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Industrial Electrical Engineering and Automation

Boiler Control

Improving Efficiency of Boiler Systems

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– improving efficiency of boiler systems

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Abstract

This master thesis is written at the division of Industrial Electrical Engineering and Automation (IEA) Lund University, Faculty of Engineering, in cooperation with AB Regin in Landskrona.

AB Regin wishes to determine whether their existing controller platforms can be used to implement a control system for boilers. The control system should be flexible in terms of boiler size, boiler fuel and boiler type.

The main aspects associated with the combustion process are reviewed, and different types of fuel commonly used in boilers are investigated and compared. The most common boiler designs are described, and definitions used in boiler context are explained.

To establish what techniques have been developed to improve boiler efficiency an empirical study is performed. The different techniques are discussed in detail, involving both control systems and design changes. Finally the measurement instruments involved in these improvement techniques are described.

Case studies are performed to find out which techniques are used in practice to improve efficiency of boiler systems. To get a good idea of common techniques, the cases include establishments that use different fuels, and range from small scale to large scale.

An effort is made to implement a boiler controller on the EXOcompact platform from AB Regin. A control algorithm is outlined and implemented for a fictional system. The system is then simulated using a demo kit from Regin. Some tests are performed to verify that the function of the control system is acceptable, and the results are discussed.

Finally the overall thesis is discussed, and issues that should be addressed in future development are listed and explained.

Preface

The work on this thesis was done in AB Regin's product development center in Landskrona, under supervision from the division of Industrial Electrical Engineering and Automation (IEA) at Lund University, Faculty of Engineering. All responsibility for the report has been divided equally by both authors, and all chapters are a result of cooperative writing. The work on the report was started in May 2010, and while working on the report we have received support from a number of people. The following people deserve special thanks:

Jonas Möller, our supervisor at AB Regin. During the time we spent on the report Jonas was always ready to help. Without such great help our work would not have gone as smoothly. We would also like to thank the staff at AB Regin in general for their warm welcome, and for supplying us with an office to work in.

Johan Billberg and Staffan Salö for their help regarding the Sysav power plant. Due to the thorough explanation of the system provided by Johan, we gained a very good overview of the operational principles of such a plant.

Martin Båfält for meeting with us and explaining the operation of Öresundsverket power plant.

Staffan Branting and Håkan Nilsson for providing information on the boilers at Nosabyskolan in Kristianstad municipality.

Roger Assarsson for explaining the operation of the biofueled boiler system in Staffanstorp.

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Finally we would like to thank our families and friends for their support.

Hjalti Kristinsson and Sofie Lang
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Acronyms

ABMA	American Boiler Manufacturers Association
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASME	American Society of Mechanical Engineers
BTU	British Thermal Unit
C	Carbon
CIPEC	Canadian Industry Program for Energy Conservation
CO	Carbon monoxide
CO_2	Carbon dioxide
H	Hydrogen
H_2O	Water
HVAC	Heating Ventilation and Air Conditioning
I/O	Input/Output
IR	Infrared
LED	Light Emitting Diode
NIR	Near Infrared
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
O_2	Oxygen
OH	Hydroxide
PB	Proportional Band

PID	Proportional-Integral-Derivative
PM	Particulate Matter
RPM	Revolutions Per Minute
SCADA	Supervisory Control And Data Acquisition
SO_2	Sulfur dioxide

Chapter 1

Introduction

1.1 Background

AB Regin was founded in 1947 when their first product, a humidistat, was launched. Several years later they launched a controller for electrical heating and since then they have developed a series of controllers and sensors. Ever since AB Regin was founded their goal has been to provide customers with a high level of indoor comfort. Through the years Regin has merged with several companies, thereby expanding their product spectrum. Their products currently include various sensors, a selection of controllers and even web-based SCADA systems. Regin prides itself in being a challenger in the field of building automation and supplying customers with first class services. Another goal of the company is to contribute to the development of technology to improve energy efficiency and sustainable development.

In 2009, AB Regin took over a company based in Germany that has been developing controllers for residential boilers. This contributed to an existing interest to investigate the market and determine viable solutions for marketing in Sweden. When AB Regin was contacted by LTH in the spring of 2010, in search of a thesis subject, they gladly offered this project.

1.2 Objectives

The goal of this masters thesis is to provide fundamental knowledge on the principles involved in boiler systems. The most effective ways of boiler optimization will be covered in depth along with a discussion on how they can be implemented in a controller. This information will then be used to determine which optimization techniques should be included in a controller. A second goal is to implement a proof of concept controller on one of AB Regin's existing controller platforms.

1.3 Outline

The following explains the outline of the report:

- Chapter 2 covers the technical background for boiler control in order to provide the reader with some basic knowledge of the technologies discussed in later chapters. The different fuels used in boilers are investigated and compared with respect to some key factors. The most common types of commercial boilers are described in short. Finally some definitions used in boiler context are explained.

- Chapter 3 covers techniques that are commonly used in boiler control systems. Each technique is explained with regard to what is involved, what can be measured and how these measurements can be used to improve the efficiency of the system. In addition to the control techniques, a number of techniques that improve efficiency through design changes will also be explained. Then the aspect of measurement instruments is covered, with explanations of the functional principles of these instruments.

- Chapter 4 details several case studies that aim at establishing what techniques are generally used in practice for boiler control. Each case includes a short summary about the company in question as well as a description of the system. In each case the main focus is on the control system itself, what techniques are used, what control parameters are relevant and what instruments are used to acquire relevant data.

- Chapter 5 illustrates the implementation process of a control system on a Regin controller platform. The steps taken towards a testable system are described in detail, beginning by explaining the methodology used for the implementation. The boiler system that is to be controlled is then described with details on what parameters are usable and what alarms that should be included. The implementation phase is then discussed, with a description of the platform used as well as information on the simulation environment and the design of the control system. Finally the system is tested and results from that testing are presented.

Chapter 2

Technical Background

This chapter provides the basic technical background for boiler control. It is intended to give the reader sufficient information on the basic theory needed to understand the following chapters as well as other literature within the subject. Then the basics of the combustion process is discussed, a short summary of the various fuels commonly used in these processes is provided and the most significant emissions and their effects is covered. The most common boiler designs will be explained along with the fuel feed systems. Finally, the chapter will provide an overview of the losses in a boiler system, how the efficiency of such a system is measured and explain some efficiency definitions often used in boiler context.

2.1 Combustion

Combustion is a chemical process in which an oxidant reacts rapidly with a fuel, liberating stored energy as thermal energy, usually in the form of high-temperature gases. In the majority of applications the oxidant used for combustion is oxygen (O_2) in air. Combustion processes have been, are and will be for the near future the prime generator of energy in our civilization. For the sake of the environment and the sustainability of civilization these processes must be well managed. Conventional fuels are comprised of various hydrocarbons, meaning that they consist mainly of carbon (C) and hydrogen (H). Combustion of hydrocarbons produce mainly carbon dioxide (CO_2) and water (H_2O) (ASHRAE, 2009).

For combustion to start, the ignition temperature of the fuel must be reached. Also, the proportions of the fuel and air must be in the proper range for combustion to begin. For example, natural gas does not burn in air concentrations less than 5 % or greater than 15 %. Components before reaction are called reactants and components after combustion are called products (Cengel & Boles, 2006).

2.1.1 Stoichiometric Combustion

The ideal combustion process during which a fuel is burned completely is called stoichiometric combustion. After stoichiometric combustion all carbon, sulfur, and hydrogen is oxidized and forms only H_2O, CO_2 and SO_2. Stoichiometric air, sometimes also referred to as theoretical air, is the exact amount of air needed for complete combustion. In practice stoichiometric combustion is seldom realized because of imperfect mixing and finite reaction rates. Combustion processes therefore operate with some excess air (Cengel & Boles, 2006).

2.1.2 Complete Combustion

A combustion is complete if all carbon in the fuel burns to CO_2, all hydrogen burns to H_2O and nitrogen and sulfur forms NO_2 and SO_2, respectively. Oxygen for combustion is normally obtained from air, which mostly contains nitrogen, oxygen, water vapor, carbon dioxide, argon and other gases. A complete combustion generally requires some amount of excess air or excess oxygen beyond the theoretical amount (ASHRAE, 2009).

2.1.3 Incomplete Combustion

Incomplete combustion is when the combustion products contain any unburned fuel or components such as C, H_2, CO or OH. For example, hydrocarbon that is not completely oxidized forms partially oxidized compounds, such as carbon monoxide, instead of water and carbon dioxide.

Oxygen has a greater tendency to combine with hydrogen than with carbon so fuel normally burns to completion forming H_2O. As a result, some carbon ends up as carbon monoxide or just plain carbon particles, soot, in the products. Incomplete combustion means that fuel is used inefficiently and can even be hazardous due to formation of carbon monoxide (Cengel & Boles, 2006).

Insufficient amount of oxygen is an obvious reason for incomplete combustion. Other reasons are too low flame temperatures, insufficient reactant residence time in the flame and insufficient mixing in the combustion chamber during the limited time that fuel and oxygen are in contact (ASHRAE, 2009).

2.1.4 Excess Air

In order to enable complete combustion in an actual process, the amount of oxygen has to exceed the theoretical level by a certain percentage. The amount of air that exceeds the theoretical amount is referred to as excess air. It is in fact impossible to predict an actual combustion and to estimate the excess air needed without measuring the products of the combustion. Excess air is not only important to ensure complete combustion, thereby ensuring that fuel is not wasted, but is also a key factor for safety reasons, for example to minimize the formation of hazardous gases like carbon monoxide (Cengel & Boles, 2006). Excess air and its extensive effects are discussed in greater detail in Section 3.1.3.

2.1.5 Combustion Gases

Combustion gases, also called flue gases, are the result of any complete or incomplete combustion and contain products from the combustion as well as excess air. If the combustion gases are cooled below a certain temperature, called dew point, some of the gases condense. It is important to be able to predict the dew point temperature since water droplets often combine with the sulfur dioxide that may be present in the combustion gases, forming sulfuric acid, which is highly corrosive (Cengel & Boles, 2006).

2.2 Fuels

The choice of fuel has a great impact on furnace performance. In this report fuels are divided into their physical state, i.e. solid, liquid and gas. Some systems are designed to use more than one type of fuel. Fuel properties differ in many aspects such as energy content, availability and how easy even distribution of the fuel is established in the boiler. Commonly used fuels are shortly introduced in the following sections.

2.2.1 Solid Fuel

A large variety of solid material can be used as fuel in a combustion process. In principle most combustible waste can be utilized as fuel. Most commonly used are coal, biofuel, peat and waste fuels. Domestic garbage is a heterogeneous fuel which differs a lot in its composition. It can contain different types of materials, such as food, plastic, wood, paper, glass and metal. This results in high demands in combustion equipment and flue gas filtering to reduce emissions. Waste is therefore mainly used as fuel in district heating production (*Energifaktaboken*, 2005).

Coal is formed in a process where organic material is under pressure during long periods of time. The process is very slow and coal is therefore considered a non-renewable energy source. The most common type of coal for energy production in Sweden is bituminous coal, or black coal. In Sweden, coal is mostly used in industry and in large combined heat and power plants (*Energifaktaboken*, 2005).

A common name for wood products, straw, reed and energy crops is biofuel. Biofuel can be transformed into woodchips, pellets, briquettes or powder, for example to make transport easier or make the fuel more uniform in shape. The combustion efficiency of pellets is very high compared to wood since the pellets are extremely dense and have a low moisture content. The uniform shape also enables automatic feeding of fuel. Wood chips are small uniform pieces of wood made from waste wood and residuals from landscaping, logging and sawmills (*Energifaktaboken*, 2005).

Peat forms in wetland bogs and consists of partially decomposed organic matter and can be transformed into pellets, briquettes or powder. The annual formation corresponds to 20 TWh in Sweden, where about 25 % of this is harvested. Peat is still considered as a fossil fuel within emissions trading (*Energifaktaboken*, 2005).

2.2.2 Liquid Fuel

Most liquid fuels are based on petroleum, produced by the refining of crude oil which has formed from plants and organisms under high temperature and pressure under the bottom of seas and oceans. The major constituents of oil fuel are carbon and hydrogen. Other constituents are nitrogen, sulfur, ash and other impurities. The classification of oil differs between countries but it is often divided into six classes according to its physical characteristics. Fuel oil classes 1-2 have low density and thereby also lower viscosity and are called distillate oils. Diesel fuel belongs to this category. The most common fuel for burners is class 1 type of oil. Distillate oils are lighter and are relatively clean fuels, primarily used for home heating where factors such as ash and low content of sulfur are important. Classes 3-6 have higher density and are called residual oils (*Energifaktaboken*, 2005; Oland, 2002).

Residual oils with high density and high viscosity must be preheated since heavy fuel oils have the tendency to solidify when cold. One common cause of poor oil burner performance is too high oil viscosity due to inadequate preheating of the oil. Sometimes distillate oils are blended with the higher viscous residual oils to create a desired mixture. Some liquid biofuel also exist such as palm oil and canola oil, produced from crushed rapeseeds. Biooil usually has a lower energy content than fuel oils (*Energifaktaboken*, 2005).

2.2.3 Gaseous Fuels

Gaseous fuels are easy to evenly distribute in order to achieve a complete combustion of the fuel. The combustion process is therefore easier to control in comparison with using solid or liquid fuels. A more exact temperature control makes it possible to affect the formation of NO_x, flue gas temperature and achieve optimal control. Gaseous fuels contain little carbon in relation to the amount of energy compared to other fuels, which results in relatively low emissions of carbon dioxide. Emissions of sulfur dioxide, carbon monoxide and soot particles are minor. Examples of gaseous fuels used for energy production through combustion are natural gas, town gas and biogas. Town gas, produced from petroleum was previously distributed in the Swedish gas distribution network. Today this has been replaced by natural gas, which is also a fossil fuel, but result in lower emissions of carbon dioxide (*Energifaktaboken*, 2005).

Natural gas is a gas mixture with methane as basis. The gaseous hydrocarbons are formed by anaerobic decomposition of organic material and is pumped up either together with oil or from separate gas wells. The composition varies depending on the source, usually with methane concentrations of 70 % and higher. Natural gas in the Swedish gas distribution network consist of 90 % methane, 6 % ethane and 2 % propane. Hydrogen sulfide is always removed from gas distributed through the public system due to the high toxicity both of the gas and its products (Svenska Gasföreningen, 2008).

Biogas refers to gas produced by biological degradation of organic matter, normally from wastewater and landfills, in the absence of oxygen. The produced gas mainly consists of methane and carbon dioxide and is considered to be a renewable energy source which does not contribute to pollution since the gas is a part of the natural cycle. To add biogas into the natural gas distribution net, the gas has to be upgraded to a higher energy content which is done by extracting carbon dioxide. Biogas is primarily used in heat production, followed by being used as vehicle fuel (Jarvis, 1998; *Energifaktaboken*, 2005).

2.2.4 Energy Content

An important parameter to compare fuels for combustion systems is the heat release rate. Heating value, or calorific value, is the quantity of heat generated by complete combustion of a unit of specific fuel (ASHRAE, 2008).

If gas is supplied through a fixed nozzle the flow rate will vary with the density which will give different release rates. A better parameter to compare gases by is the Wobbe index where the higher heating value in MJ/m^3 is divided by the specific density relative to air. Gases with similar Wobbe index will produce the same heat release in the furnace when supplied through the same nozzle at similar supply pressure (Mulliger & Jenkins, 2008).

2.3 Emissions

A byproduct of the industrial revolution in Western Europe was severe atmospheric pollution, both from visible pollutants, such as particulate material and emissions of poisonous materials, such as lead, arsenic and mercury. Since then industrial operations have seen increasing scrutiny and regulation to control these emissions. In the beginning, these regulations mostly applied to things that could be seen, felt or smelled. With the constant advances and the increasingly sophisticated ability to detect and measure very small quantities of chemicals these pollution legislatures cover more and more of the chemicals that are harmful to either humans or the environment. The latest manifestation of pollution is the climate change, caused in lesser or greater degree by human activity resulting in an increased amount of radiatively absorbent gases in the atmosphere. Some of the main pollutants associated with combustion processes are listed in Table 2.1, and a number of these are discussed in greater detail in the following sections (Mulliger & Jenkins, 2008).

Table 2.1: Emissions from combustion systems and their effects (CIPEC, 2001).

Emission	**Source**	**Effect**
Carbon Dioxide (CO_2)	Complete combustion of carbon in fuel	Global warming
Carbon Monoxide (CO)	Incomplete combustion of carbon in fuel	Smog
Sulfur Dioxide (SO_2)	Combustion of sulfur in fuel	Smog, acid rain
Nitrogen Oxides (NO_x)	Byproduct of most combustion processes	Acid rain
Nitrogen Dioxide (NO_2)	Byproduct of some combustion processes	Global warming
Water vapor (H_2O)	Combustion of hydrogen in fuel	Localized fog
Particulate Matter (PM)	Unburned or partially unburned carbon and hydrocarbons, also dirt and ash in fuel	Smog

2.3.1 Nitrogen Oxides

Nitrogen oxides (NO_x) are amongst the primary pollutants emitted into the atmosphere during the combustion process. The term NO_x refers to the cumulative emissions of NO, NO_2, and trace amounts of other species (Oland, 2002).

The majority of NO_x is initially formed as NO and is then oxidized further to form NO_2, either immediately within the combustion chamber or as the flue gases are discharged into the atmosphere. When NO_x reacts with volatile organic compounds in the presence of sunlight they form ground-level ozone (O_3), which is a major ingredient of smog. When NO_x reacts with water and air it forms very dilute nitric acid (HNO_3), causing acid rain. The formation of NO_x is generally controlled by three routes, thermal NO_x, fuel NO_x and prompt NO_x (Oland, 2002).

Thermal NO_x refers to the NO_x that is formed through high-temperature oxidation of nitrogen in the combustion air. The thermal NO_x formation rate is strongly correlated to temperature. At temperatures above 1400 °C the levels of NO_x formed become significant and the formation rate increases exponentially. A typical method to control the NO_x formation is to reduce the peak and average flame temperatures. This approach is contrary to the traditional methods of assuring complete combustion, but some compromise is needed between combustion efficiency and the formation of thermal NO_x (Oland, 2002).

