Impact of Fuel Variability and Operating Parameters on Biomass Boiler Performance

by

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A thesis submitted in conformity with the requirements for the degree of Doctorate of Philosophy
Chemical Engineering and Applied Science
University of Toronto

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Doctor of Philosophy
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2019

Abstract

Biomass boilers provide up to one-third of the energy requirement in pulp and paper mills by burning hog fuel, which is a mixture of wood-waste available at the mill site. The quality of this fuel varies significantly depending on its source and storage conditions. This fuel variability often causes biomass boiler operation to be unstable and unpredictable. This study consists of two parts: the first part investigates the impact of fuel variability on combustion and develops means for mitigating these impacts to achieve stable boiler operation. The second part identifies the most influential parameter in boiler operation using multivariate analysis, and develops a predictive statistical model for optimization of biomass boiler thermal performance. In the first part, wood species are differentiated by their initial particle density. For all wood species examined, particle density decreases throughout the combustion process but at different rates depending on the combustion stage. During the devolatilization stage, the density decreases significantly as a result of rapid mass loss. This sharp decrease causes particles to be light enough to be entrained and/or be lifted off from the grate by the flue gas. An analytical model is then developed to calculate particle entrainment velocity, and to determine whether a particle is entrained and if so, how much unburned mass is left upon entrainment.
In the second part, multivariate analysis is used to identify the most important parameters in boiler operation. The results show that moisture content is the most influential parameter and a soft sensor is consequently developed to estimate the feedstock moisture content from other parameters. A predictive Partial Least Square (PLS) model is built to predict the thermal performance of a boiler in real-time and to determine the contributing factors to process upsets. In practical applications, the entrainment model is used for fuel preparation and sizing to reduce particle entrainment. The PLS model, along with the moisture content soft sensor, can be used for process monitoring providing additional insights into causes of process variability.
Acknowledgements

First of all, I would like to thank my PhD supervisors, Prof. Honghi Tran and Prof. Andrew Jones without whom this dissertation would not have been possible. Professor Tran has been and will always be my mentor and role model in life, I appreciate and will always cherish his unconditional support, irreplaceable guidance and unimaginable patience during the course of my graduate studies. Professor Jones provided a unique perspective into the practical implications of this work while also providing valuable guidance for the scientific rigor of the research. I would also like to thank my committee: Prof. Markus Bussman, Prof. Will Cluett, Prof. Nikolai DeMartini and Dr. J.Y Zhu for their guidance and support along this journey.

This research has been part of a large research program undertaken by the Energy and Chemical Recovery Research Group at the University of Toronto. I would like to thank the other students in this group for their friendship and support whether it was for brainstorming, help on methodology or building a new experimental setup. This work was financially supported by a consortium of 22 pulp and paper related companies and the Natural Sciences and Research Council of Canada (NSERC). I would also like to thank the consortium members for their feedback and advice on the progression of this project.

I would like to thank my family: my parents Maryam and Samad, my brothers Nima and Mehdi (and his family Aida and Bardia), my in-laws Shahla and Abi, for their unconditional love, support and always believing in me. Finally, I would like to thank my partner-in-crime Navid, without his love, kindness and words of encouragements, this journey would not have started. This dissertation is dedicated to my wonderful family.
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<tbody>
<tr>
<td>GJ</td>
<td>Giga Joules</td>
</tr>
<tr>
<td>KWH</td>
<td>Kilo Watt Hour</td>
</tr>
<tr>
<td>ADMT</td>
<td>Air Dry Metric Ton</td>
</tr>
<tr>
<td>MW</td>
<td>Mega Watt</td>
</tr>
<tr>
<td>ESP</td>
<td>Electrostatic Precipitator</td>
</tr>
<tr>
<td>SG</td>
<td>Stoker Grate</td>
</tr>
<tr>
<td>BFB</td>
<td>Bubbling Fluidized Bed</td>
</tr>
<tr>
<td>MVA</td>
<td>Multivariate Analysis</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>NIR</td>
<td>Near Infrared</td>
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<tr>
<td>PCA</td>
<td>Principal Component Analysis</td>
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<tr>
<td>PLS</td>
<td>Partial Least Squares</td>
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<tr>
<td>PC</td>
<td>Principal Components</td>
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<tr>
<td>TG</td>
<td>Thermogravimetric</td>
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<tr>
<td>TC</td>
<td>Thermocouple</td>
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<tr>
<td>TP</td>
<td>Thermal Performance</td>
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### List of Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Symbol</th>
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<tbody>
<tr>
<td>F</td>
<td>Flow rate on dry basis</td>
<td>R</td>
<td>Rate of mass generation or consumption</td>
</tr>
<tr>
<td>MC</td>
<td>Moisture content</td>
<td>r</td>
<td>Reaction rate</td>
</tr>
<tr>
<td>HHV</td>
<td>Higher heating value</td>
<td>k</td>
<td>Kinetic constant</td>
</tr>
<tr>
<td>X</td>
<td>Mass fraction</td>
<td>K</td>
<td>Mass transfer coefficient</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
<td>C</td>
<td>Concentration</td>
</tr>
<tr>
<td>P</td>
<td>Pressure</td>
<td>L</td>
<td>Initial length of cube</td>
</tr>
<tr>
<td>C&lt;sub&gt;P&lt;/sub&gt;</td>
<td>Specific heat capacity</td>
<td>l</td>
<td>Length of cube during combustion</td>
</tr>
<tr>
<td>Q</td>
<td>Heat content</td>
<td>D</td>
<td>Diffusivity</td>
</tr>
<tr>
<td>η</td>
<td>Efficiency</td>
<td>V</td>
<td>Volume</td>
</tr>
<tr>
<td>λ</td>
<td>Eigen value</td>
<td>v</td>
<td>Entrainment velocity</td>
</tr>
<tr>
<td>e</td>
<td>Eigen vector</td>
<td>C&lt;sub&gt;D&lt;/sub&gt;</td>
<td>Drag coefficient</td>
</tr>
<tr>
<td>t,u</td>
<td>Latent variables</td>
<td>Re</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>w, c</td>
<td>Regression weights</td>
<td>A</td>
<td>Surface area</td>
</tr>
<tr>
<td>ρ</td>
<td>Density or mass concentration</td>
<td>H</td>
<td>Enthalpy</td>
</tr>
<tr>
<td>Bi</td>
<td>Biot number</td>
<td>h</td>
<td>Heat transfer coefficient</td>
</tr>
<tr>
<td>k&lt;sub&gt;cond.&lt;/sub&gt;</td>
<td>Thermal conductivity</td>
<td>m</td>
<td>Mass</td>
</tr>
<tr>
<td>f</td>
<td>Force</td>
<td>m</td>
<td>Mass flow rate</td>
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List of Subscripts

B  Biomass
C  Carbon
H  Hydrogen
S  Sulphur
N  Nitrogen
O  Oxygen
NG Natural gas
w  Feedwater
s  Superheated steam
Bl Blowdown
FG Flue gas
b  Biomass devolatilization
c1  Char generation
c2  Char burning
c  Core
1 Introduction

Biomass boilers produce about one third of the energy requirements in pulp and paper mills in the form of superheated steam. The fuel in such boilers is conventionally called hog fuel which is a mixture of wood-waste available at the mill site. Biomass boiler operation is challenging due to variations in hog fuel characteristics such as moisture content, size, wood species, ash, and heat content. These variations cause unstable steam production and boiler operation. Steam production rates are affected by changes in hog fuel characteristics; moreover, the hog fuel characteristics entering the boiler at any given time are unknown, making boiler performance unpredictable. Therefore, there is a need to investigate the impact of hog fuel variability on boiler operation and predict boiler performance. This chapter presents a brief background on biomass boiler operation and types of boilers, challenges in boiler operation and the motivation for this research, objectives, and thesis outline.

1.1 Energy from Biomass in Pulp and Paper

Pulp and paper mills use steam and electricity to dry pulp and paper products, heat water and process liquors, concentrate spent cooking liquor, run equipment, and light and heat space and buildings. A typical pulp and paper mill needs 23 to 35 GJ of steam and 700 to 1000 KWH of power per air dry metric ton (ADMT) of pulp produced. About 60 to 70% of this energy is supplied by burning black liquor in recovery boilers. The remaining 30 to 40% is produced by burning biomass in biomass boilers. Natural gas and fuel oil are also co-fired in biomass boilers to supplement steam and power as required [1]. Biomass boilers provide an efficient and economical solution for pulp and paper mills to dispose of wood waste while harvesting its energy content. A typical kraft pulp mill is shown in Figure 1-1.
The solid fuel that is burned in biomass boilers is known as hog fuel, which is a mixture of different types of biomass available at mill site and/or purchased from local suppliers. Sources of biomass include saw dust coming from the slasher deck, bark from the debarking drum, pins and fines from chip screening, wood residue from the wood yard, and rejects generated during chemical pulp treatment and recycled paper processing [2] plus sawmill residues, biomass collected from tree harvesting sites and purpose grown trees. It is also common for pulp and paper mills to purchase large quantities of biomass fuel, which is often more variable in quality than the biomass fuel generated on the site.

While the main components of biomass on a dry basis are relatively constant, with 45-50 wt% carbon, 5-6 wt% hydrogen, and 40-44 wt% oxygen, the moisture content, ash content and ash composition can vary widely, depending on sources and storage conditions of the feedstock.

Figure 1-2 shows different types of biomass boiler feedstock typical to kraft pulp mills with variations in fuel size, shape, and moisture content. The hog fuel in Figure 1-2a is an older...
biomass pile which has been wetted by rain and consists mainly of bark, whereas Figure 1-2b shows a biomass pile consisting mainly of wood chips that appears fairly dry.

![Figure 1-2. Different types of feedstock a) older biomass pile containing bark wetted by rain, b) fairly dry biomass pile containing wood chips](image)

Figure 1-3 shows hog fuel being transported on the conveyor to the boiler. Hog fuel piles are stored outside where they are exposed to rain, snow, and long durations of sunshine. Biomass from different piles are mixed before entering the boiler. Therefore, the characteristics of the hog fuel entering the boiler at any given time can change considerably. This variation in hog fuel characteristics impacts boiler operation resulting in unstable and unpredictable steam production which is the main challenge for biomass boiler operation.
Figure 1-3. Hog fuel piles and conveyor belt to boiler

Biomass boilers in pulp and paper mills are often referred to as hog-fuel boilers, bark boilers or power boilers. Figure 1-4 shows a schematic diagram of a biomass boiler. Biomass boilers can be up to 30m high and produce up to 500 MW of thermal energy [3]. Biomass is delivered to the boiler via conveyor belts and is fed to the bottom of the boiler. Air is also fed to the boiler (undergrate and overfire air) at quantities typically 10-30% more than the stoichiometric requirements. The highest temperature is in the lower furnace area where combustion takes place. Hot flue gas produced from combustion passes through banks of tubes in the superheater area of the boiler. The saturated steam in the tubes is heated to produce superheated steam for use in other parts of the mill such as the digester or black liquor evaporators. The flue gas exits the top of the boiler and passes through a series of heat exchangers (superheaters, generating bank, and economizers) where its remaining heat is recovered. The flue gas is then passed through electrostatic precipitators (ESP) to capture fly-ash and particulates. Finally the flue gas, which is sufficiently cooled and contains little fly-ash or particulate matter, exits via the stack.
Figure 1-4. Schematic diagram of a stoker-grate biomass boiler (Courtesy: Babcock & Wilcox)

There are two common types of biomass boilers: stoker-grate (SG) or fixed bed boilers, and bubbling fluidized bed (BFB) boilers. In SG boilers, shown in Figure 1-4, the biomass is fed into the boiler and piled on a grate where combustion takes place. Combustion air is introduced beneath the grate and travels through to reach the biomass. Stoker units are usually equipped with pinhole grates, vibrating grates, traveling grates, or reciprocating grates. Stoker-grate (SG) boilers are designed for a range of fuel characteristics and specifications. One important specification is the size range of the fuel. Manufacturers of SG boilers specify the required size which typically ranges between 0.6 cm and 7 cm [4]. If the fuel size is larger than the specified range, the thermal efficiency will decrease since the heat release rate is lower for large particles.
and larger particles will not completely burn before exiting with the bottom ash. If the fuel size is smaller than the specified range, the particles will be entrained by the flue gas and end up as unburned carbon in the fly-ash. The range of allowable moisture content is usually not specified by the boiler manufacturer and is obtained based on experience at the mill.

Bubbling fluidized bed (BFB) boilers handle more variations in fuel moisture content. In BFB boilers, shown in Figure 1-5, biomass is fed into the boiler and mixed with the fluidizing medium, usually sand, and combustion takes place in flight, this way the heat transfer area increases with the use of the fluidizing medium. Compared to SG boilers, BFB boilers are more flexible which means they can handle a wider variation in feedstock moisture content, and are more efficient. The boilers studied as part of this research are identified by a mill ID. Seven boilers have been investigated, mill A to mill G. Boilers at mills A, B, C, E, and G are SG boilers and boilers at mills D and F are BFB boilers.

Figure 1-5. Bubbling fluidized bed type boiler (Courtesy: Valmet)
A biomass boiler in pulp and paper mills typically converts about 65 - 85% of the thermal energy released from biomass combustion into superheated steam. BFB boilers generally have a higher efficiency compared to SG boilers. For both types of boilers, the fuel characteristics have an impact on the overall thermal efficiency. To optimize boiler operation and achieve the highest efficiency possible, the impact of fuel variation on biomass boiler performance needs to be understood.

### 1.2 Motivation and Objectives

The challenge in biomass boiler operation in pulp and paper mills is unstable and unpredictable steam production. The amount of steam produced in biomass boilers should be proportional to the steam demand of the mill, and in case of changes to steam demand, biomass boiler operation must be flexible to deal with sudden load changes while minimizing the need to produce steam from burning fossil fuels.

The main cause of unstable steam production is the variability of hog fuel characteristics, which changes depending on the source of hog fuel. For instance, hog fuel comprised mainly of bark is significantly different in heat content and size compared to digester rejects. Depending on the weather conditions and the location of the mill, the moisture content of the feedstock can also vary. Since the biomass piles are usually stored outside, they can be exposed to rain, snow and long durations of sunshine, and biological decay may also occur depending on how long they are stored; therefore the heat content of the piles will vary with time. To predict and adjust the steam production of biomass boilers, the impact of fuel variability on combustion and boiler operation needs to be investigated and understood.

Biomass combustion research is not a new field. In the last decade many researchers have studied biomass combustion but the focus has mainly been on emissions and environmental impacts [5–9], small-scale units with uniform feedstock [10–13], and co-combustion with coal [14–17]. However systematic studies on biomass boilers burning hog fuel in pulp and paper mills have not been performed, especially in recent years. The few studies on this topic have focused on operating experience at the mill [18,19], cogeneration [20, 21] and an empirical study on combustible carryover [22]. There is a need to systematically investigate the impact of hog fuel variability on boiler operation as it relates to the pulp and paper industry.
This study consists of two parts, the first part focuses on mitigating the instability of boiler operation and developing guidelines for fuel preparation. The second part discusses the application of multivariate analysis (MVA) to deal with the unpredictability of boiler operation.

