following are some examples:

- *Data papers and boards* are used for the manual, mechanical, electronic, and magnetic recording of data and its input and output.
- *Bookkeeping transparent paper* is made from a highly beaten stock and is therefore transparent.
- *Account book paper* or paper for bookkeeping machines is wood-free, highly supercalendered, and fully sized.
- *Paper for continuous forms* is wood-containing or wood-free and often contains recycled fibers, usually machine-finished reeled paper.
- *Index board* is wood-containing or wood-free, supercalendered, single-layered board that can also contain recycled fibers.
- *Writing papers* are used almost exclusively for manual writing. They are supercalendered and can contain varying amounts of rags. This group also includes handmade papers, moldmade papers, bond, and airmail papers.
- *School writing paper* is a machine-finished, highly sized paper with a basis weight of 60–80 g m⁻².
- *Air mail paper* is lightweight (25–30 g m⁻²) wood-free, often rag-containing paper with high opacity.
- *Carbon copy paper* is well sized, has a basis weight between 23 and 30 g m⁻², and is used in the copying of letters and manuscripts.
- *Carbonless copy papers* contain color-forming reagents, which produce a contour-true copy when subjected to pressure (exerted on underlying sheets).
- *Correspondence envelope paper* can be made from a wide range of stocks, from 100% recycled fibers to 100% virgin fibers. This paper is used exclusively in the production of envelopes and mailing bags.
- *Kraft paper* is used to make envelopes and mailing bags and is made from unbleached or bleached kraft pulp.
- *Envelope lining tissue* is an intensely colored, sometimes dip dyed wood-free tissue paper with a basis weight of 22–30 g m⁻². It is used for the lining of expensive envelopes.
- *Base paper for diazotype* is wood-free, has a basis weight of 55 to >200 g m⁻², and is used in the making of blueprint papers.
- *Copying papers* are used for copying and nonimpact printing. Basis weight varies between 70 and 90 g m⁻² and ISO brightness between 80 and 96%. The most important properties for a copying paper are a smooth run in a copy machine and good dimensional stability. It must not show curling or cockling and retain dust when copying. It is mainly made of 90–100% virgin chemical pulp fibers, but

it may contain recycled fibers up to 100%. The recycled fibers used are mainly from recovered newspaper, magazines, and copying paper. Total filler content varies between 10 and 25%.

- *Digital printing papers* (synonymous with *electronic printing papers*) are a rapidly growing group predominantly made from chemical pulp. They are mainly uncoated, but increasingly coated, fine paper grades. The bulk of this paper is delivered in sheets.
- The major categories of nonimpact printing that the papers have to suit are electrical-charge-based methods, magnetic methods, thermal methods, and ink-jet methods (Sections 24.4 and 24.5). The requirements vary according to the printing method.
- In *electrophotography*, the runnability of the paper is critical. The electrical conductivity as well as the electrical resistivity of the paper should be sufficient. Moisture content and friction are also important properties. Other required characteristics are good dimensional stability to avoid curl and cockle, for example, surface strength and surface smoothness, especially for high-resolution printing. Chemical properties of the paper surface, such as surface energy, are important for fixing the toners to the paper.
- In *ink-jet printing*, papers require characteristics that are matched with the inks and the ink drop size. First, ink-jet papers must be smooth. They must have sufficient and uniform porosity, with small pores, in order to absorb the solvent quickly and to counteract the spreading tendency. Dimensional stability is also important to avoid cockling and curling. Typical uses for digitally printed products are manuals, price lists, and various direct mail materials and also low-volume paperbacks and hard-cover books. Black-and-white applications cover more than 80% of digital paper needs at present. Basis weights vary a lot, from 40 to as much as 400 g m^{-2} [10].
- *Copy base papers* can be finished to, for example, thermocopy and photocopy papers with a wide basis weight range of 50–180 g m^{-2} .
- *Base papers for offset films* are predominantly wood-free papers that are used for making paper offset plates.
- *Carbonizing base papers* are carrier papers for a wax-bearing color mass. They are used for the production of carbon and blue papers (basis weight range of the coating is 10–14 g m^{-2}).
- *One-time carbon (OTC) base paper* is used in the production of OTC paper (basis weight range is 16–24 g m^{-2}).
- *Multiple carbon base papers* are used in the production of multiple carbon or blue papers.
- *Base papers for nonimpact printing processes* are predominantly wood-free and are specially suitable for nonimpact printing processes (thermosensitive, electrosensitive, thermostatic papers). Basis weights range from 50 to 180 g m^{-2} .
- *Blotting papers* are wood-containing or wood-free, white or colored, and sometimes have veined fibers. They possess a very high absorbency and wettability. Basis weight range is from 35 to 350 g m^{-2} .

- *Security, banknote, and archival papers* are wood-free and/or rag-containing or linter-containing. These heavy-duty nonaging papers are suitable for color printing and can be made resistant to forgery, for example, by means of a watermark. Basis weights range from 60 to 80 g m⁻².
- *Map and nautical chart papers* are wood-free, dimensionally stable, and used for printing of maps and sea charts (basis weights from 70 to 120 g m⁻²).
- *Letterpress board* is wood-containing or wood-free and may contain recycled fibers. It has a basis weight of >150 g m⁻² and is supercalendered.
- *Picture postcard board* is wood-containing or wood-free and is used for picture postcards (basis weights from 150 to 300 g m⁻²).
- *Letter file cardboard* is a solid fiber board used in the production of files. It is multilayered, vat-lined, or unlined and has a basis weight of 1000–2000 g m⁻². Special requirements are that it should be exactly planar and have a precisely maintained moisture level.
- *Filing board* is a special tough board, which is usually colored and supercalendered (basis weights from 130 to 900 g m⁻²).
- *Ticket board* is wood-containing or wood-free and often colored. It is used, for example, for streetcar tickets and entrance and weighing tickets. Ticket board is produced in accordance with regulations issued by the railroad authorities.
- *Fancy cardboard* can be pasted or unpasted and is often wood-free, for example, ivory, bristol, and opaline board. It is used in the production of visiting cards, invitations, and so on. Basis weights range from 100 to 400 g m⁻².

28.2.2

Packaging Paper and Board Grades

28.2.2.1 Overview

A large number of grades of paper and board are available for packaging and are employed for different purposes.

- Packaging paper grades range from simple wrapping paper (WP, made from mixed recovered paper) to kraft paper, and are predominantly supplied in rolls. They are made from various virgin pulps (sulfite/kraft pulp), from recycled fibers, or from mixtures of chemical pulp and recycled fibers. These grades are employed in the production of bags, beer mats, carrier bags, gift wrapping paper, and so on. Some examples are the special types of paper and board produced for use in the foodstuff sector, which must fulfill the requirements of the food laws. These papers are also widely used in the nonfood sector, for example, as coating papers. The possibilities of combination with each other and with other materials (plastics) are numerous. In this way, special packing materials can be produced for most packaging purposes. *Greaseproof papers*, for example, are used for the packaging of butter, margarine, meat, and sausage. These papers include vegetable parchment and glassyne and are provided with barrier polymers.
- *Kraft liner or test liner* and *corrugating medium* are the base for corrugated board production. Depending on their intended purpose (for the smooth surface or

the corrugated inner layer of corrugated board), these papers are produced with varying strength, stiffness, wet strength, and printability.

- *Folding boxboard (FBB)* is ideally suited for the production of folding boxes because of its properties, such as good scorability, creasing ability, groovability, and printability. This board can be coated or uncoated; the former gives a better printed format. It is usually produced from virgin fibers.
- *White line chipboard (WLC)* is used for the same purpose as FBB, but it originates mainly from recycled fibers. As FBB and WLC are produced as multilayer products, sometimes the upper layer of WLC may be manufactured from virgin fibers.
- *Machine-made board* (also solid fiber board) is produced almost exclusively from recycled fibers and is processed primarily into mailing boxes.
- For all paper and board grades described earlier, the stock is adjusted to meet the requirements in each case.

28.2.2.2 Packaging Papers

28.2.2.2.1 Kraft Papers In order to meet the high strength requirements, these papers consist of primary or a mixture of primary and secondary fibers of kraft pulp. They are used predominantly for packaging purposes. The different types of kraft paper are listed here:

- *Kraft sack paper* ($60\text{--}115\text{ g m}^{-2}$), bleached and unbleached, includes kraft bag asphalt base paper, which is used in the production of asphalt paper.
- *Extensible kraft sack paper (Clupak)* corresponds to the kraft sack papers. It has a higher elongation ($>6\%$) in the longitudinal direction. It can also be used as base paper for plastic coating ($45\text{--}350\text{ g m}^{-2}$).
- *Secondary kraft sack paper* ($70\text{--}350\text{ g m}^{-2}$) is made from at least 50% unbleached kraft primary fibers.
- *Kraft packing papers* ($40\text{--}350\text{ g m}^{-2}$) are made of slightly bleached, unbleached, or bleached fibers and must contain 80% primary fibers.
- *Kraft tissue*, bleached or unbleached, has a basis weight of $<30\text{ g m}^{-2}$. It is a one-sided smooth or fluted kraft paper that is employed for wrapping glass or metal goods; it is also suitable for packing fruit, for example, oranges.

28.2.2.2.2 Sulfite Wrapping Paper (ZP) The stock composition of this paper is on average 70% primary fiber pulp and not more than 30% fibers from recovered sulfite or kraft paper. The basis weight is $>30\text{ g m}^{-2}$.

- *WP* consist of mixed recycled fibers of varying composition; they may also contain chemical pulp ($30\text{--}350\text{ g m}^{-2}$).
- *Crepe packing material* is a highly sized and creped packing paper of any stock composition ($70\text{--}350\text{ g m}^{-2}$).
- *Mixed soda pulp paper* is made predominantly from secondary fibers and kraft pulp ($70\text{--}350\text{ g m}^{-2}$).

- *Glassyne* (20–40 g m⁻²) is a highly supercalendered paper made from strongly beaten pulp. It is largely greaseproof, but not water resistant. The high transparency is achieved by intensive supercalendering. It is frequently colored. This paper is used, for example, as WP for chocolates, covering paper in photograph albums, for dust jackets, envelope windows, and for packing high-quality preserves.
- *Supercalendered base paper for waxing* is designed to be waxed, and frequently contains titanium dioxide as filler. The waxed paper is often used as WP for candies (30–150 g m⁻²).
- *Silicon base paper* (30–160 g m⁻²) is a supercalendered paper to be used for siliconization.
- *Greaseproof paper* (40–200 g m⁻²) is made resistant to grease primarily by using a special beating process (high fibrillation) and by the addition of auxiliary agents. Compared with vegetable parchment, this paper is neither waterproof nor boilproof.
- *Parchment base paper* (35–200 g m⁻²) is unsized, highly absorptive, and is made of 100% chemical pulp fibers. It contains no chemical auxiliary agents and is employed in the production of parchment paper.
- *Vegetable parchment* [17] is a highly waterproof, greaseproof, boilproof paper product of high purity. It is used in the packing of fats, also in combination with aluminum foil or with a plastic coating. Silicon-coated parchment paper has a wide range of applications, for example, baking paper and antiadhesive papers. The basis weight is 40–130 g m⁻².
- *Coated papers* are often coated on one side and are suitable for offset and rotogravure printing. They can be painted, bronzed, and punched. They are waterproof and alkali resistant to prevent the detachment of labels in washing machines. They are used, for example, as WP for chocolates, cigarettes, and soap and as dust jackets for books and records (70–200 g m⁻² with a coat weight of 9–15 g m⁻²).
- *Coated packaging papers* (80–200 g m⁻²) are bleached kraft papers having a one-sided matt or glossy coat and are suited for the production of bags and carrier bags.

28.2.2.2.3 Corrugated Papers These papers are used for manufacturing of containerboard. As shown in Figure 28.3, at least three different papers are needed.

- 1) **Paper for the outside of the box:** This liner will often be printed and represents the goods inside. Therefore, high quality of the surface for good printing results is often essential. Nevertheless, burst strength has to be high to ensure the protection of goods.
- 2) **Paper for corrugated medium:** The main purpose of this paper is to extend the thickness of the construction and by this the bending stiffness. The strength under compressive loads is the main quality aspect of this paper.
- 3) **Paper for the inside of the box:** Burst strength and resistance against compression for this liner have to be high. However, the surface is not that important compared to the liner on the outside as this layer is usually unprinted.

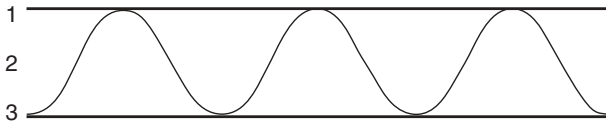


Figure 28.3 Construction of corrugated board: 1 = liner (outside box), 2 = corrugated medium, and 3 = liner (inside box).

For different purposes of use and different goods to be wrapped, several paper grades are available:

- *Kraft Liner* ($115\text{--}440\text{ g m}^{-2}$). This covering paper is made of at least 80% kraft pulp, bleached or unbleached, and has a bursting strength per basis weight (bursting index) of $3.43\text{ kPa m}^2\text{ g}^{-1}$.
- *Kraft-faced liner* is a covering paper that does not have a specified stock composition, but it has guaranteed strength properties.
- *Two-layer paper* is a double-layered covering paper.
- *Test Liner* is made from recycled fibers. Depending on the quality of the secondary fiber source, different strength levels are achievable – T1, T2, and T3. T1 is manufactured from high-quality grades and therefore offers the best strength properties.
- Liners, kraft liner as well as test liner, are traditionally brown colored. But for printing and optical purposes, the top liner (at the outside of the box) may be white, mottled (either white or colored), or even coated (once or twice, rarely three times).
- *Semichemical paper* is corrugated paper made of at least 65% semichemical pulp.
- *Fluting or corrugating medium* ($60\text{--}200\text{ g m}^{-2}$) used for the production of corrugated board has no specified stock composition; however, definite strength properties are required.

28.2.2.3 Board and Cardboard

Paperboard grades can be classified into three categories: cartonboards, containerboards, and specialty boards. The classification used is shown in Figure 28.4.

- As stated in the introduction, the terms paper and board overlap as regards basis weight; so many linerboard and corrugating medium grades have a basis weight lower than 100 g m^{-2} , and recently even down to 80 g m^{-2} and less. Products with basis weight $>600\text{ g m}^{-2}$ are usually called *cardboards*. Most of the paperboard grades are multiply products such as FBB and liquid packaging board, whereas corrugating medium is very often a single-ply product.
- Paperboards are very often used for packaging, but again there are exceptions such as plasterboard. Because of their function in the packages, strength properties are most often very important for paperboards. Cartonboards are mainly used for consumer product packaging such as food, cigarettes, milk, and pharmaceuticals. Containerboards (corrugated boxes) are used in many packaging applications starting from simple transportation containers and ending with multicolor printed display containers for stores.

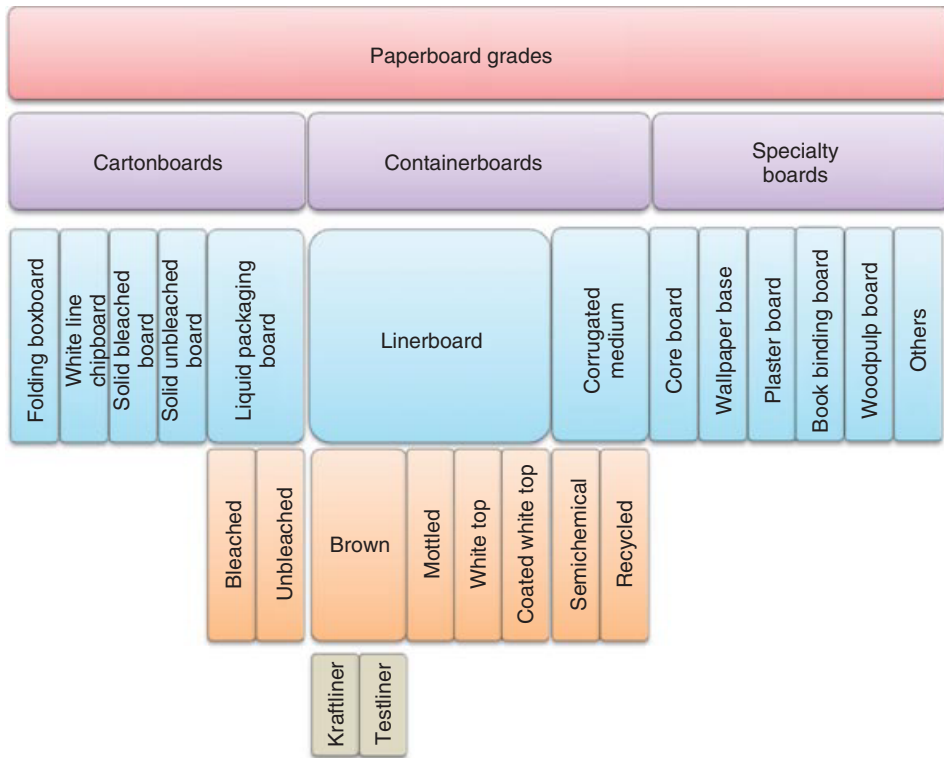


Figure 28.4 Classification of paperboard grades.

- The following board types are included in the group of FBB:
 - *Coated pulp board* made from bleached chemical pulp is usually used for folding boxes.
 - *Cast coated pulp board* is used for high-grade packaging and for folding boxes, fine pasteboard boxes, paperback covers, and so on.
 - *Chromo board*, *chromo duplex board*, and *chromo triplex board* have very different stock compositions, depending on their intended purpose.
 - *Artificial chromo board*, *triplex board*, a gray core can also be used in this case.
- Other machine-made boards in the cartonboard group include the following:
 - *Mechanical pulp board* has a light or gray core. It is used, for example, in the production of paper plates and round cheese boxes.
 - *Brown mechanical pulp board* is made predominantly from recycled fibers and has a brown colored cover and reverse. It is used for the production of mailing boxes.
 - *Chipboard* consists predominantly of recycled fibers and is employed for the production of mailing boxes, box lining, and so on.
 - *Pasted board* consists of two or more layers of mill board that have been pasted together in the dry state.