Fuel NO_x refers to the conversion of fuel-bound nitrogen found in nitrogen-bearing fuels, such as oils and coal, to NO formed during the combustion process. The conversion to NO is strongly dependent on the fuel-to-air ratio but only weakly dependent on combustion zone temperature. This means that techniques such as fuel-air mixing can reduce fuel NO_x emissions significantly (Oland, 2002).

Prompt NO_x refers to NO_x that is formed very early in the combustion process. It appears through the formation of intermediate nitrogen cyanide (HCN) species that is followed by the oxidation of HCN to NO. The formation of prompt NO_x is normally only weakly temperature dependent, but this dependency can become stronger in fuel-rich conditions (Oland, 2002).

2.3.2 Sulfur Dioxide

Sulfur is present in most fossil fuels and primarily originates from the decay processes of plants and animals. The combustion of fuels containing sulfur results in creation of SO_2, and when it oxidizes in the atmosphere it converts to sulphuric acid (H_2SO_4). The emissions of SO_2 are a significantly larger contributor to acid rain than NO_x. SO_2 by itself is highly corrosive and harmful to the environment. A significant amount of the SO_2 discharged into the atmosphere is further oxidized to SO_3 when mixed with air and then combines with water vapor to create a persistent visible plume, i.e. acid mist (Oland, 2002).

Several methods can be used to reduce SO_2 emission. One solution is to simply switch to a fuel with less sulfur content but this may have adverse effects on the boiler performance since the fuels may differ significantly in heating value. This can also affect the flame stability, change emissions and may require changes to be made in fuel handling. If switching to a low-sulfur fuel is not a viable option the use of wet or dry scrubbers may be more suitable. These scrubbers are a post-combustion method for controlling SO_2 emission very efficiently without making major changes in boiler operations. The by-products from scrubbing, calcium sulfate ($CaSO_4$) or calcium sulfite ($CaSO_3$), depending on the process, can be used as gypsum or placed in landfills (Oland, 2002).

2.3.3 Particulate Matter

In the combustion of a fuel that contains noncombustible materials, the result is the formation of ash. This ash along with any unburned carbon particles are often collectively referred to as particulate matter (PM) or fly ash. PM, such as smoke, dust, soot and haze, is emitted during the combustion process and the concentrations are dependent on the chemical composition of the fuel. In high concentration PM can contribute to poor visibility, such as haze, which is common around densely populated areas. It can also cause serious health problems since the small particles can penetrate deeply into the lungs and some can even get into the bloodstream. Particle size is measured in micrometers (μm), and emission of PM is regulated separately for particles less than 10 μm and particles less than 2.5 μm. Before flue gas is discharged into the atmosphere it may require filtering to reduce the amount of PM (Oland, 2002).

2.3.4 Carbon Monoxide

Carbon monoxide (CO) is formed in the combustion process when carbon in the fuel does not burn completely. The CO gas is odorless, colorless and highly toxic. The greatest source of CO emissions is vehicles, which accounts for approximately 60 % of total CO emission in the United States. In some cities the emissions from automobiles can even reach 95 % of the total emissions of CO. Other sources of CO emissions are industrial processes, such as combustion boilers and incinerators (Oland, 2002).

The control of the combustion process is therefore important in terms of boiler efficiency since incomplete combustion results in increased emissions of CO and PM, which means that energy is being wasted. In good combustion systems, CO should be limited to a few parts per million (ppm), normally in the range of 20-25 ppm. If CO exceeds 1000 ppm it is usually the result of air starvation or very poor fuel-air mixing and is the symptom of serious problems within the combustion process. The combustion of liquid and gaseous fuels generally generates significantly less CO emissions than the combustion of solid fuels. Therefore, combustion control is an important design and operating concern in solid fuel boilers (Oland, 2002; Mulliger & Jenkins, 2008).

2.4 Boiler Types

Boilers are manufactured in various designs and sizes, depending on characteristics of the fuel used and the heating output. Some boilers are only capable of producing hot water while others are designed to produce steam. The basic purpose of a boiler is to convert chemical energy into thermal energy, which is achieved in two fundamental processes in the boiler. First, the fuel is mixed with an appropriate amount of oxygen to allow for a sustained combustion. The heated gases from the combustion process are then used to transfer the thermal energy to a fluid or steam. Boilers can be categorized according to the method used to transfer the thermal energy. The most common types, firetube and watertube, will be explained in the following sections (Oland, 2002).

2.4.1 Firetube Boiler

In firetube boilers the hot combustion gases flow through a series of tubes that are housed inside a water-filled outer shell. As the gases flow through the tubes, it heats the water surrounding the tubes. Modern firetube boilers often have cylindrical outer shells with a round combustion chamber at the bottom, and they are mostly used in low-pressure applications in order to avoid the need for a thick outer shell. This type of boilers are often characterized by their number of passes, referring to the number of times the combustion gases flow through the outer shell. The number of passes depends on the construction details, usually ranging from one to four passes in common designs. Most designs can use a variety of fuels such as oil, gas, coal and biomass. Figure 2.1 shows the basic design of a two-pass firetube boiler (Oland, 2002).

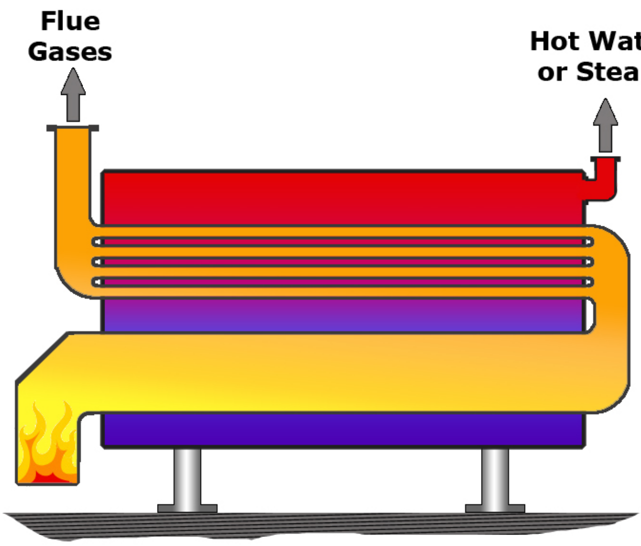

Figure 2.1: A two-pass firetube boiler.

2.4.2 Watertube Boiler

In watertube boilers the hot combustion gases are circulated around the outside of a large number of water-filled tubes. In older designs the tubes are either straight or bent into simple shapes, while in modern designs they often have complex and diverse bends. Because the pressure is contained inside the water tubes, watertube boilers can be used in high-pressure applications. Like the firetube design, watertube boilers can have a number of burners and can burn almost any type of liquid, solid or gaseous fuel. The design of the boiler can vary significantly depending on what fuel it is intended to burn.

These designs differ mainly in the way the fuel is fed to the combustion process and can therefore usually be adapted for other types of fuel than the one it was originally designed for. Figure 2.2 show the basic design of a firetube boiler (Oland, 2002).

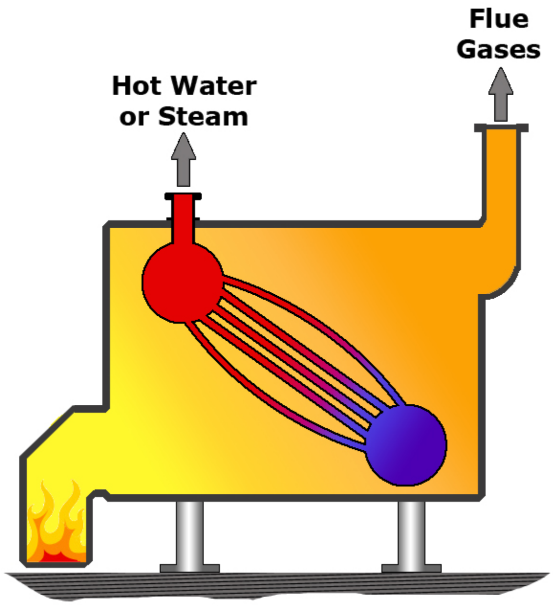

Figure 2.2: A watertube boiler.

2.4.3 Condensing versus non-Condensing

Traditionally designed boilers must operate without condensing the flue gas in the boiler. This is a precaution to prevent corrosion and means that hot-water units must be operated at a minimum of 60 °C water temperature. In non-condensing boilers a considerable amount of energy is lost as heat in the exhaust gases. By passing the flue gases through a secondary heat exchanger and thereby condensing the water vapor in the flue gas, some of this energy can be recovered. The efficiency of a boiler is highly dependent on the temperature of the inlet water, so non-condensing boiler efficiency is severely restricted by the minimum temperature requirements. Condensing boilers on the other hand are built from corrosion resistant materials and can therefore reach a much higher potential efficiency. Full condensing boilers are now widely available, and they can be of the firetube or watertube type as well as other less common design types. Figure 2.3 shows the effect of the inlet water temperature on the efficiency in a gas-fired boiler (ASHRAE, 2008).

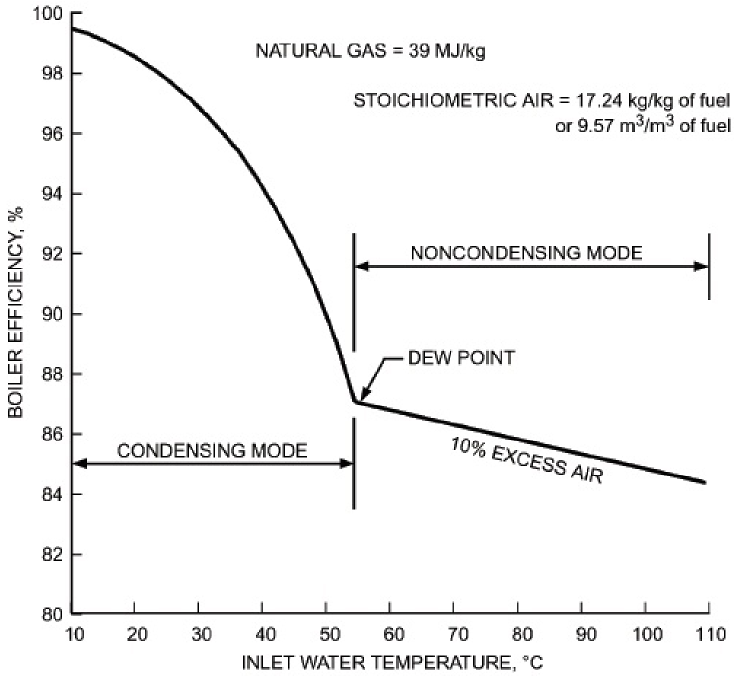

Figure 2.3: The effect of inlet water temperature on efficiency (ASHRAE, 2008).

Due to the significant increase in efficiency from condensing the flue gases a large number of non-condensing boilers have been fitted with an external condenser, commonly referred to as economizers. When these economizers are used, care must be taken to protect the non-condensing boiler from the low-temperature inlet water in case of economizer failure (ASHRAE, 2008). Economizers and methods for condensing are discussed in more detail in Chapter 3.

2.5 Fuel Feed Systems

The fuel feed system of a boiler plays a critical part in terms of boiler efficiency. The primary function of these systems is twofold, transporting the fuel to the boiler and ensuring that the fuel is distributed within the boiler in such a way that it promotes uniform and complete combustion. These systems differ widely depending on the type of fuel used (Oland, 2002).

Fuels in gaseous form are the easiest type of fuel to transport and handle. By introducing pressure difference the gas will start to flow, and the majority of gaseous fuels mix easily with air. The flow rate of gaseous fuels can be very accurately controlled with various control systems (Oland, 2002).

Similarly, the transport and handling of liquid fuels is also fairly easy to manage. The fuel is easily transported using pumps and piping networks, and by atomizing the liquid fuel upon injecting it into the combustion process the fuel mixes well with the air promoting complete combustion. The atomization is usually done by air, steam or pressure to produce droplets, making the fuel burn more like gas than liquid. Liquid fuel boilers can be controlled using various control systems that measure fuel flow rate (Oland, 2002).

When it comes to solid fuel the handling becomes much more difficult. The fuel might have to be processed prior to combustion, for example by using techniques such as crushing or shredding. The fuel is often transported using mechanical devices, such as hoppers, conveyors, vibrators, augers and blowers. The oldest and simplest method of solid fuel handling is hand firing of fuel. Fuel is manually fed onto a cast iron grate where it burns. Hand firing is very seldom used today, as the method has evolved to more sophisticated and effective techniques that will be briefly described in the following sections. The majority of solid fuel feed systems was initially designed specifically for coal firing, however, in most of them other solid fuels can either be mixed with coal or replace it entirely (Oland, 2002).

2.5.1 Stokers

A common solution for feeding solid fuels into boilers is through the use of stokers. Stokers were first used in the 18th century to burn coal. Since then they have evolved from crude machines to sophisticated electromechanical components that can rapidly respond to changes in boiler output demand and provide good fuel handling capabilities and turndown, defined as the ratio of maximum to minimum fuel flow rate. Firing systems that involve stokers must be integrated into the boiler design in order to optimize combustion and heat recovery and to minimize emissions. Stoker systems are typically categorized into either underfeed or overfeed systems (Oland, 2002).

Underfeed Stokers

In underfeed stokers both the fuel and combustion air is supplied from beneath the grate. The fuel is moved from a hopper into a retort. As more fuel is fed into the retort the existing fuel starts to rise and then spills over to the grates located on each side of the retort. As the fuel moves over the grate it is exposed to air and radiant heat and starts to burn. In some cases it is necessary to use grates that agitate the fuel bed in order to reduce the tendency for the formation of clinker. The demand for underfeed stokers has diminished due to the cost as well as environmental considerations and they are now mainly used in small boilers burning biomass. Figure 2.4 shows the cross-section of an underfeed stoker (Oland, 2002).

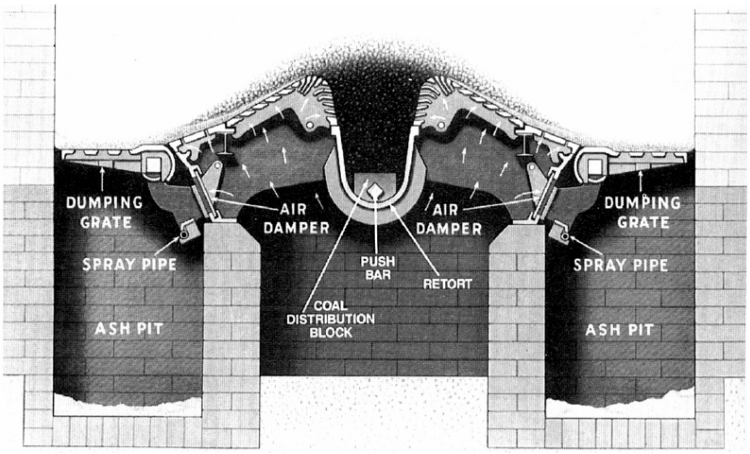

Figure 2.4: Cross-section of an underfeed stoker (Oland, 2002).

Overfeed Stokers

Overfeed stokers are generally further classified as either spreader stokers or massfeed stokers. The classification reflects the way that the fuel is distributed and burned in the boiler.

In massfeed stokers the fuel is fed continuously into the boiler at one side of the grate. A gate is used to control the amount of fuel fed into the boiler. As the fuel enters the boiler it falls by gravity onto the grate, and the speed at which the fuel moves along the grate can be adjusted. The fuel burns as it moves along the grate and as primary combustion air is fed from beneath the grate and through the burning fuel. Figure 2.5 shows a cross-section of an overfeed massfeed stoker (Oland, 2002).

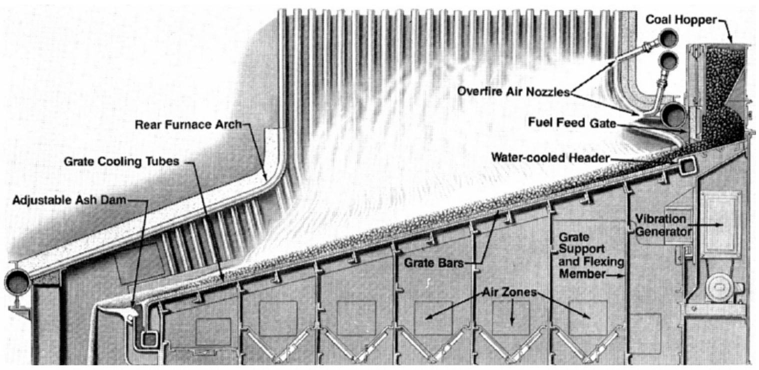

Figure 2.5: Cross-section of an overfeed massfeed stoker (Oland, 2002).

The most commonly used stokers are the spreader stokers due to their versatility. The fuel is fed into the boiler using a device that propels the fuel particles into the air above the grate. This means that the spreader can distribute the fuel evenly and to a uniform depth over the entire grate. By propelling the fuel into the air, it allows for some of the finer particles to ignite and burn in suspension while the coarser particles burn in a thin bed on the grate. Because of this suspension burning, the spreader stoker response time is better than that of the massfeed stoker. Figure 2.6 shows a cross-section of an overfeed spreader stoker (Oland, 2002).

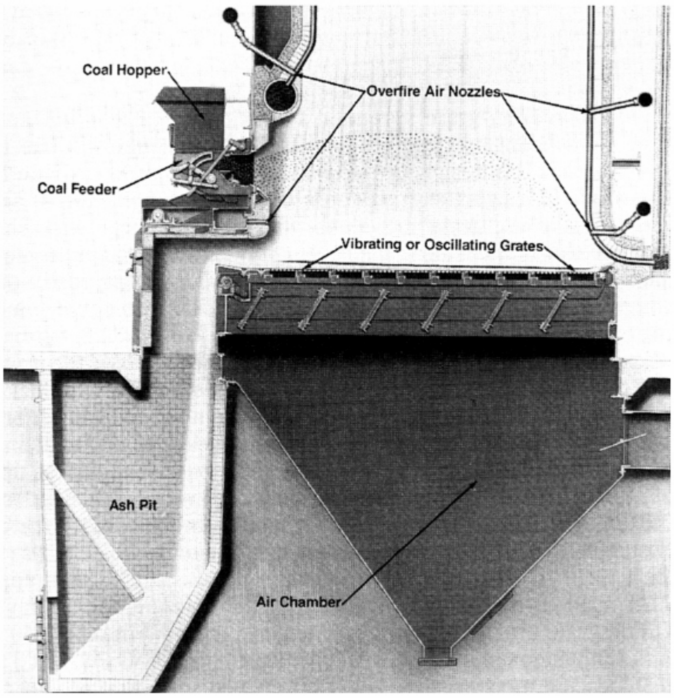

Figure 2.6: Cross-section of an overfeed spreader stoker (Oland, 2002).