Moisture content is believed to be the most important parameter in boiler operation. A systematic study on the impact of moisture content on biomass combustion has been done in the author’s master’s thesis [23]; the key findings were that an increase in moisture content will cause the time-to-ignition stage of combustion to be longer, therefore delaying the appearance of the flame. High moisture content also causes the particle to be cooler; therefore, the volatile burning stage will take place at a lower rate. These results, while providing fundamental knowledge on the impact of moisture content, were limited to single particle laboratory experiments. In the second part of this work, the importance of moisture content in boiler performance is verified, and a soft sensor for moisture content is developed to shed some light into the quality of the fuel entering the boiler.

The objectives are:

1. To investigate the impact of fuel variability, namely wood species and size, on combustion, and to develop means for mitigating these impacts.

2. To verify that moisture content is the most influential parameter in boiler operation, to develop a soft sensor for moisture content estimation, and to develop a predictive statistical model for optimization of biomass boiler thermal performance.
1.3 Thesis Outline

In this chapter a brief background was presented and challenges in biomass boiler operation were discussed. Chapter 2 is a literature review. Chapter 3 presents the methodology and apparatus used for experiments.

The first objective described in Section 1.2 is addressed by lab experiments and modeling work in Chapters 4, 5, and 6. Chapter 4 discusses the impact of wood species on combustion and the modeling of density change during combustion. Chapter 5 discusses size change of biomass particles during combustion and a shrinking core model is presented, and Chapter 6 presents an entrainment model which enables the calculation of the minimum allowable size of the fuel to mitigate unburned carbon in the fly-ash.

The second objective is addressed by data analysis and field studies in Chapters 7 and 8. Chapter 7 focuses on exploratory data analysis, verifying that the most influential parameter in boiler operation is moisture content, and the development of a moisture content soft sensor. Chapter 8 presents a predictive statistical model which enables prediction of thermal performance and its contributing factors. Chapter 9 discusses the practical implications of this research, and Chapter 10 summarizes the thesis objectives and how they were addressed, and recommendations for future work.
2 Literature Review

2.1 Combustion Reactions

When biomass is exposed to a sufficiently high temperature in an oxygen containing environment, combustion takes place. Biomass combustion takes place in three main steps: time-to-ignition or drying, volatile burning, and char oxidation or char burning [23]. In the time-to-ignition stage, the particle heats up and the moisture evaporates until the auto-ignition temperature of the volatiles (250 -300°C) is reached, and a flame is formed indicating the onset of the volatile burning stage. Once all the volatiles are released and the particle temperature reaches about 600°C, the char oxidation stage starts which is when the fixed carbon content of the particle is oxidized. After char burning the remaining inert material is ash.

The drying (vaporization of water) and devolatilization stages are heat transfer limiting, and occur rapidly at low temperatures of the biomass material (100°C for water evaporation and between 250 to 300°C for biomass devolatilization). On the other hand, the char burning stage occurs at a much higher temperature (> 600°C) than devolatilization, and is limited by oxygen diffusion.

2.1.1 Volatile Burning

Volatile burning refers to the collective release and combustion of the light hydrocarbons present in the biomass. The commonly used model of Shafizadeh and Chin [24] assumes biomass thermally decomposes to light gases (volatiles), tar and char through three parallel reactions and tar cracking may also occur yielding additional char and gas. This devolatilization model has been verified by many researchers and is widely used in the literature [25–28]. If the temperature of the gas phase is close to the auto-ignition temperature of the volatiles (250-300°C), and oxygen is available, the volatiles burn to form a visible flame.

2.1.2 Char Burning

Char conversion is modelled as a series of heterogeneous reactions (in this case reactions involving the solid char species and a variety of gaseous species) where both reaction kinetics and transport phenomena are important. Most of the reaction mechanisms for char oxidation
available in the literature are based on the work of Evans and Emmons [29] and include the following heterogeneous reactions:

\[ C + \frac{1}{2} O_2 \rightarrow CO \]

\[ C + CO_2 \rightarrow 2CO \]

\[ C + H_2O \rightarrow CO + H_2 \]

Gomez-Barea and Lackner [30] verified that char combustion occurs in a very thin layer on the particle surface, and it is reasonable to assume that char combustion is a surface reaction.

## 2.2 Biomass Characteristics and Specifications

The biomass boiler feedstock characteristics vary depending on the source, storage, and weather conditions of the fuel. These characteristics include moisture content, wood species and size.

### 2.2.1 Moisture Content

The moisture content of biomass boiler feedstock varies between 35% and 60% and the average value is typically around 50%. Depending on the type of feedstock the average value may vary. If sludge is mixed with the feedstock, the total moisture content of the fuel entering the boiler is higher. If saw dust is mixed in, the moisture content of the feed will decrease.

Orang and Tran [31] determined that moisture content mainly impacts time-to-ignition in single particle biomass combustion. The results showed that as the moisture content of the particle increases, it takes a longer time to reach the auto-ignition temperature; therefore the appearance of the flame is delayed. The flame is present for longer for biomass with high moisture content due to lower temperatures on the particle surface. Therefore, the duration of the volatile burning stage also increases with the increase in moisture content. The char burning stage is not impacted by moisture content since at the onset of char burning, there is no more water or volatiles present in the particle. It was also hypothesized in this study that if the surface temperature of the particle is not high enough (lower than the auto-ignition temperature of the volatiles), some volatiles might escape without burning, especially for high moisture content particles where the gas phase is diluted by water vapor.
2.2.2 Wood Species

Biomass boiler feedstock originates from softwood (such as pine, cedar, and spruce) and hardwood (such as maple, oak, and poplar). Apart from cell structure, the main difference between softwood and hardwood is density. Hardwood generally has a higher density than softwood and a lower lignin content. Amaral et al. [32] compared the instantaneous burning rate of one type of hardwood and softwood biomass and concluded that softwood has a higher volatile burning rate and a lower char burning rate. Their conclusion was based only on one type of hardwood and softwood and may not have universal application. Yang et al. [33] proposed a numerical model for biomass combustion and concluded that higher material density results in higher temperature on the surface where combustion takes place and higher burning rates. They validated this model with limited experimental data. Holmgren et al. [34] studied density change during devolatilization of pine particles smaller than 1mm and concluded that density decreases during the first instances of devolatilization. They did not study density change during the char burning stage or for larger particles. Gupta et al. [35] compared the initial and char density of a softwood mixture and found that the density of the char is about 68% lower than the initial density of the mixture. The impact of wood species, especially density, on biomass combustion, as well as the implications of density change during combustion need to be further investigated.

2.2.3 Size

The size range of the feedstock is specified by the boiler manufacturer depending on the type of the fuel, target heat output and design of the boiler. One such size specification for a Detroit Stoker boiler is shown in Figure 2-1. The x-axis shows the sieve opening size and the y-axis the fraction passing through. For instance, an acceptable size range for the hog fuel mixture is when between 40-80% of the weight of the entire mixture passes through a mesh with a sieve opening of 10 mm. The specification does not identify the wood species, nor does it consider changes in boiler operation, in specific the acceptable range of flue gas velocity is not specified.
Lu et al. [36] investigated the impact of cylinder-like, flake-like and sphere-like particles with different sizes on the devolatilization rate and duration. They concluded that sphere-like particles have the highest devolatilization duration and the lowest rate due to their lower surface area to volume ratio. They, however, did not address the size change of particles during devolatilization. Holmgren et al. [34] developed an empirical model for size and shape change during rapid devolatilization based on optical particle properties. Neither of these studies includes the size change of a biomass particle through different combustion stages or for the entire duration of combustion.

Figure 2-1. Size specification for Detroit Stoker Grate boiler obtained from mill B
2.3 Particle Entrainment

Particle entrainment refers to the lifting of biomass particles by the flue gas inside the boiler. Particles which are light enough to be either lifted off of the grate or while in flight can pass through the boiler and end up as unburned carbon in the fly-ash.

Prediction of particle movement and entrainment in biomass boilers is challenging due to the variation in physical properties of the fuel. For this reason, many modeling studies do not include particle velocity calculations.

Particle trajectories are included in some CFD models [36–38]. These models do not consider the differences in wood species and therefore the density change models are generalized. Kraft et al. [39] presented a probability distribution function for solving the solid phase describing the movement of biomass particles and fluidization medium in a fluidized bed boiler. Similar to other CFD models, they do not consider density change during combustion for different types of wood species. Other numerical modeling work assumes that the particles entrained are in the char oxidation stage [40] which may not be the case depending on the particle size, since small particles may be entrained right after being injected into the boiler.

Cereijo et al. [41] presented a simplified model for the combustion of suspended particles in bagasse boilers. The model includes a calculation of particle trajectories and predictions for entrainment. The particle density values used in this simulation are empirical values based on bagasse combustion experiments for spherical and cylindrical particles.

2.4 Application of Data Analysis Techniques

Processes which collect and store large volumes of data on a regular basis, like biomass boiler operation, are well suited for optimization using data analysis techniques. Process data is measured, collected and stored for real-time control of the operation, but this data can also be used for evaluating the overall efficiency of the boiler as well as developing a better understanding of some of the relationships between operating parameters. In this section, some of the applications of data analysis techniques evaluated by other researchers are presented.
2.4.1 Soft Sensors

Due to a lack of accurate measurements for many variables in biomass combustion, many researchers have focused on developing soft sensors where desired variables can be obtained from other measured parameters using appropriate data analysis programs. Liukkonen et al. [42] developed a soft sensor for predicting the size distribution of the bottom ash in a fluidized bed boiler based on multi variable linear regression. Kortela and Jamsa-Jounela [43] used a nonlinear dynamic model based on the heat balance of the secondary superheater to predict the moisture content of the feed.

Belkhir and Frey [44] present a soft sensor for efficiency, fuel flow and flue gas properties based on mass and energy balances with the following available measured parameters: primary air, secondary air, outlet oxygen and carbon dioxide. To validate the soft sensor accuracy, they estimate the amount of steam produced from the efficiency soft sensor and compare the result to the actual steam production of a biomass boiler burning only wood chips. This soft sensor shows promising results for uniform feedstock, however since the heat content of the fuel is assumed to be constant, the results are not applicable for biomass boilers in the pulp and paper industry burning hog fuel.

2.4.2 Multivariate Analysis

Multivariate analysis has been applied to many different applications in recent years; the applications related to biomass combustion or biofuels production are included in this section.

Multivariate techniques are often used in calibration of near infrared (NIR) devices, Antti et al. [45] applied multivariate analysis to NIR spectroscopy for detection of different types of wood species of wood chips for the digester feed. Lestander and Rhen [46] present a multivariate NIR spectroscopy model for measuring moisture, ash and heat content of biofuels. Nystrom and Dahlquist [47] reported on several NIR techniques which are well suited for moisture measurements when matched with multivariate calibration. Nkansah and Dawson-Andoh [48] used multivariate analysis for detecting bulk density and chemical properties (lignin, extractives and ash content) of biomass using fluorescence spectroscopy.

Dellavedova et al. [49] have performed multivariate analysis on gasification products from biomass and found correlations between input parameters, biomass properties and process
parameters, and output parameters such as product composition. Wei et al. [50] used multivariate analysis to determine fuel properties such as calorific value, elemental analysis and ash content of biofuel derived from cassava stems. Strandberg et al. [51] applied multivariate analysis for determining elemental composition, heating value and volatile content of biomass based on thermogravimetric analysis.

The application of multivariate analysis for monitoring industrial processes has been explored in various fields and industries. Sousa et al. [52] applied multivariate analysis techniques, such as Principal Component Analysis (PCA) and $T^2$ Hoteling, to thermoelectric power generation in the steel industry. The fuels in this particular application were blast furnace gas, natural gas and tar. They found that multivariate analysis can be used to predict power production, deal with changes in set points, and assist operation and maintenance teams in optimizing plant performance.

Versteeg and Tran [53] applied Principal Component Analysis (PCA) to recovery boiler operation to predict plugging and fouling and determine operating variables that may be adjusted to minimize fouling.

### 2.5 Knowledge Gap

For the systematic investigation of the impact of hog fuel variability and operating parameters on biomass boiler performance, the following questions need to be answered:

1. What are the differences between combustion of hardwood and softwood hog fuel?
2. How does the density of the hog fuel impact combustion?
3. What is the impact of density change during combustion on boiler operation?
4. How do biomass particles change in size during combustion?
5. How can particle entrainment be minimized?
6. Is moisture content the most influential parameter in boiler performance?
7. Can moisture content be estimated based on other parameters?
8. How can data analysis tools be used to enable prediction of boiler performance?
3 Methodology

3.1 Thermogravimetric Combustor

To compare the combustion behaviors of various types of biomass samples, tests need to be carried out under the same conditions. For this purpose, a thermogravimetric (TG) combustor was constructed to handle various types of samples and provide a quantitative insight into the combustion process.

Figure 3-1a schematically shows the TG-combustor used in this study. It consists of an electrical furnace, a high precision balance, a high-definition digital camcorder, and a gas control system. The furnace is a 34 cm tall octagonal cylinder with a 5 cm side length (Figure 3-1b). It has a 10 cm × 10 cm quartz glass observation window mounted on its front wall. The furnace is placed on a sliding stand that can be moved up and down along a rigid steel frame. The sliding stand is connected to a long lever arm with a pedal at the end. By stepping on the pedal, the entire furnace assembly can be lifted up quickly and locked in a fixed position closer to the balance. It can also be lowered down to its original position by releasing the position lock. The balance, capable of measuring up to 200 g with a readability of 1 mg, is placed on a well-insulated board directly above the furnace. It is completely separated from the furnace so that the sample weight measurement will not be interfered by the furnace movement and vibration. The camcorder is mounted on a tripod 75 cm away from the furnace, with its lens zoomed on the sample in the furnace through the quartz glass window. The images and videos captured by the camcorder were calibrated based on the measured initial size of the samples.

The gas control system regulates compressed air and the air is passed through an air distributor at the bottom of the furnace. The air flow rate was set at 1 L/min for all combustion experiments.

The thermogravimetric combustor is used for experiments studying the density change during combustion (Chapter 4) and for size change during combustion (Chapter 5).
Figure 3-1. a) Thermogravimetric (TG) combustor and b) cross section of the electrical furnace
3.2 Fixed-Bed Biomass Combustor

The fixed-bed biomass combustor, shown in Figure 3-2, is a 10 cm stainless steel tube composed of a two-stage combustion zone and a flue gas cooling zone. The reactor is mounted on a mobile frame on which an electric control box and a compressed air tank are also affixed. The combustion chamber is a 50 cm section from the reactor bottom. The interior is made of stainless steel 310 tubing (cylinder), lined with a 1.5 cm thick layer of insulation brick to seal it from high combustion temperatures. Heated primary combustion air is introduced from an electric air heater through a pinhole plate placed at the bottom of the combustion chamber, and distributed evenly over the area of the cylinder. The differential pressure through the combustion chamber is measured using two Wika-Type A pressure transducers.