- *Sheet-lined board* is made from mill board. It may also be pasted, is lined on one or both sides with paper, and is used for high-grade packaging.
- *Mill board* is made by winding one or several fiber webs on a press roll. Thus, high basis weights and the production of especially stable packaging material are possible.
- *Cartridge papers and boards* are usually made from recycled fibers and are used in the production of cartridges, special cartridges, cardboard tubes, and containers such as detergent drums.
- *Board for cups* is a single-layered hard board consisting of bleached pulp and is used for the production of drinking cups, and so on.

28.2.3

Hygienic Papers

The major component of all hygienic papers is tissue. The term *tissue* describes products made from lightweight, dry creped (sometimes wet-creped or uncreped) papers such as toilet paper, kitchen towels, handkerchiefs, facials, napkins, hand towels, and wipes. Such kinds of products are made from a one-ply, semi-finished, wet-laid tissue base paper that is predominantly composed of natural fibers. The origin of the fibers may be virgin or recycled. Usually, the basis weight of the base paper before creping is $10\text{--}20\text{ g m}^{-2}$, which is increased during creping by 10–20%. Tissue is usually used in multiple layers because of its low basis weight. Cellulose wadding and crepe paper also belong to the group of tissue papers, whereas nonwovens (predominantly air-laid products) do not.

28.2.3.1 Cellulose Wadding

This is a loosely structured, highly absorbent fiber product. It is made from virgin fibers. Its use includes the production of sanitary towels, surgical artificial cotton, patients' sheets, and packing cotton.

28.2.3.2 Tissue

Tissue is made of virgin or recycled fibers (or a mixture), with fine, soft creping, and closed formation. The basis weight is $<27\text{ g m}^{-2}$. Tissue has to meet a wide variety of requirements, for instance, surface softness, liquid absorbency, and tensile energy absorption as shown below. The highest quality tissue is made on machines with a through-air drying system (TAD, Section 6.11.4) or other soft tissue producing systems. Tissue is employed in the production of the following:

- *Toilet paper (bathroom tissue)* is the biggest single product made from tissue. It is made in one, two, three, or five plies with or without moderate wet strength because this type of tissue has to disintegrate in the sewage system. Toilet paper should be smooth and can be embossed, unprinted or patterned, tinted, purely white, or off-white.
- *Kitchen towels* are the second biggest product for the consumer sector. They usually have a basis weight of $20\text{--}24\text{ g m}^{-2}$. Sheets are 220–280 mm wide and

250–280 mm long. The number of sheets to a roll is normally between 54 and 100. Most kitchen towels are two-ply products. Good wet strength and high water absorbency behavior are the most important functionalities.

- *Facial tissue and handkerchiefs* have the lowest basis weight of 14–18 g m⁻². The surface is often made smoother by light calendering or softening additives. Facial tissue consists usually of two plies, while handkerchiefs have two or three plies. Because of the high quality requirements, the base tissue for most facial tissues and handkerchiefs is made either entirely from pure chemical pulp or from a mixture of pure chemical pulp and selected recycled fiber. Handkerchiefs can be one-, two-, three-, or four-layer products and must have good air permeability, absorbency, wet strength, and burst strength.
- *Serviettes* can be one-, two-, three-, or four-ply. The size and type of fold vary greatly.
- *Diapers and sanitary towel covers* have additive functionalities, which are supported by a special water absorber.

28.2.3.3 Crepe Paper

Crepe paper is a single-layered highly absorbent hygienic paper made from mechanical pulp and/or secondary fibers. The basis weight is >27 g m⁻². The most important uses are toilet paper, paper handkerchiefs, and cleaning rolls.

28.2.4

Paper and Board for Technical and Specialty Uses

This group of paper and board covers a wide range of grades. The most important subgroups comprise base papers for decor, priming and barrier foils, body, coating and soakage base papers and base papers for wallpaper, papers for electrotechnical purposes, drawing papers, photographic base papers, cigarette papers, filters and filter layers, and special cardboards for the various branches of industry, for example, pressboard (press span), car body, and shoe cardboard. All these papers and boards have a common requirement; they must exactly fulfill the defined quality criteria according to the use.

- *Chromatography papers* are porous absorbent special papers made from linters without the addition of sizing or filling agents. They are often acid washed and contain silicon compounds to render them hydrophobic. Their applications are discussed below.
 - *Reagent and indicator papers* are high-grade special papers used for impregnation with test reagents and indicator dyes.
 - *Household filter papers* are wood-free special papers that give a defined rate of filtration. They must comply with food laws. They are used, for example, in coffee filters. The rate of filtration and the separating ability depend on the degree of fiber beating.
 - *Analytical and industrial filter papers* are usually made from cotton, dissolving pulps, glass microfibers, or other artificial fibers. They possess a uniform stock

distribution and, thus, a homogeneous pore size. Analytical filters are acid washed and are made without paper-making additives. Filter layers with a basis weight of up to about 750 g m^{-2} are produced to withstand special stress, for example, in the beverage industry. Filter layers of this type, which are also used for sterilization filtration, must comply with food laws. For industrial use, the paper and filter layers may also be impregnated with melamine-urea resins or similar compounds.

- *Filter mass* is made from soft-cooked highly bleached pulps or from rags or linters and is used in the form of flocks for industrial filtration.
- *Cable and condenser paper* (capacitor tissue paper) is stiff nonporous paper made from pulp and is usually impregnated with artificial resins. These papers do not contain fillers, metal impurities, or salts. The absence of pores is achieved by fine beating of the pulp fibers and by supercalendering. Cable paper must exhibit high strength in the longitudinal direction. The thickness of condenser paper is $0.006\text{--}0.012 \text{ mm}$ and the basis weight is $6\text{--}7 \text{ g m}^{-2}$. These papers must meet International Electrotechnical Commission (IEC) regulations [18].
- *Press span* is a single-layered highly rigid product that is made from pure pulp and couched in the wet state. When used in the electrical industry, the pulp must be produced with a high degree of electrochemical purity.
- Building papers and boards include the following:
 - *Roofing felt base*, a wool-felt board (reclaimed wool) impregnated with tar/bitumen and used to produce roofing sheets.
 - *Felt and wool-felt board* made from recycled fibers and rags. They are used as the base material for textile floor coverings and as insulating material in various fields, predominantly in the automobile industry. They are also employed as separating layers on flat roofs that are covered with a plastic foil.
 - *Gypsum liner board* used for the production of gypsum wallboards (building plates).
 - *Covering papers and cardboards* includes various papers and cardboards that are used as protective coverings. These single-layered or multilayered materials can be made from various raw materials. They are used, for example, as covering papers in road construction.
- Substrate papers, saturating base papers, and coating base papers:
 - *Substrate papers* are used in many different technical systems as manufacturing aids. They are frequently removed from the finished product at the end of the production process, rewound, and reused in the same process.
 - *Saturating base papers* must be absorbent and have wet strength and often also resistance to organic solvents.
 - *Coating base papers* must be moisture resistant and stable to organic solvents. One or both sides of the paper are treated with various solutions or dispersions, which represent the requirement for the desired coating.
 - *Raw material for artificial leather* is tough kraft paper that is not dyed and is usually moisture resistant. It forms the web base for the production of artificial leather.

- *Base paper of vulcanized fiber* is absorbent, voluminous paper made from cotton rags, cotton linters, and refined pulps.
- *Photographic base paper* that is suitable for the production of photographic paper is a moisture-resistant, dimensionally stable, chemically neutral chemical pulp paper that is free from traces of iron or copper. Today, papers coated with a thin polyethylene foil on both sides have replaced barite paper. This paper is used for the uptake of light-sensitive emulsions.
- *Saturating base paper* (overlay paper) is made from special pulp and has basis weights of 15–40 g m⁻². It is highly porous, free of dirt, and protects the underlying decor in the production of laminated products.
- *Decor base paper* is a soakage base paper made from bleached or unbleached kraft pulp; it is used for resin absorption in the production of laminated plates.
- *Base papers for abrasive papers* are tough sized papers made from kraft pulp and are coated with an abrasive.
- *Calender bowl paper* is a strong, compressible, heat-resistant paper used for the manufacture of calender bowls.
- Technical drawing papers include the following:
 - *Opaque drawing papers* are fine look-through papers made from pulp and have good sizing and hardness. Erasability is the most exacting demand.
 - *Translucent drawing paper* exhibits the distinction between natural transparent paper and paper made transparent by chemical treatment. Natural transparent papers are made from pulp or linters or mixtures of the two by intensive beating of the fibers. They are well sized and exhibit good surface smoothness and look-through. Opaque papers are rendered transparent by soaking them in a solution of synthetic resin.
 - *Sketching papers* are wood-containing or wood-free, machine-finished, sized natural papers with a basis weight ≥ 80 g m⁻².
 - *Art drawing papers* and board are suited to special drawing and painting techniques, for example, watercolor paper. The latter has a rough surface, which accepts water colors but does not allow their penetration. This material also has good erasability.
 - *Base paper and board for wallpaper*: This is the general name for papers and boards that are suitable for the production of wallpaper [19]. They can be single layered or multilayered, couched or pasted, wood-containing or wood-free, and coated or uncoated. They may contain recycled fibers and may have a woodchip coat. Strip-off wallpapers or preglued wallpapers can also be produced.
- Papers for tobacco products include the following:
 - *Imitation cork paper* is a brownish yellow colored paper used for the production of cigarette tips. It has an imitation cork imprint and joins the filter to the tobacco stick.
 - *Filter encasing paper* is used for the production of acetate and/or cellulose filters. Cigarette paper has a high filler content and a basis weight of 18–28 g m⁻². To control the smoking properties, this paper has a porosity that is suited to the type of tobacco and contains additives that regulate burning.

- *Cigar or cigarillo casing paper* holds the chopped tobacco together and serves as the inner casing.
- *Long-fiber paper* is used for tea bags and artificial sausage skin and is made from fibers having an average length >3 mm. The addition of synthetic fibers is permitted.
- *Binding papers* are tough wood-free papers that are frequently embossed.
- *Cover paper and board* is a tough, elastic, durable, wood-free white paper or board that has a linen finish and is specially suited to the production of covers for brochures, paperbacks, or similar products.
- *Bookbinding board* is press rolled or mill cardboard that is pasted or unpasted and has high rigidity, dimensional stability, and perfect lining ability.
- *Car body cardboard* is a hard cardboard used predominantly as shaped parts in automobile manufacture; it is usually capable of being cupped.
- *Leather fiberboard* is an especially tough hard cardboard that is flexible and resistant to moisture.
- *Suitcase board* is an embossed hard cardboard used in the production of luggage.
- *Flong* is a coated cardboard (solid board) made from very high-grade stocks (rags). It is processed with fillers and is completely knot-free and can be subjected to hot embossing. It is used to produce the matrices for high-pressure dry stereotyping.
- *Cardboard for beer mats* is a highly absorbent groundwood cardboard that may be pulp covered. It can be punched, embossed, and printed.
- *Base papers for chart paper* have a basis weight of $30\text{--}130\text{ g m}^{-2}$ and are usually filled and sized. They have a refined surface and good dimensional stability.
- Gardener, flower, and decoration crepe:
 - *Gardener's crepe* is a white or colored, highly expandable paper that has longitudinal grooves and serves as decorative flowerpot wrappers.
 - *Flower crepe paper* is wood-free and is used to make artificial flowers.
 - *Decoration crepe paper* is flameproofed by impregnation with chemicals and is used for decorations of various types.
- *Board for playing cards* is made of two or three layers pasted together. It is coated on both sides with supercalendered surfaces. The basis weight is $280\text{--}340\text{ g m}^{-2}$.
- *Album board* is used for photograph, stamp, and other albums and is often wood-free and voluminous.
- *Hot setting paper and hot sealing paper* are coated on one side, become sticky on heating, and can consequently be fixed to another material.
- *Insect resistant or insecticide paper* is resistant to insects. It can kill insects by means of volatile components or by contact.
- *Antitarnish paper* is an impregnated or coated paper that protects other materials against corrosion by releasing substances in the vapor phase or by direct contact.
- *Photographic protective wrapping (black photo) paper* is a lightproof, black-dyed, chemically neutral paper that can be folded without breaking and is suitable for wrapping photographic film.
- *Sterilization paper* is a wood-free paper that, even when coated, can tolerate sterilization processes and is used for packing sterilized materials.

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29

Testing of Fibers, Suspensions, and Paper and Board Grades

Heinz-Joachim Schaffrath and Otmar Tillmann*

29.1

General Aspects

Three areas have to be mentioned when talking about the relevance of testing methods: *quality Management*, *Research and Development*, and *Science* [1–4].

Quality management deals, of course, with the defined properties of paper products offered to the customers. Final control must ensure that only products within the defined range of properties will leave the paper mill. But quality control is not able to create quality. This is done by a reasonable manufacturing process. Reasonable means that the manufacturing process has to be designed in a way that targets have to be defined at important steps in the process, the fulfilling of a target has to be measured, and actions or reactions have to be carried out accordingly to reach the target. Reasonable means that the design of a quality management system refers to economic targets, too. Therefore, testing is one helpful way to define and control numerical values for targets. Also it forces people to think about what they have to measure, and how and when they have to measure. How to succeed in that is described in quality management processes and may be certified by an audit according to DIN EN ISO 9001 (Figure 29.1) [1, 2].

Tests to ensure the desired quality start with control of incoming material. Not only the specification of a raw material has to be monitored, but the variations (or, more precise, the evenness) of the delivered goods, too.

Continuous processes as in present paper mills require continuous measurements to run these processes within the specification targets. This needs a correlation between customer specifications measured off-line and the process variables measured online. Exact paper testing is one means to achieve this necessity. And again, not only the mean values are important, but the degree of evenness, too.

Degree of evenness in product quality and also in the manufacturing process may be a key to economic success. It is seldom necessary to produce a quality as good as possible; more often it is better to produce a quality that is good enough but with low variations. Keywords leading into this broad field are *total quality*

* Contributed to the First Edition.

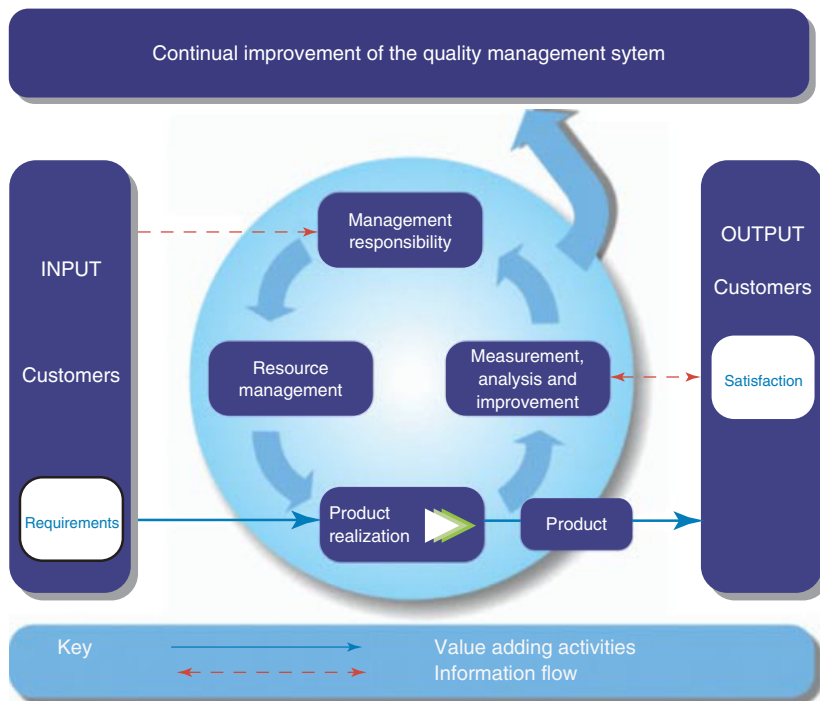


Figure 29.1 Overview of a quality management process.

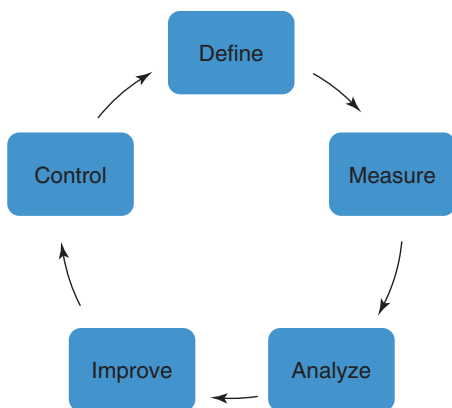


Figure 29.2 The DMAIC improvement cycle.

management (TQM) and Six Sigma (6σ) with the Define Measure Analyze Improve and Control (DMAIC) process (Figure 29.2).

Everywhere people are working and mistakes are happening. As a consequence, complaints may rise. However, paper testing can help in the decision whether a complaint has to be accepted or not.

Finally, paper testing helps to compare the own quality standards with the competitor.

Research and development takes advantage of testing methods, too. In this field, the wish to improve quality, processes, products, and finally the economic power is emphasized. Testing helps to measure the status quo and the success after changes have been made. Therein, changes in raw materials are concerned as well as new manufacturing methods, new machines, product development, or just trials to gain more information on the own process. Testing helps to calculate the return on invest (ROI), and it is necessary to prove the fit of guaranteed parameters after an investment has been carried out.

Science, however, is in symbiotic relation to testing. Precise test methods are essential to gain new expertise with the obtained test results. The results may either be the start for a new modeling of observations or help to verify existing models. Also in some cases, paper testing has already been a help to justify with forensic analysis.