2.5.2 Pulverizers

Stoker firing is extremely sensitive to fuel size, segregation and moisture content. In an effort to improve reliability, pulverized fuel firing was developed. By pulverizing solid fuels the surface area exposed to air in the combustion is increased, leading to an accelerated combustion. When a fuel has been pulverized it burns more like a gas and can therefore easily be lighted and controlled. As the fuel is pulverized, preheated air is used to dry the fuel and then carries the pulverized fuel to the burner. As the fuel enters the burner, sufficient turbulence is created by airflow so that the fuel burns in suspension. These systems are capable of rapidly adjusting for changes in boiler output demand. Pulverized fuel firing also helps to achieve minimum carbon loss and lower excess air requirements. It is, however, very costly to install, requires high efficiency fly ash collection systems as well as requiring extra power to pulverize the fuel (Elliot, 1997; Woodruff, Lammers, & Lammers, 2005).

2.5.3 Fluidized Bed

A third type of fuel handling systems for solid fuels is the fluidized bed. This technique has been rapidly developing and gaining acceptance. It is now commonly accepted as an alternative to stoker and pulverizer systems. The fluidized bed boiler originates from oil refineries and chemical plants where they were used to destroy various gaseous, liquid and solid wastes. They are capable of burning a wide range of fuels, from wet biomass to high-ash coal in addition to conventional fuels, in an environmentally acceptable manner. In a fluidized bed boiler, the fuel is mixed with an inert material, such as sand, alumina, ash or limestone, and is suspended in a combustion chamber by blowing air through the fuel bed. Fluidizing the bed provides turbulent mixing promoting complete combustion and the fluidized fuel bed behaves essentially like a fluid. In addition to improving the combustion process these characteristics allow the combustion to occur at lower temperatures, ranging from 800-900 °C instead of the normal temperatures of 1600-1900 °C. This ability is important to be able to burn low-quality fuels that are incapable of support combustion at high temperatures (Elliot, 1997; Woodruff et al., 2005).

Fluidized bed boilers can burn fuels cleanly and the lower combustion temperature results in lower emissions of nitrogen oxides. Sulfur dioxide emissions can also be controlled by introducing sulfur sorbent materials, such as limestone, to the fuel bed. This causes the SO_2 to react with the sorbent material, forming calcium sulfate which is a solid material that can be removed with the ash. By making use of this reaction a reduction of SO_2 emissions of up to 90 % can be achieved (Woodruff et al., 2005).

2.6 Boiler Efficiency

When designing a controller to improve boiler efficiency it is important to be familiar with some basic definitions. The following sections explain some of the main losses in boiler systems, efficiency definitions and what methods are used to measure the efficiency.

2.6.1 Losses in Boiler Systems

Not all energy from the fuel is converted to heat and absorbed by the boiler equipment, some of the energy is lost. The major heat losses in a boiler can be categorized into stack losses, unburned carbon losses and convection and radiation losses (CIPEC, 2001). These are only the major categories of heat loss and they will be explained in the following subsections. Other heat losses are not covered in this text and the reader should be aware that the following is not an exhaustive list.

Stack Losses

The largest energy loss in most boiler systems is the energy that is lost through the flue gases, out the stack. This heat loss occurs mainly in three ways. Some heat is lost with the moisture in the fuel and as water forms from the combustion of hydrogen in the fuel. Heat is also lost through dry gases in the stack (Woodruff et al., 2005).

The so called dry products of combustion, that is CO_2, O_2, N_2, CO and SO_2, carry a considerable amount of sensible heat up the stack. The wet products, mainly moisture from the combustion of hydrogen, carry both sensible and latent heat. The extent of the losses is mainly dependent on the temperature and volume of the stack gases. It is practically impossible to completely eliminate stack losses since that would require the stack temperature to be reduced to the ambient temperature. The losses can, however, be minimized by several techniques, such as ensuring that heat transfer surfaces in the boiler are clean and in good condition. By minimizing the amount of excess air the amount of dry gas losses can also be kept at a minimum (Woodruff et al., 2005).

Unburned Carbon

Some energy may be lost through unburned carbon due to incomplete combustion. This is often the second largest heat loss in boiler systems. In all types of boilers, combustible gases can enter the stack as a result of incomplete combustion. In stoker fired boilers the losses can be considerably higher. If the stoker is improperly controlled a large amount of unburned carbon can end up in the bottom ash (Woodruff et al., 2005).

Convection and Radiation Losses

Some of the heat from the combustion escapes from the external surface of the boiler. For a boiler at operating temperature the loss is constant. Expressed as a percentage of the boiler output, the loss increases as the output is reduced so it is at a minimum when the boiler operates at full load. The relative loss is greater for smaller boilers than larger ones. Some of this loss is unavoidable but it can be controlled to some extent by proper insulation techniques (Woodruff et al., 2005; CIPEC, 2001).

2.6.2 Efficiency Definitions

There are several efficiency definitions that are commonly used when discussing boiler systems. In some cases these definitions can differ slightly between literature sources. The efficiency definitions used in this report are therefore explained below in order to prevent any misunderstanding or confusion.

Combustion Efficiency

Combustion efficiency indicates a burner's ability to burn fuels. The combustion efficiency can be assessed by measuring the amount of unburnt fuel and excess air in the exhaust. When the fuel and oxygen are in perfect balance the combustion is said to be stoichiometric. The combustion efficiency is fuel dependent and generally, gaseous and liquid fuels burn more efficiently than solid fuels (Energy Solutions Center Inc., 2010c).

Thermal Efficiency

Thermal efficiency measures the effectiveness of the boiler's heat exchanger, i.e. the heat exchanger's ability to transfer heat from the combustion process to the water in the boiler. The thermal efficiency does not take radiation or convection losses into account and does therefore not provide a true indication of the boiler's fuel usage and should therefore not be used for the purpose of economic evaluation (Energy Solutions Center Inc., 2010c).

Fuel-to-Steam Efficiency

The fuel-to-steam efficiency is a measurement of the overall efficiency of a boiler. It accounts for the effectiveness of both the combustion process and the heat exchanger as well as the losses due to radiation and convection. The fuel-to-steam efficiency is a true indicator and is the measurement that should be used for economic evaluation (Energy Solutions Center Inc., 2010c).

2.6.3 Measuring Efficiency

The American Society of Mechanical Engineers (ASME) prescribes a standard for measuring boiler efficiency. The ASME Power Test Code, PTC 4, specifies two methods for determining efficiency: the Input-Output Method and the Heat Loss Method. The two methods are briefly described below.

Input-Output Method

As indicated by the name, this efficiency measurement method is based on the output-to-input of the boiler. The input and output, both expressed in British thermal units (BTUs), are determined through instrumentation and the resulting data is used in calculations that determine the fuel-to-steam efficiency (Energy Solutions Center Inc., 2010c).

Heat Loss Method

The Heat Balance efficiency measurement method is based on accounting for all heat losses of a boiler. The total stack, radiation and convection losses in percents are subtracted from 100 % and the resulting value is the fuel-to-steam efficiency of the boiler (Energy Solutions Center Inc., 2010c).

Chapter 3

Empirical Studies

This chapter covers techniques that are commonly used in boiler control systems. Each technique is explained with regards to what is involved, what can be measured and how these measurements can be used to improve the efficiency of the system. In addition to the control techniques, a number of techniques that improve efficiency through design changes will also be explained. After the coverage of the techniques, the aspect of measurement instruments is covered, with explanation of the functional principles of these instruments.

3.1 Combustion Control

The efficiency of a boiler system is important in several ways. The constantly rising cost of fuel used means that by increasing the efficiency by several percent, substantial savings can be made on a yearly basis. By maximizing the amount of energy extracted from the fuel, not only does the fuel usage decrease and thereby reduce cost but it also has a significant effect on the emissions from the system. Improving the efficiency of the combustion process can severely reduce the amount of harmful compounds, such as PM, in the flue gas. The following subsections discuss some of the basic control techniques that are commonly used in boiler systems (CIPEC, 2001).

3.1.1 Control Schemes

A combustion control system for a boiler combines load control, air control and fuel control in order to ensure optimum and safe operation of the overall system. This section discusses common control schemes used for controller interconnection. The next subsections will describe the individual control aspects in greater detail.

Two-Position Control

The most basic control techniques for boiler systems are so called two-position controls. The simplest form of this controller type is the on-off control, where the boiler operates at specified settings until the set-point or demand is reached and then turns off. When the output falls below a certain value the boiler starts up again. The fuel to air ratio in such systems is determined by calibration, and since the boiler is either on or off, fuel and air flow is limited to a single value. This method is used in small boilers where the cost of more efficient and precise controls is not justifiable. A slightly more advanced control is the high-low control, where the boiler operates in a high-fire condition until a set-point or demand is reached. The boiler then reverts to a low-fire mode until triggered to high-fire again (Elliot, 1997; Natural Resources Canada, 2000).

Jackshaft Control

The next stage of complexity is the jackshaft control. In systems using this control technique, a single actuator adjusts a jackshaft according to changes in the master control signal. The air and fuel control devices are then connected to this jackshaft by a series of linkages and cams, so that when the actuator moves they move with it. The fuel-to-air ratio can be adjusted by manipulating the cam valves and linkage angles. This type of system is calibrated before it goes into operation, and involves combustion tests at various settings where setscrews are adjusted to get the desired level of excess air (Elliot, 1997; Natural Resources Canada, 2000).

Jackshaft control systems generally do not include any measurement instruments, and therefore have no feedback to the control algorithm. For this reason these systems must be set up with sufficient air to ensure safe operation, which usually is more than the optimum for efficiency. Due to their simplicity and inherent safety however, they are still widely used for small boilers. In fact, no other method has proved as reliable as the mechanical linking of the single-position control (Elliot, 1997; Natural Resources Canada, 2000).

Parallel Control

Parallel control systems provide separate controllers for fuel and air, and are therefore suitable for automated control. Originally, parallel systems did not contain measurement instruments so the controllers had to be calibrated in a similar way as the jackshaft control. This control method is not recommended for boilers that burn gas or oils, because a malfunction in either the fuel or air controller would allow for unsafe operating conditions on load changes. Parallel systems can be extended with fuel and air flow rate measurements, and can with little extra cost be converted to the much more advanced cross-limiting controller which is described below (Elliot, 1997; Natural Resources Canada, 2000).

Cross-Limiting Control

The cross-limiting control system is a sophisticated system that addresses some of the shortcomings of the parallel system. Essentially, it is a parallel system that provides fuel and air flow rate measurements and separate powerful controllers for fuel and air. Theses controllers enforce a signal interlock that prevents unsafe operation on load changes. On load increase, the air control signal always leads the fuel signal, and on load decrease it lags the fuel signal, as illustrated in figure 3.1. The interlock provides a certain degree of safety, but also means that at load changes the excess air is forced to a higher level than the optimum. Because the system measures fuel and air flow rates, it is capable of correcting for some variations, for example combustion air temperature changes that can affect the excess air ratio (Elliot, 1997; Natural Resources Canada, 2000).

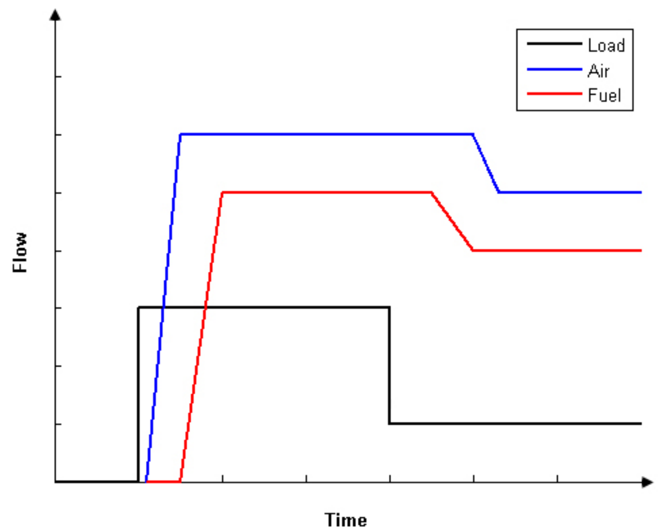

Figure 3.1: Cross-limiting of air and fuel signals.

3.1.2 Load Control

The load controller calculates the setpoints for both the air and fuel controllers. The function of the load controller may differ somewhat depending on the size and setup of the boiler system. The main characteristic that determines the load control method is whether the system is operating with steam or hot water.

Steam Systems

In systems that produce steam, the parameters that determine the load are the steam pressure and the steam flow rate. The header steam pressure, that is the pressure at the boiler, is often the master control parameter. The pressure is a direct indicator of the actual energy produced in a boiler. Some systems complement the pressure measurements with the steam flow rate to get a more accurate control signal. The flow rate of steam is used as a feed-forward signal to anticipate changing air and fuel control requirements. The measuring and monitoring of steam pressure also serves as an indication of safe operation, for example by raising alarms if pressure exceeds recommended levels in any parts of the boiler (Elliot, 1997).

To further improve the performance of steam boilers, the temperatures of inlet and outlet feedwater is measured. The information from these measurements is then used to further improve control calculations, as well as to indicate maintenance issues such as the need to clean heat transfer surfaces (Elliot, 1997).

Hot Water Systems

In systems that only produce hot water, either for heating or tap water, temperature measurements are of greater importance than pressure. By monitoring the temperature of both the inlet and outlet feedwater, the controller determines the load demand and calculates set-points for the fuel and air controllers. These systems usually strive to maintain a certain output temperature, so measuring the inlet temperature gives information on how great the load is. This target temperature can then be adjusted according to other temperatures, for example the outdoor temperature. This is usually the case in systems that provide district heating, as well as domestic heating systems (Elliot, 1997).

Using the outdoor temperature to adjust the load set-point is called outdoor reset control. This type of control has been the standard solution for many years in district heating plants, reducing operational cost because the plants can be operated at lower temperatures during warmer periods. With advances in technology this technique has become financially viable for residential boilers as well. To complement this control for residential boilers, the system can make use of indoor temperatures as well. The indoor temperature then serves as a feedback signal for the control, improving the system and reducing the operational cost even further (Energy Solutions Center Inc., 2010d).

3.1.3 Air Control

As was stated in Section 2.1, the term excess air refers to the amount of air in the combustion process that exceeds the theoretical or stoichiometric amount. In practice it is impossible to maintain effective combustion using the exact stoichiometric amount of air. This is due to several reasons, for example the fact that burners are unable to mix air and fuel completely. Each type or design of burner and furnace has a specific optimum level of excess air which often is highly dependent on the type of fuel used. Controlling the amount of excess air is one of the most effective methods for improving boiler efficiency. If the amount of excess air is not correctly controlled however, the result can be severely reduced energy efficiency. The amount of excess air is in fact such an important aspect of boiler efficiency that a generally accepted rule of thumb is that reducing excess oxygen by 1 % results in a 1 % reduction in fuel use (Turner & Doty, 2007; CIPEC, 2001).

In order to compensate for incomplete mixing of fuel and air a certain amount of excess air is needed to optimize the combustion process. If it is below a certain limit, the fuel will not burn completely resulting in elevated amount of CO and soot in the flue gases. The combustion efficiency is reduced, which means higher fuel cost and in the long term this can result in reduced thermal efficiency due to soot buildup in heat exchangers. Likewise, if the amount of excess air is too high the energy efficiency also suffers because an increased amount of energy is used to heat the flue gases, energy that is simply lost up the chimney (Turner & Doty, 2007).

When investigating the impact of controlling excess air it is important to keep in mind that the air-to-fuel ratio to be controlled is always based on mass rather than volume. This is due to the fact that the density of air and gaseous fuels change with both temperature and pressure. If not accounted for in the controller, seasonal changes in temperature and barometric pressure can cause the amount of excess air to vary significantly (CIPEC, 2001).

The excess air controls are not only aimed at reducing fuel use and increasing efficiency. There is also the safety involved by ensuring that complete combustion is achieved. When incomplete combustion was discussed in Section 2.1.3 it was briefly mentioned that it results in formation of CO. In addition to the toxic gas, incomplete combustion also results in emissions of various other unburned compounds, such as soot. If these compounds collect somewhere within the boiler, for example in complex linkages in the burner, a rise in excess air later on may have catastrophic effects. When the process no longer is starved of oxygen, these compounds may explosively combust

(Energy Solutions Center Inc., 2010c).

Staged Combustion

The most basic combustion process used in boilers is to have a single source of combustion air. In order to increase the efficiency of the combustion process as well as reducing various emissions a technique called staged combustion has been introduced and is widely used. This technique varies in complexity depending on the size of the boiler system. A staged combustion commonly used in boilers is the so called staged air technique. In systems using this technique the airflow is divided into primary air and overfire air.

The primary air is usually supplied directly to the fuel, varying slightly in point of entry depending on the type of burner and fuel. In this primary combustion zone the oxygen concentration is kept below the stoichiometric amount, common practice is to keep the concentration below 80 % of the stoichiometric amount. This sub-stoichiometric combustion causes nitrogen in the fuel to form N_2, thereby significantly reducing the formation of NO_x. It also increases the residence time and increases the temperature. Improperly controlled primary air flow rate may result in increased amounts of unburnt fuel in the flue, decreased residence time, increased amount of NO_x and other problems that have a negative impact on efficiency (Schuster & Lundborg, 2000).

In solid fuel burners, especially in those using biomass, primary air has additional functions. Since the fuel may contain moisture, the air flow is used to dry the fuel first and the sub-stoichiometric conditions cause gasification of the fuel. Section 3.2.1 covers the ways of handling moisture content in more detail. In systems using grates, mainly stokers, the primary combustion zone can be divided into three areas; drying, gasification and char burning. Figure 3.2 shows this division of the combustion zone (Ehleskog, Lundborg, Schuster, & Wrangensten, 2002).