Above the primary combustion chamber is a 25 cm long secondary combustion zone where secondary air is introduced to complete the combustion. A compressed air tank is used to keep the pressure of both primary and secondary air flows constant. A glass window on the side of the reaction chamber allows visual monitoring of the combustion zone. Above the secondary combustion section is the flue gas cooling zone, which extends to a total length of 1.3 m. It consists of a vertical 0.7 m section followed by a 0.6 m horizontal section. At the end of the flue gas cooling zone, a cyclone is used to capture ash particles before the flue gas exits into the fume hood. The combustion zones are insulated with a 13 cm thick layer of aluminosilicate insulation brick while the flue gas cooling section is insulated with an 8 cm thick layer of insulation brick.

The flue gas is sampled before exiting through the fume hood and sent to the flue gas analyzers. K-type thermocouples (TC) are used at different locations as shown in Figure 3-2. The water content of the flue gas is measured using a MAC125 Moisture Analyzer with a measurement range of 0 to 60% by volume; the carbon monoxide and oxygen content are measured using a Teledyne AI Max 5 Analyzer, and the measurement ranges are 0-1000ppm and 0-25 wt% for carbon monoxide and oxygen respectively.
The biomass combustor in fixed-bed mode is used in experiments comparing hardwood and softwood combustion described in Chapter 4, and validating the entrainment model in Chapter 6.

3.3 Steady State Heat and Mass Balance

A steady state heat and mass balance is constructed for the entire biomass boiler system, the details of which are outlined in the following sections.

3.3.1 Inlet/outlet conditions and energy losses

To evaluate boiler performance, a steady state heat and mass balance is constructed as shown in Figure 3-3.
Figure 3-3. Heat and mass balance for biomass boiler

The control volume is shown by dashed lines in Figure 3-3. Entering into the control volume is biomass, fossil fuels, air and feedwater, where:

- $F_B$ (kg/h) is the biomass flow rate on a wet basis,
- $MC_B$ (%) is the moisture content of the biomass on a wet basis,
- $HHV_B$ (kJ/kg) is the higher heating value of the biomass,
- $x_C$ is the mass fraction of carbon in the dry biomass,
- $x_H$ is the mass fraction of hydrogen in the dry biomass,
- $x_S$ is the mass fraction of sulphur in the dry biomass,
- $x_N$ is the mass fraction of nitrogen in the dry biomass,
- $x_O$ is the mass fraction of oxygen in the dry biomass,
- $x_{\text{ash}}$ is the mass fraction of ash in the dry biomass,
- $F_{\text{NG}}$ (kg/h) is the flow rate of natural gas with HHV$_{\text{NG}}$ (kJ/kg) higher heating value,
- $F_{\text{oil}}$ (kg/h) is the flow rate of fuel oil with HHV$_{\text{oil}}$ (kJ/kg) higher heating value,
- $F_{\text{air}}$ (kg/h) is the flow rate of air with $T_{\text{air}}$ ($^\circ$C) temperature and MC$_{\text{air}}$ (%) moisture content,
- $F_{\text{w}}$ (kg/h) is the feedwater flow rate with $T_{\text{w}}$ ($^\circ$C) temperature and $P_{\text{w}}$ (kPa) pressure.

Exiting the control volume are steam, blowdown, ash, and flue gas, where:
- $F_{s}$ (kg/h) is superheated steam flow rate with $T_{s}$ ($^\circ$C) temperature and $P_{s}$ (kPa) pressure,
- $F_{\text{Bl}}$ (kg/h) is the blowdown flow rate with $P_{\text{Bl}}$ (kPa) pressure,
- $F_{\text{ash}}$ (kg/h) is the flow rate of ash with $T_{\text{ash}}$ ($^\circ$C) temperature,
- $F_{\text{FG}}$ (kg/h) is the flow rate of flue gas with $T_{\text{FG}}$ ($^\circ$C) temperature,
- $x_{\text{CO2}}$ is the mass fraction of carbon dioxide in the flue gas,
- $x_{\text{CO}}$ is the mass fraction of carbon monoxide in the flue gas,
- $x_{\text{H2O}}$ is the mass fraction of water vapor in the flue gas,
- $x_{\text{SO2}}$ is the mass fraction of sulphur dioxide in the flue gas,
- $x_{\text{O2}}$ is the mass fraction of oxygen in the flue gas,
- $x_{\text{N2}}$ is the mass fraction of nitrogen in the flue gas.

From the mass balance, the flue gas composition can be calculated when the ultimate analysis of the fuel is available, with the following equations:

$$F_{\text{CO2}} = F_{\text{FG}}x_{\text{CO2}} = \frac{44}{12}F_{\text{B}}x_{\text{C}}(1 - \frac{MC_{\text{B}}}{100})$$  \hspace{1cm} (1)

$$F_{\text{H2O}} = F_{\text{FG}}x_{\text{H2O}} = \frac{36}{4}F_{\text{B}}x_{\text{H}}(1 - \frac{MC_{\text{B}}}{100}) + \left(F_{\text{B}}\frac{MC_{\text{B}}}{100} + F_{\text{air}}\frac{MC_{\text{air}}}{100}\right)$$  \hspace{1cm} (2)

$$F_{\text{SO2}} = F_{\text{FG}}x_{\text{SO2}} = \frac{64}{32}F_{\text{B}}x_{\text{S}}(1 - \frac{MC_{\text{B}}}{100})$$  \hspace{1cm} (3)

$$F_{\text{N2}} = F_{\text{FG}}x_{\text{N2}} = \frac{28}{14}F_{\text{B}}x_{\text{N}}(1 - \frac{MC_{\text{B}}}{100}) + 0.77F_{\text{air}}$$  \hspace{1cm} (4)
\[ F_{O_2} = F_{FG}x_{O_2} = \frac{32}{16}F_Bx_0(1 - \frac{MC_B}{100}) + 0.23F_{air} - \left( \frac{32}{12}F_Bx_C + \frac{32}{4}F_Bx_H + F_Bx_S \right)(1 - \frac{MC_B}{100}) \] (5)

where \( F_i \) (kg/h) is the total flow rate of each flue gas compound with \( i = \text{CO}_2, \text{H}_2\text{O}, \text{SO}_2, \text{N}_2 \) and \( \text{O}_2 \). The heat balance is shown in the following equation:

\[
F_B \left(1 - \frac{MC_B}{100}\right)HHV_B + F_{NG}HHV_{NG} + F_{oil}HHV_{oil} + F_wH_{TwP_w} + F_{air}C_{p_{air}}T_{air} = F_{Bl}H_{P_{Bl}} + F_sH_{T_sP_s} + F_{FG}C_{p_{FG}}T_{FG} + F_{ash}C_{p_{ash}}T_{ash} \] (6)

where \( C_p \) (kJ/kg\(^\circ\)C) is the specific heat capacity of each compound and \( H_{T_P} \) (kJ/kg) is the enthalpy of each compound at temperature T and pressure P.

Energy losses used to calculate efficiency are listed in Figure 3-4, where:

- \( Q_1 \) (kJ/h) is the heat content of the fuel (biomass, natural gas and oil),
- \( Q_2 \) (kJ/h) is the heat content of combustion air entering the boiler,
- \( Q_3 \) (kJ/h) is the feedwater heat content,
- \( Q_4 \) (kJ/h) is the heat content of the dry flue gas exiting the boiler,
- \( Q_5 \) (kJ/h) is the heat content of the water vapor in the flue gas,
- \( Q_6 \) (kJ/h) is the heat loss due to water vapor in the air,
- \( Q_7 \) (kJ/h) is the heat loss due to unburned carbon left in the ash,
- \( Q_8 \) (kJ/h) is the radiation heat loss,
- \( Q_9 \) (kJ/h) is the heat loss due to incomplete combustion,
- \( Q_{10} \) (kJ/h) is the sensible heat of fly-ash,
• $Q_{11}$ (kJ/h) is the unaccounted heat losses, and
• $Q_{12}$ (kJ/h) is the heat content of steam.

**Figure 3-4. Energy input and output for biomass boiler**

Heat and mass balances are used in Chapter 7 for developing the moisture content soft sensor.

### 3.3.2 Performance and Efficiency Prediction

Based on the parameters shown in Figure 3-4, the efficiency of the boiler, $\eta$, is calculated from the percentage of energy used for steam production over the total energy from the fuel and combustion air, which is the following equation:

$$\eta = \frac{Q_{12} - Q_3}{Q_1 + Q_2} \times 100$$  \hspace{1cm} (7)

Thermal performance (TP) is a measure for boiler efficiency and it does not take into consideration parameters such as manufacturer’s loss margin, therefore eliminating the
differences in boiler design and only requiring the properties of the superheated steam and the fuel:

\[ TP = \frac{F_s}{F_B} \]  

The relationship between TP and other parameters is discussed in detail in Chapter 7.

### 3.4 Multivariate Analysis

Multivariate Analysis (MVA) is a statistical method used for the analysis of datasets which contain more than one variable; it is especially well suited when the variables are highly correlated. Principal Component Analysis (PCA) and Partial Least Squares Analysis (PLS) are two MVA methods used in this research. The main challenges associated with working with large amounts of data is dealing with dimensionality, multicollinearity, noise, and missing data. PCA and PLS methods are suitable for handling these challenges [54]. A detailed description of both methods can be found in Erikson et al. [55] and a brief background on PCA and PLS is presented here.

#### 3.4.1 Principal Component Analysis (PCA)

Principal components (PCs) are linear combinations of all the variables in a given dataset and are obtained based on matrix algebra calculations. First the data is organized into a series of columns and rows which make the dataset. The columns in this dataset correspond to the variables, here biomass boiler operating parameters, and the rows correspond to individual observations (Figure 3-5).
Initially each observation exists in a p-dimensional space, where p is the number of variables in the dataset (Figure 3-6a). For instance, if the dataset consists of 20 variables, each observation would exist in a 20-dimensional space. The purpose of PCA is to find a plane (in 2 dimensions) or a hyperplane (in more than 2 dimensions) that would exist in the p-dimensional space, such that when the observations are projected on this (hyper)plane (Figure 3-6b) the overall variability in the observations is maximized. The resulting plot, which is defined by the PCs, is the score plot (Figure 3-6c).

Principal components are specific linear combinations of p random variables $X_1, X_2, X_3, \ldots, X_p$ where these linear combinations represent a selection of a new coordinate system resulting from the rotation of the original system with $X_1, X_2, X_3, \ldots, X_p$ as the coordinate axes. The new axes are a representation of the direction with the maximum variability and give a simpler description of the covariance structure.

Principal components depend only on the covariance matrix $\Sigma$ of $X_1, X_2, X_3, \ldots, X_p$ and do not require a multivariate normal assumption. For the random vector $X^*=[X_1, X_2, X_3, \ldots, X_p]$ with covariance matrix $\Sigma$ and eigen values $\lambda_1 \geq \lambda_2 \geq \lambda_3 \geq \ldots \geq \lambda_p \geq 0$, the principal components are the uncorrelated linear combinations $PC_1, PC_2, PC_3, \ldots, PC_p$ with $\text{Var}(PC_i)$ as large as possible. Therefore, the $i^{th}$ principal component is:

$$PC_i = e_{i1}X_1 + e_{i2}X_2 + e_{i3}X_3 + \cdots + e_{ip}X_p \quad i = 1,2,3,\ldots, p \quad (9)$$
With:

\[ \text{Var} (PC_i) = e_i^2 \Sigma_i = \lambda_i \quad i = 1,2,3, ..., p \]  

\[ \text{Cov} (PC_i, PC_k) = e_i^2 \Sigma_{ik} = 0 \quad i \neq k \]  

The magnitude of \( e_{ik} \) measures the importance of the \( k \)th variable to the \( i \)th principal component, regardless of the other variables, and \( e_{ik} \) is proportional to the correlation coefficient between \( PC_i \) and \( X_k \) [56].

### 3.4.2 Partial Least Square (PLS)

PLS regression is a combination of PCA and multiple linear regression with the goal of analyzing or predicting a set of dependent variables from a set of independent variables or predictors. The objective of PLS regression is to predict \( Y \) from \( X \) and to explain their common structure (Figure 3-7).

![Figure 3-7. Data organization in PLS](image)

In PLS regression, the \( X \) and \( Y \) matrices are decomposed as a product of a common set of scores and a set of loadings:
\[ X = TP^T \]  \hspace{1cm} (12)

where \( T \) is the score matrix containing the latent variables \( t \), and \( P \) is the loading matrix, and \( Y \) is estimated as:

\[ Y = TBC^T \]  \hspace{1cm} (13)

where \( B \) is a diagonal matrix with the regression weights \( w \) as diagonal elements and \( C \) is the weight matrix of the dependent variables. In order to determine \( T \), two sets of weights \( w \) and \( c \) need to be found to create linear combinations of the columns of \( X \) and \( Y \) in such a way that these two linear combinations have maximum covariance. The first pair of vectors are obtained by:

\[ t = Xw \]  \hspace{1cm} (14)

\[ u = Yc \]  \hspace{1cm} (15)

where \( t^Tu \) is maximal. After the first latent vector is found, it is subtracted from \( X \) and \( Y \), and these steps are repeated until \( X \) becomes a null matrix \([57]\).

The main difference between PCA and PLS is that the PCs in PCA find the maximum variability in a dataset by projecting the observations onto a (hyper)plane, whereas PLS finds the maximum covariance between the input and output variables.

### 3.4.3 Analysis of Plots

The software SIMCA 15 is used in this work for the iterative process of PCA and PLS, and the analysis of the results is done through several plots which are explained in this section.

The score scatter plot displays \( t_1 \) vs \( t_2 \) (the first latent variable \( t \) plotted against the second latent variable) along with the confidence ellipse based on Hoteling \( T^2 \), which is a multivariate version of Student’s \( t \)-test, with significance level 0.05. Observations situated outside the ellipse are considered to be outliers as explained by the PLS model. The observations closest to the origin of this plot, are closer to average values across all \( X \) variables.
Loading plots display the correlation structure of the variables and they show the importance of the X variable in the approximation of the X matrix. In PLS models, \( w^*c \) is plotted, where \( w^* \) is the weight that combines the original X variables to form the scores t. Plotting the X weight \( w^* \) and Y weight \( c \) in the same plot displays the correlation structure between X and Y which is used for interpretation of how the X and Y variables combine in the projection and how the X variables relate to the Y variables. Variables with large \( w^* \) or \( c \) values are situated far away from the origin, on the positive or negative side, and X variables with large values in \( w^* \) are highly correlated with Y.