The proper selection of relevant analysis and test methods for raw materials, intermediate, or final products obviously has importance for the success of a testing program. Process and product analysis are the main areas for a large variety of very heterogeneous testing methods. Process analysis tries to define the control variables of the process that allow it to run smoothly and produce products with the necessary properties. The aim of product analysis is to define the properties that relate to the use of a specific product or material. The test results obtained should be representative of all of the papers from which the sample has been taken. Reliable representative measuring results require

- representative sampling as far as quality and quantity are concerned
- adequate sample preparation
- calibrated measuring equipment
- defined measuring circumstances
- careful, accurate measurement.

29.2

Testing of Fibrous Material

According to DIN 6730, paper (and board, respectively) is defined as plain material, obtained mostly from vegetable fibers, formed by dewatering of a suspension with the help of a wire. Besides, the vegetable fibers such as wood (the main component of fibers), linters, or flax (used in specialty papers) and inorganic material such as calcium carbonate or china clay may be expected. Only in rare cases, manmade fibers are added, too.

29.2.1

Composition

To determine the fiber composition of a paper or a suspension, a light microscope is often sufficient (fiber microscopy). Owing to the varying fiber morphology,



Figure 29.3 Fiber microscopic image showing the raw fiber and pulp materials.

both the fiber raw material and the kind of pulping process can be determined. Chemical dyeing methods are used for contrast enhancement and quantitative determination of fiber composition (ZM IV/55/74; TAPPI T 401 om-93, Harders-Steinhäuser, Faseratlas [5]). As an example, the Herzberg stain [5] consisting of chlorine-zinc-iodine colors chemical pulp in blue and mechanical pulp in yellow because of the different lignin contents. Combined with calcium nitrate (Alexander), softwood chemical pulp appears in a red shade and hardwood and straw pulp in a blue–violet shade (Figure 29.3).

29.2.2

Length and Length-Related Properties

Fiber length distribution can be measured with a light microscope, too. However, this method is very time consuming. Nowadays, optical systems give precise information about fiber length, fiber width, fiber wall thickness, degree of fibrillation, and more. For that, a laser is used, which determines the fiber's projected length L_p . In addition, a CCD camera captures an image of the detected fiber. Image analysis helps to obtain the center line length L_c and other information, such as fiber width, wall thickness, fibrillation index, and so on (Figure 29.4).

Projected length and center line length are commonly used to describe the fiber deformation. The number is called *curl index* and gives a hint how far a fiber shape

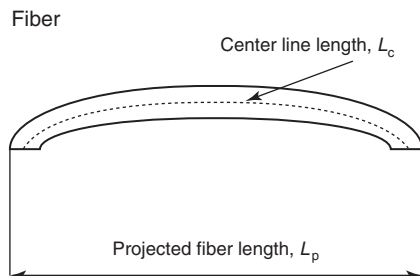


Figure 29.4 Image analysis of fiber length distribution to obtain the center line length L_c and other information, such as fiber width, wall thickness, and fibrillation index.

is different from a straight fiber

$$\text{curl index} = \frac{L_c}{L_p} - 1$$

If a sharp bend or a sharp angle in the fiber shape is detected, the algorithm will define that as a fiber kink. Depending on the ratio of width and length, such a detected element will be regarded as a fiber or a vessel.

All detected elements together can be classified, for example, by fiber length, the result of which will be the classes fines, short fiber, and long fiber. In addition, the shape of the fiber will lead to a classification such as vessel or fibrillated fiber and unfibrillated fiber.

The arithmetic average fiber length often gives information to compare or differentiate pulps. But these length numbers are not related to the fiber mass. In some cases, it may be useful to get a connection between fiber length and mass. Mechanical pulp, as an example, has a higher mass per unit fiber length as chemical pulp because of the lignin content. This relation is expressed by the fiber coarseness C . According to one fiber sample with the mass m (oven dried in milligrams) and the average center line length \bar{L}_c (in meters), the coarseness C is calculated as

$$C = \frac{m}{\bar{L}_c} \left(\frac{\text{mg}}{\text{m}} \right)$$

29.2.3

Fiber Fractionation

Instead of using image analysis for fiber classification for a long period of time, fibers has been fractionated and classified by means of sieves and slotted or drilled plates. A combination of Haindl fractionator (for shive analysis) and McNett fiber classifier is shown in Figure 29.5. ZELLCHEMING method ZM V/1.4/86 describes the use of this equipment, which detects shive content and different fiber classes

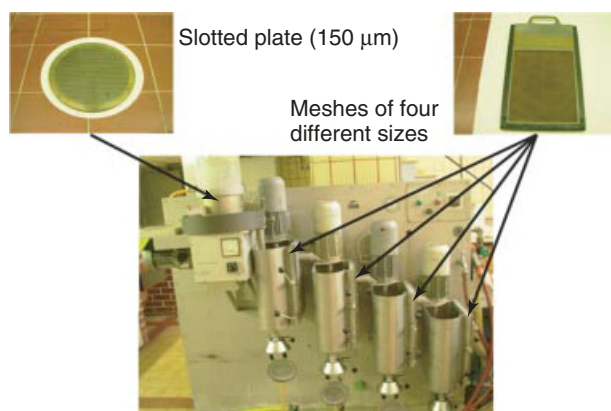


Figure 29.5 A combination of Haindl fractionator (for shive analysis) and McNett fiber classifier.

in one process. Ten grams (oven dried) of a suspension has to pass the system, starting at the slotted plate, followed by meshes of different sizes. The number of the mesh gives the number of wires per inch. For hardwood, the meshes 35 (48), 65, 100, and 200 are recommended; for softwood 20 (28), 48, 65, and 150. The retention on the slotted plate is regarded to give the shive content. However, with secondary fibers, this fraction will contain macrostickies and plastic particles, too.

The retention of each mesh can be determined, too. Using the fiber mass of 10 g at the beginning, the fraction that passed the last mesh can be calculated. With these figures, a pulp can be characterized by its fractions. This is, of course, not as exact as the fiber length distribution obtained with the image analysis but can often sufficiently characterize a pulp.

29.3

Testing of Fiber Suspensions

During the manufacturing of paper, fibers are usually suspended in water. Water opens the hydrogen bonding between the fibers in the disintegration step at the beginning of the manufacturing process. In the following process, water is the transport medium; it helps to add chemical additives and allows adjusting sheet properties as formation (by dilution) or Machine Direction (MD)/Cross Direction (CD) relationship (by jet–wire ratio). Hence, it is of high importance to measure parameters of a fiber suspension, which give hints on the expected paper properties.

29.3.1

Sampling

The first step for good results in the laboratory is the correct sampling procedure. If a sample is taken be it from a chest or another open bin, or from a pipe, it must always be ensured that the sample is representative for the suspension. Samples out of the pipes are taken with the help of valves. These should be placed in a straightforward flow and never at an elbow joint (Figure 29.6). Otherwise separation processes caused by centrifugal forces may influence the results. The suspension has to be taken from the pipe center.

For sampling, it is recommended to open the valve, wait a few seconds, and then take the sample to avoid that the sample is contaminated by some old plug. This procedure should be repeated at least three times to get a representative mixture.

In most cases, the suspension can be taken to the laboratory and tested at once, in due course, at least within the next 3 h. Otherwise it has to be taken into account that biodegradation may start very soon. Chemical pulp may be stored in a refrigerator for several days if necessary. Pulp from secondary fibers can be conserved with a biocide and a fungicide additionally. Mechanical pulp may be frozen, which cannot be recommended for the pulps mentioned before.



Figure 29.6 Sampling out of the pipes with the help of valves.

29.3.2

Consistency

One of the most important parameters to describe a suspension is stock concentration or consistency, c . The determination is given by DIN EN ISO 4119. It is specified that at least two measurements have to be done. The unit is percentage mass. First, the mass of the taken sample, m_s , is determined. Then, the sample is filtered to separate water and fibers. This is done with a paper filter from which the dry mass, m_F , must be known. After filtration, the filter plus the wet fibers will be dried until no more change in dry mass, m_d , can be detected. With these numbers, the consistency is calculated as follows:

$$c = \frac{m_d - m_F}{m_s} \times 100 (\%)$$

In the manufacturing process, the consistency is measured inline using different systems [6]. The dominant technique is the use of shear forces (the higher the consistency, the higher the shear forces; attention: ash content influences this method significantly) by means such as static blade transmitter, moving blade transmitter, or rotating consistency transmitter. Another method uses microwaves. These transmitters make use of the effect that the velocity of a microwave in a suspension is higher when the water content is higher (attention: conductivity of the liquid and air bubbles has significant effect on the results). Other inline techniques use optical properties or even gamma radiation.

29.3.3

Shives and Flake Content

Besides the consistency, either the shive content or the flake content or both are of interest. Shives are fiber bundles that stick together because the lignin between the fibers has not been weakened enough to allow a separation. Shives may be determined by fractionation according to ZELLCHEMING method ZM VI/1/66 with a slotted plate of 150 μm slots. Flakes are fiber bundles that stick together because the hydrogen bonding has not been opened yet. They may be determined by fractionation according to ZELLCHEMING method ZM V/18/62 with a drilled plate. The diameter of the holes in the plate depends on the kind of pulp to examine. Unbeaten softwood kraft pulp should be measured with 1.2 mm holes, beaten softwood kraft pulp with 0.9 mm, sulfite pulp and recovered paper of higher grades with 0.7 mm, and hardwood and mixed recovered paper with 0.5 mm.

29.3.4

Fiber Classification

A fiber suspension can be separated into different fractions using different slotted plates, drilled plates, or meshes. Here the Haindl–McNett equipment (Figure 29.5) is a very common classifier, but others are in use, too. The different fractions give some hints on fiber length distribution in terms of long fiber, short fiber, and fines.

In the laboratory as well as online optical systems with laser, cameras and image analysis are in use (Section 29.2). Results obtained with this equipment are much more meaningful than just regarding at different fiber fractions. The fiber length distribution is highly precise, and some additional information on fiber curling, fiber kinks, and fibrillation degree is delivered. All these parameters may be used to interpret dewatering behavior of a suspension in the wire and press section and the paper characteristics found later in the sheet.

29.3.5

Beating Degree

A rough but very popular manner to estimate dewatering behavior and some paper characteristics to be expected is measuring the beating degree, also called *freeness*. Two measuring devices – very closely related – are in use, the Canadian Standard Freeness (CSF; described in TAPPI T224om or ISO 5267-2) and the Schopper-Riegler number (SR; described in DIN EN ISO 5267-1). Both devices use the fact that the fibers in a suspension form a layer during dewatering on a mesh. This layer has an increasing resistance against the ongoing dewatering. In the beginning, dewatering takes place fast and becomes slower and slower when the layer is building up. The dewatering resistance is influenced by the thickness of the formed layer (which can be influenced by the consistency during the test), the porosity of the formed mat (this is given by the fiber characteristics as length

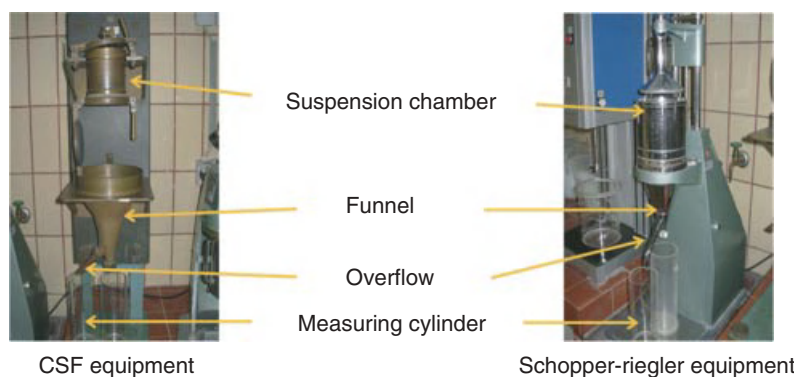


Figure 29.7 CSF apparatus and shopper riegler apparatus.

distribution and degree of fibrillation, but pH-dependent swelling, too), and the viscosity of the water. (Hence, temperature and presence of charged particles have to be defined.)

CSF affords that a filter pad has to be formed with the suspension. This pad is dried and afterward the pulp is soaked in distilled water at 20 °C for at least 4 h and disintegrated again. A dilution of 0.3% has to be adjusted to 20 °C.

One liter of this suspension will be drained in the CSF apparatus (Figure 29.7). The drained water has to pass a funnel with an orifice. If the water flow is high (as in the beginning of the test), not all the water can pass the orifice and this water will be captured in the overflow. When the test is finished, the amount of water captured in the overflow measuring cylinder can be determined in milliliters. The lower the beating degree, the faster the water can pass through the formed fiber mat, the more milliliters will be captured in the overflow. This means a high CSF value indicates a low beating degree. According to ISO 5762-2, this procedure may also be carried out with water defined by ISO 14 487 (conductivity $\leq 0.25 \text{ mS m}^{-1}$).

SR operates in a similar way, but the consistency is only 0.2%. The test is carried out with water according to ISO 14 487, but without dewatering, drying, and redisintegration. The pulp suspension can be used as taken, diluted if necessary, and adjusted to 20 °C. The overflow measuring cylinder has a scale from 100 at the bottom to 0 at the top. The SR number can be read from this scale. A high SR number indicates a high beating degree. Pure water gives an SR number of 4.

29.3.6

Water Retention

In addition to the flow of water between fibers, a flow of water out of the fiber lumen or the fiber walls occurs during pressing. A number to express the effort, which is needed to eliminate this water either during pressing or during drying, is the water retention value (WRV; ZELLCHEMING method ZM IV/33/57). For that, a small amount of a pulp suspension is put into a centrifuge. At high speed, the

fibers are spin dried. The mass m_W of these still wet fibers is measured, and the remaining water in the fibers is determined by drying. With the dry mass m_D of the fibers, the WRV can be calculated as follows:

$$\text{WRV} = \frac{m_W - m_D}{m_D}$$

29.3.7

Water Properties

Besides fiber and filler content in a suspension, the quality of the water is of interest, too. Parameters such as temperature, pH value, conductivity, and viscosity have already been mentioned. Others are hardness, cationic demand, chemical oxygen demand (COD), and biological oxygen demand (BOD).

Water hardness gives an indication on the content of alkaline earth metals and may be measured according to DIN 38409 H6.

COD and BOD are of interest in waste water treatment, but these numbers are established to judge the quality of process water, too. They give a hint on dissolved organic material in a suspension. The COD value tells how much oxygen from a chemical compound with strong oxidative properties is consumed by the dissolved material (DIN 38 409-41 or -43). The higher the COD level, the higher the amount of dissolved organic material. The value is given in milligrams per liter.

BOD is the amount of oxygen that is needed by a microbiological population over a certain time (mostly five or seven days). The indication is the same as COD, but it only shows the biodegradable matter. As the value is indicated in milligrams per liter, too, BOD is always lower than COD.

Known from experience, there is a significant amount of colloidal dissolved substances in the process water circuits. These substances disturb the intended action of the chemical additives by absorbing them. Most of these particles have an apparent negative charge on their surface and are therefore called *anionic trash*. This charge may be sheared by movements between two walls close to each other. Evoking this by an oscillating piston in a small cell, an electric current is produced leading to a potential difference. This can be measured with particle charge-detecting devices (Figure 29.8). The liquid in the cell may now be titrated with a cationic polymer until the potential is dropped to 0. The amount of polymer used in milliliters is called the *cationic demand of the liquid*.

29.3.8

Stickies

Measurement of the cationic demand is highly important when looking at the broke system of a mill (starch and binders may influence the cationic demand very much) or using secondary fibers as a source. With recovered paper, all kinds of binders, starch applications, and other colloidal material are introduced into the mill water circuits. This may lead to undesired chemical reactions.

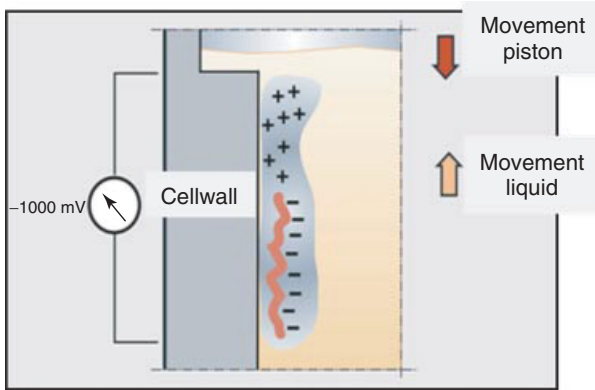


Figure 29.8 Particle charge-detecting devices.

One of them is the precipitation of sticking particles. Together with hotmelts, pressure-sensitive adhesives, and other adhesives, they form the wide variety of stickies, one of the biggest problems in paper recycling. Stickies are macrostickies and microstickies as well as primary and secondary stickies. Primary stickies originate from gluing material in the recovered paper. Secondary stickies originate from certain precipitations during the paper manufacturing process. *Macrostickies* are defined as those which may be separated by a classifier with a slotted plate, where 100 μm slot width is recommended. The determination is described in INGEDE method 4 (Figure 29.9). Microstickies are those which pass the slots.

Macrostickies have to be separated from dirt. This is the reason why a white corundum powder is applied. Stickies and dirt are dark and do not contrast on dark sheet. But only stickies have the adhesive property to capture the powder. Therefore, the gluing particles are colored white and can be detected by an image analysis system.

Until now, there is no generally accepted method for determination of microstickies. One approach is the use of flow cytometry [7]. The forward scattering light of a particle and the fluorescence measured during passing a capillary are taken as a hint on hydrophobic properties. As the fluorescence derives from a color that is absorbed by hydrophobic surfaces, the used color is of high importance for significant results. Stickies may be regarded as hydrophobic.