In order to ensure complete combustion overfire air is introduced. This air is supplied above the combustion bed and depending on the size of the boiler, it may be supplied in one or more stages, referred to as secondary air, tertiary air and so on. This maintains the combustion at relatively low temperatures further reducing the formation of NO_x. The overfire air is often placed and operated in such a way that it induces turbulence, thereby increasing residence time and better mixing of air and fuel (Ehleskog et al., 2002; Oland, 2002).

In some systems, a certain amount of the flue gases is recirculated to the primary air. In such systems the combustion zone has a lower oxygen con-

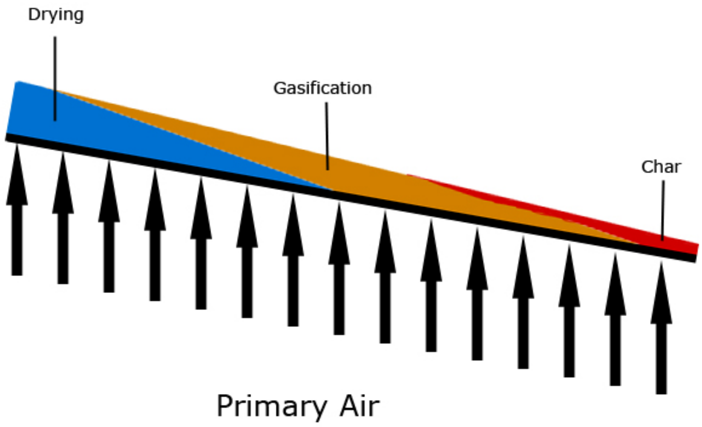

Figure 3.2: Combustion bed.

centration which can reduce peak flame temperatures. This can help to significantly reduce the formation of thermal NO_x (Oland, 2002).

Excess Air Control

As previously stated the amount of excess air is an important aspect of boiler efficiency. The idea behind excess air control is to identify the point where losses from unburnt fuel and heat losses in the flue are minimized. This point is commonly referred to as the smoke point, and since the rate of energy loss due to incomplete combustion is six times greater than that for excess air, it is preferable to operate the boiler as close to this point as possible without falling below it. In many boilers the level of excess air is set to a fixed value that is found through calibration. In such a system the amount of excess air is often set to a rather high value in order to make sure that the boiler operates within safety limits. In more sophisticated control systems the excess air level is continuously monitored and adjusted. This allows for a more conservative control and the concentration of excess oxygen in the flue gases can be reduced. This is done by measuring oxygen with sensors placed at strategic locations in the flue, and adjusting the air flow rate to achieve a certain set-point in oxygen (Turner & Doty, 2007).

For each burner, fuel and load, there exists a specific optimal oxygen concentration in the flue gas to minimize both heat losses and losses through unburnt fuel, depending on several characteristics of the system. The type of fuel plays a large part in determining the excess air needed, solid fuels usually require more excess air than liquid or gaseous fuels to mix properly. The fuel feed system can also affect the excess air requirement since some systems promote better mixing between fuel and air than others, for example atomization of liquid fuels and suspension burning of solid fuels. Lastly, given a specific fuel and burner, the optimal level of excess oxygen varies with the firing rate. The excess air requirement is usually at a minimum when the boiler is operated at full load, and increases as the firing rate is reduced (Turner & Doty, 2007; Elliot, 1997).

To improve the control of excess air even further, other compounds in the flue can be measured as well and used to make the control more precise. This can be done for example by using CO values to optimize the O_2 controller. Most control system vendors and consultants prefer to use O_2 as the primary control variable and use CO to refine the control where it is economically justifiable. Implementing O_2 based excess air controller on a system can be expected to gain up to 80-90 % increase in efficiency while the addition of CO to the controller will likely only give an additional 0.1 to 1 %. Combining the information from monitoring both CO and O_2 provides an accurate image of the firing conditions in the boiler. CO as a function of O_2 in the flue for a specific firing rate forms a curve from which the optimal operating point can be found. In Figure 3.3, an example of such a curve is shown, and the optimal amount of oxygen in the flue is just before the knee in the curve. Monitoring CO in the flue can therefore enable the controller to determine an optimal set-point for the specific conditions, and dynamically adjust this set-point independently of fuel type (Ehleskog et al., 2002; Turner & Doty, 2007).

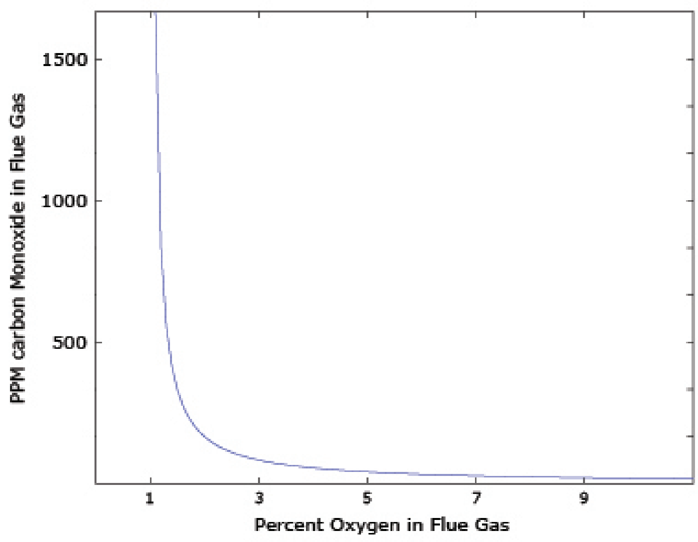

Figure 3.3: Hypothetical CO-O_2 characteristic curve.

In addition to O_2 and CO, excess air controllers may also use other parameters, such as CO_2, hydrocarbons and opacity. In solid fuel bed burners for example, the normal excess air control techniques may not suffice since the air and fuel combining mechanisms are less precise. These boilers typically use staged combustion so air is supplied as primary air and overfire air. The excess air level can be properly controlled by adjusting these air flow rates as a function of fuel feed rate. Studies indicate that CO is primarily a function of the overfire air and is virtually independent of the primary air flow rate. The CO signal is therefore used to manipulate the overfire air while the CO_2 signal is used to manipulate the primary air flow rate, aiming to maximize the CO_2 formation. The primary air control is a complex task since the optimal level of CO_2 varies with fuel energy content, its moisture content, bed distribution and flow rate. A simple control strategy is to iteratively adjust the primary air flow rate in steps, searching for a moving peak level of CO_2 (Elliot, 1997).

A variety of devices can be used to measure the CO, CO_2, O_2 as well as other compounds in the flue gases, such as lambda sensors and various spectroscopy techniques. The most commonly used instruments are described in Section 3.4.3.

Pressure Control

If a furnace is operating at a fixed temperature, pressure will change with mass flow of flue gases and fuel input rate. As high temperature gases are discharged at a level higher than the inflow air, negative pressure arises. This will cause ambient air to leak into the furnace, lowering the temperature and more energy is required to heat the extra air. In furnaces where volatile gases are present, a slightly negative pressure is required to eliminate the risk of hazardous gases leaking out (U.S. Department of Energy, 2005).

Four types of draft systems are used in furnaces; natural, induced, forced and balanced draft. Natural draft, also called the chimney effect, is when hot gases rise through the stack, creating a vacuum that draws new air into the furnace. Induced draft is when a fan draws air out from the stack while in forced draft a fan pushes air into the furnace. Combining the use of both induced and forced draft fans is called balanced draft. The airflow can be controlled by adjusting speed of draft fans or damping exiting flue gases (U.S. Department of Energy, 2005).

Measuring pressure is useful, not only for draft control but also to monitor the overall combustion process. Pressure correlates with O_2 levels and the pressure derivative with CO peaks. Measuring pressure is not sensitive to sensor placement like temperature measurements, since temperatures can differ locally. Temperature in the combustion chamber can also be used for the same purpose, since the measurements correlate, but will give a relatively local image. The challenge is to filter pressure fluctuations caused by changed operation conditions (Johansson, 2007).

3.1.4 Fuel Control

In Section 2.5, the most common methods of handling fuels were mentioned. Each fuel feed system needs specialized control signals to operate in such a way that optimum boiler performance is achieved. These controllers are usually rather simple in design, but vary slightly in complexity depending on the type of fuel.

For systems firing gaseous fuels, the main parameter is the flow rate which is controlled by valves. By measuring the flow rate through these valves the amount of energy delivered to the boiler can be very accurately controlled. Other parameters that affect the control system are, for example, pressure in the gas supply pipe. The gas is generally not stored on-site, but rather supplied through pipe networks. To ensure that the gas supplied to the burner is at the correct pressure there may be need for pressure controllers or pressure boosters to decrease or increase the pressure, respectively (Woodruff et al., 2005).

For liquid fuels the control is slightly more complex. In most cases the liquid fuel is stored in tanks on-site, and from there it is pumped to the burner. In order to achieve satisfactory operation from the burner the fuel needs to be supplied at a certain pressure. The fuel pumps must therefore be controlled in combination with valves to maintain this fuel pressure. Depending on the type of fuel used, some additional monitoring may be needed. For example when using fuel oils, the oil temperature must be controlled. Heavy oils need preheating and must be maintained at a certain temperature in order to achieve optimum performance. The temperature of all oils must be monitored to ensure that it is kept below the flash point of the particular oil used (Woodruff et al., 2005).

Because of the diverse ways in which solid fuels can be handled in burners, the controls can vary somewhat as well. The functional principles of the most common designs, that is, underfeed and overfeed stokers, pulverizers and fluidized bed were described in Section 2.5 and these are the designs that will be covered from a control standpoint.

All stokers are designed to supply a solid fuel to a grate where it is exposed to heat and air and consequently burns. The different stoker designs differ mainly in how the fuel is fed into the burner. In underfeed stokers, one or more actuators move fuel from a hopper to the retort, from where it then flows onto the grates on either side. In massfeed stokers, a gate controls the amount of fuel that can flow from the hopper onto the grate. This gate can be either hand or computer controlled. The amount and speed of fuel in spreader stokers is controlled by adjusting the speed of the distributor actuator. For all of these designs the fuel falls onto a grate where it burns as it moves along the grate. The fuel can be moved by using moving grates or vibrating grates. From a control standpoint the stoker systems can therefore be considered to have two controllable variables; amount of fuel fed into the burner and the movement of the grate. In pulverizers and fluidized bed systems the controllable parameter is the amount of fuel fed into the system (Woodruff et al., 2005).

In order to detect any irregularities in the fuel bed in stoker boilers, IR-spot meters can be installed and the signal used as a feedback to the feed actuator. Other possibilities of determining the depth of the bed and to detect irregularities include video monitoring, IR cameras and image analysis. These techniques are explained in Section 3.4.2. Measuring the flow rate of gaseous and liquid fuels is rather straightforward by means of flow meters. For solid fuels other techniques are used to measure fuel flow rate, and they are described in Section 3.4.1.

3.2 Solid Fuel Control Techniques

In addition to the techniques discussed in the previous section, other techniques have been developed to further improve efficiency. Most of these rely on the combustion control systems and can rarely operate independently. They can therefore mostly be considered to complement the combustion control and are mainly used to improve the combustion of solid fuels since that particular combustion process is somewhat more complex than that of liquid and gaseous fuels. The following sections describe the most commonly used techniques for solid fuels in practice.

3.2.1 Monitoring Fuel Moisture Content

Control based on information about moisture is relevant when using heterogeneous fuel, mainly solid fuel, such as biofuel where the moisture content may vary. The optimum setting for a boiler is affected by the amount of moisture and it is therefore of importance to collect this information to achieve a better combustion. A boiler is usually designed to operate within a certain moisture interval. If the fuel contains a higher content of moisture, changes have to be made in the primary air flow rate or preheating is required to achieve a sufficient temperature in the combustion chamber for gases to completely burn. Boilers can be manually adjusted to a certain moisture level according to given settings from the boiler supplier, usually a relation between fuel and air flow rate is then given. The relation changes with variations in moisture which makes it of interest to measure the content continuously and to change control parameters accordingly. Methods for determining moisture content are divided into direct and indirect methods, the first one analyzing the fuel before combustion and the other determining fuel content by measuring moisture in flue gases (Marklund & Schuster, 1991).

Direct Method

There are a number of methods to determine moisture content directly in the fuel. The most common and simple technique is to measure the weight of a sample, before and after drying it, and use the difference in weight to estimate the moisture content. This method has to be performed manually, involves difficulties of getting a representative sample and the time from sampling until result can be very long, usually 24 hours. This cannot be considered to be an absolute method since volatile organic compounds also vaporize and affect the weight. More practical methods are of interest, which can be adapted for automation with more continuous measurements on-line (Eriksson, Njurell, & Ehleskog, 2002).

A direct on-line method might be in favor since it would give a faster and more accurate result, and would give the possibility to control variations at an earlier stage. The chosen method of measuring moisture content and the need for fast control depends on the feeding system. For example, boilers with small portions of fuel burning at a time where the reaction therefore is fast, such as a fluidized bed, will require faster control and updates as often as each minute. The opposite would be combustion in stokers which is a slower process with longer time constants and where a mean value would be sufficient (Eriksson et al., 2002). Methods for determining fuel moisture content are described in Section 3.4.1.

Indirect Method

The indirect method is based on the assumption of a relation between moisture in fuel and moisture in flue gases. By analyzing the flue gases, moisture content in fuel can be calculated. Moisture in flue gases originates from mainly three sources; hydrogen in the fuel forming water during combustion, moisture in the fuel, and humidity in the inlet air. Measuring moisture in fuel using an indirect, rather than a direct method, is easier but introduces more uncertainties since moisture in flue gases depends on more parameters than just fuel moisture content. The indirect method enables continuous measurements and is suitable when there is no interest in fast changes since measurements are made after combustion (Marklund & Schuster, 1991). Common techniques for determining moisture content in flue gases are described in Section 3.4.3.

3.2.2 Flame Front Positioning

The motivation for flame front positioning is to achieve a more stable combustion process; less dependent on variations in fuel quality and moisture content. A more stable process would result in reduced emissions and higher efficiency. Combustion control, which is usually based on measurement parameters from flue gases, will always involve a certain time delay. This means controlling on possibly outdated measurements, affecting the process too late to give the desired effect. By studying the combustion and positioning the flame front, a quicker response is given from the control system. Another reason for monitoring during combustion is the difficulty to determine the exact origin of increased concentration of CO when measuring flue gas content (Bubholz, Myringer, & Nordgren, 2007).

On the fuel bed more than one flame front exist, commonly two. One definition is dividing the fronts into upper and lower, where the upper is the front closest to the fuel feeding. Between the fronts is the flame zone where visual flames can be seen over the grate. Below the lower flame front is the glowing zone, where no distinct flames can be seen, which then ends with the glow front (Bubholz et al., 2007). The three fronts are illustrated in figure 3.4.

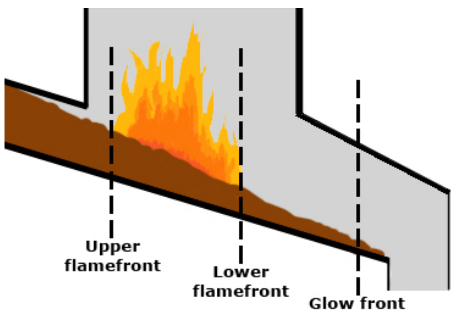

Figure 3.4: Illustration of the flame fronts and the glow front.

Which front that should be stabilized and how to develop an algorithm is not trivial. The flame front position depends on the speed at which the fuel moves along the grate. The speed should correspond to how fast fuel is combusted so complete combustion is achieved at the end of the grate to avoid unburnt fuel in the ashes. To keep an even depth of fuel along the grate it is desirable to keep the fuel feed speed and grate speed as even as possible. A thin fuel bed will mean that combustion is completed earlier along the grate and the upper flame front will be close to the feeding system. A thicker layer of fuel will move the flame front along the grate and a risk of high amounts of unburnt fuel in the ashes exists. It is therefore not possible to only change one speed when moving the flame front position (Bubholz et al., 2007).

A quick change in moisture content in the fuel will cause disturbance in the operation. In the following simple example of a possible course of events, a control system with O_2, temperature and load control is used. When wet fuel enters the grate, the temperature will drop which causes the control system to increase primary air flow rate in an attempt to increase efficiency. This will cause already dry fuel to burn faster and parts of the grate will be laid bare and therefore more new wet fuel is fed into the system. Since the wet fuel dries up slowly the temperature will drop, slowing the process down and the control system will again try to compensate by supplying more primary air causing temperature to drop even more. Wet fuel will be transported further along the grate before being ignited with the risk of insufficient time for combustion, resulting in unburnt fuel in the ashes. To avoid cooling down the system too much and causing a negative chain of reactions in case of wet fuel, a control system gradually increasing fuel feeding speed and primary air flow rate could be implemented. A dryer fuel would instead result in a flame position too close to the fuel inlet since less time is needed for drying and combustion can start earlier along the grate (Bubholz et al., 2007).

A boiler system can not be controlled solely based on flame front but it can be used as a complement to other control methods such as O_2, temperature and load (A. Persson & Helgesson, 2004). Techniques used for monitoring during combustion with respect to flame front positioning are described further in Section 3.4.2.

3.3 Other Ways of Improving Efficiency

Efficiency of boiler systems can be improved by other means than automatic control systems, such as the recovery of waste heat and blowdown control. To be able to recover waste heat some design changes as well as some investment of new equipment may be required. Blowdown control also poses some restrictions depending on system design and may also require some changes in design and equipment. Because the focus of this report is on automatic control, these techniques will only be covered in short for the reader's information.

3.3.1 Waste Heat Recovery

Waste heat refers to the heat generated in the boiler process, and is then emitted directly to the environment, becoming unavailable as useful energy. Heat that is emitted to the environment at a high enough temperature may in many cases be recovered, resulting in some form of economic gain (Turner & Doty, 2007; Thumann & Mehta, 2008).

Waste heat can be recovered using a number of techniques, and used in several ways. In boiler systems the waste heat is commonly used to preheat either the combustion air or the boiler feedwater. The heat exchangers used to recover the heat have many synonyms, but in this report gas-to-gas heat exchangers are referred to as recuperators and gas-to-liquid heat exchangers as economizers (Thumann & Mehta, 2008).