Interpreting a PLS model with many components and a multitude of responses can be a complex task. A parameter which summarizes the importance of the X variables, both for the X and Y models, is the Variable Influence on Projection, VIP. For PLS, VIP is a weighted sum of squares of the PLS weights, \( w^* \), which also considers the amount of explained Y variance in each dimension. For a given model and problem there will always be only one VIP vector, summarizing all components and Y variables. One can compare the VIP of one term to the others. Terms with large VIP, larger than 1, are the most relevant for explaining Y.

The VIP values describe the importance of terms in the model both with respect to Y, i.e. its correlation to all the responses, and with respect to X (the projection).

For each Y variable SIMCA computes regression coefficients. These express the relation between the Y variables and all the terms in the model. The regression coefficients relate to the centered and scaled data, and are plotted in the coefficient plot.

MVA is used in Chapter 7 to study the relationship between boiler parameters and to determine the most influential operating parameters on thermal performance, and in Chapter 8 to build a predictive statistical model for determining thermal performance.
4 Effect of Wood Species on Combustion

There are two groups of wood species: softwoods and hardwoods. Softwoods are conifers which are evergreen species, such as cedar, pine, and spruce. Hardwoods are angiosperms which change color and lose their leaves every fall such as maple, oak, and poplar. The pulp produced from each wood species has particular qualities, for example softwood pulp yields a stronger product where as hardwood pulp is softer. Softwood pulp also contains longer fibers than hardwood pulp, so softwood pulp is stronger (more bonds made with other fibers) while hardwood pulp is smoother when used in a sheet. Depending on the pulp production at the mill, hog fuel wood species will vary. In this chapter, the impact of wood species on combustion is discussed.

4.1 Elemental Analysis

Biomass is mainly composed of carbon, hydrogen, and oxygen, with trace amounts of sulphur and nitrogen. The elemental composition of the fuel has a direct impact on the heating content and flue gas composition as seen in the mass balance presented in Section 3.3. For example higher carbon content results in higher heating value and higher CO₂ concentration in the flue gas if enough oxygen is available for complete combustion.

Hog fuel samples were received from mill B and the elemental composition of the hardwood and softwood mixes are shown in Figure 4-1. The softwood hog fuel has higher carbon content and therefore higher heating value.
In order to see differences between softwood and hardwood hog fuel in continuous combustion, experiments were carried out in the fixed-bed biomass combustor discussed in Section 3.2. Softwood and hardwood fuel mixtures were first oven dried, then fed into the combustor at 1 kg/h and the primary air flow rate was increased from 3.1 to 4.3 m³/h by 0.3 m³/h increments. The results are shown in Figure 4-2, where the temperatures along the fixed-bed biomass combustor (TC1, TC2, and TC3) are shown, for softwood and hardwood combustion with varying primary air flow rate. For all primary air flow rate values, the temperature from softwood combustion is higher than that of hardwood combustion which is expected since the heating value of softwoods are higher than that of hardwoods.

![Figure 4-1 Elemental analysis of hog fuel received from mill B](image-url)
Figure 4-2. Temperature of biomass combustor at different zones for combustion of softwood and hardwood

4.2 Particle Density

Different wood species have varying initial densities. Figure 4-3 shows the initial density of the wood species examined in this study. To measure density, the weight of each sample was divided by the volume, which was determined by volume displacement in sand. Hardwoods generally have a higher initial density than softwoods.
During combustion, particles become lighter as well as shrink in size. To study density change during combustion, cubic samples were prepared and burned at 800°C in the TG combustor. Figure 4-4 (from left to right) shows a pine cube at the start of combustion (time = 0s), during the volatile burning stage (time = 25s), and during the char burning stage (time = 1m 5s).

Figure 4-3. Initial particle density of oven dried hardwood and softwood samples

Figure 4-4. Combustion of oven-dried pine at 800°C (time in mm:ss)
The weight change profile of the particle during combustion was obtained from the balance. Figure 4-5a shows the weight change profile for a cubic pine sample with 0% moisture content burning at 800°C. The first minute of combustion is the volatile burning stage and the remaining three minutes is the char burning stage for this particle. Based on the slope of the weight change profile in these two stages, volatile burning is more rapid compared to char burning.

The volume change profile for combustion of pine at 800°C is shown in Figure 4-5b. The volume decreases during both the volatile burning and char burning stages. The volume change during the volatile burning stage is more rapid than the char burning stage.

From the weight and volume change data, the density change of the pine cube during combustion is calculated and the results are shown in Figure 4-5c. During the first minute of combustion (volatile burning stage) the density drops rapidly to about 75-80% of the initial value. During the char burning stage, the density of the particle continues to decrease but at a lower rate. This implies that during the volatile burning stage, the weight loss is greater than the volume loss, resulting in a sharp decrease in density. During the char burning stage on the other hand, the decrease in mass and volume occur at a similar rate; therefore the density decrease is slower.
Figure 4-5. Combustion of oven-dried pine at 800°C a) weight change b) volume change c) density change
Figure 4-6 shows the density change of different oven-dried wood species during combustion for three hardwood samples (maple, oak and poplar), and three softwood samples (spruce, pine and cedar). During the first two minutes of combustion, there is a sharp decrease in density for all wood species and this decrease is consistent with the amount of volatile released during the devolatilization stage. The density change during volatile burning is faster compared to that of char burning. Depending on the flue gas velocity, the sharp decrease in density during the early stages of combustion may cause the biomass to become light enough to be entrained in the flue gas.

Figure 4-6. Density change during combustion at 800°C for different wood species
4.3 Bulk Density

The bulk density of a hog fuel mixture depends not only on the wood species and the particle density associated with that specific wood species, but also on the size and shape of the mixture which depends on fuel preparation. In this study, the bulk density of oven-dried hog fuel mixtures was determined. The mixtures were identified only as hardwood and softwood. The exact wood species were not known. The mixtures were continuously fed into the lab-scale fixed bed combustor. The combustion residues (a mixture of char and ash) were collected from the bottom of the cyclone after each experiment.

Figure 4-7 compares the bulk density of oven-dried biomass, char and ash mixtures with comparable particle sizes for softwoods and hardwoods. Similar to particle density, hardwoods generally have a higher initial bulk density than softwoods. Moreover, the combustion residue (char and ash) from hardwood combustion has a consistently higher bulk density than that from softwood combustion. The observed difference in ash density results in hardwood ash that would occupy only about half the volume of softwood ash.

![Figure 4-7. Bulk density of biomass, char and ash for hardwood and softwood hog fuel.](image-url)
The density of the mixture is different depending on the amounts of ash and unburned char in the mixture. Figure 4-8 shows hardwood and softwood ash density with increasing char content. Since char density is lower than ash density, when the char content of the mixture is higher, the density of it is lower. For a given char content, the density of char and ash mixtures from burning hardwoods is higher than that obtained from burning softwoods.

Figure 4-8. Impact of carbon content on the density of mixtures of char and ash
4.4 Particle Density Modeling

The material studied experimentally thus far in this chapter is the solid phase of the biomass during combustion. To model density change during combustion, the principles of conservation of mass are applied to an infinitesimally small control volume within the solid phase of the biomass [58] as shown in Figure 4-9.

![Diagram of control volume for conservation of mass equations during combustion of biomass cube with length L](image)

**Figure 4-9. Control volume for conservation of mass equations during combustion of biomass cube with length L**

Equation 16 and 17 show the general concept of conservation of mass applied to the control volume.

\[
\begin{align*}
\text{rate of mass change in control volume} & = \text{mass flow rate into control volume} - \text{mass flow rate out of control volume} + \text{rate of mass generation or consumption due to reactions} \\
\frac{dm}{dt} & = \dot{m}_{\text{in}} - \dot{m}_{\text{out}} + \dot{m}_{\text{reaction}}
\end{align*}
\]
Where \( m \) denotes the mass of a substance in the control volume, \( \dot{m}_{\text{in}} \) and \( \dot{m}_{\text{out}} \) are the mass flow rates into and out of the control volume respectively, and \( \dot{m}_{\text{reaction}} \) is the rate of generation (positive) or consumption (negative) of mass due to chemical reactions in the control volume. Mass flow rate is equal to the density of the substance multiplied by the volumetric flow rate, and the volumetric flow rate can be written as the velocity of the substance multiplied by the cross-sectional area. Assuming that mass enters the control volume at \( x, y \) and \( z \) and exits at \( x + dx, y + dy \) and \( z + dz \), the mass flow rates flowing in and out of the control volume can be written as equations 18 and 19:

\[
\dot{m}_{\text{in}} = \rho u|_{x} \ dy \ dz + \rho v|_{y} \ dx \ dz + \rho w|_{z} \ dx \ dy
\]  (18)

\[
\dot{m}_{\text{out}} = \rho u|_{x+dx} \ dy \ dz + \rho v|_{y+dy} \ dx \ dz + \rho w|_{z+dz} \ dx \ dy
\]  (19)

In the above equations \( u, v, \) and \( w \) are velocities in the \( x, y, \) and \( z \) direction respectively. The rate of mass change from chemical reactions can be written in terms of the rate of reaction per unit volume (\( R \)) multiplied by the volume of the control volume:

\[
\dot{m}_{\text{reaction}} = R \ dx \ dy \ dz
\]  (20)

The mass of the substance can be expressed as its density \( \rho \) multiplied by the volume of the control volume:

\[
\frac{dm}{dt} = \frac{d\rho}{dt} \ dx \ dy \ dz
\]  (21)

Substituting equations 18-21 back into equation 17 and dividing both sides by \( dx \ dy \ dz \):

\[
\frac{\partial \rho}{\partial t} = \frac{\rho u|_{x} - \rho u|_{x+dx}}{\partial x} + \frac{\rho v|_{y} - \rho v|_{y+dy}}{\partial y} + \frac{\rho w|_{z} - \rho w|_{z+dz}}{\partial z} + R
\]  (22)

Taking the limit as \( dx, dy \) and \( dz \) approach zero, the governing equation for the conservation of mass is achieved:
\[
\frac{\partial \rho}{\partial t} = - \left( \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} \right) + R
\]  

(23)

where \( \frac{\partial \rho}{\partial t} \) denotes the change in mass concentration or density \( \rho \) of a substance with time \( t \), \( \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} \) denote the convective flux of the substance in the \( x, y \) and \( z \) directions with velocity \( u, v \) and \( w \) respectively, and \( R \) denotes the reaction term which is the rate of generation or consumption of the substance per unit volume due to chemical reactions.

To capture the density change of the solid phase during the entire combustion reaction, the governing equation for the conservation of mass (equation 23) is applied to the solid phase. In the case of combustion of a motionless biomass sample, the velocity component in all directions is zero \( (u = 0, v = 0, w = 0) \), therefore the convective flux terms are equal to zero.

The chemical reactions taking place in the solid phase depend on the different stages of biomass combustion: biomass devolatilization, char generation and burning. The contribution of these combustion stages must be included in the reaction term \( R \), i.e. \( R \) equals the rate of reaction of biomass devolatilization \( r_b \), plus the rate of reaction of char generation and burning \( r_c \). The contribution of ash is ignored since ash concentration is low for most biomass species. With these assumptions, the governing equation for conservation of mass in the solid phase during combustion becomes \([33, 59]\):

\[
\frac{\partial \rho_s}{\partial t} = r_b + r_c
\]  

(24)

where \( \rho_s \) is the mass concentration of the solid phase which is also equal to the apparent density of the sample, \( r_b \) is the reaction rate for biomass devolatilization, and \( r_c \) is the reaction rate for char generation and char burning. Solving this equation will provide the density of the solid phase for any \( t \) during combustion without the need to explicitly determine the combustion stage.
Biomass devolatilization, char generation and char burning are assumed to be first-order reactions. To obtain the reaction rates, the change in mass concentration of each stage (biomass and char) is modelled by applying the conservation of mass as shown below [60].

\[
\frac{\partial \rho_b}{\partial t} = r_b = -k_b \rho_b
\]

(25)

\[
\frac{\partial \rho_c}{\partial t} = r_c = k_{c1} \rho_b - k_{c2} \rho_c
\]

(26)

where \( \rho_b \) is the mass concentration of uncreated biomass, \( k_b \) is the kinetic constant for biomass devolatilization, \( \rho_c \) is the mass concentration of char, and \( k_{c1} \) and \( k_{c2} \) are the kinetic constants for char generation and char burning respectively. The boundary conditions are outlined below.

At \( t = 0 \), \( \rho_b = \rho_0 \)

(27)

At \( t = 0 \), \( \rho_c = 0 \)

(28)

where \( \rho_0 \) is the initial biomass density. Equations 25 and 26 are solved with boundary conditions 27 and 28:

\[
\rho_b = \rho_0 e^{-k_b t}
\]

(29)

\[
\rho_c = \frac{k_{c1} \rho_0}{k_{c2} - k_b} (e^{-k_b t} - e^{-k_{c2} t})
\]

(30)

Substituting Equations 29 and 30 back into Equation 24 and differentiating with the initial condition at \( t = 0 \), \( \rho_s = \rho_0 \), the density of the solid phase during combustion can be obtained from the following equation:

\[
\rho_s = \rho_0 \left( \frac{k_{c1} + k_{c2} - k_b}{k_{c2} - k_b} e^{-k_b t} - \frac{k_{c1}}{k_{c2} - k_b} e^{-k_{c2} t} \right)
\]

(31)

Here, the initial biomass density (\( \rho_0 \)) can be measured directly. The kinetic constants (\( k_b, k_{c1} \)) are determined experimentally (calculations in Appendix A) and the results are shown in Figure 4-10 and Figure 4-11. For the kinetic constant for char oxidation \( k_{c2} \), the value \( 1.9 \times 10^{-3} \text{ s}^{-1} \) is
used which is commonly used in the literature for char oxidation of different types of biomass [61].

Figure 4-10. Kinetic constant $k_b$ for different types of wood species combustion at 800°C

Figure 4-11. Kinetic constant $k_{c1}$ for different types of wood species combustion at 800°C
Figure 4-10 and Figure 4-11 show that for biomass samples with a higher initial density, the values for $k_0$ and $k_{c1}$ are higher. It is also clear that both kinetic constants are generally higher for softwoods than they are for hardwoods, this might be due to the presence of pores and vessels in the hardwood structure, resulting in smaller available surface area for the surface reaction of oxygen [62].

Comparing the kinetic constants to values from [63], it is observed that the volatile burning kinetic constant are in a similar range ($0.01 – 0.02$ $1/s$) with the assumption that volatile burning occurs at an average temperature of $500^\circ$C. The kinetic constant for char formation is reported as $0.0014$ $1/s$ for $900^\circ$C which is close to the lower limit of experimental values found in this work.

Based on Equation 31 with kinetic constants obtained from Figure 4-10 and Figure 4-11, the density change for different types of wood species is determined and the results for a hardwood (maple) and a softwood (spruce) are shown in Figure 4-12 and Figure 4-13.