29.3.9

Dirt

Dirt content is of course of interest, too. After forming a hand sheet, a paper may be examined by image analysis. A threshold has to be chosen to determine the gray value that has to be regarded as dirt. TAPPI T563 om gives a description how visible dirt can be counted. This method gives an approach to consider the visual impact of a dirt spot. Instead of just taking the physical area of dirt, the contrast

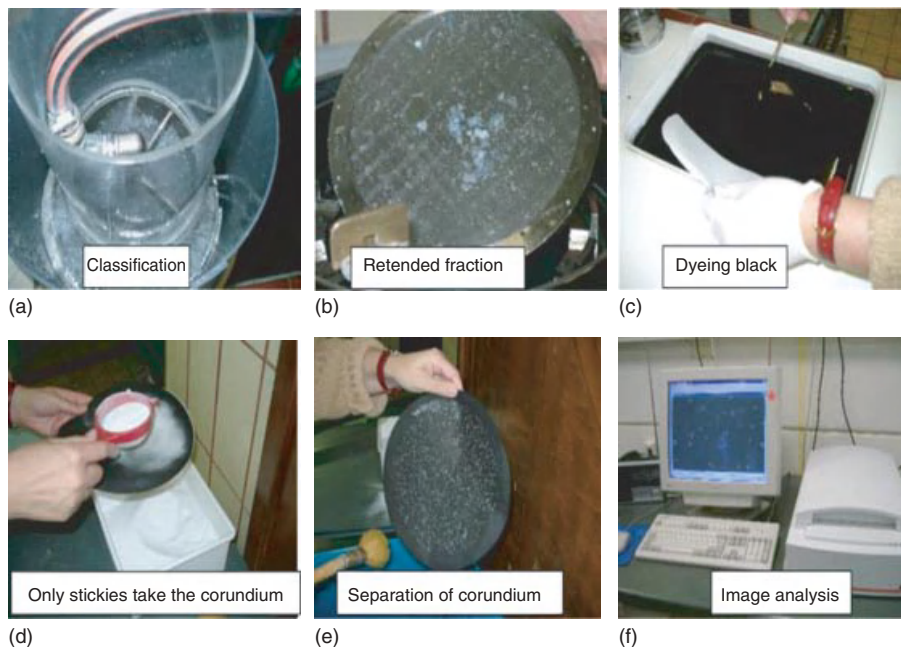


Figure 29.9 INGEDE method.

influences the weighting of a spot. The resulting number is called equivalent black area (EBA).

29.3.10

Brightness

Finally, the brightness of a pulp suspension is of interest. To measure optical properties such as brightness, whiteness, or luminescence, a paper mat has to be formed with a Büchner funnel (ISO 3688).

29.4

Testing of Paper and Board

A straightforward process for cut size and reel paper is described in ISO 186.

As a result of their hygroscopic properties, paper and board must be tested under standard climatic conditions and the samples must be conditioned in this climate for at least 4 h before testing (sample conditioning). In ISO 187, the preferred climatic conditions for paper testing are specified as 23 °C and 50% relative humidity. In the following, the most relevant test methods for paper and board testing are discussed.

29.4.1

Basic Properties

The basic properties of paper include the dimensions and the mass. In the case of sheet material such as paper, the *basis weight* m_A is determined in accordance with ISO 536. The value m_A is the ratio of the mass m to the area A of a sample

$$m_A = \frac{m}{A}$$

Standard deviation of basis weight may be taken as a rough number for paper formation. However, formation may be analyzed with β -ray equipment to determine the small-scale mass distribution in a sheet of paper. Another way to characterize the formation of paper is the observation in transmitted light (Figure 29.10). Advantage of this method is the close connection to the papermaker way of judging the cloudiness and the possibility to use image analysis for characterization. The disadvantage is the strong correlation to opacity, which is influenced not only by mass distribution but also by distribution of components with different optical properties (i.e., fillers), too.

Another basic property of paper is the *caliper*. As paper is compressible, the caliper must be defined in terms of the measuring instrument. ISO 534 specifies an instrument with two parallel planar measuring surfaces of 200 mm², which act on the sample with a surface pressure of 100 kPa. The resulting distance between the surfaces is the caliper D of the paper. It has to be decided whether one paper sheet or a staple of 5 is measured. All must be stated in the report. Tissue may be measured according to DIN EN 12 625 with a contact pressure of 2 kPa and a contact area of 10 cm². Even the speed of lowering the piston on the tissue is defined with $2.0 \pm 0.2 \text{ mm s}^{-1}$. A paper construction such as containerboard has to be measured according to ISO 3034. For caliper determination, the pressure is

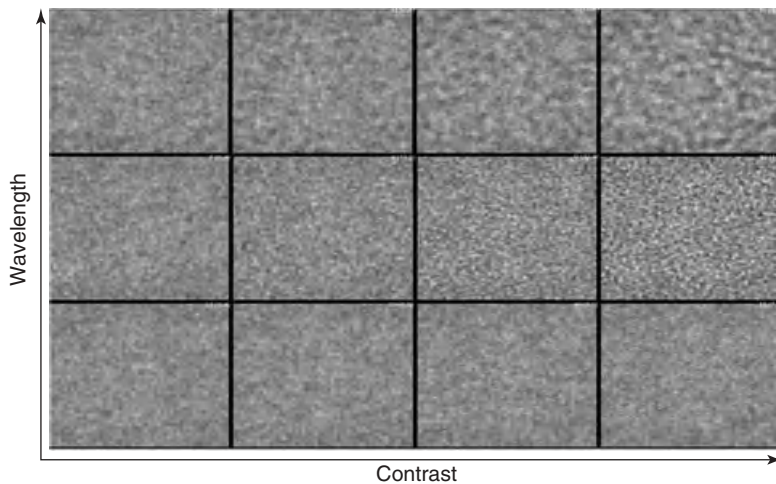


Figure 29.10 Characterization of the formation of paper in transmitted light.

defined as 20 kPa and the contact area has to be 10 cm². The lowering speed of the piston is given as 2–3 mm s⁻¹.

The ratio of the basis weight to the caliper is the *density* of the paper. The reciprocal density is the *specific volume*.

The moisture expansion (ME) of paper, that is, the change in dimensions with changing ambient climate, is also a basic property. According to DIN 53 130, the ME is the ratio of the change of length ΔL of a sample paper strip, resulting from a change in the ambient climate from 23 °C/45% to 23 °C/83% relative humidity to the original length L_0 . The temperature can also be 20 °C in each case.

$$\text{ME} = \frac{\Delta L}{L_0}$$

The ME test is standardized in ISO 8226-1 and ISO 8226-2. Consequences of the dimensional instability of paper due to climatic changes are, cockling or curl (Figure 29.11).

29.4.2

Composition and Chemical Paper Testing

The term *moisture content* refers to the amount of water in the paper in equilibrium with a defined ambient climate. It is determined gravimetrically in accordance with ISO 287 (1985). A dry sample is produced by drying the paper to a constant weight at 105 °C. The moisture content is expressed in percentage based on the moist sample.

Chemical testing is used to determine the components of paper. This is of significance in papermaking for quality control and process control. Another important field of chemical paper testing is the control of papers for the packaging of food.

The entire spectrum of analytical methods used for the chemical testing of paper ranges from gravimetric methods to spectroscopy, electrochemical, and enzymatic methods, as well as microbiological tests and sensoric tests on taste and odor. The *Robinson test* is an example for the latter; the Hemhoff test may be used as an example for a simple microbiological analysis.

Curl:

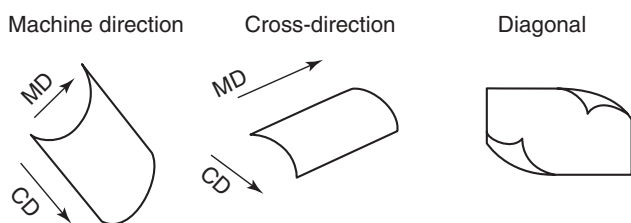


Figure 29.11 Examples of cockling or curling.

When paper is used for packaging purposes, no off-taste or off-odor from the package must contaminate the product itself. Odor and taste from paper can arise from a number of sources such as wood resins in mechanical pulp or residual chemicals in pulp making or the paper may have internal biological activity, which can also produce odorous substances. The most sensitive instrument available to measure the odor and taste of a substance is a human being. Members of trained panels assign numerical ratings and record their impression of tainting flavors or volatile odors experienced. The test methods available are the triangle test (the test states whether differences between specimens are found, DIN 10 951), the pair test (a test describing the differences between specimens, DIN 10 954), and the Robinson test (a taste test identifying how much taint a paper has given to a taste medium; chocolate very commonly being used, DIN 10 955). Besides the trained panel, gas chromatography (GC) and mass spectrometry (MS) are used to identify the originating chemical compound. The so-called electronic nose, an original invention from the military world, has also been utilized to detect off-odors.

However, especially for paper and board, getting into contact with food chemical analysis is quite important. In some cases, the content of single ions or heavy metals in the paper or board is of interest, but in some cases, the migration of chemical substances into the food has to be watched. A well-accepted method is the tenax migration. During this test, tenax as a surrogate for solid food is in contact with the packaging to be examined. After a certain time, the amount of certain chemical compounds such as mineral oils and phthalate that have migrated into the tenax can be determined. Similar tests can be carried out with liquids such as water, vegetable oil, emulsions, or solutions.

Most of the testing methods to determine the composition are destructive. The components to be determined must be extracted with water or organic solvents. For example, the resin content of paper is determined gravimetrically in the extraction residue using an organic solvent as an extracting agent.

The inorganic fillers contained in paper are determined as residue on ignition (ash content). In accordance with ISO 2144, the sample is ignited at 900 °C until no change in weight is observed. The ignition residue is then determined gravimetrically and expressed as a percentage of the original weight of the sample. Other ignition temperatures are used for chemical pulp (575 °C) and filter papers (800 °C) (DIN 54370). Determination of CaCO₃ is calculated from the difference in weight loss between 575 and 900 °C (CO₂). X-ray microanalysis is employed for the quantitative determination of the types and amounts of fillers. Elements such as calcium, magnesium, and metals in trace amounts can be analyzed by atomic absorption spectroscopy. For the determination of organic substances in paper extracts, IR spectrophotometric and chromatographic methods are applied, for example, GC for volatile components and high-performance liquid chromatography for thermally sensitive constituents.

Other chromatographic methods are used for the determination of chlorides, nitrates, and sulfates or for the differentiation and characterization of dyes and optical brighteners.

Apart from the analytical methods mentioned above, the sum parameters are of special importance. These include the ash content, pH (ISO 6588), electrical conductivity of aqueous extracts (ISO 6587), and the resin content of paper.

Apart from the ISO standards mentioned above, other standards for chemical testing of paper are, for example, the ZELLCHEMING, SCAN, and TAPPI test methods.

29.4.3

Strength Properties

Tensile strength and *strain at rupture* are determined as values characteristic of paper strength (ISO 1924-2 and -3; Figure 29.12). The tensile strength F_t together with the sample width b (usually 15 mm) give the tensile strength per unit width σ_T^b , measured in terms of Newton per meter.

$$\sigma_T^b = \frac{F_t}{b}$$

Together with the sample thickness, the tensile strength can be expressed in kilopascals. However, the thickness of paper is not easy to be determined as paper is a porous and compressive material. Therefore, the tensile strength per unit width is much more common or the *tensile index* σ_T^w instead. This index results from tensile strength per unit width expressed in Newton per meter divided by basis weight m_A , expressed in grams per square meters (as a hint: ISO 1924 uses w to express the basis weight).

$$\sigma_T^w = \frac{\sigma_T^b}{m_A}$$

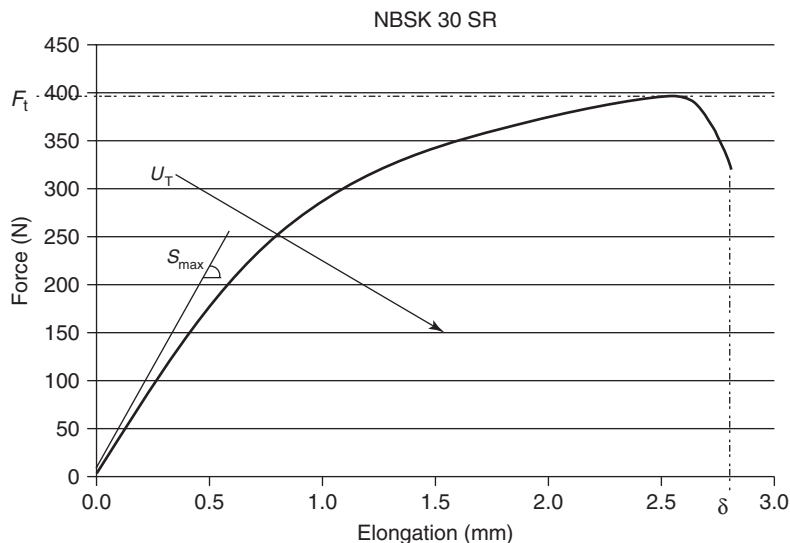


Figure 29.12 Tensile strength and strain at rupture.

In paper technology, the *breaking length* is also of some importance as a calculated value. It is the length of a freely suspended paper strip of any constant width and thickness that just breaks at the point of suspension because of its own weight. The breaking length L is usually given by the unit kilometers and calculated from the tensile strength force F_t of the paper measured in Newton, the basis weight m_A in grams per square meter, the width of the strip b in meter, and the gravitational constant $g = 9.81 \text{ m s}^{-2}$.

$$L = \frac{F_t}{m_A \times b \times g}$$

Nevertheless, the breaking length is no longer mentioned in ISO 1924. More importance is found in the tensile energy absorption (TEA), named W_T^b and expressed in joules. TEA is especially important for bag paper. The TEA value represents the nonelastic portion of the deformation energy and thus that portion of dissipated energy, which should be high in the case of bag paper. Together with the width b and the length l of the tested sample, the calculation is

$$W_T^b = \frac{U_T}{b \times l}$$

wherein U_T is the area under the force–elongation curve (Figure 29.12).

During the test, the paper strip is more and more elongated while the corresponding force is measured. The elongation δ may be divided by the original length l of the paper strip. This leads to the strain ε and at the moment of break to the breaking strain ε_T

$$\varepsilon_T = \frac{\delta}{l}$$

The maximum slope of the force–elongation curve S_{\max} , found in the beginning of the curve, can be taken to calculate the modulus of elasticity E expressed in megapascals. Therefore, the thickness t of the sample is needed. Again, as in a former remark, it must be known that the paper thickness is not exactly to determine. As a consequence, the Young's modulus can only be taken as an estimation

$$E = \frac{S_{\max} \times l}{b \times t}$$

All these equations do not take into account the viscoplastic properties of paper. To obtain comparable results, ISO 1924 defines a constant rate of elongation of 20 mm min^{-1} (ISO 1924-2) or 100 mm min^{-1} (1924-3).

Instead of carrying out a destructive rupture test, it is possible to obtain a *tensile stiffness index* (TSI) by an ultrasonic gage system. The velocity of sound in a material is proportional to its stiffness or Young's modulus. From research in this field, it is known that the Young's modulus correlates with the tensile strength [8]. This enables the possibility to measure the sound velocity in a paper at different angles and by this to calculate a *tensile stiffness orientation* (TSO). With these numbers, it is possible to give a forecast on tensile strength in different directions as well as recognize whether the main fiber orientation is in MD as expected or slightly in a differing angle, the TSO angle. The system delivering these numbers is called TSO

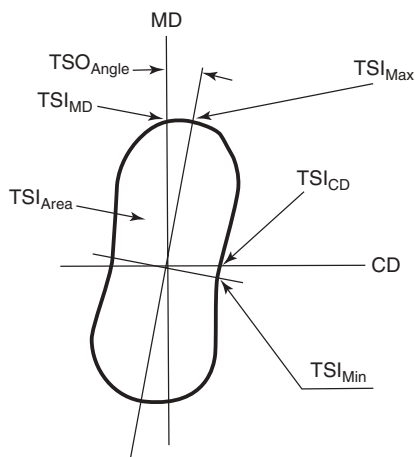


Figure 29.13 Typical *tensile stiffness orientation* (TSO) plot.

tester. In Figure 29.13, a typical plot is shown [9]. Two other numbers, TSI_{MD} and TSI_{CD} , can be used to calculate the MD/CD ratio, which is the same that will be obtained if tensile strength in MD and CD will be measured. The MD/CD ratio is a number that gives a quick impression on the paper anisotropy. A low MD/CD ratio is often wanted for paper sheets, whereas a high MD/CD ratio is useful for paper reels.

The *bursting strength* is important in the characterization of packaging papers. The bursting strength of paper is determined in accordance with ISO 2758 and that of board in accordance with ISO 2759. In the testing instrument, the free area of the sample stretched in a circular frame is exposed to increasing pressures until it ruptures.

Packing materials are also characterized by their bursting strength. For instance, set values are stipulated in DIN 55 468 Part 1 for the strength of corrugated boards and used for classification (Table 29.1). The same standard specifies set values for the *puncture resistance*. This strength property is determined, mainly for cardboard and corrugated board, by measuring the resistance offered by a sample to the penetration of a pyramidal body (ISO 3036 and DIN 53 142-1). There is also a puncture test method available (DIN 53 142-2), which describes a linear penetration of the pyramidal body. And finally, the edge crush test (ECT) according to ISO 3037 is used to complete the quality numbers, which describe the grade of corrugated board.

Bursting and tensile strengths are both to be measured at an undamaged sample. Nevertheless, it is often of interest how a paper may behave if it is already damaged. To get reproducible results, a defined slot, hole, or crack has to be applied to a test piece. Then the fracture toughness, expressed in joules per meter, can be determined. Concerning paper, this test is still under discussion. However, an ISO standard is proposed and distributed as working group draft ISO/WGD 15746.

State of the art is the determination of the *tear resistance* (Elmendorf). A sample is torn with the help of a pendulum device starting from a predetermined cut. The

Table 29.1 Corrugated board grades according to DIN 55468-1.