Recuperators

Various designs of recuperators exist, but they all have the same purpose, to transfer heat from the flue gases to the combustion air. As the combustion air is preheated, it carries additional energy into the combustion zone. As a consequence, less energy needs to be supplied by the fuel thereby reducing the fuel use. In addition, the reduced fuel use means that less combustion air is needed, resulting in reduced stack losses by lowering the stack temperature and reducing the amount of flue exhaust (Thumann & Mehta, 2008).

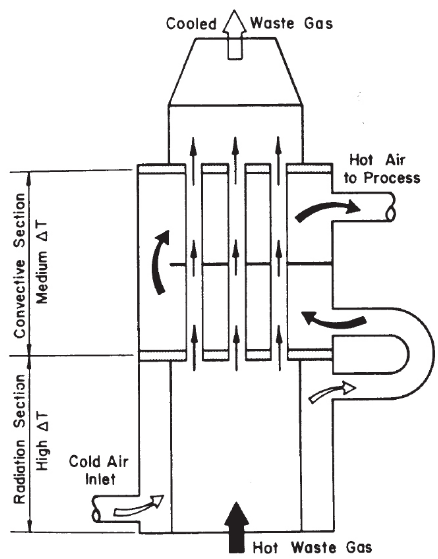

Figure 3.5: Combined radiation and convection recuperator (Turner & Doty, 2007).

The simplest design of recuperators is the metallic radiation recuperator, consisting of two concentric metal tubes. The inner tube carries the flue gases and the outer shell carries the combustion air. The name of this design comes from the fact that the majority of the heat from the exhaust gases is transferred to the metallic inner tube by means of radiative heat transfer. The heat is then transferred to the combustion air via convective heat transfer. Another common design is the tube type, or convective recuperator. In this design the flue gases are carried through a number of small diameter tubes as the combustion air is passed around the outside of the tubes one or more times. These two designs have also been combined in order to maximize the effectiveness of the heat transfer. Figure 3.5 shows a schematic of the arrangement of a combined radiation and convection recuperator (Turner & Doty, 2007).

Economizers

The most common method of preheating boiler feedwater is the use of finned-tube heat exchangers. It consists of numerous tubes with fins, welded or otherwise attached, on the outside of the tubes. The fins serve the purpose of increasing the surface area of the tubes. The feedwater is fed through these tubes as the flue gases are passed over them. These finned-tube heat exchangers are commercially available prepackaged in modular sizes and can be made from materials that are capable of withstanding the corrosive compounds in the exhaust. Figure 3.6 shows a usual setup of an economizer in a boiler system (Thumann & Mehta, 2008).

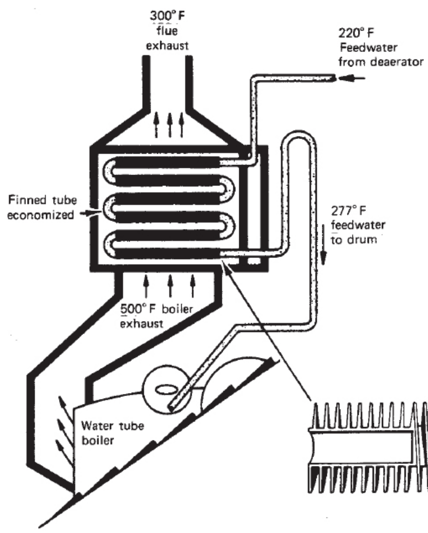

Figure 3.6: Boiler economizer (Turner & Doty, 2007).

3.3.2 Blowdown Control

Boiler blowdown control is an important function in boilers operating with steam. When water evaporates, the content of minerals and impurities in the remaining water increases in concentration. Impurities remain and accumulate inside the boiler and the increased concentration damage piping or process equipment, block valves, reduce heat transfer capability and cause corrosion and disturbances in the process. A certain amount of water in the boiler must therefore be blown down and discharged from the boiler to ensure safe levels of impurities. Blowdown leads to losses, in terms of heat, pressure and possibly boiler chemicals and should therefore be minimized (F. Persson & Ramsbäck, 1987).

A measurement of boiler contamination and an indication of how to schedule blowdown is referred to as total dissolved solids (TDS). Measurement instruments for TDS are based on determining the conductivity of the boiler water. Pure water is a poor conductor while water with high levels of TDS conducts electricity well. The electrical signal is then interpreted into concentration and parts per million. A less sophisticated method is to use a clear-sight-glass where the operator visually decides what is an acceptable level and when to perform blowdown (Energy Solutions Center Inc., 2010a).

Boiler water can be discharged periodically or continuously. All systems are designed for periodical blowdown where water is taken from the bottom of the boiler to remove sludge and settled particles. In continuous blowdown systems, water is discharged from the surface at a certain rate, manually or automatically determined. Manual blowdown, where an operator sets the blowdown valves and the water flow to a certain rate, is practicable with only small changes in water quality and steam demand. In automatic blowdown systems, TDS is monitored by conductivity and the blowdown rate is adjusted to stay close to maximum allowable TDS levels and thereby minimize the amount of hot boiler water discharged from the system (Energy Solutions Center Inc., 2010a).

Water discharged by blowdown has a high temperature and must be cooled down, often by diluting it with cold water, before discharged into the sewer system. A blowdown heat recovery system, where blowdown water is used to preheat incoming water reduce the amount of energy lost and shorten payback time by recovering some of the thermal energy. If blowdown is performed periodically and no storage tank for blowdown water exists, it might be difficult to preserve heat since large amounts of water is discharged in a short period of time. Systems for waste heat recovery are described in more detail in Section 3.3.1 (Energy Solutions Center Inc., 2010b).

3.4 Measurement Technology

In this section some methods for measuring and monitoring the combustion process are shortly described. A division is made into methods used before, during and after combustion, i.e. monitoring fuel, combustion chamber and flue gases.

3.4.1 Fuel Monitoring

Methods for fuel monitoring differ in many aspects such as penetration depth, sensitivity to surface characteristics and dependency on fuel flow rate. When monitoring solid fuel it is of importance to find a contact free method not disturbing the flow rate of fuel. In the following sections only techniques used in commercially available products for fuel monitoring will be described, while other untested methods exist.

Near Infrared Spectroscopy

Near infrared spectroscopy (NIR) is a technique using the near infrared electromagnetic spectrum. The near infrared spectrum is between the visible light and the infrared, i.e. between 850 nm and 2500 nm. The fuel sample is radiated by at least two different wavelengths, one for measuring and one for reference. The measurement wavelength is chosen to be absorbed by water but to reflect against the fuel while the reference is chosen to reflect against both water and fuel, i.e. 100 % reflection. The ratio between the reflected beams is then inversely proportional to moisture content. This technique can be used to measure other contents by choosing other wavelenghts. The NIR method is fast and independent of feeding rate which makes it suitable for on-line control. The penetration depth is limited to about 5 mm, which makes the technique sensitive to surface moisture. Color, surface structure and external lightsources might also have a negative effect on the result. Higher frequency will give higher resolution (Eriksson et al., 2002).

Microwave Technology

As microwaves are sent through a material, water molecules will start to move causing reduction in intensity and a phase delay. This can be interpreted and translated into moisture content when detected on the opposite side of the fuel. Variation in fuel composition will cause problems and is a source of error. Therefore measuring coal rather than biofuel, which is a more heterogeneous fuel, will give higher accuracy. The result from using microwaves can be improved by increasing the range of wavelengths. To determine moisture content the bulk density will also have to be measured, which can be done by using radiometry. In radiometry gamma rays are radiated through the material and the decrease in intensity is a measurement of density (Eriksson et al., 2002).

Neutron Technology

Methods based on neutron technology make use of the fact that hydrogen atoms reduce the speed of neutrons more effectively than other atoms. By radiating material with neutrons and measuring the neutron concentration with a detector, which only reacts on slower neutrons, on the opposite side, the fuel moisture content can be calculated if the bulk density is known. In combination with neutron technology, gamma rays may be used to determine the bulk density as previously discussed. One problem with the method is the inability to distinguish between hydrogen in water and hydrogen chemically bound in the material, which means that the hydrogen content of the fuel has to be known (Eriksson et al., 2002).

3.4.2 Combustion Monitoring

Difficulties for monitoring within the combustion chamber are associated with the rough environment including high temperatures, thermal radiation, soot and particles. Equipment must have fireproof protective glass, be cooled with water or air and in some cases be self cleaning when optics and sensors get blocked.

Ultrasonic Sensors

The frequency spectrum of sound waves is generally divided into three ranges; frequencies below 20 Hz are catergorized infrasound, the audible sound ranges from 20 Hz to 20 kHz, and finally the ultrasonic sound waves have frequencies above 20 kHz. Ultrasonic waves are used for a vast number of applications, including medical instruments, welding, flaw detection in materials and range finding (Rodin, Jacoby, & Blom, 2003).

In boilers, ultrasonic sensors can be used to monitor the fuel bed thickness on the grate. This can serve as a feedback measurement to the fuel controller to verify if the correct amount of fuel enters the burner, as well as detecting any irregularities in the fuel bed. The ultrasonic range measurement is done by emitting a sound signal and then measuring the time it takes for the signal to echo back. The speed of the sound signal depends on the transmission medium, in this case the combustion air, and the temperature. In order for the ultrasonic measurements to be usable the temperature in the combustion chamber must therefore be monitored as well. Since the combustion chamber may contain some amount of airborne particles they may cause disturbances in the measurements. Lower frequency signals are better suited for such an environment than higher frequencies (Rodin et al., 2003).

Camera and Video Monitoring

Using cameras and videos is one common method for monitoring during the combustion and gives useful information about the process for operators to manually make adjustments. Commonly used applications are monitoring flame front position and fuel depth as well as detecting if some part of the grate is laid bare. The camera placement is of importance and it is desirable to detect as much of the grate as possible. Infrared (IR) based cameras can also be used for this purpose but are usually more expensive than ordinary cameras. Visual supervision by operators will also be lost by using IR-cameras (Bubholz et al., 2007).

Image Analysis

With a simple camera and image analysis software it is possible to obtain information about the combustion process which can be used in a control system to regulate air flow and fuel feed rates. There are no high demands on image resolution, instead low resolution is preferable since noise from sparks can be avoided. High resolution will also result in large image sizes prolonging the processing time needed. Image analysis can be implemented for any burner, independent of size and fuel type used (A. Persson & Helgesson, 2004).

An image analysis algorithm could include the following steps (see also Figure 3.7) to automatically detect the flame front position along the grate. An image is sampled and converted into grayscale where each pixel has a value between 0 (black) and 255 (white). The grayscale image is then converted into a binary image where all pixels above a certain value are assigned the value 1 and all pixels below are assigned 0, resulting in a binary image where flames are white and the rest of the picture is black. The flame front can be defined in different ways. One way is to introduce a coordinate system and find the widest area of ones and then moving line by line until only 20 % of the ones are left (A. Persson & Helgesson, 2004).

Infrared Camera

An infrared camera detects thermal radiation from the combustion process and gives information of different temperatures along the grate, thereby information on where the flame is placed. IR-cameras are sensitive to disturbances such as thermal radiation from particles and combustion of gases within the chamber. The results from IR will not be disturbed by soot and particles physically blocking the view, which is a problem when using regular cameras (Bubholz et al., 2007).

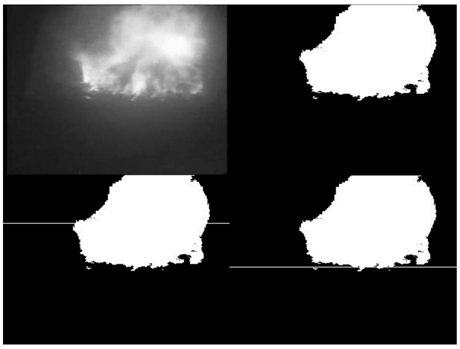

Figure 3.7: Image analysis of flame front position (A. Persson & Helgesson, 2004).

Since IR-cameras are more expensive, it could be desirable to only monitor parts of the grate. Depending on what resolution is needed it is possible to use IR-pyrometers which have a range of vision of a few degrees and return a mean temperature. Another reason for using several IR-pyrometers instead of one camera is the difficulty, due to lack of space, to position the camera for a good view over the entire grate. Disturbances from hot ashes can be reduced by controlling a filtered value based on previous measurements (Rudling, 1999).

3.4.3 Flue Gas Monitoring

Measuring moisture content in flue gases puts high demands on sensors and instruments with respect to accuracy and repeatability. In addition to the high temperature, which is an obvious limiting factor, particles and the highly corrosive environment affect the choice of sensors. Flue gases can contain large amounts of soot and particles, sometimes glowing, which can block and destroy filters and lenses.

Lambda Sensor

The lambda sensor, also know simply as oxygen sensor, was originally developed by Robert Bosch GmbH in 1967. It has since then evolved considerably and is standard in all gasoline engine vehicles to improve efficiency and reduce emissions. In recent years the lambda sensor has also been used in diesel engine vehicles for more precise metering of injection volumes and to lower emissions. The sensor has mainly been used in the automotive industry, but can easily be used to control other combustion processes. Because of how widely used the lambda sensors are, there exists extensive knowledge on their function and behavior. They are also mass produced making them relatively cheap and easy to come by. Because of the low price they can be considered a viable solution for all sizes of boiler systems (Robert Bosch

GmbH, 2010; Svensson, 2003).

The name of the sensor comes from the parameter name λ which describes the relationship between the actual fuel-to-air mass ratio and the stoichiometric fuel-to-air mass ratio, given by Equation 3.1.

$$\lambda = \frac{(m_{\text{air}}/m_{\text{fuel}})_{\text{in mixture}}}{(m_{\text{air}}/m_{\text{fuel}})_{\text{stoichiometric}}} \tag{3.1}$$

As can be seen from this equation a value of $\lambda < 1$ means that there is an excess of fuel, and the mixture is then termed rich. Likewise, a value of $\lambda > 1$ means an excess of air, termed a lean mixture (Lampe, Fleischer, & Meixner, 1994).

A number of experiments have been done to determine the usability of lambda sensors to monitor and control the combustion process, most with positive results. One of the main problems is that due to their small size it may be difficult to get a representative sample since the oxygen concentration may vary along the area of the burner. The solution to this problem is to place the sensors further downstream of the combustion where the flue gases are more completely mixed. This, however, may cause a new problem, since this increases the delay in the control signal and may cause problems in the controller. The position of the sensors is therefore very important when used in boiler system control (Svensson, 2003).

Spectroscopy

Spectroscopy is a study of matter and its properties by the use of electromagnetic spectra. When a chemical is heated so that light is emitted, it yields a specific series of lines in a spectrum. These lines can be used to gather information about the chemical by determining where in the spectrum they are and what patterns they form. Spectroscopy technique is used in applications within many areas, such as chemistry, astronomy, biology and physics, and can be performed using frequencies ranging from microwaves to X-rays. For each frequency interval a specific technique is used to obtain the information needed, like the NIR technique explained in Section 3.4.1. Examples of other common types of spectroscopy are Mössbauer, Raman and Fourier Transform Infrared Spectroscopy (Nationalencyklopedin, 2010).

The advantage of using spectroscopy techniques rather than the more simple method of lambda sensors is that many of the spectroscopy techniques allow for measurements to be made in situ, meaning that the measurements are made in the combustion chamber itself. This greatly reduces or even eliminates the troublesome time delay affecting the lambda sensor control systems. Instruments to perform spectroscopy measurements are very expensive and therefor only a viable option in large scale boilers, where the investment cost of such a control system has a shorter payback time (Nationalencyklopedin, 2010; Fleckl, Jäger, & Obernberger, 2010).

Chapter 4

Case Studies

In order to establish what techniques are generally used in practice for boiler control, several case studies are performed. This chapter details these case studies, where each case includes a short summary about the company in question as well as a description of the system. The main focus of these cases is on the control system itself, what techniques are used, what control parameters are relevant and what instruments are used to acquire relevant data.

4.1 Sysav

Sysav is owned by 14 municipalities in the south of Skåne, and recycles and treats domestic waste as well as combustible waste from businesses and recycling centers. Today more than 96 % of all waste collected is recycled in forms of materials and energy which means that only a small part is sent to landfills. The Sysav plant in Malmö is the most energy efficient waste-to-energy plant in Sweden, producing electricity and hot water for the district heating network, and delivers 60 % of all district heating to customers in Malmö and Burlöv. Sysav is constantly striving for better, environmentally friendly solutions by developing technologically advanced and creative solutions to deal with waste in the most sustainable way (Sysav, 2010c).

The waste-to-energy plant in Malmö consists of four boilers where the two oldest are hot water boilers which came into operation in 1973 producing district heating with a capacity of 100,000 tonnes of waste per year. The other boilers operate with steam and were taken into operation in 2003 and 2008, both producing electricity and district heating with twice the capacity. The boilers are also equipped with oil burners for auxiliary combustion used during start-up, shut-down and when the waste energy level is not high enough to keep the correct combustion temperature. According to regulations combustion of waste must take place above 850 °C. The plant produces

Figure 4.1: The Sysav waste-to-energy plant (Offesson, 2010).

approximately 1,400,000 MWh of district heating per year and 250,000 MWh of electricity. The newest boiler, Boiler 4, was chosen for this case study and is described more in detail in the following sections (Sysav, 2010a).

4.1.1 The Installation

During a day shift 300 lorries and trucks arrive at Sysav, dumping waste into the waste bunker which can contain up to 12,000 m^3 of waste. The waste is manually fed into the boiler via a travelling crane during daytime and is handled automatically during nighttime. To avoid clogging, waste is placed on the edge of the feed chute, allowing the waste to slide down and is then pushed onto the grate and into the combustion chamber via a pusher. When not feeding the boiler, the traveling crane is mixing the waste to get an as uniform energy value as possible to achieve a more even combustion process. An overview of Boiler 4 is shown in Figure 4.2 (Sysav, 2010a).

The 100 m^2 grate is divided into five individually controllable grate paths, along the grate direction, and consists of both static and movable parts. The motion of the grate is directed upwards, against the natural direction of the waste due to gravity. In this way already burning material is fed back and placed under new fuel, causing continuous mixing of the fuel bed. The principle is shown in Figure 4.3.