![Figure 4-12. Density change comparison of model results and experiments for combustion of different sample weights of maple at $800^\circ$C](image)
Based on the figures above, the model is in good agreement with experimental values, both for the softwood and the hardwood example. At the beginning of combustion, the density of the solid phase is equal to the unreacted biomass density. As devolatilization takes place, the unreacted biomass concentration decreases and char is generated. Towards the end of combustion, the solid phase is made entirely of char and at the end of combustion what remains is ash. During the transition between devolatilization and char burning, the solid phase includes both uncreated biomass in the middle of the sample, and char on the outer layers. The density change model captures the devolatilization and char burning stage, as well as the transition between the stages with one equation.

Cubic particles were used in this section to determine the kinetic constants experimentally, and their size ranged in length from 0.5 cm to 2 cm. For other particle sizes, the kinetic constants need to be determined experimentally.
The model described in this section is applicable for thermally thick biomass particles with Biot number ranging from 1 to 100. The Biot number is the ratio of the resistance to heat transfer from outside of the particle due to convection to the resistance inside the particle due to thermal conduction:

$$\text{Bi} = \frac{h L}{k_{\text{cond}}}$$ (32)

Where $h$ is the convective heat transfer coefficient, $L$ is the characteristic length of the particle and $k_{\text{cond}}$ is the thermal conductivity of the particle. When $\text{Bi} \ll 1$, the particle is thermally thin, meaning that the resistance to conduction within the material is much smaller than the resistance to convective heat transfer from the outside. In this case, the temperature inside the particle is uniform. When $\text{Bi} > 1$, the particle is thermally thick, meaning that there is a temperature gradient within the particle, this will cause the outer layers of the particle to be at a higher temperature compared to the inner layers, resulting in different combustion stages taking place within the particle, i.e. char burning on the outer layers and devolatilization in the inner layers.

The results of density change for all wood species studied can be found in Appendix B.
5  Size Change of Particles during Combustion

The size distribution of biomass feedstock has an impact on boiler operation; larger particles take longer to burn and smaller particles may become too light and be entrained in the flue gases. Therefore, the optimum size range of the fuel depends on boiler operation as well as the required residence time for complete combustion. In this chapter, the size change of oven-dried biomass particles during combustion is studied. Combustion takes place on the surface of the biomass particle, and there is an unreacted core which shrinks in size. Therefore the shrinking core model can be applied to model size change during biomass combustion.

5.1 Shrinking Core Model

Most studies on biomass combustion are based on spherical biomass samples [40, 60- 61]. In this study cubic samples were considered since they are closer to the actual shape of hog fuel. A shrinking core model is applied for the size change of the particle assuming that the combustion reaction occurs only at the cube surface, and inside the cube there is an unreacted cubic core. As the combustion reaction takes place, the particle shrinks in size and what is left behind is an ash layer. As combustion takes place, this ash layer grows.
For the combustion reaction to take place, oxygen needs to reach the surface of the sample. This means that oxygen must first diffuse through the fluid film surrounding the cube surface, then diffuse through the porous ash layer to reach the unreacted core, as shown in Figure 5-1.

A mass balance for oxygen is constructed to determine the change in core length, $l_c$, with time. At pseudo steady state conditions, the diffusion of oxygen through the fluid film equals the diffusion of oxygen through the porous ash layer which equals the reaction of oxygen on the particle surface:
\[
K_0(C_O - C_{\text{ash}}) \cdot 6L^2 = \frac{6D}{\left(\frac{1}{L_c} - \frac{1}{L}\right)} (C_{\text{ash}} - C_{\text{surface}}) = k_b C_{\text{surface}} 6l_c^2
\]

where \(K_0\) is the mass transfer coefficient for oxygen through the gas boundary layer, \(C_O\) is the concentration of oxygen in the bulk, \(C_{\text{ash}}\) is the concentration of oxygen on the ash surface, \(L\) is the total initial length of the cube, \(l_c\) is the length of the cube during combustion or the core length, \(D\) is the diffusivity of oxygen in the ash layer, \(C_{\text{surface}}\) is the concentration of oxygen on the particle surface, and \(k_b\) is the biomass combustion reaction constant.

Assuming oxygen diffusion through the ash layer is the rate limiting step, which is also shown in other studies [64–67], Equation 33 can be simplified. The derivation of the oxygen diffusion term is explained in Appendix C.

The reaction rate on the sample surface occurs very rapidly, therefore oxygen concentration on the surface of the sample \((C_{\text{surface}})\) is essentially zero. Also oxygen diffusion through the fluid film is very fast that \(C_O\) is approximately equal to \(C_{\text{ash}}\). The rate of consumption of oxygen equals the consumption of biomass, as shown in Equation 34:

\[
\frac{6DC_O}{\left(\frac{1}{L_c} - \frac{1}{L}\right)} = - \frac{d(\rho_s V)}{dt} = - \frac{d(\rho_s l_c^3)}{dt}
\]

To verify the assumption made, that the rate limiting step is oxygen diffusion through the ash layer, the density change of the particle during combustion is ignored for now. The resulting equation can be solved algebraically:

\[
\frac{6DC_O}{\left(\frac{1}{L_c} - \frac{1}{L}\right)} = - 3\rho_0 l_c^2 \frac{dl_c}{dt}
\]

Equation 35 is rearranged to Equation 36:

\[
- \frac{dl_c}{dt} = \frac{2C_O/\rho_0}{(L - l_c)l_c} \frac{1}{LD}
\]
Equation 36 is integrated and rearranged to Equation 37:

$$t = \frac{\rho_0 L^2}{2DC_o} \left( 1 - 3 \left( \frac{L_c}{L} \right)^2 + 2 \left( \frac{L_c}{L} \right)^3 \right)$$  (37)  

From this, the total time for biomass combustion, $t_{\text{total}}$, can be calculated as shown in Equation 38.

$$t_{\text{total}} = \frac{\rho_0}{2DC_o} L^2$$  (38)  

The linear relationship between $t_{\text{total}}$ and $L^2$ is linear as shown in Equation 38, this can be used to validate the assumption for the rate limiting step. Figure 5-2 shows the experimental results for this relationship. The experimental total combustion time is measured from the insertion of the dry sample into the TG combustor until the end of combustion when the sample stops glowing. The total combustion duration and $L^2$ have a linear relationship for varying sizes and wood species, therefore the assumption for the rate limiting step is valid.

![Figure 5-2. Assumption verification for a shrinking core model](image-url)
To validate the assumption that oxygen diffusion through the ash layer is the rate limiting step, the impact of density change during combustion was ignored. However as discussed in detail in Chapter 4, the particle density decreases during combustion. To have a more accurate model to predict the change in length during combustion, Equation 34 is differentiated again, this time considering density change during combustion:

\[
\frac{6DC_0}{\left(\frac{1}{L_c} - \frac{1}{L}\right)} = l_c^3 \frac{dp_s}{dt} + 3l_c^2 \rho_s \frac{dl_c}{dt}
\]

(39)

The expressions for \(\rho_s\) and \(\frac{dp_s}{dt}\) obtained in Chapter 4 are substituted into Equation 39, and rearranged to:

\[
\frac{dl_c}{dt} = \frac{6DC_0 - l_c \left( \frac{k_b k_{c2}}{k_{c2} - k_b} e^{-k_{c2}t} - \frac{\rho_0 k_b (k_{c1} + k_{c2} - k_b)}{k_{c2} - k_b} e^{-k_b t} \right)}{3 \rho_0 \left( \frac{k_{c1} + k_{c2} - k_b}{k_{c2} - k_b} \right) e^{-k_{c2} t} - \frac{3 \rho_0 k_b}{k_{c2} - k_b} e^{-k_b t}}
\]

(40)

Equation 40 is solved numerically using Euler’s method. The results are shown in Figure 5-3.
Figure 5-3. Change in side length of a cubic particle of poplar during combustion at 800°C with initial length of 1.5cm

5.2 Model Validation

Equation 40 can be used to determine the change in length of a cubic particle of known initial density during combustion. To validate this model, experiments are carried out in the TG combustor described in Section 3.1. The length of the particles is measured from the recorded video during combustion and validated against the calculated values from the shrinking core model.
Figure 5-4. Modeling and experimental results for length change of aspen during combustion at 800°C with different initial lengths
Figure 5.5. Modeling and experimental results for length change of poplar during combustion at 800°C with different initial lengths.
Figure 5-6. Modeling and experimental results for length change of spruce during combustion at 800°C with different initial lengths

The model results are in good agreement with experimental observations for different cube lengths and wood species.
6 Particle Entrainment Model

Thus far, the change in particle density and size during biomass combustion have been discussed. The density decreases rapidly during the first minutes of combustion making particles more susceptible to be entrained in the flue gases. In this chapter, entrainment experiments performed in the fixed biomass combustor are discussed first. An entrainment model is then presented for calculating the entrainment velocity for cubic particles of a given wood species. The equations for density change and length change during combustion, developed in the previous chapters, are used in this model.

6.1 Entrainment Experiments

Entrainment experiments were carried out in the fixed-bed biomass combustor, which was described in Section 3.2, to establish a relationship between primary air flow rates, total fly-ash collected, carbon in the fly-ash, and flue gas velocity. Hardwood and softwood hog fuel mixtures, received from mill E, were oven dried then burnt, at a fuel flow rate of 1 kg/h, and a primary air flow rate was changed from 3.1 to 4.3 m$^3$/h by 0.3 m$^3$/h increments.

Figure 6-1 shows the total amount of fly-ash collected for experiments of hardwood and softwood combustion at a fuel flow rate of 1 kg/h with increasing primary air flow rates. It is clear from this figure that an increase in primary air flow rate results in an increase in the total amount of fly-ash collected for both hardwoods and softwoods. It should be noted that the hog fuel in these experiments was burnt as-received, meaning that the size distribution ranged from saw dust-like particles to 2-3 cm chips, as well as thinner particles up to 5 cm long. This variation in particle size and shape resulted in a range of collected fly-ash amounts as shown by the large variation for each primary air flow rate.
The fly-ash collected after each experiment was burnt at 600°C as per ASTM D7348 – 13 which outlines the standard test methods for Loss on Ignition (LOI) of solid combustion residues [69]. The results are shown in Figure 6-2 for each primary air flow rate. From this figure, the variation in the percentage of carbon in the fly-ash does not seem to have the same linear relationship with increasing primary air flow rate. Fly-ash collected from softwood combustion seems to have higher carbon content for all primary air flow rates compared to hardwoods. This is due to the differences in initial density of softwoods and hardwoods as discussed in Chapter 4. Since softwoods have a lower initial density, they are entrained earlier during combustion than hardwoods and therefore have a lower residence time in the high temperature combustion zone of the fixed bed biomass combustor during combustion. This results in higher carbon content in the fly-ash resulting from softwood combustion.
Comparing the results of Figure 6-1 and Figure 6-2, it can be concluded that the total amount of fly-ash does increase with increasing the primary air flow rate, i.e. an increase in flue gas velocity. However the carbon content of the fly-ash does not seem to be impacted by the flue gas velocity. Nevertheless, since more fly-ash is collected, the total amount of carbon in the fly-ash does increase with an increase in flue gas velocity.

6.2 Entrainment Velocity

To determine whether a particle will remain on the combustion bed, the forces acting on the biomass particle need to be balanced. The forces are gravity, drag and buoyancy, and for the force balance, the sum of the buoyancy and drag force equals the force of gravity.

\[ f_{\text{gravity}} = f_{\text{buoyancy}} + f_{\text{drag}} \]  

\[ f_{\text{gravity}} = \rho_s g l_c^3 \]
where $\rho_s$ is the density of the particle at any given time during combustion in kg/m$^3$, $\rho_{FG}$ is the flue gas density in kg/m$^3$, $g$ is the gravitational force in m/s$^2$, $l_c$ is the particle length at any given time during combustion in m, $v$ is the entrainment velocity in m/s, and $C_D$ is the drag coefficient. From this balance, the minimum entrainment velocity of the particle is calculated. The entrainment velocity is equal to the flue gas velocity required to entrain the particle from the boiler bed. As the particle burns, its entrainment velocity decreases, making it easier to be entrained by the flue gases. If the change in entrainment velocity with time is known, it can be used to calculate the residence time of particles on the bed. The time it takes for the entrainment velocity to reach the flue gas velocity is equal to the residence time of the particle on the boiler bed.

Plugging Equations 42, 43 and 44 into Equation 41 and rearranging, the entrainment velocity can be calculated based on the following equation:

$$v(t) = \left[\frac{(\rho_s(t) - \rho_{FG})l_c(t)}{3\rho_{FG}C_D(t)}\right]^{1/2}$$

where $v$ is the entrainment velocity in m/s, $\rho_s$ is the density of the particle at any given time during combustion in kg/m$^3$, $\rho_{FG}$ is the flue gas density in kg/m$^3$, $g$ is the gravitational force in m/s$^2$, $l_c$ is the particle length at any given time during combustion in m, and $C_D$ is the drag coefficient. In this equation, the change in density and length with time are calculated based on Equations 31 and 40 respectively.

### 6.3 Drag Coefficient

One important parameter which determines the drag force acting on the particle is the drag coefficient $C_D$. The drag coefficient depends on the particle shape, size and sphericity as well as flow characteristics designated by Reynold’s number. Since the particle shape in the feedstock of
biomass boilers are rarely spherical or uniform, the following empirical correlation derived by Holzer and Sommerfeld was used [70]. This correlation takes into account the sphericity of the particle, meaning how close the surface area of the particle is to a sphere of the same volume, it also considers the surface area of the particle in the direction of the flow and parallel to it. Therefore, the fall direction of the particle will make a difference in the value of the drag coefficient if the particle is not symmetrical.

$$C_D = \frac{8}{Re \sqrt{\varphi_{\|}}} + \frac{16}{Re \sqrt{\varphi}} + \frac{3}{\sqrt{Re \varphi^3}} + \frac{0.421 \cdot 10^{-1.0 \log \varphi^{0.2}}}{\varphi_{\perp}}$$  \hspace{1cm} (46)

$$\varphi_{\|} = \frac{A_{eq}}{\frac{1}{2}A - A_{\|}}$$  \hspace{1cm} (47)

$$\varphi = \frac{A_{eq}}{A}$$  \hspace{1cm} (48)

$$\varphi_{\perp} = \frac{A_{eq}}{A_{\perp}}$$  \hspace{1cm} (49)

where $A$ is the surface area of the particle, $A_{\perp}$ is the cross-sectional area of the particle perpendicular to the flow, $A_{\|}$ is the cross-sectional area of the particle parallel to the flow, and $A_{eq}$ is the cross-sectional area of the volume equivalent sphere.

The particle Reynolds number is calculated based on the following equation:

$$Re = \frac{\rho v l_c}{\mu}$$  \hspace{1cm} (50)

Where $v$ and $l_c$ are variables related to the particle (entrainment velocity and size of the particle respectively), $\rho$ and $\mu$ on the other hand are the density and viscosity of the fluid. During combustion, the entrainment velocity and particle length change, therefore the particle Reynolds number also changes throughout combustion, which results in a change in the drag coefficient.