	Grade	Bursting strength (kPa)	Puncture resistance (J)	CCT value (kN m ⁻¹)
One flute	1.01	–	2.5	3.5
	1.02	–	3.0	4.0
	1.03	–	3.5	4.5
	1.04	–	4.0	5.5
	1.05	–	4.5	6.5
	1.10	600	3.0	3.5
	1.20	850	3.5	4.0
	1.30	1100	4.0	4.5
	1.40	1350	4.5	5.5
	1.50	1600	5.0	6.5
Several flutes	2.02	–	5.5	6.5
	2.03	–	6.0	7.0
	2.04	–	6.5	7.5
	2.05	–	7.0	8.5
	2.06	–	7.5	9.0
	2.20	850	6.0	6.5
	2.30	1100	6.5	7.0
	2.40	1350	7.5	8.0
	2.50	1600	8.5	8.5
	2.60	1900	9.5	9.0
	2.70	2200	10.5	9.5
	2.90	–	15.0	14.0
	2.91	–	18.0	16.0
	2.92	–	22.0	18.0
	2.95	–	27.0	21.0
	2.96	–	30.0	24.0

These values are not valid for corrugated board manufactured only with D, E, F, and G flute sizes. If the board is manufactured with one flute size B, the required values of the puncture resistance can be reduced by 10%.

work required for a tear of a given length is measured. The test is described in ISO 1974. A comparable number is the tear according to Brecht-Imset as fixed in DIN 53115. A pendulum is used, too, to describe the lost energy during continuing to tear a paper with a defined crack.

z-Directional strength refers to the ability of paper or board to resist tensile loading in a direction perpendicular to the plane of the paper (*z*-direction). After exceeding the *z*-directional strength of the paper, a break in the paper structure occurs in the sheet but not at its surface. The *z*-directional strength is therefore not equivalent to the surface strength or linting tendency of the paper. Many test methods to measure *z*-directional strength of paper are available. Some methods have also been standardized, such as TAPPI T541 om and TAPPI T569 om. On the basis of TAPPI T569 om, an ISO standard is under discussion.

The z-directional strength (DIN 54 516) is determined by measuring the maximum force per unit sample width required to split the sample.

The *crush resistance* of paper under compressive stress is measured as the short span compression strength. To prevent the sample kinking, the free span length must be very small (typically 0.7 mm). The resistance measured according to DIN 54 518 gives the ultimate crushing load per unit width.

Testing paper grades that are used for corrugated board, the Concora medium test (CMT; ISO 7263) and the corrugated crush test (CCT, according to a Scandinavian test method, SCAN P 42) are useful. Both tests take laboratory flutings.

Corresponding tests at containerboard samples are the flat crush resistance (FCT; ISO 3035) and the edge crush resistance (ECT; ISO 3037). In the former test, a circular sample of corrugated board is exposed to increasing pressure between two parallel planar plates until the corrugation collapses, and the maximum load is measured. In the second test, the load is applied in the direction of corrugation starting from the edge of the sample. The edge crush resistance is used in DIN 55 468 Part 1 for the classification of corrugated boards.

The *folding strength* is an important property of both packaging and graphic papers. It can be determined as described in ISO 5626 as the Schopper double-fold value, in ISO 5626 as the Köhler-Molin folding endurance value, or in TAPPI 511om as the folding endurance of paper (MIT tester). The sample is subjected to specified tension in these cases. The Brecht–Wesp pressure folder functions without tension. A sharp fold in the sample is produced between two rolls and repeated up to 50 times in the same position. The ratio of the tensile strength of the folded sample to that of the unfolded sample is the folding strength.

Wet strength is needed to describe the strength properties of paper or board under wet conditions. Two common test methods may help to get an impression on wet strength. There is the tensile strength and stretch under wet conditions as described in ISO 3781, and there is the bursting strength after immersion in water according to ISO 3689. Concerning tissue products ISO 12 625 has to be applied and gives the wet strength of tissue rewetted under defined conditions.

29.4.4

Load-Deformation Properties

Some load-deformation properties have already been described when dealing tensile strength (Figure 29.12). It was mentioned that paper has viscoelastic and viscoplastic properties. This means that some of the deformation taking place under load is irreversible (plastic deformation). Also if the load is kept constant, still some more elongation will take place, reversible as well as irreversible, therefore viscoelastic/plastic.

Viscoelastic/plastic behavior may be characterized by the storage modulus and the loss modulus. Both are obtained in a dynamic mechanical analysis (DMA). DMA measures stiffness as storage modulus and the dampening as loss modulus [10]. The ratio of the loss to the storage modulus is called $\tan \delta$ and can be taken as a measure of the energy dissipation of the paper during the test. The test is carried

out by applying a sinusoidal force and measuring the corresponding elongation together with the phase shift of force to displacement.

Often required is the resistance to flexural stress, measured as the *bending stiffness* under approximately pure elastic deformation, as defined in DIN 53 121. This test is usually performed with a two-point beam method. To guarantee elastic deformation, maximum bending angles, which depend on the span length and the sample thickness, are specified. This may be circumvented by the resonance length method (ISO 5629) in which the resonance length of a free sample strip is measured. Resonance is generated via a clamp vibrating at 25 Hz.

Deformations in board and cardboard can also be produced by creasing. Testing the properties of *creases* requires defined production processes, for example, DIN 55 437 Part 1. In Parts 2 and 3 of this standard, methods are described for the manual folding of the creases and the visual evaluation of the folding or the technical evaluation of the creases with a folding moment tester.

29.4.5

Surface Properties

A large number of methods are available for evaluating the topography of paper surfaces. The Bekk *smoothness* is determined according to ISO 5627 as follows. At a defined pressure difference, the time in seconds in which a specified amount of air requires to flow radially inward between the paper surface and a ring-shaped glass plate and on into a vacuum chamber is measured. The smoother the surface of the paper, the longer the pressure equalization takes. The determination of *roughness* according to Bendtsen (ISO 8791-2) is related to the Bekk method for the determination of smoothness. In this case, however, the direction of the air flow is reversed and the magnitude of the air flow is measured. The air escapes under defined conditions between the measuring ring of the measuring head and the paper surface under constant overpressure. The Parker-Print-Surf (PPS; ISO 8791-4) gives values expressed in micrometers. Air escaping a pressure chamber passing a thin metal ring into a measuring chamber delivers well-accepted values in the printing industry. For a general description of roughness or smoothness, see ISO 8791-1.

The same basic *smoothness* measurements are applicable for coated paper as for base paper. As rotogravure printing is the most demanding printing method for paper surface, a special test method is used only for that purpose. The so-called Helio-test is performed with an IGT tester. In this simulated printing test, the number of missing dots, counted visually, provides information on the printability.

Sometimes the *topography* of the paper surface is described using profile measurements laser scanning. The scanning profilometer uses point sensors in conjunction with high-precision x - and y -stages to capture profiles and 3D data. The stages move the sample under the sensor and the sensor passes the captured height data to the computer for evaluation.

Another surface property of paper is the *abrasion resistance*. The mechanical abrasion resistance of surfaces is determined in the friction wheel process (DIN 53

109). In this process, the amount of abrasion, which is obtained by abrading the conditioned or wet sample with an abrasion wheel of defined quality under defined conditions, is measured.

The coefficient of friction has to be mentioned, too. It may be measured with the inclined plane method (DIN 53 119-2), but this device will only deliver the static coefficient of friction. Using a tribographic equipment (DIN 53 119), the static coefficient of friction may be determined as well as the dynamic coefficient of friction.

Finally, the electrical resistance of the paper surface is of interest for some papers, either used for insulation or where electrostatic forces have to be applied during the paper printing and converting. The method is described in the European standard EN 11491.

29.4.6

Optical Properties

An object, for example, a paper surface, is termed *white* when the illumination intensity and the absorption capacity of the surface are independent of the wavelength. Deviations confer a more or less pronounced color shade on the surface.

In the paper industry, a special process is used to characterize the *brightness* because this is one of the most important optical properties of paper. The determination of the reflectance factor (ISO brightness) is based on ISO 2470. For this test, a filter is used, which has an intensity maximum at a wavelength of 457 nm. The reflectance (blue component) R_{457} measured in a reflectometer under specified conditions is known as *brightness*. It is expressed as a percentage of the brightness of a white standard.

But papers with the same ISO brightness value may look very different, even if compared under the same light source. This is due to the filter used during the measurement. To achieve a better differentiation between several papers, the *CIE whiteness* may be used. This value is based on the CIE-Lab color space and takes the color shade of a paper into account. The value may be given according to ISO 11 475, if a light source containing ultraviolet components (D65, outdoor daylight) is used, or according to ISO 11 476, if the light source C (indoor illumination conditions) is used.

Colored papers can be described by the L^* , a^* , and b^* values from the CIE-Lab color space. ISO 5631 gives the details. L^* is the value describing the lightness and can only achieve positive numbers. a^* may become negative for green and positive for magenta color coordinates in the CIE color space. In the same manner, negative b^* will indicate blue and positive b^* will indicate yellow.

Most white papers and paperboards, and therefore also secondary fiber materials, currently contain an optical brightener. Brightness measurements for such materials depend on the relative proportion of UV radiation in the illuminant used for the determination. The standard test methods for ISO brightness have not defined the standard illuminant for use in the determination. The relative amount of UV has also not been defined. As a result, widely different R_{457} reflectance factors exist

for the same kind of fluorescent material. The problem has recently been solved. A revised ISO method, ISO 2470, states that the UV radiation of the illumination must correspond to the relative amount of UV in the standard illuminant C (indoor illumination conditions) when measuring fluorescent objects.

Another optical property of paper is its *transparency*, that is, a measure of its light transmittance. It is calculated from the reflectance factors R_0 , R_w , and $R_{(w)}$, which are determined in accordance with DIN 53 147. The reflectance factor of the individual sheet on a completely black background is R_0 , R_w is the reflectance factor of the individual sheet on a white background, and $R_{(w)}$ is the reflectance factor of the white base.

The *opacity* is a measure of light tightness. It is defined in ISO 2471 (1998) as the ratio of the reflectance factor R_0 to the reflectance factor R_∞ . Both reflectance factors are determined in accordance to DIN 53 145. R_0 is measured as the reflectance factor of an individual sheet on a completely black background and R_∞ as the reflectance factor of an “infinitely” thick stack of the same paper.

Both, transparency and opacity, are calculated following the Kubelka–Munk theory [11]. This theory describes the light passing a paper sheet under the influence of light scattering and light absorption. It results in measurements of two values, s for scattering and k for absorption (DIN 54 500). s and k values are quite helpful to predict optical paper properties obtained from pulp mixtures as these values can be calculated by linear mixing rules [12], which cannot be done with numbers such as R_{457} , L^* , a^* , or b^* and opacity or transparency.

Gloss describes the ability of the paper to reflect light to the opposite of the incoming angle. An angle of 75° is commonly used and standardized in TAPPI T480 om and ISO 8254-2. Observing gloss at an angle of 45° is standardized in DIN EN 14 086.

Dirt may also be regarded as an optical property. Paper made from recycled fibers will often contain dirt spots originating from ink residues. These spots may be detected by a scanner and an image analysis algorithm. However, dark spots on a dark background lead to another optical impression than dark spots on a white background. For leveling purposes, the optical impression is calculated to a comparable value called *equivalent black area*. TAPPI T563 om gives details of how the number is generated.

29.4.7

Printing Properties

Printing properties may be divided into *printability* and *runnability*.

The printability of paper results from complex interactions between printing ink, printing process, and paper. Practice-oriented printability tests must be performed to evaluate these properties. Test printers are also suitable for this purpose. Instruments for offset printing, gravure printing, and flexographic printing can be used with standard printing inks under laboratory conditions to test the dry pick resistance or the wet pick resistance of papers. Missing dots, mottling, and

ink penetration properties can also be tested. Conversely, the behavior of various printing inks toward standard papers can also be evaluated.

Ink absorption is the ability of a paper surface to absorb ink during printing. If ink absorption is too slow, there may be a risk of setoff. Generally used tests are the K&N test, the Lorilleux Porometrique test, the Microcontour test, or the Croda test, depending on the test ink used. All the above-mentioned tests follow similar test procedures: The ink used is applied to a paper surface in a thickness of 0.1 mm; after 2 min, nonabsorbed ink is wiped off. The brightness of the colored area is measured and subtracted from the original brightness of the paper to give the ink absorption value as a percentage. The test area can also be used for visual evaluation of the evenness of absorption. If the area is mottled, there is a risk of mottle during printing.

Using an image analyzer for testing, printed image and printing process has increased during the past decade. This is due to the improved capability of the analyzers and because the importance of the quality of the printed image has increased. The image analyzer and its use in paper testing have already been mentioned earlier in connection with paper tests. The image analyzer is used to measure the uniformity of paper (print mottle, number of missing dots, and properties of dot), surface properties of paper (fiber rising, picking, and contact angle measurement), and many other properties of paper, that is, width of cracking at the fold.

Furthermore, defined proof copies produced with the test printers can be used to test full ink coverage, color density, color gloss, shade, abrasion resistance, stacking ability, and contact yellowing.

More reliable results obviously come from tests that closely simulate the actual printing process. That is why tests developed for full-scale printing machines give the best predictions of the actual printability properties of a paper [13].

A stained pattern observed in a printed product is called *mottling*. There are several types of mottling: first color mottling, wet repellence mottling, and back-trap mottling. First color mottling results from unevenness of the physical surface structure of the coated sheet (roughness and pore structure) and the unevenness of optical surface properties (brightness and gloss). Wet repellence mottling occurs when the fountain solution layer between coating and ink interferes with ink transfer. Back-trap mottling leads to uneven ink setting in the coating layer. Mottling can be tested during normal print conditions either in a print house or in a research environment. For its investigation, large areas ($5 \times 5 \text{ cm}^2$) of solid and halftone are needed. For checking first color mottling, packing is removed from the first, third, and fourth units: no water under the cyan ink and no back-trapping after ink transfer mean no water or back-trap mottling. To test wet repellence mottling, packing is removed from the first unit: if there is no water under the cyan ink, then no water mottling is given. For back-trap mottling, packing is removed from the third and fourth units: when no back-trapping after ink transfer occurs, then no back-trap mottling is given.

An unwanted variation in density, color, or gloss in print is called *print unevenness*. The size and intensity of the variations are measured. Print density variations

(graininess 0.5–2 mm; mottle 2–8 mm) are measured from an even black and/or cyan tone of at least 40% and as an average of eight images with a size of $51 \times 51 \text{ mm}^2$.

Runnability of paper in a printing machine is influenced by strength properties such as tensile strength, but surface strength, too. When passing the nip of a printing press, the paper surface may be damaged. This leads to fibers or coating particles leaving the paper surface and sticking to the surface of the printing roll. In consequence, during every turn of the roll, a small spot may be seen in the printed image. To get a hint on the paper surface, strength methods such as Dennison wax-picking test (TAPPI T459om) or resistance to picking (ISO 3783) can be applied.

Dusting or linting is an accumulation of cutter or slitter dust on the blanket around edges of the web and an accumulation of fibrous materials or/and pigment on the blanket of the print press. These phenomena influence both print quality and production efficiency. Dusting and linting are tested on a full-scale heatset press at a printing speed of $50\,000 \text{ sheets h}^{-1}$ (6.2 m s^{-1}) under normal press conditions. Usually 30 000 copies of each paper have to be printed. The accumulated lint on the printing blanket from 50% halftone and the nonprinting area is collected with a tape and weighed. The lint can be analyzed with a microscope to determine the origin of the lint (small shives, fibers, ray cells fines, etc.).

Piling results in the accumulation of coating particles and ink on the tail edge of the solid printing area or/and the halftone area on the blanket. The accumulation is tacky material of the same color as the ink. Piling is also tested on a full-scale heatset press at a speed of $60\,000 \text{ sheets h}^{-1}$ (7.4 m s^{-1}), with a special tacky ink on the first and second units, a high water feed on the first unit to lower the surface strength and a low water feed on the fourth unit (adjusted with graphometric; the goal is to reach a level between the normal water feed and the toning level). Further print conditions are a special layout; papers are printed to a constant density and 30 000–40 000 copies of each paper are printed. The degree of piling will be classified as “extreme piling” (printed amount less than 20 000 copies at good printing quality, danger of web break), “major piling” (printing amount 20 000–40 000 good copies, danger of web break), “minor piling” (printing amount up to 40 000 good copies), and “no piling” (printing amount significantly above 40 000 good copies).

29.4.8

Behavior toward Liquids

The behavior of liquids toward paper is characterized by the processes of wetting and penetration. In both cases, the characteristic physical property is the *surface tension*. This value can be measured directly and tensiometrically in the case of liquids and indirectly, via the contact angle of test liquid droplets, in the case of solids such as paper. A liquid wets the surface of paper only if its surface tension is lower than that of the paper. The same holds for the wetting of the capillary walls on penetration of liquids into the capillaries of the paper.

If the *wetting* and the *penetrating capacity* of liquids are to be changed, the surface tension of the paper must also be changed. This is achieved, for instance, by sizing the paper, a process which must fulfill the requirements regarding printability with aqueous inks. According to DIN 53 126, paper is considered to be printable if a standard ink line drawn with an adjusted drawing pen has neither run nor penetrated into the paper after 24 h.

The *water absorption* W_A (Cobb) (ISO 535) refers to the amount of water that is absorbed by a certain area of paper on one-sided contact for a specified exposure time. The time of exposure to water must be chosen such that a sufficient amount of water enters into the fiber matrix but does not penetrate to the opposite side of the sample. Instead of water, the absorption can be tested with oil (SCAN P 37). This is due to the fact that a lot of printing colors are based on oil.

Some papers are used to absorb liquids and indicate some properties by color change. An example is paper for pH indication. To gain numbers of the absorption capacity, the capillary rise is determined (ISO 8787). However, to analyze hygiene products, the absorption capability has to be measured in different manners, not yet standardized.