The grate is also divided into five zones where the first zone is the drying

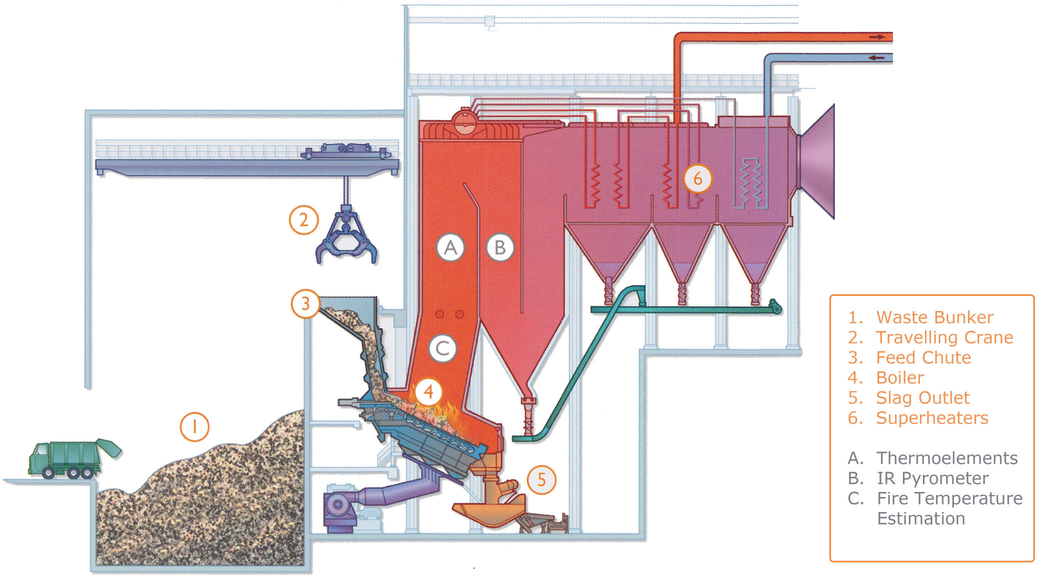

Figure 4.2: Illustration of Boiler 4 at Sysav (Sysav, 2010a)

zone, in zone 2 the combustion is the most intense. Waste is further combusted in zone 3 and 4 while in zone 5 the waste is completely combusted with only slag remaining. The slag consists of scrap metal, glass, stone and other noncombustible substances which are then submerged in water for cooling. The water also plays another part which is to prevent hot combustion gases from leaking out of the furnace. Primary air is provided from under the grate (underfire air), and secondary air containing recirculated flue gases is added above the combustion bed (overfire air) (Sysav, 2010b; MARTIN GmbH, 2008a).

Flue gas fans make sure that a slight negative pressure is kept in the furnace to avoid leakage of hazardous flue gases. Flue gases formed during the combustion process are passed through three vertical ducts, transferring heat to tubes filled with circulating water. In the three superheaters, the steam reaches a temperature of 400 °C and a pressure of 40 bar. The steam is directed to a turbine driving a generator to produce some of the electricity produced in the plant. After passing the turbine the steam is directed to a condenser where district heating water is heated. Large parts of the plant are for cleaning flue gases in several stages. This part of the system falls outside the scope of the report and will therefore not be covered (Sysav, 2010a).

4.1.2 The Control System

The control system can be divided into several subsystems regulating fuel feed rate, grate speed and air flow rates. In the following sections the different subsystems will be described. First, some of the monitoring parameters and sensor placements are mentioned.

A parameter on which grate speed can be regulated on is free surfaces which is determined by an equation based on parameters like damper positions, primary air flow rate and pressure. Free surface is interpreted as the fuel bed layer thickness where a high value corresponds to a thin layer and a low value corresponds to a thick layer. The parameter is used in fuel bed layer resistance control, further described later in this chapter (J. Billberg, personal communication, October 15, 2010).

Temperatures are measured in the flue gases in different places of the furnace and boiler passes for flue gas, shown in Figure 4.2. Thermo elements are placed in the first boiler pass while IR pyrometers are placed in the second boiler pass measuring radiation temperature from the flue gases. Due to high flow rate through the furnace, the measured temperatures can be considered to be without any delay. The temperature above the grate is estimated from these values and must always be greater than 850 °C according to EU regulations associated with combustion of waste. In case of a temperature drop the auxiliary oil burners are taken into operation. The grate is monitored visually by cameras directed upwards from the end of the grate to see the flame position (J. Billberg, personal communication, October 15, 2010).

The process is controlled by measuring O_2 in the flue gases beyond the superheaters. Again, due to a high flow of flue gases this value is considered to be instantaneous. The value is fed back and used to regulate primary air flow rate which is further described later in this section. A more complete flue gas analysis is performed after the processes of flue gas cleaning, just before being discharged through the stack into the atmosphere. These emission values are used for environmental reports (J. Billberg, personal communication, October 15, 2010).

Fuel control

The goal of fuel control is to keep the thermal output as constant as possible by regulating fuel supply and grate movement. Fuel control can be regulated in three different modes; furnace temperature, steam flow rate or steam flow rate combined with IR pyrometer temperature. In normal load operation, control regulations are made on steam flow rate and IR pyrometer temperature while the other two modes are used during start-up, shut-down and special operating situations like in case of a clogged feed chute. The feeder reacts on changes in the load set-point by changing the feeder cycle frequency (MARTIN GmbH, 2008a).

Feed speed and stroke length control

Waste is continuously fed into the furnace by a pusher as shown in Figure 4.3. To achieve maximum efficiency the pusher piston should be fed with as many strikes as possible per time unit, which means that the furnace will be fed with a large number of small portions of waste. The length of each stroke and the speed is automatically determined by the control system. Well optimized parameters adapt to the desired load and compensate for variations of the waste quality (MARTIN GmbH, 2008b).

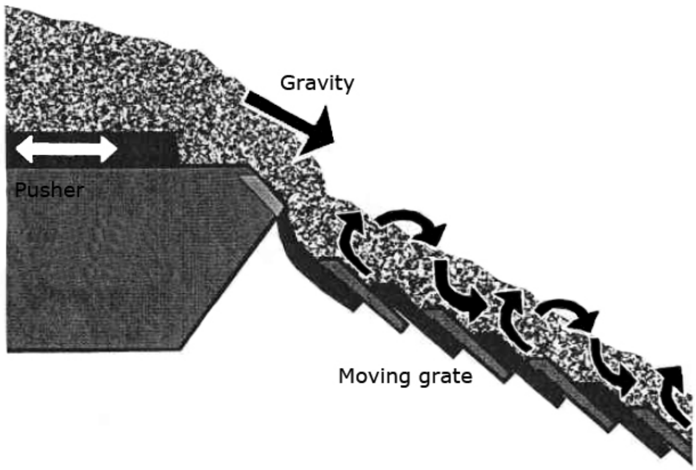

Figure 4.3: Principle of grate movement (MARTIN GmbH, 2008b).

Underfire air control

The primary air fans make sure that the set-point of 42 mbar is kept before the air flow is divided between the zones. Dampers regulate the air flow rate and can be controlled independently. The position of the dampers is adjusted as a function of the oxygen content of the flue gases, continuously measured at the boiler outlet, and from the set-point value. The primary air is preheated to approximately 90 °C but the temperature can be raised in case of extra moist fuel (J. Billberg, personal communication, October 15, 2010).

For safety reasons O_2 levels below 6 % are not permitted. If the O_2 value drops, the primary air dampers open to increase the flow rate. Fluctuating values are an indication of a poorly tuned combustion. For operators, the O_2 measurements together with the visual information constitute the most important information on how to optimize the combustion. To retrieve correct measurement values the measurement equipment must work continuously and be properly maintained and calibrated (MARTIN GmbH, 2008b).

Overfire air control

Secondary air, or overfire air, is important for the flames to mix well and gases to oxidize completely. The air is supplied through nozzles placed in the furnace walls above the fuel bed, the flow rate is then changed by adjusting the pressure. The control variable for secondary air is steam demand and is automatically controlled as a function of this, i.e. the overfire air flow rate is varied in proportion to the boiler load. To set the correct values for overfire air supply the combustion must be studied according to a few points. The visual flames may never reach higher than the ceramic protective coating, flue gases above the flames must be clear and transparent and CO values in the flue gases should be kept as low as possible. The set-points for the overfire air flow rate can be changed by the operator in case of varying waste composition, varying the pressure within certain limits (MARTIN GmbH, 2008a, 2008b).

Fuel bed layer resistance control

Fuel bed layer resistance control is intended to regulate the grate and feeder speed with the intention to keep the permeability for the underfire air, i.e. the fuel bed resistance, as constant as possible, independent of load and fuel. This control minimizes the influence of varying fuel quality and boiler load. A common control method though, is to ignore fuel bed resistance and run at constant grate speed (J. Billberg, personal communication, October 15, 2010).

4.2 Öresundsverket

Öresundsverket was originally built in three stages in the years 1953-1963, and was finally inaugurated in 1965. This was the largest power plant in Sweden at that time with a production capacity for 400 MW of electricity and 250 MW of heat, using coal and oil as fuel. In 1993, the plant was taken out of operation, and the chimneys where torn down in 1998. The plant itself was retained in a conserved state, and in 1999 the layout studies were started to determine how to build a new power plant in the old buildings (E.ON, 2009).

The new power plant was taken into operation in the autumn of 2009, and is once again the largest power plant in Sweden of its type. The power plant uses natural gas, and like the old plant it is capable of producing 400 MW of electricity and 250 MW of heat. At full capacity the plant can supply 70 % of the residential electricity needs in the Skåne province, and account for 40 % of the total district heating requirements in Malmö. The power plant is managed and maintained by E.ON (E.ON, 2009).

4.2.1 The Installation

The Öresundsverket power plant differs somewhat from the normal boiler power plants. Instead of an actual furnace the plant uses a gas turbine. This turbine has a production capacity of 290 MW of electricity, and since the exhaust gases from the turbine are extremely hot, the heat is used to produce steam. The turbine weighs 330 tons, is 12 meters long and has a diameter of five meters. The turbine is powered with 18 natural gas burner modules, that are supplied with combustion air at a pressure of 18 bar (M. Blåfält, personal communication, Oktober 21, 2010).

The steam produced is used to power a steam turbine with a production capacity of 150 MW. The turbine is a so called 3-pressure turbine, meaning that steam at three different pressure levels are fed to it. High pressure steam is produced at 565 °C and 138 bar, middle pressure at 565 °C and 24 bar, and finally low pressure steam at 345 °C and 5 bar. The last step, the low pressure steam, can be by-passed in the turbine and used for district water heating instead. This results in a reduction in electricity production of 50 MW in exchange for a production of 250 MW of heat. When there is no need for district heating, for example during summer time, the plant produces only electricity, and sea water is used to cool the steam from the turbine (M. Blåfält, personal communication, October 21, 2010).

The system has relatively low CO emissions, partly due to a high oxygen concentration in the combustion air. The CO emissions may increase slightly when operating at part load, and can become significant during start-up and shut-down of the turbine. The NO_x emissions are very low, and are more or less constant at 25 ppm. When the power plant operates in co-production, i.e. producing both electricity and heat, the exhaust gases are at approximately 71 °C while they are approximately 81 °C when only producing electricity. The overall efficiency of the power plant is 58 % when it produces only electricity, but when it also provides district heating the efficiency amounts to 89 % (M. Blåfält, personal communication, October 21, 2010). Figure 4.4 illustrates the operation of the Öresundsverket power plant.

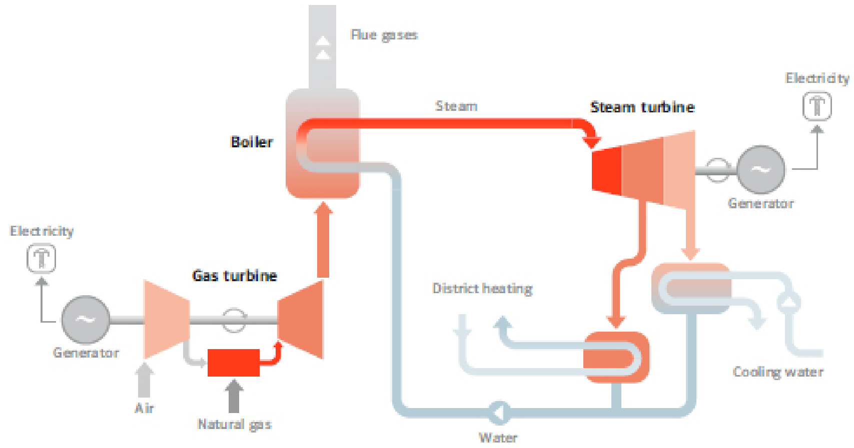

Figure 4.4: The principal operation of the Öresundsverket power plant (E.ON, 2010).

4.2.2 The Control System

Since the system is somewhat different from a regular boiler system, the control system is also slightly different. The principles of combustion always remain the same so that will be the main focus in this case. Instead of using the flue gases to preheat the combustion air, which is often done in burners, a certain amount of steam is used to heat the natural gas to a temperature of 200 °C. This is done to elevate the energy content of the gas. The combustion air, however, is kept as cold as possible and is fed into the turbine by means of a fan that operates at a constant 3000 RPM (M. Blåfält, personal communication, October 21, 2010).

The control of the combustion process is rather simple compared to for example the Sysav power plant control discussed in Section 4.1. The controlling parameter is the exhaust temperature from the turbine, with a set-point in the interval of 630-650 °C. The controller then regulates the gas flow rate with a valve accordingly, while the air flow rate is simply choked using dampers. From the temperature of the exhaust, the controller can calculate other parameters such as pressure. Various components are measured in the flue gases, such as O_2, CO, NO_x and CO_2, but those are only used to ensure that the emission regulations are fulfilled. The turbine operates at a relatively high amount of excess air, with an average of 11-12 % concentration of O_2 (M. Blåfält, personal communication, October 21, 2010).

The second half of the power plant, the steam turbine, generally has little or no impact on the controller. An exception is when the steam turbine is started up, since the turbine must be slowly heated and the gas turbine must therefore reduce the output to match the demand of the steam turbine (M. Blåfält, personal communication, October 21, 2010).

4.3 Nosabyskolan

Nosabyskolan is a school for about 400 students located in the northeastern part of Kristianstad. The municipality of Kristianstad has for the past years chosen to actively work for a reduced oil dependency. One step has been to exchange the fuel used in the oil fired boilers in the buildings managed by the municipality where district heating is not available. So far, 43 boilers using wood pellets as fuel and one boiler burning straw have been installed. About half of them are old redesigned boilers, previously burning oil or coke, where the burners have been exchanged to adapt to the new fuel. This development has meant more manual work but reduced the oil consumption, from 2000-3000 m^3 oil to 300 m^3 per year, meaning reduced emissions and cost (S. Branting, personal communication, October 28, 2010).

Heating at Nosabyskolan is provided by one oil burner and two pellet burners, where the oil burner is intended for support in case of failure or extra heat demand (S. Branting, personal communication, October 28, 2010). In the following sections the pellet burners used at Nosabyskolan, EcoTec and Hotab, and their functions will be described shortly.

4.3.1 The Installation

Generally, smaller boilers demand supervision and inspections more frequently than larger boilers to maintain an efficient combustion. They are more sensitive to variations in fuel quality and have an increased tendency for clogging with soot, which results in poor combustion. The boilers in Kristianstad are swept and decarbonized every eight weeks during the cold season. Twice every year flue gas measurements are performed manually, tuning the boiler parameters to maintain the efficiency demands of 90 %, set by the municipality (H. Nilsson, personal communication, October 28, 2010).

EcoTec

The EcoTec burner is fitted on a cast iron boiler using pellets as fuel, delivering up to 250 kW of heat. Pellets are fed via a screw onto an underfed rotating burner dish. Air is provided as primary, secondary and tertiary air. Primary air is supplied from under the fuel and secondary as overfire air, also with the function of blowing away ashes from the burner dish. Tertiary air is supplied further above the fire providing extra air and also helping to remove ashes. The burner then requires manual ash removal and is regularly vacuumed (H. Nilsson, personal communication, October 28, 2010). A sketch of the EcoTec burner system is shown in Figure 4.5.

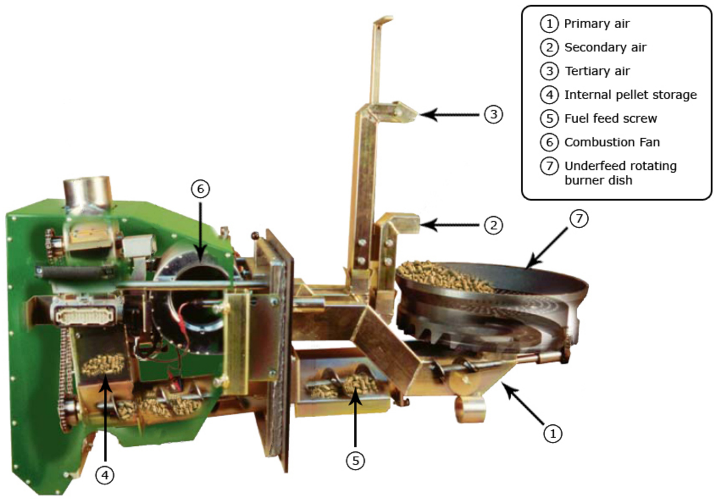

Figure 4.5: Illustration of EcoTec boiler (Sahlins EcoTec AB, 2008).

The fuel-to-air ratio is manually set and adjusted. In case of reduced effect, the fuel feed speed is reduced to ensure sufficient time for complete combustion (H. Nilsson, personal communication, October 28, 2010).

Hotab

The Hotab burner is fitted on a three-pass firetube boiler, delivering up to 250 kW of heat. A stoker screw feeds the system with pellets placing the fuel on a bed. Air is provided as primary air from under the bed and secondary air from nozzles on the sides of the burner chamber. Ash is automatically removed by a stoker rake passing after a set time interval. Additional ash removal is required manually (H. Nilsson, personal communication, October 28, 2010).

4.3.2 The Control System

The control systems for the two boilers at Nosabyskolan differ somewhat. While the EcoTec system keeps a manually set ratio between fuel and air supply the Hotab system is regulated on the O_2 value. Both burners require manual start-up, by adding charcoal lighter fluid and igniting the pellets.

Alarms from both systems are read and supervised centrally but all adjustments must be done manually on-site. More parameters such as momentary effect could also be interesting to supervise and monitor centrally (H. Nilsson, personal communication, October 28, 2010).