Figure 6-3a shows the drag coefficient change during combustion of a poplar cubic particle with an initial length of 1.5 cm. Initially the drag coefficient of the particle increases steadily during combustion and then towards the end increases more rapidly. Towards the end of the char
burning stage, the particle has lost most of its mass but has maintained its volume and form. At this stage, the particle will have a high drag coefficient meaning it can be lifted off the grate with less force.

![Figure 6-3. Change in a) drag coefficient and b) Reynold’s number during combustion of 1.5 cm wide cubic poplar particle](image)

Figure 6-3b shows the change in particle Reynolds number during combustion of a cubic poplar particle with initial length of 1.5 cm. The figure shows that the particle Reynolds number decreases throughout combustion. However, similar to the density change of the particle during combustion, Reynolds number decreases more rapidly during the volatile burning stage (the first few minutes). During the char burning stage, the Reynolds number decreases at a lower rate.

6.4 Model Results

Based on the entrainment model results, the change of volume and mass during combustion can be calculated. The results for volume and mass change of a cubic poplar particle with initial length of 1.5 cm are shown in Figure 6-4.
From the above mentioned equations (entrainment, density, size, and drag coefficient), the entrainment velocity of any given particle is calculated throughout the combustion process. The result for poplar with an initial length of 1.5 cm is shown in Figure 6-5.
Figure 6-5. Entrainment velocity decrease during combustion of poplar with 1.5cm initial length

For a known flue gas velocity, Figure 6-5 can be used to determine how long the particle will stay on the boiler bed. For example, if the flue gas velocity is 10 m/s, after about 120 s (2 minutes) the entrainment velocity of the 1.5 cm cubic poplar particle will equal 10 m/s, which means that this particle is entrained after 2 minutes. At this point, the mass consumed during combustion can also be calculated; the remaining mass of the particle (which is mainly char at this point) ends up as unburnt carbon in the fly-ash.
6.5 Model Verification

To compare the results obtained by the model with experimental observations, continuous combustion experiments were carried out in the fixed-bed biomass combustor described in Section 3.2. Aspen cubes with an initial length of 1cm were prepared and fed into the combustor at fuel rates 0.6 kg/h and 1 kg/h. For each experiment, from the fuel rate and primary air flow rate, the flue gas velocity was calculated, and the fly-ash collected was burned at 600°C to determine the amount of unburned carbon. Figure 6-6 shows the experimental and model values of unburned carbon with change in flue gas velocity. Calculation of the flue gas velocity can be found in Appendix D.

![Figure 6-6. Validating entrainment model: experimental results for combustion of cubic 1cm³ aspen particles compared to model results](image)

Based on these results, the model predicts the amount of unburned carbon with good agreement with experimental observations for 3 m/s and 5.5 m/s flue gas velocity.
6.6 Model Application and Industrial Relevance

Figure 6-7 shows the relationship between entrainment velocity and mass consumed for different poplar particle sizes.

![Figure 6-7. Entrainment velocity and mass consumed for poplar particles with varying initial lengths](image)

As more mass is consumed, the entrainment velocity decreases. This means that as the combustion proceeds, the particle loses mass and shrinks, making it easier to be lifted off the grate by the flue gas, i.e. lower entrainment velocity. It is also clear that different particle sizes have different entrainment velocities throughout combustion. Smaller particles have a lower entrainment velocity and would be entrained off the grate at a lower flue gas velocity. For example, if the flue gas velocity is 15m/s, the 1cm particle will be entrained when only about 60% of its mass is consumed during combustion, whereas the 2cm particle will be entrained when more than 80% of its mass is consumed during combustion.

The differences in entrainment velocity are especially significant if there is a mixture of hog fuel species in the feedstock. This is shown in Figure 6-8, where entrainment velocities for maple
(hardwood) and pine (softwood) are compared. Pine particles which have a lower initial density have a lower entrainment velocity which must be considered when determining the smallest allowable feedstock particle size.

Figure 6-8. Entrainment velocity of maple and pine

For example, if the flue gas velocity is 20 m/s with a hog fuel mixture of maple and pine cubic particles ranging in initial length between 1 cm to 2 cm, based on the plotted model results in Figure 6-8, the pine particles with 1 cm initial length will be entrained once they are fed into the boiler and will never land on the grate. The maple particles with 1 cm initial length and pine particles with 2 cm initial lengths will also be entrained when only about 30% of their mass is consumed. Only the maple particles with 2 cm initial length will stay on the grate long enough for about 80% of the biomass particle to be consumed in combustion.

Figure 6-9 shows the change in entrainment velocity during combustion for a number of hardwoods and softwoods 1 cm³ in volume. The differences in entrainment velocity for particles
with varying initial density are shown in this figure, where particles with a higher initial density will have a higher entrainment velocity.

The implications of this entrainment model are that given the initial density of the feedstock, and known flue gas velocity, the size of the feedstock particles can be calculated in such a way to minimize particle entrainment. This would also decrease the unburned carbon in the fly-ash which will result in higher efficiency and safer ash handling and disposal.

**Figure 6-9. Entrainment velocity of cubic particles 1cm³ during combustion**
7 Impact of Moisture Content on Thermal Performance

Boiler performance can be described by several different parameters. The most obvious one is the amount of steam produced, where a higher steam production rate per unit mass of fuel has a beneficial financial impact. Steam production by itself does not provide any further insight into how much of the energy provided to the boiler has been converted to steam. Therefore, boiler efficiency ($\eta$), as described in Section 3.3, would be a better variable to describe boiler performance. To calculate efficiency, streams entering and exiting the boiler must be identified along with their temperatures, pressures, enthalpies or specific heat capacities. This would require several different parameters describing the state for each stream. To simplify matters in quantifying boiler operation, the following parameter is defined:

$$TP = \frac{F_s}{F_B}$$

(51)

where TP is thermal performance, $F_s$ is the flowrate of steam and $F_B$ is the flowrate of biomass on a wet basis.

This parameter provides a measure of efficiency for boiler operation without the need to have detailed heat input and output specified. Operating data from 7 biomass boilers at pulp and paper mills were received, and Figure 7-1 shows the range of TP values, shown by the error bars, for the boilers studied; the steam flow rate for all boilers has been normalized to 400 °C and 4.4 MPa, as shown in Equation 52.
Figure 7-1. Thermal performance ranges for all boilers studied

\[ TP_{\text{normalized}} = TP \times \frac{H_{T,p}}{H_{400^\circ C, \ 4.4 \ MPa}} \]  

(52)

where \( H_{T,p} \) (kJ/kg) is the specific enthalpy of the superheated steam at temperature \( T \) (°C) and pressure \( P \) (MPa), calculations are shown in Appendix E.

From Figure 7-1, TP values can be as low as 1 (one ton of steam produced per ton of biomass combusted), and as high as 8. The range of TP values also differs from boiler to boiler; mill A has a TP range from 1 to 6.5, whereas mill C is from 2 to 4. Mill E operates at the highest TP range with an average value of 5 and the upper limit reaching 7.5. These differences are an indication of the variability and large range of boiler operation.

Moisture content of the feedstock is believed to be the most influential parameter in boiler operation. Figure 7-2 shows the variation in thermal performance with increasing moisture content, both from theoretical heat and mass balances and from operating data collected from industrial scale biomass boilers. The theoretical TP values were divided into high TP, typical
operation, and low TP and calculated from heat and mass balance. Table 7-1 summarizes the parameters used to calculate the theoretical values in Figure 7-2.

![Figure 7-2. Impact of feedstock moisture content on thermal performance](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low TP</th>
<th>Typical Operation</th>
<th>High TP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excess Air (%)</td>
<td>40</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>Feedwater Temperature (°C)</td>
<td>120</td>
<td>150</td>
<td>180</td>
</tr>
<tr>
<td>Radiation and Unaccounted Heat Losses (%)</td>
<td>10</td>
<td>5</td>
<td>0</td>
</tr>
</tbody>
</table>

Based on theoretical calculations, TP is larger than zero up to a moisture content of 78%, however in practice, it is observed that the maximum operable moisture content is about 60%. This is because an increase in moisture content causes longer time-to-ignition durations as well
as lower temperatures which may lead to loss of volatiles and eventually boiler blackout [71]. It is also clear that even based on the heat and mass balance, the theoretical values can vary significantly depending on what value is chosen for other parameters such as feedwater temperature, inlet excess air, and heat loss due to radiation to name a few. With the assumption of having unburned carbon in the fly-ash or bottom ash, the TP value decreases further.

Thus, it is evident that moisture content is not the only influential parameter affecting thermal performance and efficiency of the boiler. Multivariate Analysis (MVA) is used to consider the impact of all the operating parameters on boiler thermal performance.

7.1 Exploratory Data Analysis

Exploratory Data Analysis is performed to analyze data sets and find their main characteristics, relationships and patterns. Multivariate Analysis (MVA) is used to build a Partial Least Square (PLS) model as described in Section 3.4.2. Hourly average operating data for one month from mill G is used to build this model, and the model operating parameters are described in Table 7-2 where the predictor variable is set as TP (Thermal Performance) and 14 of the other operating parameters, including feedstock moisture content, are set as exploratory variables. The feedstock moisture content for mill G is a measured value from a sensor installed on the feedstock conveyor. It should be noted that this model initially included 24 exploratory variables, however based on additional assessment into the relationship between the operating parameters and removal of duplicate parameters, 14 parameters were kept as a final set of X variables.
Table 7-2. Model variables for mill G PLS model

<table>
<thead>
<tr>
<th>Y Variable</th>
<th>Operating Parameter [unit]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP</td>
<td>Thermal performance [ton steam/ton biomass]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>X Variables</th>
<th>Operating Parameter [unit]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SensMC</td>
<td>Feedstock moisture content [%]</td>
</tr>
<tr>
<td>CO</td>
<td>Flue gas carbon monoxide [ppm]</td>
</tr>
<tr>
<td>HogTemp</td>
<td>Hog fuel temperature [°C]</td>
</tr>
<tr>
<td>Opacity</td>
<td>Flue gas opacity [%]</td>
</tr>
<tr>
<td>GasBurAir</td>
<td>Gas burner air flow rate [klb/h]</td>
</tr>
<tr>
<td>UGAirT</td>
<td>Undergrate air temperature [°C]</td>
</tr>
<tr>
<td>ID Fan Spe</td>
<td>Induced draft fan speed [Amps]</td>
</tr>
<tr>
<td>OFFlw</td>
<td>Overfire air flow rate [klb/h]</td>
</tr>
<tr>
<td>NGFlw</td>
<td>Natural gas flow rate [ft³/h]</td>
</tr>
<tr>
<td>TotBarkAir</td>
<td>Total bark air flow rate [klb/h]</td>
</tr>
<tr>
<td>BoilerOutT</td>
<td>Boiler bank outlet temperature [°C]</td>
</tr>
<tr>
<td>AirHeatOut</td>
<td>Air heater outlet temperature [°C]</td>
</tr>
<tr>
<td>UGFlw</td>
<td>Undergrate air flow rate [klb/h]</td>
</tr>
<tr>
<td>O₂</td>
<td>Outlet excess O₂ [%]</td>
</tr>
</tbody>
</table>

The score plot in Figure 7-3 shows the first two latent variables for all 567 data points in the model. Most of the data points fall in the 95% confidence interval shown by the ellipse. The outliers corresponding to abnormal data points, such as boiler shut downs and startups, have been eliminated. The outliers shown in this figure are instances of non-average values for some of the operating parameters which may provide additional understanding to the relationship between these operating parameters, and therefore they were intentionally retained in the model.
Figure 7-3. Score plot for mill G PLS model

The loading plot in Figure 7-4 shows an overview of the relationship between all parameters in the model. Any variables close to each other in the same quadrant have a strong positive correlation, and parameters in opposite quadrants have a strong negative correlation. Variables closer to the origin of the plot are less influential on the model, and parameters far away from the origin have a more significant impact on the model. It is clear that the parameters that have the most significant impact on this model are TP (since it is the assigned Y variable), excess O₂, moisture content, carbon monoxide and undergrate air flow rate.
The findings from the loading plot are further validated by the Variables Influence on Projection, VIP plot as shown in Figure 7-5. Any variables with a VIP value higher than one are influential in the model. In the VIP plot, moisture content has the highest VIP value followed by the ID fan speed and carbon monoxide concentration in the flue gas.
The coefficient plot in Figure 7-6 shows the correlation of the X variables with TP, the parameters with a positive coefficient value have a positive correlation with TP variable, and the parameters with a negative coefficient have a reverse or negative relationship with TP. The relative strength of these correlations depends on the value of the coefficient. For this model, the most positively correlated parameter is the outlet $O_2$ and the most negatively correlated parameter is moisture content.
Figure 7-6. Coefficient plot for mill G PLS model

Considering the results from loading, VIP and coefficient plots, the most influential operating parameter on thermal performance of biomass boilers is the feedstock moisture content. It is also evident that for an instance of high moisture content, thermal performance is low, which agrees with results from the heat and mass balance as well.

Moisture content is thought to be one of the most influential parameters in biomass boiler operation. Using multivariate analysis and considering the impact of all operating parameters on thermal performance, moisture content is verified as the most influential parameter.
7.2 Moisture Content Soft Sensors

In the previous section, it was seen how moisture content is the most influential parameter on thermal performance of biomass boilers. Therefore, it would be beneficial if the moisture content of the feedstock is known. Current near infrared, NIR, based technologies show promising results for uniform feedstocks such as saw dust or wood pellets [72]. However these devices cannot be calibrated for non-uniform feedstocks such as hog fuel. For this reason, indirect methods of moisture calculation were investigated, using heat and mass balances, and measuring the water vapor composition in the flue gas. The results of both efforts are presented in this section.

7.2.1 Heat and Mass Balance

The first soft sensor investigated in this study is the use of heat and mass balance to calculate moisture content when other operating parameters are directly measured and available, such as steam flow rate, air flow rates and temperatures, hog fuel flow rate, outlet excess O₂, etc. Two case studies were conducted where the moisture content of the feedstock was measured directly by the oven-drying method performed by the mill staff, and then compared to the value calculated from heat and mass balances.