In the determination of *grease permeability* (DIN 53 116), red-colored palm kernel oil is used as the testing agent. The passage of fat through the sample under specified conditions is then evaluated. This test will last over 36 h if level 1 is to be tested. As a quick alternative, the KIT test (TAPPI T559 cm) is used in paper mills to accompany the manufacturing process. In this test, 15 different percentages of castor oil, toluene, and *n*-heptane are mixed with solutions and applied on a paper or board surface. The KIT number gives the number of the solution, which is the last one that has not penetrated through the paper after 15 min. The higher the KIT number, the better a paper withstands grease penetration.

29.4.9

Exclusion of Gases and Vapors

As a rule, papers have only a limited ability to exclude gases and vapors. In particular, the air permeability (e.g., for filtration properties) and the water vapor permeability are important.

There are some standardized test methods available for the determination of the mean *air permeability*, that is, the Bendtsen method (ISO 5636-3), the Schopper method (ISO 5636-2), or the Gurley method (ISO 5636-5).

A gravimetric method for the determination of *water vapor permeability* is described in ISO 12 572. This method is suitable for building materials. For foils, laminated paper, and board, DIN 53 122-1 is also recommended.

29.4.10

Additional Testing

Some additional tests are common to judge the functionality of paper. In today's efforts to enhance the use of recycled fibers, the recyclability of a paper or board

product becomes more and more important. Some standards have been developed so far as there are methods PTS-RH: 021-I for paper products for deinking and PTS-RH: 021-II for packaging papers. Deinkability test are carried out according to INGEDE method 11. Determination of macrostickies is made following INGEDE method 4.

Aging of paper is of interest for documents. Accelerated aging by heat and/or moisture treatment is described in ISO 5630-1, -2, and -3. As a result, paper can be sorted into a classification range of long-term stability (DIN 6738).

29.4.11

Measurements of Coated Surface

Different printing methods have their own requirements for coated paper and paperboard. The coating amount has a big influence on the physical and optical surface properties. Physical properties are smoothness, gloss, surface strength, ink absorption, dusting/linting, piling, and visual defects. Optical properties are brightness, whiteness, color shade, opacity, mottling, and print unevenness. Taste and odor are important properties, especially for paper and paperboard grades used for food packages. The tests for these properties are mentioned above.

Coat weight measurement in the laboratory is based on the ash content of base paper and the ash content of coated paper. Several different technologies have been used to measure online coat weight. The Beta or dry weight technique measures dry weight before and after the coating operation and the coat weight is calculated by difference. Weight and moisture sensors are required at both locations. The ash or X-ray absorption method is similar except that ash sensors are used instead of basis weight measurement. IR absorption is the newest technique to be used, as with X-ray fluorescence, latex, and/or carbonate in the coating color are measured. The methods are used in differential mode, that is, two scanners are applied.

The primary objective in pigment coating is to improve the printability and appearance of the material, no *visual defects* should appear. Typical defects are holes, spots, blade scratches, and streaks and creases. Visual defects are controlled using online detectors and visual checking. Visual checking is done in two places: The machine crew takes a cross-sample from the web at the top of each machine reel and examines it under strong light sources with different light angles to mark the defects. In laboratories, sheets are checked visually under a light source, and defects are counted and recorded. The online devices measure faults such as slime holes, wrinkles, creases, edge nicks, turnovers, and blade stripes. Detection and counting of dirt specks are done online today. With low-viscosity colors, upstanding fibers in the surface cause pimples because the color climbs up these lumps of coating. Faults such as whiskers on the surface, loose fibers, coarse fibers, dust, lint, and fuzz are usually only determined by inspection.

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30

Book and Paper Preservation

Manfred Anders

30.1

Introduction

Most modern paper lacks the durability and permanence that has characterized its use since its earliest application in recording the history of man and his civilization. Although fundamental papermaking techniques have changed little in nearly 2000 years, two innovations in the nineteenth century, namely, (i) the use of alum as a component of size and (ii) the replacement of cotton fiber by wood pulp, are responsible for this predicament.

There has been an unbelievable development in the production of documents since the invention of printing with movable letters by Gutenberg. Within a short period of time, the necessary fibers for paper production could no longer be supplied by rags. After an intense search, wood was discovered as an alternative. Ground wood pulp was used and later also chemical pulp, whereas in the latter, the lignin is removed in a chemical process and so a “woodfree” pulp is produced.

The beginning of industrial paper manufacture dates from the middle of the nineteenth century, and with the development of paper machines, a new sizing method which could be integrated into the mechanical process became necessary. The sizing of paper is necessary for its writing property, otherwise it would act like blotting paper. The “sizing in the mass,” wherein rosin is precipitated onto the fibers by means of acid-forming alum or aluminum sulfate in the pulp, was part of the mechanical paper manufacture until the 1980s. At present, a pH neutral and synthetic sizing agent is used. Papermaker’s alum easily forms sulfuric acid on exposure to water in air; in turn, this acid easily catalyzes the depolymerization of cellulose by hydrolysis. Further, cellulose from wood pulp is more susceptible to this attack than linen- or cotton-derived fiber. At present, it is accepted that the inherent acidity of such papers accounts for 85–90% of the destruction in book papers, resulting in a half-life for fold endurance of an estimated 7.5 years [1]. The most important factors affecting the paper degradation have been reviewed in many publications [2].

Barrow [3] was one of the first to describe the problem and correctly identify the cause at the Virginia State Library beginning in the 1930s. Before his work,

book and paper conservators relied as much on art as on science. While highly skilled, these professionals often selected materials and treatment without adequate consideration of the long-term consequences.

The discovery and the use of wood pulp (1840 by Keller) and acid sizing, mostly with alum or aluminum sulfate (1807 by Illig), are the main reasons for the current problems of deterioration of books in libraries and archives. Even at that time, it was known that acid-sized wood pulp paper was not as stable against aging as traditionally made rag paper. At present, the books most threatened by deterioration are those that were made in the last 150 years and not, as many people may assume, the older works from centuries ago.

There has been a fundamental change in papermaking in recent years. The development of synthetic sizing enables the industry to produce paper with neutral to slightly alkaline pH. With calcium carbonate as a filler, this paper has a sufficient alkaline reserve against acid contaminants from the environment. The paper has a better aging permanence than previous modern papers [4, 5].

The main cause for paper deterioration in libraries and archives is the acid-catalyzed hydrolysis of cellulose, the ingredient that gives permanence to the paper. The aging permanence of paper is closely connected with the acid concentration in the paper. The priority in preservation measures is in most cases the deacidification of acid paper. At present, about 80 years after Barrow's pioneering work, mass deacidification of books and archive materials has become a commercial reality [6].

30.2

Mechanisms of Paper Deterioration

30.2.1

Paper Deterioration by Aging

The aging mechanisms can be divided into biological, physical, and chemical processes (Figure 30.1). While using and storing paper appropriately, only the chemical processes are decisive. Paper nearly universally involves cellulose, although its source and methods of processing have evolved steadily throughout the centuries. As production costs dropped significantly, the application of paper dramatically expanded so that its traditional applications, particularly its use in books and official records, were dwarfed by other functions. Such widespread use of paper reduced the emphasis on permanence.

The sizing of paper continues to be the predominant cause of paper deterioration. In the early 1800s, about the time of Robert's invention of the Fourdrinier machine for continuous paper manufacturing, gelatin sizing was abandoned in favor of alum or alum-rosin blends. Papermaker's alum, $\text{Al}_2(\text{SO}_4)_3 \cdot 18 \text{H}_2\text{O}$, is easily hydrolyzed by water to form sulfuric acid [7]. Acid-catalyzed hydrolytic attacks cause degradation of cellulose by random scission of the hemiacetal links, leading to breakage of chain linkages (Figure 30.2). Even a few scissions per molecule

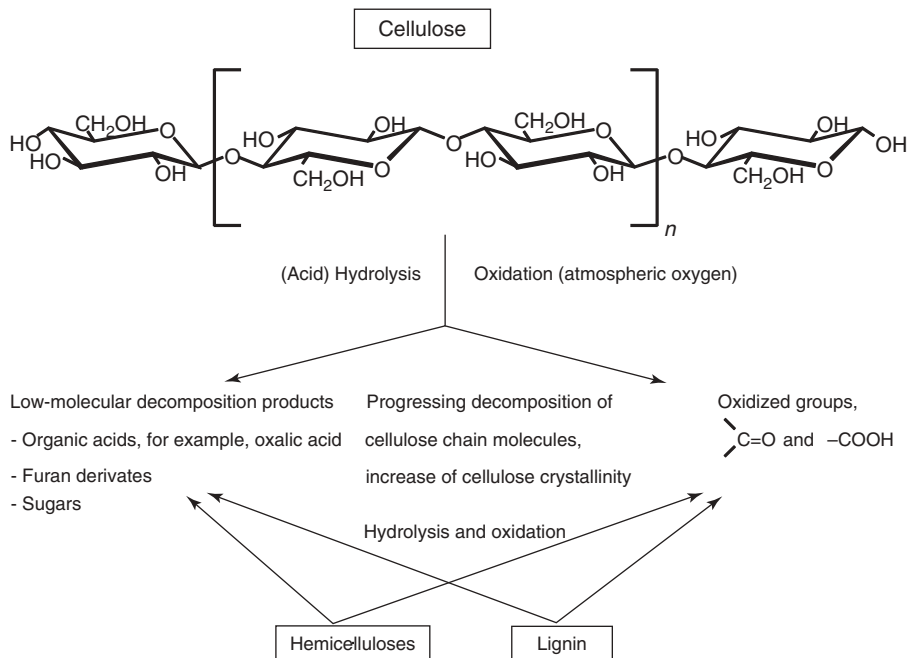


Figure 30.1 The main decomposition ways of paper fibers.

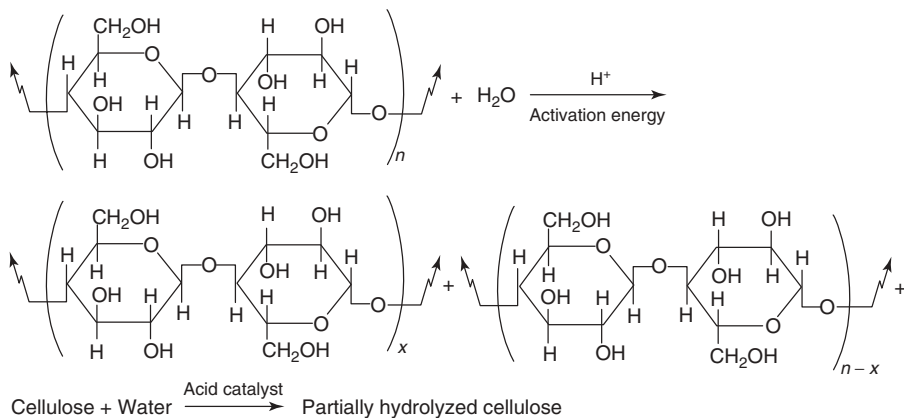


Figure 30.2 Acid-catalyzed hydrolysis of cellulose.

cause a substantial loss in physical properties [8]. In 1851, the discovery of the soda process for separating cellulose from wood added a further dimension to the problem as paper derived from wood pulp is more susceptible to acid attacks than the cotton cellulose obtained from linen and rags.

The lack of paper permanence is attributable to both internal and external influences [9]. In addition to sizing materials, internal factors include the type of

fiber, coatings, and the presence of acidic and metallic compounds [10, 11]. External variables are the conditions during storage and use. Heat and humidity accelerate the deterioration of paper, and atmospheric pollution is frequently the source of external acid attacks [12]. A comparison of identical volumes stored in the New York Public Library and the Royal Library in The Hague proved the importance of proper storage, as the New York books were found to be in a far more advanced stage of deterioration [13].

It was not until 1926, when Gösta Hall from Sweden developed a satisfactory method for accelerated aging [14], that researchers had the means to simulate the effects of the natural aging process. Although Edwin Sutermeister of the S.D. Warren Company recognized as early as 1901 that stable paper should contain an alkaline filler, it was left to William Barrow of the Virginia State Library to pull the disparate elements of early researchers together in a scientific analysis of the problem [15].

As acid-catalyzed hydrolysis of cellulose is responsible for up to 90% of paper's loss of permanence, researchers have concentrated on deacidification as the primary solution to the impermanence of modern papers. Paper deacidification involves the introduction of a strong base to convert acid species to their corresponding neutral salts, and the establishment of a neutral buffer to protect the paper against future acid-catalyzed damage. The first recorded attempt to neutralize paper was by Arthur Church at the Victoria and Albert Museum in London who, in 1891, advocated the immersion of paper in a methanolic solution of barium hydroxide [16].

Subsequent attempts to develop effective deacidification focused on aqueous techniques, which offered the additional benefit of modest strengthening through reestablishment of hydrogen bonding. Otto Schierholz, working for the Ontario Research Foundation in Toronto, secured a patent in 1936 for his work, which involved dipping paper in a solution of alkaline earth bicarbonates [17]. In 1943, Barrow described a two-step process, involving immersion in a calcium hydroxide bath and subsequent treatment with calcium bicarbonate. Commentators differ as to whether Barrow was aware of the earlier Canadian work. Further refinement of the technique included the 1957 development by James Gear *et al.* at the United States National Archives of a one-step process involving magnesium bicarbonate, and the use of the more soluble magnesium hydroxide by scientists at the Library of Congress in 1978. While effective and proven, these techniques involve painstaking care as they are applied to single sheets.

30.2.2

Oxidative Deterioration Processes

Although the above-mentioned acid-catalyzed hydrolysis is the main cause for the deterioration of cellulose and the connected loss of permanence, the influence of oxidation cannot be neglected. The oxidative damage is much more complex in its various chemical reactions, synergistic effects, and secondary reactions and not at all completely researched.



Figure 30.3 Approximately 200 years old manuscript attacked by ink corrosion.

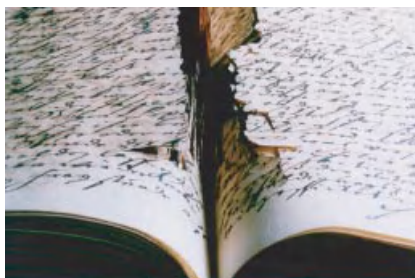


Figure 30.4 Approximately 200 years old manuscript attacked by ink corrosion.

Cellulose can be oxidized not only by various oxidants such as pollution gases from the air (ozone, NO_x , etc.) and bleaching agents in the wood pulp production but also by atmospheric oxygen. In the oxidation by atmospheric oxygen, an additional activation or catalysis is needed.

Acids as well as bases have a catalyzing effect. The catalysis by heavy metal ions is really effective. A well-known example of this mechanism is the ink corrosion, which leads to a total destruction of paper in the area of ink because of the excess of iron ions in the ferro-gallic ink and the acid [18–26]. Some of the most valuable manuscripts are affected (Figures 30.3 and 30.4). Temperature and electromagnetic radiation, especially UV rays, have an activating effect [27].

The observed reactions are often summarized under the term *autoxidation* as reaction products of such oxidation processes: organic acids such as ethanoic acid, formic acid, and oxalic acid, cause a further acidification of the paper. Owing to these oxidation processes, the acid-catalyzed hydrolytic deterioration of cellulose is accelerated.

30.2.3

Alterations due to Paper Aging

30.2.3.1 Yellowing

Paper ages by becoming yellow and brittle. An intensification of the yellowing is observed with continuous aging. There are various reasons for the yellowing of paper.

Many of the reaction products of the aging processes, such as oxidation products and condensed furan derivatives are dark colored. More and more of these colored reaction products are produced with continuous aging. In wood-containing, that is, lignin-containing papers, the yellowing is extremely intense. Especially photooxidation of lignin cause significant yellowing [28, 29]. Fortunately, such susceptibility apparently can be reduced by treating the paper with a magnesium-containing compound, and it is proposed that the magnesium is directly bound to the lignin, thus blocking the color-generating reactions [30, 31].

30.2.3.2 Embrittlement of Paper

The alterations in paper that result from aging can be seen most obviously on the basis of the angles of cracks after a strain-to-crack measurement. The ratio between individual fiber strength and the bonding strength between the fibers changes during the aging of paper. The strength of individual fibers decreases because of the shortening of cellulose molecules as the result of deterioration mechanisms in the course of aging. On the other hand, the interfiber bonding is strengthened by linking reactions and salt bonds: the fibers are linked one to the other inflexibly and strongly. The fiber–fiber bonds are developed on the fiber surface so that the structure of their surface, where an increasing number of reactive groups are developed by oxidation processes, is decisive. As a consequence of aging, inflexible bonds between fibers are created. In the case of a mechanical strain, the attacking forces cannot be spread to nearby fibers because the fibers are linked inflexibly. During a mechanical strain, such as in tearing, in an aged paper, the deformation energy is spread less in the paper but concentrates on individual fibers that are already weakened and then break.

If new paper is torn the fibers slide apart without breaking. This can be shown with pictures from a scanning electron microscope of the angles of cracks of aged and nonaged paper after a strain-to-stress measurement (Figure 30.5). The fibers of the new paper only slid apart, whereas in the aged paper they broke. This means that the fiber–fiber bonds in new paper and the individual fibers in aged paper are the mechanically weaker points.