EcoTec

The EcoTec system has three warning systems to prevent backfire. The feeder system portions fuel into the boiler and also physically separates the internal pellets supply and the burning pellets. In case of backfire a thermo element will terminate fuel feed. The burner is also equipped with a fire extinguisher which is required for burners over a certain effect (H. Nilsson, personal communication, October 28, 2010).

An optoguard is installed to ensure the presence of flames in the combustion chamber. If that is not the case and no flames are detected the control system will shut down fuel feed to avoid more pellets to be fed into the system. The optical light needs to be cleaned manually every fortnight (H. Nilsson, personal communication, October 28, 2010).

Hotab

The level of primary air is decided from the amount of fuel loaded and will be a set value. Pressure output from the fans is not linear which means that primary air levels are tuned manually to suitable levels to keep a good combustion process. Secondary air fans are regulated based on O_2 levels in the flue gases after combustion with a set-point value of 10 % O_2. The set-point for O_2 is about 10 %. If the level drops below a set value, the stoker screw will stop and no more fuel will be fed into the burner until the O_2 level rises again. Each time the ash rake passes over the fuel bed, the O_2 value will increase. Therefore, at each rake the fans will compensate for this. A pressure sensor controls the flue gas fan, ensuring a slight negative pressure within the combustion chamber. Stoker screw, primary-, secondary- and flue gas fans are each connected to frequency converters (H. Nilsson, personal communication, October 28, 2010).

4.4 Staffanstorp Värmeverk

The district heating plant in Staffanstorp provides 500 customers with district heating within Staffanstorp. Most of the customers are private houses, but also some commercial properties and multi dwelling houses. The plant consists of a 5 MW boiler using wood chips as fuel installed in the year 2000, and three auxiliary boilers burning natural gas, delivering a total of 26,000 MWh per year. The wood chips are byproducts from sawmills and must contain a certain amount of moisture since flue gas condensers are used to extract thermal energy (R. Assarsson, personal communication, November 1, 2010).

4.4.1 The Installation

Wood chips are kept in containers in an adjacent room. A traveling crane feeds the boiler and blends fuel between the containers to receive a more homogeneous fuel mixture. The fuel is then fed onto the grate by a feeding screw. The grate is stair shaped with a total area of 6 m^2, containing four movable stairs moving back and forth which will cause the fuel to fall from one stair down to the next. A stair shaped grate will give a more even load than a flat grate. Flue gas fans keep a slight negative pressure in the burner (R. Assarsson, personal communication, November 1, 2010).

4.4.2 The Control System

The load demand is determined by the outdoor temperature and follows a certain curve. The combustion control is based on O_2 control with excess air set-point around 2.5 %. To keep the correct O_2 level, secondary air fans are adjusted, and if that is not sufficient, primary air fans are also adjusted. In case of high CO levels, O_2 is regulated according to set-points following a curve. If the O_2 levels drop, the system has three minutes to adjust or the fuel feeding system shuts down (R. Assarsson, personal communication, November 1, 2010).

Flames are detected by measuring the temperature. Many parts of the control system are built on conditional rules, for example if flames are not detected, the primary air flow rate is changed. The plant in Staffanstorp is supervised and managed remotely at Öresundsverket and requires only a daily inspection on-site. Start-up must also be performed on-site (R. Assarsson, personal communication, November 1, 2010).

Chapter 5

Implementation

This chapter explains the implementation process of a control system on a Regin controller platform. The steps taken towards a testable system are described in detail, beginning with an explanation of the methodology used for the implementation. The boiler system that is to be controlled is then described with details on what parameters are usable and what alarms should be included. The implementation phase is then discussed, with a description of the platform used as well as information on the simulation environment and the design of the control system. Finally the system is tested and results from that testing are presented.

5.1 Methodology

The goal of this phase of the report is to implement a so called proof of concept solution. The concept to be proven is that the existing platform from Regin, described in Section 5.3.1, is sufficient to be able to control a small or medium scale boiler system, i.e. to determine if the controller platform has enough inputs and outputs for the control system. The reason for the limitation of the boiler system to small or medium scale is due to the limited time frame of the report as well as the fact that a large scale controller requires a significantly larger number of inputs and outputs.

In order to implement this proof of concept solution, a system must first be specified. The boiler system to be controlled is described in Section 5.2, including both hardware setup as well as controllable parameters and security aspects. Once the system has been specified, the actual controller can be implemented.

The controller implementation starts with an introduction to the platform that is used, and the simulation environment used for testing purposes. From the controllable parameters defined in the boiler system, the controller loops are then designed, explained and finally programmed on the platform. Once the controller has been implemented, the simulation environment is used to perform some tests, and the results from the testing phase are discussed.

5.2 The Boiler System

Since no actual system can be used for this purpose, a simulation is used instead. The following sections will describe the system that is to be simulated in detail.

5.2.1 System Description

The system to be used in this controller implementation is chosen to be a solid fuel watertube boiler, that is used to produce steam. A cross-section of the boiler system is shown in Figure 5.1. The numbers in the figure mark some of the main components of the system:

1. Primary fan: Primary air is supplied beneath the fuel grate by means of a single fan. The air flow is then divided into five zones to promote a better combustion, which is achieved by means of vent dampers.

2. Secondary fan: Secondary air is supplied above the combustion air, from an independent fan.

3. Fuel hopper: In order to monitor that there exists enough fuel, a level indicator signals low fuel level.

4. Fuel Gate: The flow of fuel from the hopper is controlled by a gate that can be moved up or down, and is driven by an electric motor.

5. Grate: The grate is driven by an electric motor and uses a conveyor belt setup. The grate is 0.5 m wide and 2 m long, amounting to an area of 1 m^2.

6. Ash pit: Ash is discharged at the end of the grate.

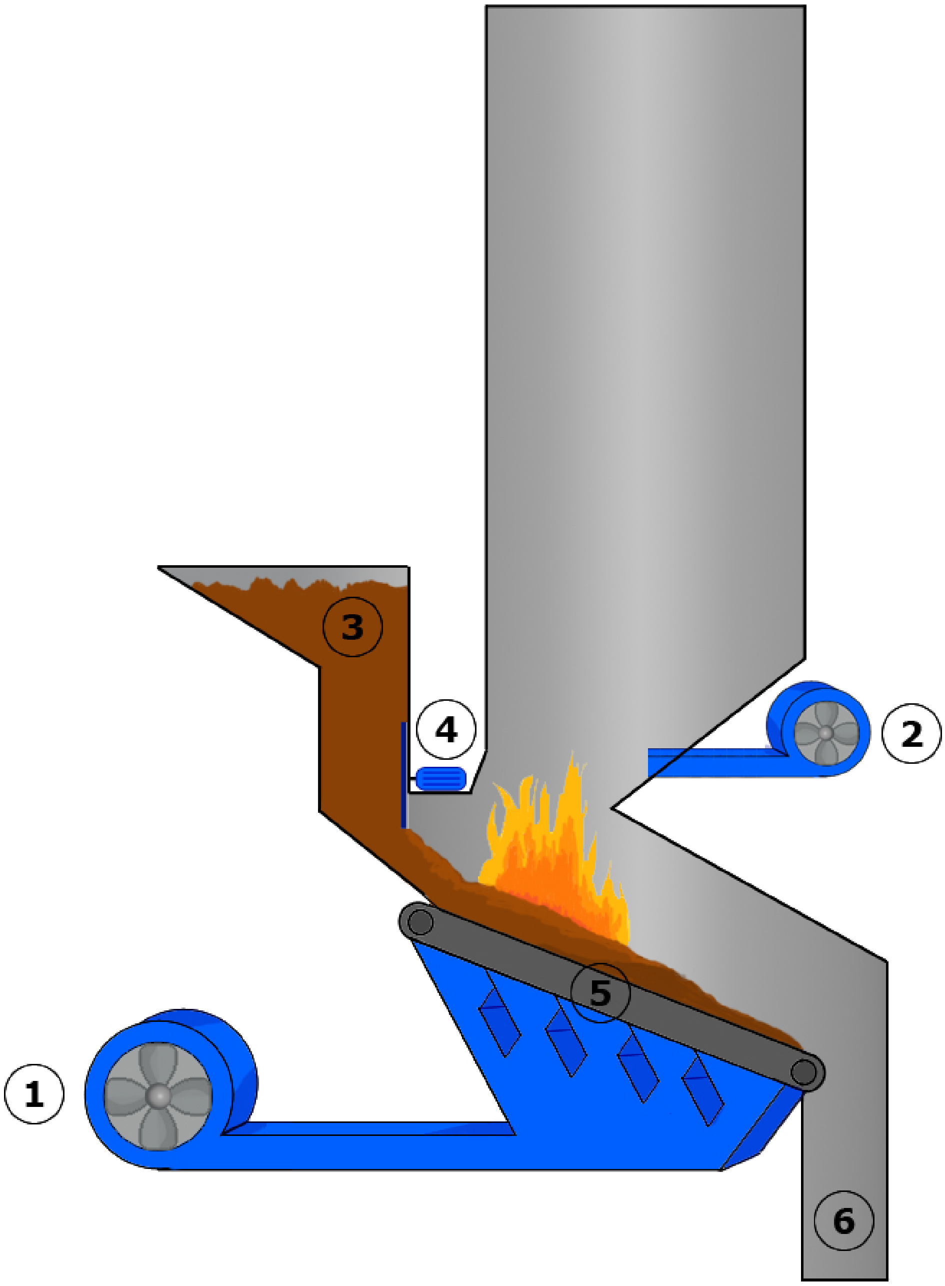

Figure 5.1: A cross-section of the simulated boiler system. The labels are explained in the text.

5.2.2 Control Parameters

From the description of the system several control parameters are evident. The primary air flow rate is controlled by varying the signal to the primary fan. The division of the primary air into zones could be automatically controlled, but in this case it is manually controlled. This is done because of the limited number of available outputs on the controller, which is described in Section 5.3.1. Like the primary air, the secondary air flow rate is also controllable. Other control parameters are the position of the fuel gate and the speed of the grate.

In addition to the parameters already mentioned, various sensors are used to monitor the process. The O_2 content in the flue is measured, and used in the air controller. Furthermore, pressure sensors are placed both beneath the grate and above the grate. The pressure difference helps to determine the thickness of the fuel bed. A pressure sensor is also placed in the steam dome, which serves as a parameter for the load control. To monitor the temperature of the flue gas an IR-pyrometer is placed in the flue. The control parameters are summarized in Table 5.1.

Table 5.1: Control parameters

Signal	I/O	Type
Steam Pressure	Input	Analog
O_2	Input	Analog
Undergrate Pressure	Input	Analog
Overgrate Pressure	Input	Analog
Flue Gas Temperature	Input	Analog
Fuel Level	Input	Digital
Primary Air Flow Rate	Output	Analog
Secondary Air Flow Rate	Output	Analog
Fuel Gate Position	Output	Analog
Grate Speed	Output	Analog

5.2.3 Alarms

There is a number of variables that must be monitored in a boiler system for safety reasons as well as to ensure acceptable operation. In the event that these values violate their respective conditions, an alarm should be signaled. In this system an alarm is raised on the event that the O_2 level falls outside a predetermined interval. An alarm should also be raised in case the pressure in the steam dome exceeds a specified limit. Finally a level sensor in the fuel hopper raises an alarm in the event that the fuel level is dangerously low.

5.3 Practical Implementation

With a system and all relevant parameters defined, it is possible to start the implementation. The following sections describe the control platform used, the simulation environment and finally the steps taken in the actual implementation of the controller algorithm.

5.3.1 Control Platform

The platform that is used for the controller implementation is the EXOcompact, shown in Figure 5.2. The EXOcompact is a freely programmable controller, very useful in various stand-alone applications as well as for system integration. It is available is three sizes with 8, 15 or 28 inputs and outputs (I/O), and has several other options, such as a display and support for several communication protocols. The controller used in this implementation is the C280D-S model, which has 28 I/Os and an integrated display. It communicates via a RS485 connector using the EXOline protocol (Regin AB, 2010).

Figure 5.2: The EXOcompact controller (Regin AB, 2010).

The controller is programmed using a language designed by Regin, named EXOL. The programming environment is also designed by Regin and is named EXOdesigner (Regin AB, 2010).

5.3.2 Simulation Environment

As has been stated before, the controller cannot be tested on a real boiler system. To simulate the system, a demo kit from Regin is used. This kit is a briefcase in which an EXOcompact is fitted, and all I/Os are connected. The controller has five analog outputs that are connected to voltmeters with a range of 0-10 V and seven digital outputs that are connected to light emitting diodes (LED) to display the signals. The controller has eight digital inputs that are connected to single-pull single-throw switches. Four additional inputs are analog, and they are connected to a potentiometer as well as a switch that determines whether the input reads voltage or resistance. The remaining four inputs are so called universal inputs, meaning that they can be either analog or digital. If a universal input is chosen to be analog, it has the same setup as the other analog inputs.

Using this demo kit to simulate a boiler system, the functionality of the control can be demonstrated by manually changing inputs, to provoke a change in the outputs. The implemented controller will not be directly usable in a real application. It is, however, considered a sufficient proof of the concept.

5.3.3 Controller Loops

The most common control techniques were explained in Chapter 3. The control algorithm implemented in this phase is chosen to be a parallel controller, and is composed of an air controller, a fuel controller and a load controller that provides set-points for the first two controllers. Figure 5.3 shows the configuration of the control system in a block diagram.

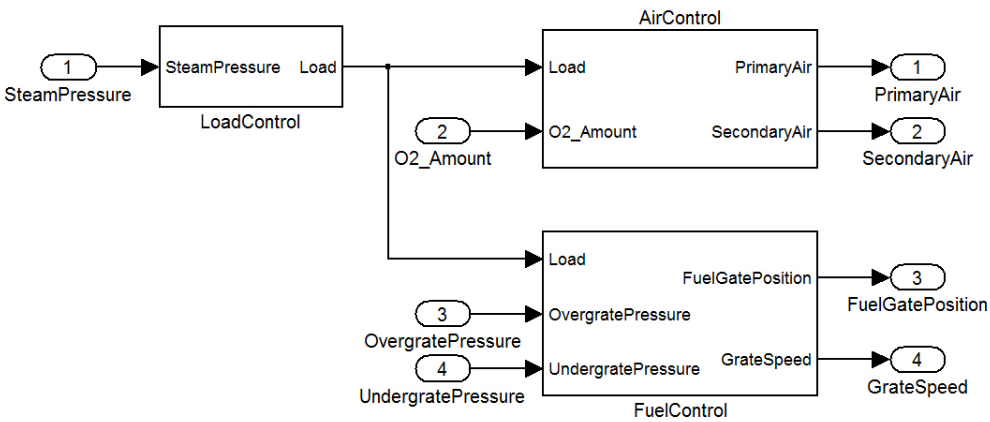

Figure 5.3: Block diagram of the overall control system.

The load controller is a fairly simple controller, using a PID controller to determine the load. The controller has a predetermined set-point for the pressure in the steam dome. The measured pressure is used to determine the error, which in turn is fed to the PID controller. The output from this controller is limited to the interval 2-10 V, representing a percentage interval of 20-100 %. The signal is limited to a minimum of 20 % so that the combustion is maintained, since if the load where to be 0 % the combustion would need to be manually started every time the demand rises. This value is then sent to the air and fuel controllers. Figure 5.4 shows the block diagram for the load controller.

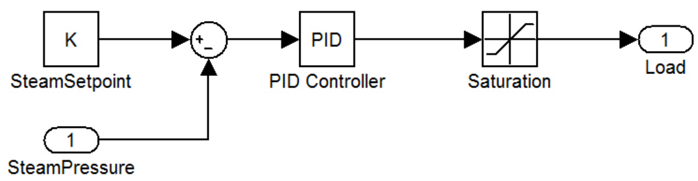

Figure 5.4: Block diagram of the load control system.

The air controller module is slightly more complex, but also uses a PID regulator. The signal from the load controller is divided between the primary and secondary air signals, so that 70 % of the total air flow is provided through primary air, and the remaining 30 % are supplied as secondary air. The measured O_2 concentration and the O_2 set-point are fed into a PID controller. The output from the PID controller is then used to adjust the secondary air signal, according to oxygen needs. The output signals sent to the fans are limited to the interval 1-10 V. The reason for setting a lower limit of 1 V on each output is to reduce the risk of unsafe operating conditions. Figure 5.5 shows the block diagram for the air controller.

The fuel controller is the most complex of the three controllers. The air pressure above and below the grate is measured, and these values are used to estimate the fuel bed thickness. This thickness estimation is then converted to a value that is used as an input to a PID controller where the load signal is the set-point value. The output from the PID controller is then fed to both the fuel gate and to the grate motor. Before sending each of the signals to their respective actuator, they are converted to a representative value and limited to a interval of 0-10 V. Figure 5.6 shows the block diagram for the load controller.

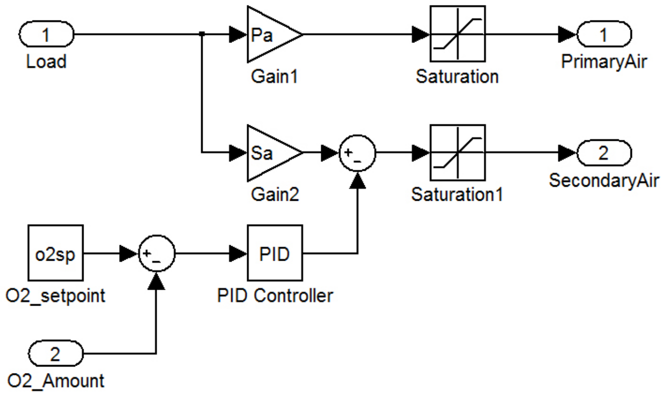

Figure 5.5: Block diagram of the air control system.