The first case study was conducted on a SG boiler at mill E. Feedstock samples were collected five times a day for four days. Table 7-3 shows the operating parameters and calculation results for this case study. In initial calculations, the calculated and measured excess O₂ values were not close, which implied that the measured hog fuel flow rate was not equal to the amount of fuel burnt. At any given time, there is an inventory of fuel piled on the grate and the amount of fuel burning to produce steam does not equal the amount of feed flow rate onto the grate. Therefore, the amount of hog fuel burnt was also calculated based on the amount of consumed air (calculations in Appendix F).
Table 7-3. Case study results for mill E

<table>
<thead>
<tr>
<th>Date/Time</th>
<th>Feed Rate (ton/h)</th>
<th>Moisture Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calculated</td>
<td>Measured</td>
</tr>
<tr>
<td>5/10 6 AM</td>
<td>55.7</td>
<td>46.6</td>
</tr>
<tr>
<td>5/10 8 AM</td>
<td>44.4</td>
<td>45.6</td>
</tr>
<tr>
<td>5/10 10 AM</td>
<td>41.1</td>
<td>54.7</td>
</tr>
<tr>
<td>5/10 4 PM</td>
<td>46.7</td>
<td>40.1</td>
</tr>
<tr>
<td>5/11 6 AM</td>
<td>75.7</td>
<td>48.8</td>
</tr>
<tr>
<td>5/11 8 AM</td>
<td>64.9</td>
<td>49.4</td>
</tr>
<tr>
<td>5/11 10 AM</td>
<td>52.4</td>
<td>40.0</td>
</tr>
<tr>
<td>5/11 12 PM</td>
<td>46.8</td>
<td>43.3</td>
</tr>
<tr>
<td>5/11 2 PM</td>
<td>47.7</td>
<td>47.3</td>
</tr>
<tr>
<td>5/11 4 PM</td>
<td>66.5</td>
<td>53.1</td>
</tr>
<tr>
<td>5/12 6 AM</td>
<td>78.4</td>
<td>45.6</td>
</tr>
<tr>
<td>5/12 8 AM</td>
<td>80.2</td>
<td>52.4</td>
</tr>
<tr>
<td>5/12 10 AM</td>
<td>73.3</td>
<td>73.4</td>
</tr>
<tr>
<td>5/12 12 PM</td>
<td>65.5</td>
<td>49.2</td>
</tr>
<tr>
<td>5/12 2 PM</td>
<td>58.8</td>
<td>52.2</td>
</tr>
<tr>
<td>5/20 9 AM</td>
<td>85.3</td>
<td>72.4</td>
</tr>
<tr>
<td>5/20 11 AM</td>
<td>97.6</td>
<td>70.1</td>
</tr>
<tr>
<td>5/20 1 PM</td>
<td>94.6</td>
<td>83.0</td>
</tr>
<tr>
<td>5/20 3 PM</td>
<td>69.6</td>
<td>74.6</td>
</tr>
<tr>
<td>5/20 5 PM</td>
<td>61.0</td>
<td>60.0</td>
</tr>
</tbody>
</table>
The result of the SG boiler case study is shown in Figure 7-7, where the maximum error was 11%, and the MSE (mean squared error) was 7.35. The soft sensor accurately shows changes in moisture content which is more useful than the absolute value in operation.

![Figure 7-7. Case study results for moisture content calculations for SG boiler at mill E](image)

The second case study was conducted on a BFB boiler in mill F, where feedstock samples were collected five times a day for three days and oven dried. The moisture content was also calculated based on heat and mass balance of the boiler, and the results are shown in Table 7-4 and Figure 7-8. The maximum error for this case study was 11% and the MSE (mean squared error) was 7.02.
Table 7-4. Case study results for mill F

<table>
<thead>
<tr>
<th>Date/Time</th>
<th>Excess O₂ (%)</th>
<th>MC (%)</th>
<th>Calculated</th>
<th>Measured</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/10/16 6:00 AM</td>
<td>3.4</td>
<td>3.3</td>
<td>47</td>
<td>52</td>
<td>9</td>
</tr>
<tr>
<td>5/10/16 8:00 AM</td>
<td>2.6</td>
<td>3.5</td>
<td>55</td>
<td>54</td>
<td>3</td>
</tr>
<tr>
<td>5/10/16 10:00 AM</td>
<td>2.7</td>
<td>3.1</td>
<td>53</td>
<td>52</td>
<td>3</td>
</tr>
<tr>
<td>5/10/16 12:00 PM</td>
<td>3.0</td>
<td>3.4</td>
<td>50</td>
<td>53</td>
<td>7</td>
</tr>
<tr>
<td>5/10/16 2:00 PM</td>
<td>3.8</td>
<td>3.3</td>
<td>49</td>
<td>53</td>
<td>8</td>
</tr>
<tr>
<td>5/11/16 6:00 AM</td>
<td>2.6</td>
<td>3.1</td>
<td>51</td>
<td>49</td>
<td>4</td>
</tr>
<tr>
<td>5/11/16 8:00 AM</td>
<td>2.2</td>
<td>3.2</td>
<td>56</td>
<td>50</td>
<td>11</td>
</tr>
<tr>
<td>5/11/16 10:00 AM</td>
<td>3.3</td>
<td>3.3</td>
<td>48</td>
<td>49</td>
<td>2</td>
</tr>
<tr>
<td>5/11/16 12:00 PM</td>
<td>2.8</td>
<td>3.2</td>
<td>50</td>
<td>47</td>
<td>7</td>
</tr>
<tr>
<td>5/11/16 2:00 PM</td>
<td>2.9</td>
<td>3.2</td>
<td>49</td>
<td>48</td>
<td>2</td>
</tr>
<tr>
<td>5/12/16 6:00 AM</td>
<td>3.0</td>
<td>2.9</td>
<td>48</td>
<td>49</td>
<td>2</td>
</tr>
<tr>
<td>5/12/16 8:00 AM</td>
<td>2.6</td>
<td>2.8</td>
<td>52</td>
<td>52</td>
<td>1</td>
</tr>
<tr>
<td>5/12/16 10:00 AM</td>
<td>2.6</td>
<td>2.8</td>
<td>53</td>
<td>53</td>
<td>0</td>
</tr>
<tr>
<td>5/12/16 12:00 PM</td>
<td>3.0</td>
<td>3.1</td>
<td>51</td>
<td>52</td>
<td>3</td>
</tr>
<tr>
<td>5/12/16 2:00 PM</td>
<td>2.9</td>
<td>3.1</td>
<td>52</td>
<td>53</td>
<td>2</td>
</tr>
</tbody>
</table>
To validate this method further, the moisture content for mill G was calculated based on the method described here and the results were compared to moisture content measured by the available moisture sensor. The results are shown in Figure 7-9.

Figure 7-8. Case study results for moisture content calculations for BFB boiler at mill F
Furthermore, a PLS model was built for mill G operating parameters including both the measured and calculated moisture content to compare the measured and calculated moisture content impact in multivariate analysis. On the loading plot in Figure 7-10, the variables CalcMC (calculated from heat and mass balance) and SensMC (measured by the moisture sensor) are close to one another in the same quadrant on the loading plot, which is another indication that the calculated values are closely correlated with the measured moisture content.
Figure 7-10. Loading plot for mill G PLS model with calculated and measured moisture content

The VIP plot shown in Figure 7-11 shows that the measured and calculated moisture content values are the two most important variables in this model. The measured moisture content from the moisture sensor seems to describe more of the variability of the process data, this impact is masked in the calculated moisture content, since this value is based on other operating parameters. Nevertheless, based on the direct comparison of calculated and measured values, as well as results from the PLS plot, it can be concluded that moisture content can be calculated from other operating parameters using heat and mass balances.
Figure 7-11. VIP plot for mill G PLS model showing both measured and calculated values for moisture content

7.2.2 Water Vapor in Flue Gas

One other method for indirect moisture measurement is to measure the water vapor in the flue gas. Field studies were done on biomass boilers at mill A and mill H to see whether measuring the water vapor in the flue gas can be used to calculate moisture content accurately.

Figure 7-12 shows a simple setup which was used to extract flue gas from the biomass boiler at mill A and mill H.
The flue gas water vapor was calculated based on heat and mass balance as described in Section 3.3 (calculations in Appendix F). The flue gas water vapor was measured and compared to the calculated values with good agreement, as shown in Table 7-5 and Figure 7-13.

**Table 7-5. Trial results of flue gas water vapor measurements**

<table>
<thead>
<tr>
<th></th>
<th>Mill A</th>
<th>Mill H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial #</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Trial Data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flue gas volume (L)</td>
<td>59.5</td>
<td>55.3</td>
</tr>
<tr>
<td>Boiler house temperature (°C)</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>Dry flue gas standard volume (L)</td>
<td>52.6</td>
<td>48.9</td>
</tr>
<tr>
<td>Water collected (L)</td>
<td>10.8</td>
<td>9.1</td>
</tr>
<tr>
<td>Water vapor (vol%)</td>
<td>17.2</td>
<td>15.7</td>
</tr>
<tr>
<td>Process Data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture content (%)</td>
<td>45.6</td>
<td>52.0</td>
</tr>
<tr>
<td>Water vapor (vol%)</td>
<td>17.5</td>
<td>15.5</td>
</tr>
<tr>
<td>Error (%)</td>
<td>1.7</td>
<td>1.0</td>
</tr>
</tbody>
</table>
The results from these field studies show that moisture content can be calculated based on the water vapor in the flue gas with high precision (maximum error is 6.5 % and MSE is 4.3 in the above mentioned field studies). Other studies have been done with similar methods on Circulating Fluidized Beds (CFB) where the moisture content of the feed is calculated with high precision (less than 4% error) by measuring the relative humidity in the flue gas [73].

### 7.3 Changes in Moisture Content

Since moisture content (MC) is the most influential variable in boiler performance, a more in-depth analysis is needed for the effect of moisture content on thermal performance while considering other influential variables to help better understand their interaction. Figure 7-14 shows response contours from a PLS model for TP with changes in MC for the biomass boiler at mill A. Each graph looks at TP response contours while considering changes in MC, shown on the x-axis, and one other influential parameter, shown on the y-axis.
Figure 7-14. Mill A thermal performance response contour for changes in moisture content and a) lower furnace temperature, b) total air flow, c) ID fan current and d) ID fan outlet temperature.
Figure 7-14a shows the effect of lower furnace temperature and moisture content on thermal performance, and the highest TP is for high furnace temperature and low moisture content. This is in agreement with the findings from the four boilers investigated in Figure 7-2 where it was speculated that lower furnace temperature has a significant impact on TP especially for high moisture content values.

Figure 7-14b shows total air flow and moisture content with thermal performance. High TP values occur for low total air flow and low moisture content. This shows that increasing total air flow results in diluting the flue gas and decreases the heat content available for steam production, therefore lowering TP. ID fan current and temperature represent flue gas flow rate and temperature respectively.

An increase in flue gas flow rate is an indication of more fuel burnt in the boiler and therefore more heat available for steam production which results in higher TP if combustion takes place efficiently (Figure 7-14c).

The flue gas temperature on the other hand, shows a negative correlation with TP (Figure 7-14d). When the temperature of the flue gas is high, it means that the heat content of the flue gas has not been utilized to its fullest at the superheaters, economizer, or heat exchangers, resulting in a lower TP.

The response contours in Figure 7-14 clearly show that regardless of the y-axis variable, TP decreases with increasing MC. However, to predict TP values more accurately, other influential variables shown must be taken into consideration.
8 Predictive Model for Boiler Thermal Performance

One challenge in biomass boiler operation is unpredictability. Due to the variability of fuel characteristics, the thermal performance of the boiler may change suddenly. It is desirable to have a predictive model as an additional monitoring tool to help operators identify upsets and determine the best method for mitigation. In this chapter, the application of multivariate analysis (MVA) for the purpose of building a predictive statistical model for biomass boiler operation is presented. The soft sensor presented in Chapter 7 is used in the models to calculate the moisture content of the feedstock.

8.1 PLS Model

A PLS model for operating data from mill A is presented here, and Table 8-1 shows the variables used in the model.
Table 8-1. Mill A operating parameters used in PLS model

<table>
<thead>
<tr>
<th>Y Variables</th>
<th>Operating parameter [unit]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP</td>
<td>Thermal performance [ton steam/ton biomass]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>X Variables</th>
<th>Operating Parameter [unit]</th>
</tr>
</thead>
<tbody>
<tr>
<td>InAirT</td>
<td>Inlet air temperature [°F]</td>
</tr>
<tr>
<td>OilFlow</td>
<td>Oil flow rate [kph]</td>
</tr>
<tr>
<td>GasFlow</td>
<td>Natural gas flow rate [kscfm]</td>
</tr>
<tr>
<td>WindboxAir</td>
<td>Windbox air flow rate [kpph]</td>
</tr>
<tr>
<td>ArchAirFlw</td>
<td>Arch air flow rate [kpph]</td>
</tr>
<tr>
<td>WindsweptAirFlow</td>
<td>Windswept air flow rate [kpph]</td>
</tr>
<tr>
<td>BurnerAirFlow</td>
<td>Burner air flow rate [kpph]</td>
</tr>
<tr>
<td>TotalAirFlow</td>
<td>Total air flow rate [kpph]</td>
</tr>
<tr>
<td>BarkAirFlow</td>
<td>Bark air flow rate [kpph]</td>
</tr>
<tr>
<td>DAStorageT</td>
<td>Deaerator storage temperature [°F]</td>
</tr>
<tr>
<td>ExcessO2</td>
<td>Outlet excess O₂ [%]</td>
</tr>
<tr>
<td>IDFanCurrent</td>
<td>ID fan current [amps]</td>
</tr>
<tr>
<td>IDFanOutT</td>
<td>ID fan outlet temperature [°F]</td>
</tr>
<tr>
<td>NLowerFurnaceT</td>
<td>Lower furnace temperature [°F]</td>
</tr>
<tr>
<td>SOGFlow</td>
<td>Scrubber off gases flow rate [scfm]</td>
</tr>
<tr>
<td>CNCGFlow</td>
<td>Concentrate non condensable gases flow rate [scfm]</td>
</tr>
<tr>
<td>ROCONCFlow</td>
<td>Reverse osmosis concentrate [gpm]</td>
</tr>
<tr>
<td>MoistContent</td>
<td>Moisture content [%]</td>
</tr>
</tbody>
</table>
Similar to the models described in Chapter 7 for exploratory data analysis, first PCA is used to convert the data matrix to a few informative plots. The scatter plot in Figure 8-1 shows how the observations are projected into two dimensions. Each data point on the scatter plot represents one instance for all variables, in this case average hourly values for all operating parameters. The ellipse represents a 95% confidence interval of the data and the origin of the graph represents the average value across all variables. Points clustered together on the scatter plot on each quadrant have similar collective characteristics [55].