30.3

Development of Mass Deacidification Processes

30.3.1

Overview

The term *deacidification* denotes the treating of a paper-based object to neutralize its acidic content, with the aim of prolonging the object's useful life. Most deacidification measures also provide a reserve of alkalinity to neutralize acids that may be generated in the future either from within the paper itself or by introduction from its storage environment. There are many statements in literature about different deacidification systems and agents, its advantages, use, and also

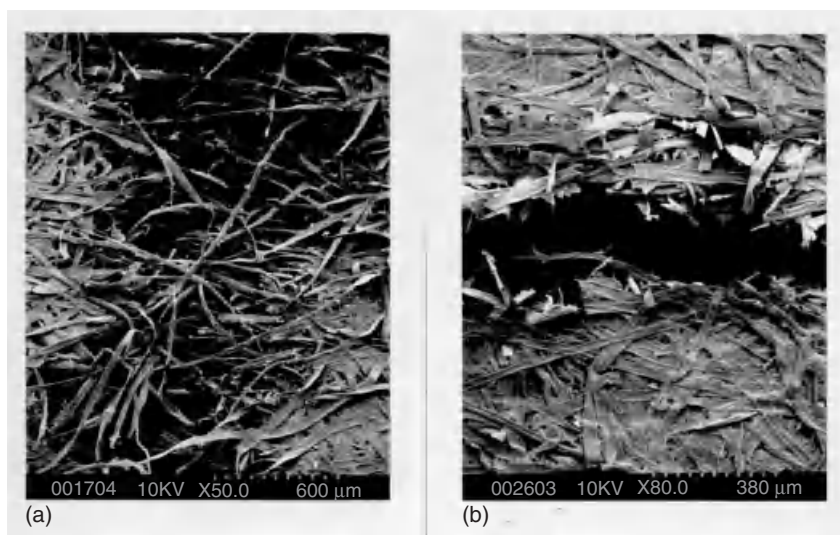


Figure 30.5 Scanning electron microscope pictures of the angles of cracks of nonaged (a) and aged (b) paper after a strain-to-stress measurement.

comparative examinations [32–47]. In the treatment, a long-term acid protection (exogenous influences) is to be achieved, and therefore, an additional alkaline buffer is deposited in the paper [48–55]. In the following, the most important methods are introduced.

On the one hand, the deacidification systems can be divided into *single sheet methods* and *mass deacidification methods*. On the other hand, the methods can differ in the polarity of the solvents used. Polar solvents have a swelling effect on cellulose, or rather paper, and can dissolve some of the colors and inks, and therefore, mostly nonpolar solvents are used in mass deacidification systems. Single sheet methods with water as a treatment medium are the classical methods.

Mass preservation is designed to meet the needs of national and major research libraries and archive groups. With a mean collection deterioration rate of 4.7% [56] and limited resources, a treatment based on painstaking manual work is inconsistent with the need. Furthermore, greater emphasis has been placed on nonaqueous deacidification techniques to compensate for some of the intrinsic limitations of aqueous methods.

Nonaqueous deacidification systems contain a deacidification agent and an organic solvent that serves as the carrier. The solvents offer the advantage of rapid penetration and drying. The latter is particularly important in minimizing the obvious appearance of treatment, most notably cockling. Liquid techniques can function economically over a broad treatment range. The approach of Church in the late nineteenth century was updated by Baynes-Cope [57] in the mid-1960s. This followed his experimentation in 1961 with a magnesium methoxide solution, which, while quite effective, was impractical in terms of preparation and storage.

Independently, Richard Smith from the University of Chicago developed a process that utilized a magnesium methoxide compound, which was dissolved in a mixture of methanol and chlorofluorocarbons (CFCs) [58]. This overcame many of the problems associated with earlier approaches regarding stability and ease of use.

Ethanolate and propanolate of magnesium, which are dissolved in the appropriate alcohol and a nonpolar halogenated hydrocarbon, can also be used as deacidification agents. By transformation of the magnesium alcoholate in the appropriate carbonates (alkoxy magnesium carbonate) using (dry) carbon dioxide, a further improvement of the solubility and permanence could be reached.

30.3.2

History of Commercial Mass Deacidification

In the last 30 years, some mass deacidification processes have been developed by national libraries and companies, which could not gain acceptance. A short description of the most important are as follows:

In contrast to procedures working with solvents, a vapor-phase approach offers prospects for minimal preselection and maintenance of document integrity because no solvents are involved. At least one researcher likened this approach to a “fountain of youth” among deacidification methods [59]. Gas-phase processes work best on a substantial scale because the facilities characteristically have high capital intensity.

Early attempts at gaseous deacidification included the work reported in 1962 by Kathpalia at the Nehru Library in New Delhi, involving exposure of books to high concentrations of ammonia [60]. The compound proved to be too weak a base to neutralize completely strong acid and the ammonia buffer was highly impermanent. At about the same time, Barrow working in the United States and Baynes-Cope in England combined ammonia and short-chain amines, including butylamine, diethylamine, and piperidine, and observed similar results – a short-term alkalization that was reversed as the amine left the treated paper.

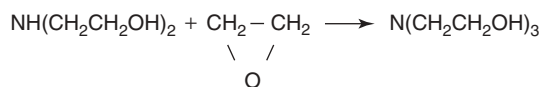
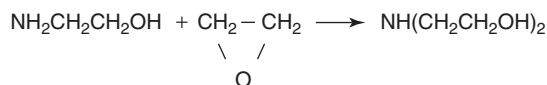
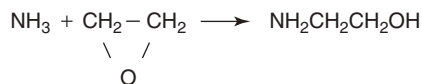
A more promising approach was advanced by Langwell who placed cyclohexylamine carbamate impregnated sheets in books [61]. The active compound diffuses into the book paper to neutralize acidity, but no alkaline reserve is established and the neutralization is reversible. Finally, morpholine treatment was promoted by Kusterer and others working at the Barrow Laboratory in 1977. Besides the lack of permanence, significant discoloration was observed in the paper of treated books.

Kelly and Williams [62] at the Library of Congress designed a mass deacidification process in 1977 that utilizes diethyl zinc (DEZ), which can be applied as a vapor using specialized equipment. The compound easily diffuses between the pages of closed books, neutralizing the acidity and establishing a uniform, controllable reserve of zinc oxide. DEZ reacts with water in the paper, yielding an insoluble deposit of zinc(II)oxide (ZnO), an alkaline material. The DEZ system is potentially hazardous, as DEZ reacts violent with water and ignites on contact with air in a violent exothermic reaction. There was a series of accidents at the DEZ pilot plant. Perhaps for these reasons, the system was withdrawn from the market.

30.3.2.1 BPA Process and DAE Process

Book Preservation Associates (BPA) was formed in 1988 as a wholly owned subsidiary of ETO sterilization, a processor of spices, medical products, and cosmetics. In the BPA process, books or other library materials are placed in closed boxes in a vacuum chamber. The pressure is reduced, and the books are exposed to ammonia for 6 h. The chamber is then purged and evacuated. Ethylene oxide is introduced, and the materials are held for 12 h at nearly atmospheric pressure. The chamber is alternately purged and evacuated up to 25 times before treated materials are removed. The total cycle time is 24 h [63]. Books are placed in an aeration room for two days to permit off-gassing of the ethylene oxide before being returned to libraries.

The process was designed to create high-molecular mass, primary, secondary, and tertiary amines within the cellulose matrix of the book paper. The *in situ* generation of amines, together with free ethylene oxide, neutralizes acidity and establishes an alkaline reserve of about 1%. Ethanolamine generation during treatment is described as follows:



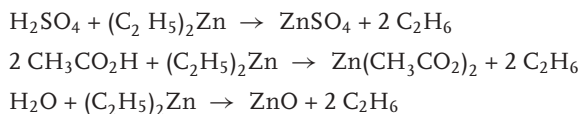
Developers of the process reported that the mono-, di-, and triethanolamines are formed in approximately equal amounts with a modest dominance by the monoethanolamine. The reaction depends on the ratio between reactants and is adjusted intentionally. BPA personnel report that the pH drops approximately 1.5 points in the two months following the treatment.

The process could not gain acceptance on the market because of the inadequate alkaline reserve (no depot effect of the deacidification) and further side effects. Nevertheless, new attempts are being made in Japan by the National Diet Library to try to use this process again after some alterations. Commercial operation at Nippon Filing Co. Ltd. began in 1998. In the dry ammonia ethylene oxide (DAE)-process, the two reagents are introduced in a vacuum chamber over 48 h period to form stable ethanolamines *in situ*. The ethanolamines formed by this Japanese process are described as more stable than those produced by the earlier BPA-method, despite the fact that the reagents used in each technique are the same. So side effects and minor permanence of the deacidification are nearly the same.

30.3.2.2 The DEZ Process

The DEZ process was developed by the Library of Congress in Washington over more than 15 years, progressing from simple laboratory experiments to an operating small-scale commercial unit. Much of the latter work was in cooperation with Texas Alkyls, one of three major producers of compounds such as DEZ. Akzo secured an exclusive license for the DEZ process and tried to commercialize the technology.

As strong alkylating agents, metal alkyls react easily with acids to form the corresponding neutral salts. DEZ also reacts with residual water in the paper to form a stable, permanent buffer of zinc oxide. Unlike most other processes, the neutralization of existing acidity is independent of the formation of the alkaline reserve. Thus highly acidic and neutral papers are both provided with an optimum alkaline reserve. The key reactions are summarized below [64]



The buffer established by the DEZ process is more neutral (saturated solution with a pH of 7.3–7.5) than that of magnesium or calcium salts used in other deacidification methods.

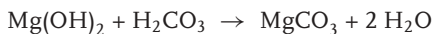
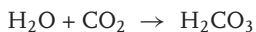
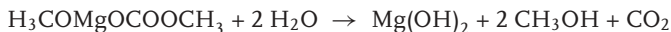
The process consists of three steps: pretreatment, permeation, and postconditioning; the total cycle time is 55–60 h. Akzo operated a treatment facility near Houston, Texas, with a capacity of about 40 000 books per year. Owing to its high reactivity, liquid DEZ is dangerous if mishandled. Poor design and operating procedures on the part of an earlier contractor threatened to halt further development of the process because of the inoperative first pilot plant. The issue of safe handling was fully resolved in the second facility. Nevertheless, the process did not become accepted and was stopped.

30.3.2.3 The Wei T'o Process

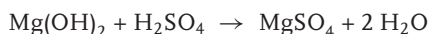
Wei T'o associates, developers of a nonaqueous liquid deacidification process, derives its name from an ancient Chinese god regarded as the protector of books. The National Archives of Canada operated a treatment facility in Ottawa with a capacity of about 40 000 books per year until 2002. The process is based on the work conducted by Richard D. Smith, a graduate student at the University of Chicago in the mid-1960s. In 1989, Union Carbide acquired the exclusive rights of the process and intended to market the technique as part of a paper preservation service unit.

The deacidification agent is methoxymagnesium methyl carbonate carried in a solvent system composed of methanol, trichlorotrifluoroethane (Freon 113), and dichlorodifluoromethane (Freon 12). The CFCs have been replaced by perfluorocarbons. Books are placed in wire baskets and dried to a moisture content of 0.5%. The pretreated materials are immersed in the treatment solution for 1 h under modest pressure. Drying is initiated by evacuating the chamber and recovering the solvents. Final drying is performed under vacuum. During this stage, the deposition of the magnesium compounds occurs. Careful control of pressure regulates the evenness of deposition [65].

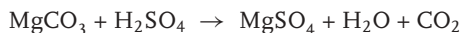
Following deposition, the active agent reacts with water from the air to form a mixture of intermediate magnesium compounds [16]



These magnesium compounds react with strong acids to form the corresponding neutral salts. For example, magnesium hydroxide converts sulfuric acid to magnesium sulfate



Magnesium sulfate is also generated by the reaction of magnesium carbonate with acid



Residual magnesium hydroxide, carbonate, and hydroxide carbonates form the alkaline buffer that protects paper from subsequent acid attacks.

Similar chemistry is practiced by the Bibliotheque Nationale at its treatment facility in Sable sur Sarthe/France. The unit has an annual capacity for 60 000 vol. However, the French process uses ethoxymagnesium carbonate as the deacidification agent.

Many authors have evaluated aspects of the performance of the Wei T'o system. It is important to determine which version of wei T'o was being used before directly comparing these studies, as it has had so many iterations over time.

30.3.2.4 The British Library Process

The British Library has achieved excellent results in its effort to deacidify and strengthen book paper in a bulk process that has been under development since 1980. The method involves graft copolymerization techniques initiated by low-intensity γ -radiation. This work has been performed by the Industrial Chemistry Group of the University of Surrey under British Library supervision and sponsorship.

Short-chain monomers, in particular ethyl acrylate and methyl methacrylate in a volume ratio of 5 : 1, are introduced in liquid form without solvents in a closed system. Low-intensity γ -radiation polymerizes the monomers under ambient conditions. In addition, the liquid monomer mixture has been modified to include an amine-substituted alkyl methacrylate to neutralize acidity and establish a buffer against future acid catalyzed hydrolysis [66]. The presence of a small amount of a diacrylate leads to cross-linking and hence strengthening of the paper.

Paper strength, as measured by fold endurance, is enhanced by a factor of 5–10 and a gain in weight of 15–20% occurs. No dimensional changes in treated books have been observed. Researchers have concluded that the polymer is deposited within the cellulose network of the paper as well as on and between the fiber surfaces. The treated books retain their original appearance and pages do not stick

together at the prescribed polymer deposition levels. Disadvantages of the process are the minor depolymerization of cellulose caused by γ -irradiation, as well as a 10–20% increase in paper weight. The main problem is the residual monomer and oligomer content which are poisonous. In the end, this process also could not be realized.

30.3.2.5 The FMC or Lithco Process

In 1988, Lithco started developing a nonaqueous deacidification technique. Magnesium butoxytriglycolate, the active ingredient, is solubilized in Freon 113 as about 10% solution. Later, heptane was used as solvent instead of Freon 113. The FMC Corporation marketed the process for its ability to both deacidify and strengthen book paper. There does not seem to be any substantiation of this strengthening effect in the literature.

The process consists of three steps: preconditioning, impregnation, and postconditioning. Books or other library materials are dried rapidly by dielectric heating to a moisture content of about 2%. The documents are immersed in the deacidification solution for deposition of the neutralization agent. Finally, excess solution is drained, excess chemicals are rinsed out, the solvent is removed under vacuum, and the books are removed. Total cycle time is less than 5 h.

The butoxytriglycolate ligands are intended to interact with cellulose to strengthen the paper through hydrogen bonding. Similar chemistry based on zinc compounds has also been explored by Lithco on a more limited basis. In addition, the company utilizes dielectric heating to speed the drying during both the first and last steps [67].

Early work was conducted in a demonstration unit capable of processing 20 standard bound volumes per batch. Lithco commissioned a larger pilot unit with a capacity for 1000 books per day in May 1990. In practice, the stabilizing effect through the monobutyl-triglycolether could not be observed. The opposite could be observed more often: owing to the oleaginous substance, a loss in permanence occurred. This process also did not become accepted and therefore was stopped.

30.4

Current Commercial Processes

30.4.1

Papersave Process®

The Papersave process® was developed by Battelle (Frankfurt) and is often called the *Battelle process* in older literature. The inventor was Jürgen Wittekind [68]. The patents of this technique are held by the company Zentrum für Bucherhaltung (ZFB).

In this mass deacidification process, titanium magnesium ethanolate (METE) dissolved in hexamethyldisiloxane (HMDSO) is used as deacidification agent. Titanium ethoxyl has the task of dissolving the magnesium ethoxyl in the form



Figure 30.6 Chamber of the Papersave mass deacidification plant with a capacity of 60 t per year.

of a titanium magnesium double ethoxyl in HMDSO. The magnesium alcoholate performs the deacidification. This METE complex reacts with ambient humidity to form magnesium hydroxide, which is then converted by atmospheric carbon dioxide to an alkaline reserve of MgCO_3 .

The advantage of this process is the use of the nonpolar solvent HMDSO in which nearly no component of the documents is soluble. The addition of alcohol as a solubilizing agent, as in other processes, is not necessary because of the production of the double alkoxide. Only the alcohols that are set free in the hydrolysis of the deacidification agent can become a problem in some cases.

The Papersave process comprises three steps: (Figures 30.6 and 30.7): first, the books, which remain in a closed treatment chamber during the entire process, need predrying. The normal moisture content of 5–7% is temporarily decreased to less than 1%. The drying process takes place under vacuum conditions accompanied by a mild heating to not more than 120°F (50°C). Owing to optimization of the drying technology, the previously used microwave technology has been replaced by a more favorable method.

Second, deacidification follows the predrying. The books are impregnated with an alkali solution. The treatment chamber is completely flooded with the treatment chemical. The deacidification chemicals are alcoholates of magnesium and titanium dissolved in HMDSO. Owing to the previous drying, the closed books standing in the chamber absorb the solution such as a sponge.

Third, the books are again dried after the treatment solution has been drained. The solvent absorbed during impregnation dries away, while the deacidifying chemicals (magnesium and titanium compounds) remain in the paper.

The entire process takes three days. After the books have been removed from the chamber, they regain lost humidity and return to their normal moisture content. This process is finished after approximately three weeks. During this period, the books exude alcohol because of the reaction of the treatment chemicals with water.

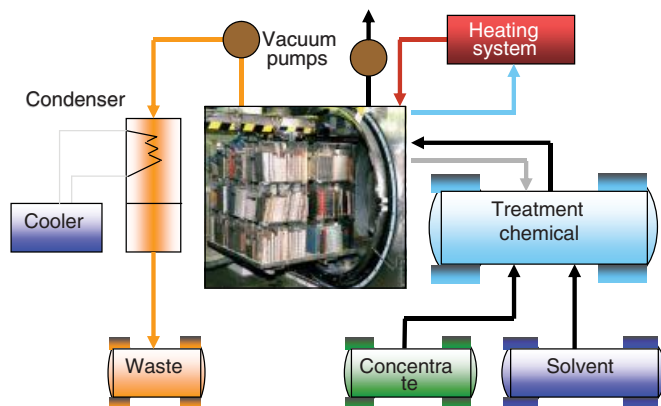


Figure 30.7 Scheme of the papersave mass deacidification plant.

Therefore, the treated books are stored in a well-ventilated room before being returned to the customer.