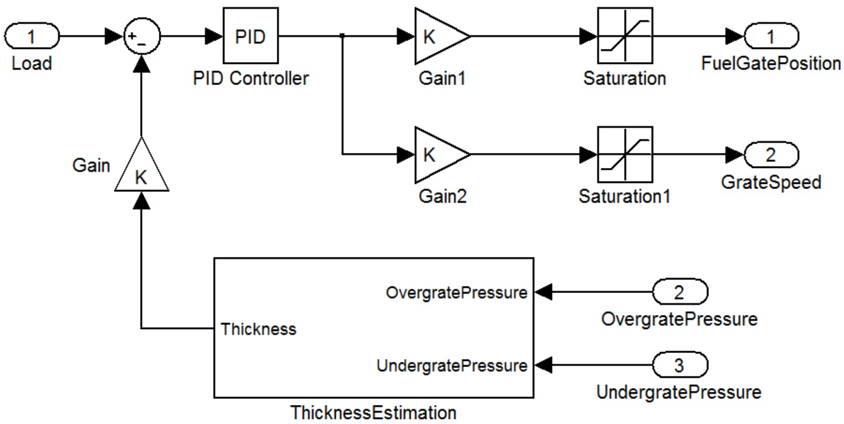

Figure 5.6: Block diagram of the fuel control system.

Tuning of PID controllers

In case the reader is unfamiliar with the concept of PID controllers this section starts with a short summary on the subject before advancing to how they are tuned for use in this boiler control system.

The name PID is an acronym for Proportional-Integral-Derivative, which in fact somewhat explains its function. The textbook version of the PID algorithm is shown in Equation 5.1

$$u(t) = K\left(e(t) + \frac{1}{T_{\mathrm{I}}}\int_0^t e(\tau)d\tau + T_{\mathrm{D}}\frac{de(t)}{dt}\right) \tag{5.1}$$

where $u(t)$ is the control signal and $e(t)$ is the error, that is the difference between the measured process variable and its set-point value. The constant

K determines the proportional term which only depends on the current error. T_{I} is called integration time, and it determines the integral term based on the history of the error. The derivative term depends on the future value of the error, acquired through simple extrapolation prediction (Årzén, 2009; Phillips & Harbor, 2000).

The controller parameters can be altered to improve the controller dynamics. By setting $T_{\mathrm{D}} = 0$ and $T_{\mathrm{I}} = \infty$, the controller only has a proportional term and therefore will always have a steady state error. Increasing the proportional gain can reduce this error, but with a higher gain there also is increased tendency of oscillations in the control signal. Introducing the integral term will eliminate the steady state error, and as can be seen from equation 5.1 the strength of the integral term will increase as T_{I} decreases. The integral term also tends to increase oscillations in the control signal. The derivative term will help to reduce overshoot and oscillations in the control signal, and the damping will increase as T_{D} increases but will decrease again if the derivative time is too long (Årzén, 2009; Phillips & Harbor, 2000).

The PID controllers are very widely used in industry, but in a large number of cases the controllers only use the proportional and integral terms and disable the derivative. Through the years a large number of features have been added to the PID controllers, such as automatic tuning, gain scheduling and continuous adaptation. In the case of this implementation the controller is the basic controller, and due to the slow response time of the system there is no need to use the derivative term so the controllers will be a PI controllers (Årzén, 2009; Phillips & Harbor, 2000).

Due to the fact that the controller is made without access to an actual system, the tuning of the PID controllers is only approximate. The proportional gain (K) is determined by estimating the appropriate rise time for the specific control signals. In order to get a better value for the proportional gain, the proportional band (PB) is also considered. The proportional band is defined as

$$\mathrm{PB} = \frac{1}{K} \tag{5.2}$$

The PB therefore specifies how a change in the input relates to a change in the output. For example, if a controller has a PB of 10 and a set-point at 0, it means that a change in the input from 0 to 10 results in a change in the output of 100 %. Similarily, if the change was from 0 to 5 for the same controller, the output would be increased by 50 %.

The integral time, also known as reset time, for a PID controller used in a boiler system is quite large due to the slow response times. The fastest controller is the air controller, since a change in oxygen content can be applied quickly. Since the value from the O_2 sensor may fluctuate somewhat, the value is filtered. The load control, however, is very slow since the process of heating the large amount of water takes a long time. Finally, the fuel control is also rather slow, although not as slow as the load control. The values chosen for the controllers are shown in Table 5.2.

Table 5.2: PID control parameters

	K	T_I	T_D
Load Control	5	30	0
Air Control	10	1	0
Fuel Control	5	20	0

5.4 Testing

Testing of the controllers should show the functionality of the implementation. There are several aspects that should be tested in particular to prove that the controllers work according to specifications. The following list details the main aspects to be verified by testing:

- A change in the measured steam pressure should result in a cascading change in the three controllers. The output of the load controller should vary according to the steam pressure change. The change in the load signal should result in both a compensation of air flow rate and fuel feed dynamics.
- Fluctuations in O_2 in the flue gases should result in a compensation from the secondary air flow.
- If the concentration of O_2 falls outside the range of 4-9 %, an alarm should be raised.
- If the fuel level indicator detects low fuel, an alarm should be raised.
- If the pressure in the steam dome exceeds 8 bar, an alarm should be raised.

5.5 Results

Since the controller is implemented using the EXOL programming language, most of the functions needed for the controller already exist. These functions, i.e. the PID, alarm handling, filtering and more, make the control program itself very simple and straightforward.

Once the program has been compiled and loaded to the EXOcompact, testing is performed to verify that all the requirements mentioned in Section 5.4 are met. By using the demo kit to change the inputs the behavior of each controller section is monitored. Several test iterations reveal that all requirements are in fact fulfilled. During some of the test iterations the integration times specified for the controllers were reduced to speed up the reaction times. In an actual system these time constants might have to be considerably longer, for example for the load controller where actual integration time is in minutes rather than seconds. Since all requirements were fulfilled, the implementation is considered a success.

Chapter 6

Discussion

6.1 Conclusions

The goal of this thesis has been to investigate various techniques that improve the efficiency of boiler systems. Improvements in these boiler systems takes different forms, such as reducing the operational and maintenance costs, reduce the fuel consumption or reducing the emission of polluting gases to the environment. To get started on the thesis, an extensive study was performed on the technical background associated with boiler systems. This was followed by an empirical study with the purpose of establishing the techniques that have been developed and tested through the years to improve boiler systems. To find out which of these techniques have been found effective and economically viable for practical use, a case study of four establishments was performed.

The case studies revealed that the economical viability of the various control techniques was in fact somewhat dependent on the size of the boiler system. For small scale systems, only the simplest techniques such as O_2 control are commonly used, while the larger scale systems make use of a wide range of control techniques. The reason for this is that the investment cost of many of the control systems is high. Even if the savings from the installment of these techniques is for example several percent reduction in fuel use, the total use of fuel in small scale systems is so low that payback time for the improvements is too long. For large scale systems on the other hand, where the fuel use is considerably greater, the payback time may be very short.

An additional goal of the thesis is to establish if an efficient boiler controller can be implemented on the EXOcompact controller platform from AB Regin. Therefore a proof of concept was developed using three control sections, load control, air control and fuel control. The limiting factor for the implementation of the controller is the number of I/Os on the EXOcompact.

It turned out that the base unit is sufficient to control a small to medium scale boiler system, largely depending on the boiler design and setup. The system used in the proof of concept is categorized as a medium scale system, but such systems sometimes have a considerably larger number of sensors requiring more inputs, or more actuators that control the process requiring more outputs. The EXOcompact can, however, be connected to a second module, thereby doubling the number of I/Os. If the control system is to be used for large scale systems, a platform that offers a larger number of I/Os must be used.

The choice of which techniques covered in this thesis are best suited for implementation in a boiler control system is dependent on several parameters, such as boiler size, fuel type and implementation cost. The largest factor is the size of the system to be controlled, since it affects the other parameters as well. It was mentioned above that the payback time for the various techniques is a large factor as well, and this is directly dependent on the system size. The techniques best suited for implementation therefore depend largely on what section of the market AB Regin aims to launch an eventual system. For the small and medium scale market, the best solution is to implement a robust and exact O_2 control system, coupled with a flexible fuel controller so that the controller can handle the most common types of fuel. If the control system aims at large scale boiler systems, the other techniques become financially acceptable. This includes for example using more parameters for the air control, monitoring of fuel quality and flame position in solid fuel systems, or other ways to complement the base controllers by using additional measurement data.

Because the overall goal of this thesis is to gather information on the techniques that are available and how these work, it is difficult to make a definite choice regarding which techniques should be included in a controller. To be able to make such a choice, a detailed cost based analysis of each of the techniques needs to be performed. This analysis should also take into account whether the goal of the techniques is to reduce for example fuel cost, or other operational cost of a boiler system, or if it aims at making the system in question more environmentally friendly by reducing emissions.

6.2 Future Development

Although a proof of concept has been implemented, there is a large number of issues that have to be addressed in order to develop a usable boiler control system. The major issues are listed in the following text.

First of all, the controller designed for the proof of concept was only a parallel controller. To ensure safe operation it should be extended to be cross-limiting as discussed in Section 3. This was dismissed in the concept solution due to the limited time frame and the somewhat loosely defined system.

To make the control system more efficient, a model of the combustion process is needed. To make the controller flexible with regard to boiler types and setup, generic models for the most common boiler system configurations has the potential to reduce the installation cost. With several generic models defined, their parameters can be adjusted to represent the system that should be controlled, reducing or even eliminating the need for custom controller designs. The concept solution uses PID controllers, but once models have been acquired for the processes involved in boiler systems these should be exchanged for more effective control algorithms.

If the PID control algorithm is used in further development, some improvement should be made. Due to the very slow processes in a boiler system, the PID controllers should be extended with anti-windup to prevent unstable operation. In addition, gain scheduling should be considered. This is likely to improve the operation since the processes often behave differently during for example start-up and during full load. With gain scheduling the PID controller can adjust for these variations.

An alternative to continued use of PID controllers is to implement a predictive or adaptive controller. Although the PID can be extended to be adaptive to some extent by implementing so called auto-tuning PID controller, other algorithms may improve the operation even more. There exists a large number of effective predictive control methods, many of which may be very suitable for control of a boiler system. The choice of a predictive algorithm cannot be made at this point since no actual process model is available. The advantage of using an adaptive or predictive control algorithm is greatest in large scale systems, and systems where fuel quality varies. In larger systems, the time constants of the system may become very large, and to optimize the process it is beneficial to make use of a predictive controller to eliminate the time delays. Likewise, if a system uses a fuel that varies in quality, for example wood chips or waste, the process could be optimizes significantly by implementing adaptive algorithms that adjust the control parameters according to the fuel quality.

Even after the implementation of a controller, there are other issues that also need to be addressed. One of those issues is the development of a computer interface that can be used for these systems. This is a feature that may not be relevant for small scale boiler systems, but for medium systems it may prove useful. If the controller is meant to control large scale systems such an interface is likely to be necessary.

The improvements discussed above are only some of the issues that should be addressed in future development. This is far from being an exhaustive list, but is merely meant to provide some idea of where to go from here.

Bibliography

ASHRAE. (2008). *ASHRAE Handbook - HVAC Systems and Equipment.* Atlanta, GA, USA: ASHRAE.

ASHRAE. (2009). *ASHRAE Handbook - Fundamentals.* Atlanta, GA, USA: ASHRAE.

Bubholz, M., Myringer, Å., & Nordgren, D. (2007). *Utvärdering av drift och miljö med hjälp av kamerabaserad flamfrontsstyrning i rosterpannor.* Stockholm, Sweden: Värmeforsk Service AB.

Cengel, Y. A., & Boles, M. A. (2006). *Thermodynamics - An Engineering Approach.* USA: McGraw-Hill.

CIPEC. (2001). *Boilers and Heaters: Improving Energy Efficiency.* Canada: CIPEC.

Ehleskog, R., Lundborg, R., Schuster, R., & Wrangensten, L. (2002). *Avancerad processtyrning av fastbrännsleeldade rostpannor.* Stockholm, Sweden: Värmeforsk Service AB.

Elliot, T. C. (1997). *Standard Handbook of Powerplant Engineering.* NY, USA: McGraw-Hill.

Energifaktaboken. (2005). Stockholm, Sweden: Stockholm ÅF Energi & Miljöfakta.

Energy Solutions Center Inc. (2010a). *Blowdown.* `http://www.energysolutionscenter.org/boilerburner/Eff_Improve/Operations/Blowdown.asp`. (Accessed September 28, 2010)

Energy Solutions Center Inc. (2010b). *Blowdown Heat Recovery.* `http://www.energysolutionscenter.org/boilerburner/Eff_Improve/Efficiency/Blowdown_Heat_Recovery.asp`. (Accessed September 28, 2010)

Energy Solutions Center Inc. (2010c). *Boiler Efficiency.* `http://www.energysolutionscenter.org/boilerburner/Eff_Improve/Primer/Boiler_Efficiency.asp`. (Accessed June 11, 2010)

Energy Solutions Center Inc. (2010d). *Boiler Reset Control.* `http://www.energysolutionscenter.org/boilerburner/Eff_Improve/Efficiency/Boiler_Reset_Control.asp`. (Accessed September 23, 2010)

E.ON. (2009). *Öresundsverket - more reliable and environmentfriendly energy supplies.* Malmö, Sweden: E.ON Värmekraft Sverige AB.

E.ON. (2010). *Öresundsverket - One of the world's most efficient power plants.* Malmö, Sweden: E.ON Värmekraft Sverige AB.

Eriksson, L., Njurell, R., & Ehleskog, R. (2002). *Fukthaltsmätning av biobränsle.* Stockholm, Sweden: Värmeforsk Service AB.

Fleckl, T., Jäger, H., & Obernberger, I. (2010). *Combustion diagnostics at a biomass-fired grate furnace using FT-IR absorption spectroscopy for hot gas measurements.* Porto, Portugal: Bioenergisysteme Gmbh.

Jarvis, Å. (1998). *BIOGAS - Renewable Energy from Organic Waste.* http://www.sbgf.info/_filer/BIOGAS_PDF_Eng.pdf. Stockholm, Sweden. (Accessed August 16, 2010)

Johansson, A. (2007). *Aktiv förbränningskontroll - en studie av lämpliga styrparametrar i eldstaden.* Stockholm, Sweden: Värmeforsk Service AB.

Lampe, U., Fleischer, M., & Meixner, H. (1994). *Lambda Measurement with* Ga_2O_3*.*

Marklund, J., & Schuster, R. (1991). *Indirekt fuktbestämning av bränsle.* Stockholm, Sweden: Stiftelsen för Värmeteknisk Forskning.

MARTIN GmbH. (2008a). *Description of the MARTIN combustion control system.* Munich, Germany.

MARTIN GmbH. (2008b). *MARTIN Rückschub-roster, SYSAV Malmö 4.* Munich, Germany.

Mulliger, P., & Jenkins, B. (2008). *Industrial and Process Furnaces.* USA: Butterworth-Heinemann.

Nationalencyklopedin. (2010). *Nationalencyklopedin.* http://www.ne.se.ludwig.lub.lu.se/molekylspektroskopi. (Accessed October 12, 2010)

Natural Resources Canada. (2000). *An Energy Efficiency and Environmental Primer for Boilers and Heaters.* Canada: Natural Resources Canada.

Offesson, A. (2010). *Sysav, Bildbank.* http://www.sysav.se/Templates/StdPage.aspx?id=4415. (Accessed October 22, 2010)

Oland, C. B. (2002). *Guide to Low-Emission Boiler and Combustion Equipment Selection.* TN, USA: Oak Ridge National Laboratory. http://www.ornl.gov/~webworks/cppr/y2001/rpt/112910.pdf.

Persson, A., & Helgesson, J. (2004). *Indikation av förbränningssituationen genom bildanalys av rostens eldstad.* Stockholm, Sweden: Värmeforsk Service AB.

Persson, F., & Ramsbäck, B. (1987). *Styrning och reglering av utblåsning av pannvatten.* Stockholm, Sweden: Stiftelsen för Värmeteknisk Forskning.

Phillips, C. L., & Harbor, R. D. (2000). *Feedback Control Systems, 4th Edition.* NJ, USA: Prentice-Hall Inc.

Regin AB. (2010). *Products and Systems for Building Automation.* Sweden: Regin AB.

Robert Bosch GmbH. (2010). *Bosch lambda sensor.* http://www.bosch-lambdasonde.de/en/index.htm. (Accessed October 11, 2010)

Rodin, Å., Jacoby, J., & Blom, E. (2003). *Rostövervakning - Nya metoder för reglering coh övervakning av förbränningsroster.* Stockholm, Sweden: Värmeforsk Service AB.

Rudling, L. (1999). *Optimering av askutbränning vid rosteldade anläggningar med hjälp av IR-sensorer. Demonstration av teknikens tillämpbarhet.* Stockholm, Sweden: Värmeforsk Service AB.

Årzén, K.-E. (2009). *Real-Time Control Systems.* Lund, Sweden: Lund Univesity.

Sahlins EcoTec AB. (2008). *EcoTec.* Skåne, Sweden.

Schuster, R., & Lundborg, R. (2000). *Möjligheter till förbättrad drift av skogsindustrins barkpannor genom optimerad förbränningsteknisk styrning - etapp 2.* Stockholm, Sweden: Värmeforsk Service AB.

Svenska Gasföreningen. (2008). *Naturgas.* http://www.gasforeningen.se/upload/files/publikationer/infomaterial/naturgasbroschyr.pdf. Stockholm, Sweden. (Accessed August 20, 2010)

Svensson, M. (2003). *Lambdabaserad reglering.* Stockholm, Sweden: Värmeforsk Service AB.

Sysav. (2010a). *Heat and electricity from waste - Sysav's waste-to-energy plant.* Malmö, Sweden.

Sysav. (2010b). *Kraftvärmeverket - avfall blir el och värme.* http://www.eon.se/upload/eon-se-2-0/dokument/privatkund/produkter_priser/fjarrvarme/lokala-fjarrvarmesidor/sysav.pdf. Malmö, Sweden. (Accessed October 25, 2010)

Sysav. (2010c). *Årsredovisning 2009.* Malmö, Sweden.

Thumann, A., & Mehta, D. P. (2008). *Handbook of Energy Engineering, 6th Edition.* FL, USA: Taylor & Francis Ltd.

Turner, W. C., & Doty, S. (2007). *Energy Management Handbook.* FL, USA: Taylor & Francis Ltd.

U.S. Department of Energy. (2005). *Furnace Pressure Controllers.* http://www1.eere.energy.gov/industry/bestpractices/pdfs/furnace_press_control_process_htgts6.pdf. Washington DC, USA: U.S. Department of Energy. (Accessed October 6, 2010)

Woodruff, E. B., Lammers, H. B., & Lammers, T. F. (2005). *Steam Plant Operation.* USA: McGraw-Hill.