By this treatment, the following results are obtained: the acids contained in the paper are completely neutralized by the magnesium compounds. The pH of the paper after treatment is raised to between 7 and 9. The pH of some papers can exceed 9 for a short-period after treatment. In the following months, the pH of the paper decreases to levels below 9 because of the transformation of magnesium alcoholates and magnesium hydroxides in magnesium carbonate. After neutralization of the acids, 0.5–2 wt% of superfluous magnesium carbonate remains in the paper and serves as the alkaline buffer. Thus, acids subsequently formed or introduced into the paper by environmental influences can be neutralized within the paper.

This process has proved itself in practice during the last 15 years and is offered by ZFB GmbH in Leipzig/Germany, which works on the conservation and preservation of library and archive goods. The company was founded in 1997 by hiving off the section Center for Book Conservation from the German Library in Leipzig. Battelle (Frankfurt) was taken over by ZFB in 2001. In Switzerland, a Papersave deacidification plant with a capacity of 120 t per year was also opened in 2000, operated by Wimmis Nitrochemie under license from ZFB.

30.4.1.1 ZFB:2 Procedure

The ZFB:2 procedure is a newly developed procedure of the company ZFB in Leipzig, Germany; market launch was in 2012 (Figure 30.8).

The ZFB:2 procedure uses a suspension of calcium carbonate and magnesium oxide dispersed in heptane as vehicle. The procedure is suitable for books as well as for archival material. The treatment baskets, filled with books or archival material, are placed in the treatment chamber and are saturated with the dispersion – in doing so, the alkaline particles infiltrate the paper. After finishing the treatment, the solvent which is absorbed by the books is drawn off in vacuum. The deacidification agent remains in the dried books and neutralizes the acids in the books. It establishes an alkaline reserve to protect the books of further acidic damages.



Figure 30.8 Treatment chamber of the ZFB:2 mass deacidification plant (annual capacity ~100t of paper).

The new ZFB:2 procedure is based on more than 15 years of practical experience with mass deacidification procedures and manifold research projects. As many as possible advantages of the previous procedures have been combined. One example is the physically gentle treatment of the objects within a treatment basket (as in the papersave procedure). The predrying and also a time-consuming reconditioning of the treated objects are no more necessary because of the use of particles. The deacidification agent consists of calcium carbonate and magnesium oxide particles. It is possible to apply both components in any mixing ratio.

What is crucial, is the little size of the calcium carbonate and magnesium oxide particles, which allows the particles to infiltrate the paper. The second important thing is the fact that the dispersion is absolutely nonpolar, which indicates the absence of alcohol and other polar additives. That is the reason why side effects such as bleeding of colors and inks are decreased. These side effects often cause trouble in the recent mass deacidification procedures. Or they may even forbid that a part of the books can be deacidified. Furthermore, calcium carbonate as mild and side effect-free deacidification agent is established in the aqueous manual book treatment since decades.

30.4.2

The Bookkeeper Process

The Bookkeeper process involves the use of magnesium oxide particles in a perfluorocarbon carrier. Unlike the other processes described earlier, the alkaline agent is not dissolved. The process employs a fine submicrometer suspension of MgO particles in perfluoroheptane. The alkaline agent consists of insoluble MgO particles, which are understood to form $\text{Mg}(\text{OH})_2$ by *in situ* reaction with moisture from the paper. No alcohol is involved and a surfactant is employed to keep the neutralization agent evenly distributed in the fluorocarbon solvent. The technique was developed by Koppers Chemical Company in 1981, who transferred the rights of the process to Richard Spatz in 1987. Book Preservation Technologies, in which Spatz is a principal, continues the development of the method.

Books are placed open on a supporting grate which is loaded into a treatment chamber. No predrying is required. The chamber is flooded with the treatment solution and the grate is mechanically agitated so that the pages are exposed and completely wetted. Then the system is drained and evacuated for 90 min to remove the suspending medium [69]. Total process time is 5 h or less. The process can be operated in batch or continuous mode. The Bookkeeper process relies on the migration of paper acid to the magnesium oxide for neutralization to occur.

The treated books show partially a dusty layer of magnesium oxide and damage because of the intense mechanical strain during the deacidification process. At present, this process is used in the Library of Congress (Washington) in America and is also offered commercially in the Netherlands.

30.4.3

Magnesium Oxide Dust

The companies Libertec and SOBU from the area of Nürnberg (Germany) offer a paper deacidification by means of a nonaqueous process [70]. In this process, fine magnesium oxide particles are blown into the opened books as dust, which is then fixed in the paper by humid air. The books are clamped individually into a gadget and then treated. The treated books show an irregular deacidification and a dusty coating on the paper, especially in the book fold. This process is less effective at achieving desired levels of deacidification than aqueous and nonaqueous processes. These processes tend to deposit the alkaline agents on the paper surfaces, as opposed to the solvent procedures that actually penetrate the fiber networks.

30.4.4

CSC Booksaver

The development of the Conservación de Sustratos Celulósicos (CSC) Booksaver process began in the 1990s by the Universitat Politècnica de Catalunya (UPC) together with the Spanish company CSC. The process involves the introduction of a solution of propoxy magnesium carbonate in 1-propanol with a heptafluoropropane propellant (HFC227). Advantage of this system is the relative stability of the deacidification agent when brought into contact with paper of typical moisture content. Disadvantage of this process is the 1-propanol as cosolvent; it causes bleeding of inks and dyes.

30.4.5

Aqueous Processes

30.4.5.1 Bückeburger Process

An automated process for the conservation of single sheets was evolved in the Federal Archive of Lower Saxony in Bückeburg as a consequence of a development

of the PTS (Papiertechnische Stiftung) in Munich/Germany. The aqueous process consists of three treatment stages:

- 1) Fixation of the writing and printing substance by means of a polyamine condensation product and a polycondensed aromatic sulfonate (development of this system by works in Stuttgart [71]).
- 2) Deacidification and generation of an alkaline reserve with an aqueous magnesium bicarbonate solution.
- 3) Sizing with cellulose ether (MC/CMC) for the increase of permanence.

All processes are carried out in dippings. The most progressive plant works with only one dipping that combines all three chemical systems. Only single pages can be treated, books have to be debound for this treatment. This process can be used for archive materials.

30.4.5.2 The Austrian National Library Process

Work on an effective deacidification process for bound newspapers began in the Austrian Library in 1973. The technique, which has been in regular operation in Vienna since 1987, involves immersion in an aqueous solution of calcium hydroxide and methyl cellulose. Borax is then used as deacidification agent.

The process steps include preparation, treatment, drying, and rebinding. Covers are removed from bound newspapers, and the materials are placed in a vacuum chamber. Following immersion in the treatment solution, the paper is shock frozen at -30°C to prevent the formation of large crystals that would damage the paper web. Final drying consists of freeze-drying to avoid the pages sticking together. Treated papers show no significant change in dimensions and permit the use of the original covers [72]. Although testing and preselection is required, the Library has successfully applied the technique to various other archival materials. The current capacity is 3000 bound volumes per year.

30.5

Strengthening Old and Brittle Paper

30.5.1

Overview

No deacidification treatment can restore the internal fiber network and the fiber strength, in cases where the paper is very weak strengthening is required to restore the artifact. There are some successful new possibilities in the deacidification of paper up to mass deacidification processes by nonpolar solvents (for example, the ZFB:2-process), whereas no new achievements have been reached in the strengthening of paper, especially not in nonaqueous treatments. The experiences of papermakers are only of limited use in the strengthening of old papers because the papers cannot be changed in structure and compound during restoration or preservation.

The chain deterioration of cellulose during paper aging is irreversible and cannot be cancelled. A renewing of the fibers is not possible but there are possibilities to stabilize brittle paper and the following measures are worthy of consideration:

- 1) Elastic “conglutination” (sizing) of the paper texture with macromolecular substances (cellulose ether and gelatin).
- 2) Formation of macromolecules in the paper texture by polymerization, for example, the Parylene process. Here, the most commonly discussed method to accomplish only strengthening involves the gas-phase deposition of poly-*p*-xylene. Parylene is the generic name for the various members of the polymer series of *p*-xylenes developed by the Nova Tran Corporation. The technique is capable of establishing a thin, durable coating of the polymer on the paper. No deacidification is accomplished; however, and the high cost of treatment has discouraged widespread use.
- 3) Inserting or applying a stabilizing matrix, normally a thin stabilizing paper.

30.5.2

Preservation of Originals by (Mechanical) Paper Splitting (Leipzig Paper Splitting Technique)

If a work has to be maintained as an original because of its value, even if the paper is seriously damaged, then deacidification is not sufficient. In these cases, a stabilization of the paper is necessary [73]. This can only be achieved by preservational techniques such as wet treatment, leaf casting (if parts are missing), application of thin stabilizing material [74], or paper splitting [75].

Paper splitting [76] was developed at first as a manual technique for preservation and new permanence of highly damaged paper for valuable works by Günter Müller, Jena/Germany. The ZFB in Leipzig developed a paper splitting machine (Figure 30.9). This machine includes a laminating unit, a splitting unit, and a removing unit. First, the binding has to be removed from the book, that is, the single sheets have to be separated. In the laminating machine, the sheets are embedded in gelatin between two carrier sheets. The carrier sheets in roll form are spread with gelatin by means of sizing machines. In the splitting machine, the composite of original sheet and carrier material produced in the laminating machine is pulled apart, that is, it is split. Then, a thin but sturdy core paper (often with an alkaline buffer) is brought in between the two sides and glued together with the halves of the original paper with cellulose ether (for example, methyl cellulose) mixed with calcium carbonate as deacidification agent and alkaline reserve. After that, the split sheets are supplied to the removing unit where the carrier sheets are removed by means of an enzyme (protease). Finally, the stabilized sheets are bound again.

Even despite occasional ethical doubts the paper splitting process is often the only practicable method for highly damaged paper, for example, paper that is an advanced stage of damage by microorganisms or ink corrosion.

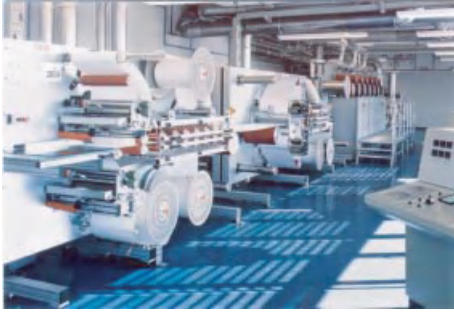


Figure 30.9 Paper splitting machine of the ZFP Leipzig.

30.6 Commercial Prospects

The need for paper deacidification is enormous. It is reckoned that between 70 and 80% of the library and archive collections consist of acid paper and are therefore exposed to a dynamic deterioration process. The reaction is self-accelerating because the acid deterioration is an autocatalytic process. This means that in the course of the deterioration process more and more acids are produced. The acids in the paper can be neutralized, and an alkaline reserve can be deposited. With that, the acid-conditioned deterioration reaction in paper can be stopped effectively but cannot be cancelled. If the deterioration is too far advanced, more complex preservation processes than mass deacidification (e.g., paper splitting) are needed so that the paper can be used again. The earlier the acid corrosion is stopped, the easier and cheaper is the treatment. An early deacidification is therefore the most effective method to save money in the preservation of documents.

Most collections are in the property of public institutions and it is unsure how much money will be available for the preservation of these important cultural assets. This uncertainty makes it more difficult for the private sector to act and plan economically.

The most compelling evidence for the need for mass deacidification is the substantial involvement of national libraries in the development of treatment methods. Research libraries and archive groups universally seek a low-cost option that will permit preservation of collection materials in their original form. Current deacidification techniques represent a viable and cost-effective preservation solution to the problem of acid paper. Although, it is currently difficult to define costs in order to make convincing comparisons among processes, mass deacidification is unquestionably far less costly than reformatting options such as microform or digitalization. In addition, users of research libraries and archives collections continue to prefer original format materials.

More than one mass deacidification method will be adopted by the library and archives community. The problem is so big and the needs are so diverse that a single institution may well choose to pursue multiple treatment options.

The aim of new developments is to evolve technical less complex methods with less expensive chemical systems. A further aim is, in addition to the deacidification, to achieve more improvements in the paper, for example, strengthening, protection against oxidation, and protection against microbial infections, by the use of additives. The new ZFB:2-process seems to have the potential for these improvements.

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31

Paper Associations

Herbert Holik

Table 31.1 Paper associations and their addresses of different countries.

Country	Association	Address
Australia	APPITA (The Technical Association of the Australian and New Zealand Pulp and Paper Industry)	APPITA, Carlton Clock Tower, Suite 47, Drummond Street, Carlton Victoria 3053, Australia
Austria	ÖZEPA (Österreichische Vereinigung der Zellstoff- und Papier-Chemiker und Techniker)	ÖZEPA, Gumpendorfer Street 6, 1061 Wien, Austria
Brazil	ABTPC (Associacao Brasileira Tecnica de Celulose e Papel)	ABTPC, Rua Zequinha de Abreu, 27, Pacaembu, BR-01250-05 Sao Paulo – CEP, Brazil
Canada	PAPTAC (Pulp and Paper Technical Association of Canada)	PAPTAC, 740 Notre-Dame Street West, Suite 1070, Montreal, QC H3C 3X6, Canada
Chile	ATCP (Asociacion Tecnica de la Celulosa el Papel de Chile)	ATCP, Janequeo 884 dep-402, RCH-Concepcion, Chile
China	CTAPI (China Technical Association of the Paper Industry)	CTAPI, 12 Guanghua Road, Chaoyang District, VRC-Beijing 100020, China
Colombia	ACOTEPAC Colombia	Calle 94 No. 25-70, Via Mercasa Edificio Cenpapel, 1er. Piso, CO-Pereira – Risaralda, Colombia
Finland	PI (The Finnish Paper Engineers' Association)	The Finnish Paper Engineers' Association, Snellmaninkatu 13, FIN-00171 Helsinki, Finland
France	ATIP (Association Technique de l'Industrie Papetiere)	154, Boulevard Haussmann, F-75008 Paris, France
Germany	Zellcheming	Zellcheming, Emilstrasse 21, D-64293 Darmstadt, Germany
Great Britain	PITA (Paper Industry Technical Association)	PITA, 5 Frecheville Court, Bury, Lancashire BL9 0UF, Great Britain

(continued overleaf)

Table 31.1 (continued)

Country	Association	Address
Hungary	PNYME (Papíres Nyomdai Müszaki Egyesület)	PNYME, Fő Utca 68, PO Box 433, 1371 Budapest, Hungary
India	IPPTA (Indian Pulp and Paper Association)	IPPTA, PO Box 47, CPPRI Campus, Paper Mill Road Near Himmat Nagar, Saharanpur 247 001, UP, India
Italy	ATICELCA (Italian Technical Association of the Pulp and Paper Industry)	ATICELCA c/o Assocarta, Bastioni di Porta Volta 7, 20121 Milano, Italy
Japan	Japan TAPPI	Japan TAPPI, Kami Pulp Kaikan Building, 11th Floor, 9-11 Ginza 3-chome, Chuo-ku, J-Tokyo 104 8139, Japan
Korea	KTAPPI (Korean Technical Association of the Pulp and Paper Industry)	KTAPPI, Suite 701, Chungmu Building, Yoido-Dong, 44-13, Yongdungpo-Gu, 150-010 Seoul, Republic of Korea
Lettland	LPRA (Latvijas Papira Razotaju Asociacija)	Latvijas Papira Razotaju Asociacija, Pilsonu iela 1, LV-410 Ligate, Lettland
Mexico	ATCP – Asociacion Mexicana de Tecnicos de las Industrias de la Celulosa y del Papel, A.C.	ATCP, Lafayette 138, Anzurez, MEX-11590 Mexico D.F., Mexico
Norway	PTF (Papirindustriens Tekniske Forening)	Papirindustriens Tekniske Forening, Postboks 7072 Majorstuen, 0306 Oslo, Norway
Poland	SPP (The Association of Polish Papermakers)	SPP, PO Box 200, 90-950 Lodz, Poland
Portugal	TECNICELPA (Associacao Portuguesa dos Tecnicos das Industrias de Celulose e Papel)	TECNICELPA, Rua Amorim Rosa, 38-1. Dt., 2300-450 Tomar, Portugal
Russia	BUMPROM (Russian Association of Pulp and Paper Organizations and Enterprises)	BUMPROM, Glavpochtamt, PO Box 748, 101000 Moskau, Russia
Sweden	SPCI (The Swedish Association of Pulp and Paper Engineers)	SPCI, PO Box 5515, 114 85 Stockholm, Sweden
Slowenia	DITP (Društvo Inženirjev in Tehnikov Papirnistva)	DITP, Bogisiceva 8, PO Box 1728, 1001 Ljubljana, Slovenia
Spain	ASPAPEL (Asociacion Espanola de Fabricantes de Pasta, Papel y Carton)	ASPAPEL, Avenida de Baviera 15, 28028 Madrid, Spain
South Africa	TAPPSA (Technical Association of the Pulp and Paper Industry of Southern Africa)	TAPPSA, PO Box 1633, ZA-Kloof 3640, Kwazulu Natal, Republic of South Africa

Table 31.1 (continued)

Country	Association	Address
Taiwan	Taiwan Technical Association of Pulp and Paper Industry	10, Hoping West Road, Sec.2, PO Box 72-10, Taipei, Taiwan, China
Tchechia und Slovakia	SPPC (Spolecnost Prumyslu Papiru a Celulozy)	SPPC, Novotneho Lavka 5, 11668 Praha 1, Tchech Republic
USA	TAPPI (Technical Association of the Pulp and Paper Industry)	TAPPI, 15, Technology Parkway South, Norcross, GA 30092, USA
Venezuela	apropaca – Asociacion Venezolana de Productores de Pulpa, Papel y Carton	Apropaca, Edif. Johnson & Johnson, Piso 2, Oficina 2B, Avenida Romulo, Gallegos, Los Dos Caminos, YV-Caracas, Venezuela

Based on Zellcheming Archives (information by W. Busse 2010).

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