![Figure 8-1. Score plot for Mill A PLS model](image)

Most of the data points lie in the 95% confidence interval shown by the ellipse, supporting that this model is a good representation of the operating data for this boiler. Table 8-2 shows the model summary and the variance captured by each component; the 5 component model explains 65.8% of the variability in the x variables, 94.4% variability in the y variable. The $Q^2$ value is a measure of how well the model predicts the y variable, in this case 94.6%.
Table 8-2. Goodness of fit and Eigen values for mill A PLS model

<table>
<thead>
<tr>
<th>Component</th>
<th>$R^2_X$</th>
<th>$R^2_X$(cum)</th>
<th>Eigenvalue</th>
<th>$R^2_Y$</th>
<th>$R^2_Y$(cum)</th>
<th>$Q^2$</th>
<th>$Q^2$(cum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.214</td>
<td>0.214</td>
<td>3.85</td>
<td>0.514</td>
<td>0.514</td>
<td>0.51</td>
<td>0.51</td>
</tr>
<tr>
<td>2</td>
<td>0.18</td>
<td>0.394</td>
<td>3.25</td>
<td>0.301</td>
<td>0.815</td>
<td>0.617</td>
<td>0.812</td>
</tr>
<tr>
<td>3</td>
<td>0.109</td>
<td>0.503</td>
<td>1.96</td>
<td>0.0761</td>
<td>0.891</td>
<td>0.407</td>
<td>0.889</td>
</tr>
<tr>
<td>4</td>
<td>0.08</td>
<td>0.583</td>
<td>1.44</td>
<td>0.0375</td>
<td>0.929</td>
<td>0.337</td>
<td>0.926</td>
</tr>
<tr>
<td>5</td>
<td>0.075</td>
<td>0.658</td>
<td>1.35</td>
<td>0.0155</td>
<td>0.944</td>
<td>0.212</td>
<td>0.946</td>
</tr>
</tbody>
</table>

To better understand the relationship between the parameters used to build this PLS model, the loading plot is used, as shown in Figure 8-2.
The variables appearing on the same quadrant in the loading plot (like TP and lower furnace temperature) have a strong positive correlation, and the variables appearing on opposite quadrants (like TP and Moisture Content) have a strong negative correlation. The same could be inferred for X variables depending on their relative location on the loading plot. For example, Excess O$_2$ and Total Air Flow Rate appear on the same quadrant and close to one another which is an indication that they have strong positive correlation. This is in line with the physical relationship between these two parameters: when the Total Air Flow Rate increases, the Excess O$_2$ exiting the boiler will also increase.

The coefficient plot shown in Figure 8-3 shows the cumulative regression coefficients computed by the model expressing the relationship of the Y variable with all the X variables included in the model.
It is interesting to note the differences between the relationship of Gas Flow Rate and Oil Flow Rate on TP. Based on the coefficient plot, Oil Flow Rate seems to have a significant positive correlation with TP, however looking at the loading plot, even though Oil Flow Rate is aligned with the first principal component, i.e. it lies on the x-axis of the loading plot, the point itself is close to the origin of the loading plot meaning that it does not have a significant impact on the overall model.

Gas Flow Rate on the other hand, seems to have a negative relationship with TP. This can be an indication that high values of Gas Flow Rate occur at low TP values, which means that Gas Flow Rate is used to mitigate low TP instances. This is an example of how statistical correlations do not show cause and effect, meaning that the high Gas Flow Rate for instance, does not cause low TP, rather high Gas Flow Rates occur when TP is low.
8.2 Predictor Variables

So far, the models included in this work have had one predictor variable, TP. TP is a measure of how much steam is produced from the heat supplied from biomass combustion. Based on TP alone, no information on combustion quality or rate is inferred. An investigation into using other predictor variables for optimization of boiler operation has been done and is discussed in this section.

Excess O\textsubscript{2}, which is the weight percentage of oxygen in the flue gas, is an indicator of how much unused or unconsumed oxygen is remaining at the outlet after combustion. If the inlet air flow rate is equal to the stoichiometric value, then all of the oxygen available in the inlet air would be consumed in combustion and the Excess O\textsubscript{2} would be zero. However, there is always excess air supplied to the boiler to ensure complete combustion. On the other hand, since the temperature of the inlet air is lower than the temperature of the lower furnace area, too much air will dilute the flue gas and cause the flue gas temperature to drop.

Changes in Excess O\textsubscript{2} can be used as an indicator for combustion quality: if everything else stays the same, a sudden increase in Excess O\textsubscript{2} indicates poor combustion quality. However, it is often not the case that only one variable changes, and boiler operation is dynamic. For instance, if the fuel flow rate increases without any change to the inlet air flow rate, Excess O\textsubscript{2} in the outlet will decrease, this does not mean that the combustion quality has improved, rather it is an indication that more air is consumed. With lower excess air available, incomplete combustion may have taken place which would not be evident by just looking at Excess O\textsubscript{2}. On the other hand, if the total air flow rate increases, by increasing the under grate air for example to expedite drying of high moisture content feedstock, Excess O\textsubscript{2} will increase, which again will not be an indication of change in combustion quality.

Therefore, it is hypothesized that using a normalized version of Excess O\textsubscript{2} as a predictor variable will explain more of the variability of the data and provide more insight into combustion quality. To test this hypothesis, Excess O\textsubscript{2} is normalized by total air and total biomass flow rate. PLS models are built with the following predictor variables: TP, Excess O\textsubscript{2}, O\textsubscript{2}/air, O\textsubscript{2}/fuel.

This is performed for three boilers and the loading plots for each model are shown in Figure 8-4, Figure 8-5, and Figure 8-6 below.
Figure 8-4. Mill E Loading Plot
Figure 8-5. Mill G Loading Plot

Figure 8-6. Mill B Loading Plot
Comparing the loading plots shown in Figure 8-4, Figure 8-5, and Figure 8-6, the locations of O₂, O₂/air, and O₂/fuel in each plot are very close suggesting that they are highly correlated, which is expected, and that they explain the same variability with respect to the rest of the model. To further test the hypothesis, individual models with two predictor variables, TP and O₂, TP and O₂/air, and TP and O₂/fuel, were created and a summary of results is shown in Table 8-3.

<table>
<thead>
<tr>
<th></th>
<th>Mill B</th>
<th></th>
<th>Mill E</th>
<th></th>
<th>Mill G</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R²X(cum)</td>
<td>R²Y(cum)</td>
<td>Q²(cum)</td>
<td>R²X(cum)</td>
<td>R²Y(cum)</td>
</tr>
<tr>
<td></td>
<td>0.66</td>
<td>0.58</td>
<td>0.58</td>
<td>0.62</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>0.86</td>
<td>0.59</td>
<td>0.58</td>
<td>0.62</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>0.88</td>
<td>0.62</td>
<td>0.62</td>
<td>0.88</td>
<td>0.88</td>
</tr>
</tbody>
</table>

The models using normalized O₂ as a predictor variable do not show significantly higher values for R² and Q² suggesting that the variability explained by each model does not improve. Therefore, using a normalized version of O₂ as a predictor variable does not provide further insight into the process.

### 8.3 Online Application

Since process upsets are caused by the variability of hog fuel, it is desired to detect the onset of these process upsets as early as possible, to mitigate their impact and continue stable and optimized boiler operation. The PLS model enables such a prediction. For the mill A model described in Section 8.1, 350 additional data points were used to evaluate the predictability of the
model. The results are shown in Figure 8-7, where the predicted TP value is shown on the x axis and the measured TP is shown on the y axis.

![Figure 8-7. Predicted and measured TP values based on mill A PLS model](image)

It is clear from Figure 8-7 that there is good agreement between the measured and predicted values. Any data point on the prediction plot, such as point A, which has the lowest TP value, both predicted and measured, can be investigated further. The contribution plot for this particular data point is shown in Figure 8-8, which shows that one of the contributing factors to this low TP value is high moisture content. The other large contributing factors seem to indicate that natural gas is being co-fired in this case, presumably because the high moisture fuel is not burning well and/or generating enough heat for steam production.
Figure 8-8. Contribution plot for point A (low TP) on the prediction set

Figure 8-9 shows the contribution plot for point B on the prediction set where TP is high. For this particular point, feedstock moisture content, burner air flow rate and total air flow rate are lower than average which has resulted in an instance of high TP.
Figure 8-9. Contribution plot for point B (high TP) on the prediction set

With the prediction set, the range of any of the X variables could be changed to see what the impact on TP would be. For example, Figure 8-10 shows the impact of MC on point A: if the MC value is the lowest value observed in this model (22%), TP increases to 5 and if MC has the highest value (51%), TP drops to almost 2.
8.4 Model Applications

The predictive PLS model presented here can be used as an online tool for optimization of boiler performance. By choosing parameters measured by reliable and accurate instrumentation, the accuracy of the model would increase. The X variables can be chosen in a way to avoid parameters with long lags or those which are far away from the physical feedstock, which require a longer residence time for any changes to be seen. This way, when a decrease in TP is predicted by the model, the contributing factors can be examined and the correct course of action can be determined by the operator. By mitigating the impacts of a process upset early on, TP will not decrease further and the need to co-combust natural gas or fuel oil to maintain a certain TP value is eliminated.
9 Practical Implications

The results of this thesis work have important practical implications in industrial biomass boilers. The entrainment model can be used to determine optimum fuel specifications in fuel preparation. Results related to moisture content variation shed some light into the importance of moisture content in boiler operation, and the soft sensor developed provides an estimation of the moisture content of the feedstock. The predictive statistical modelling provides an additional monitoring tool to predict process upsets and determine the contributing factors to upsets. This chapter presents further details on the practical implication of the research results.

9.1 Fuel Preparation

As shown in the informational flow diagram in Figure 9-1, for a given steam flow rate and known steam properties, the amount of biomass required can be calculated based on heat and mass balance presented in Section 3.3. Once the necessary biomass flow rate is calculated, the flue gas velocity resulting from combustion of the fuel is calculated (sample calculations in Appendix D). The entrainment model developed in this research is then used to determine the minimum allowable particle size of the fuel.
The entrainment model can be used to calculate the minimum allowable particle size for any given wood species. Figure 9-2 shows the minimum particle size for different wood species calculated for 90% burnout, i.e. particles will be entrained after 90% of the mass is consumed during combustion and only 10% unburned mass remaining.
Particles with a higher initial density can have smaller particle sizes without concern for entrainment, and the minimum allowable particle size increases as the density decreases for a given flue gas velocity.

### 9.2 High Moisture Content Fuel

The hog fuel in biomass boiler feedstock usually contains 40-60% moisture content. Figure 9-3 shows the density change of a cubic pine sample with 45% moisture content during combustion at 800°C. The density values shown on the y-axis of this figure are normalized by dividing each value by the initial density of the sample, therefore the as-is normalized density is shown as 1. As the wet particle burns, its density decreases significantly, this decrease is proportional to the amount of water in the sample. When the density of the particle approaches the dry density, volatile burning takes place and a flame appears. The density of the particle continues to decrease during the char burning stage but at a lower rate. The density of a wet biomass particle entering the boiler decreases proportional to the moisture and volatile content. Therefore, the particle becomes very light soon after entering the boiler. This is especially important when...
different wood species with varying initial densities are present in the fuel mixture; for the same particle size, particles with a lower density will be entrained sooner.

![Normalized Density vs. Density Change](image)

**Figure 9-3. Change in density during combustion of cubic biomass sample with 45% moisture content**

The soft sensors described in Chapter 7 can be used to estimate the moisture content entering the boiler. Knowing the moisture content of the feedstock, appropriate measures can be taken for instances of higher than average moisture content. In the next section, use of the soft sensor along with the PLS predictive model is explained.
9.3 Online Process Monitoring

The PLS model described in detail in Chapter 8 can be used as an online tool for real time process monitoring as described in Figure 9-4.

![Figure 9-4. Informational flow diagram for practical application of the PLS model](image)

From the available operating data, the required parameters for the moisture content soft sensor are extracted to setup the moisture content soft sensor. Several samples from the feedstock can be oven-dried to determine their actual moisture content and validate the soft sensor results. The values from the moisture content soft sensor are then added to the rest of the available operating data and used to create the PLS model. If the thermal performance (TP) of the boiler is not readily available, a new variable needs to be created by dividing the steam flow rate by the biomass flow rate. All available operating parameters, including the moisture content soft sensor, are assigned as exploratory variables (or Xs) and TP is assigned as the predictive variable (or Y). The PLS model resulting from these variables is subsequently used to predict TP values. When TP starts to decrease, the contributing factors need to be closely examined. This would be an additional tool for the operators to monitor boiler operation and assess the best course of action in case of process upsets.
10 Summary

This thesis on investigating the impact of fuel variability and operating parameters on biomass boiler operation. The approach included both experimental and modeling work, as well as field studies and statistical analysis. The major contributions of this work include:

- Studying the impact of density change during combustion,
- Developing an entrainment model to predict particle entrainment and unburned mass left upon entrainment,
- Developing a moisture content soft sensor to estimate the moisture content of the feedstock from other operating parameters,
- Development of a PLS model enabling prediction of thermal performance and process upsets.

10.1 Addressing Objectives

The first objective of this study was to investigate the impact of fuel variability, namely wood species and size, on combustion, and to develop means for mitigating these impacts. The impact of wood species on combustion was investigated and it was determined that density change plays a significant role in biomass combustion. It was seen that hardwoods generally have a higher initial density than softwoods, as well as higher char and ash densities.

The density change during combustion of different wood species was investigated in detail. It was observed that during the first minutes of combustion which correspond to the volatile burning stage, the density of particles drops significantly. In the char burning stage density continues to decrease but at a lower rate. This change in density of the solid phase during combustion was modelled using first principles. The resulting model includes kinetic constants for biomass combustion and char formation which were determined experimentally.

The size change of biomass particles during combustion was modelled using a shrinking core model, with the assumption that oxygen diffusion through the ash layer is the rate limiting step. The results of density and size change during combustion were used in an entrainment model to calculate the minimum entrainment velocity for particles to be entrained by the flue gas.
The entrainment velocity was calculated by balancing the forces acting on a particle which include gravity, buoyancy and drag. To calculate the drag force, the drag coefficient was calculated based on an empirical equation found in the literature suitable for non-spherical non-uniform particles. The entrainment model enables the prediction of particle entrainment when the flue gas velocity inside the boiler is known. This can be used to determine the smallest allowable particle size for a given wood species to minimize entrainment. One implication of this part of the work is that different wood species with different densities result in different values for the minimum allowable particle size. This should be taken into account when a mixture of different wood species is present in the hog fuel.

The second objective of this thesis was to verify moisture content as the most influential parameter in boiler operation and to develop a predictive statistical model for optimization of biomass boiler thermal performance. Multivariate Analysis (MVA) was used to determine moisture content as the most important parameter in boiler operation. Since not all boilers are equipped with moisture content sensors, a soft sensor was developed for moisture calculations based on other operating parameters. Several field studies were conducted to verify the accuracy of the soft sensor. Water content in the flue gas was measured at several field studies and found to be a good complementary parameter that can be used in the soft sensor to accurately calculate the moisture content of the feedstock.

Thermal Performance (TP) was used as the predictor variable in Partial Least Square (PLS) models to first understand the relationship between TP and other operating parameters, and second to use the model to predict TP from other operating parameters. This model was tested with several boilers and showed good accuracy in describing the variability of process data. This model can be used to predict the onset of poor performance and determine the contributing factors which can be used to mitigate the situation and optimize boiler performance.
10.2 Recommendations for Future Work

The main focus of this PhD thesis was on fixed bed or Stoker Grate (SG) boilers. Impact of fuel variability on Bubbling Fluidized Bed (BFB) boilers needs to be examined in detail. The impact of density change during combustion for instance, will have different implications for fluidization and minimum fluidization velocities.

The application of the entrainment model to particles of other shapes and aspect ratios needs to be validated further. As mentioned, hog fuel consists of irregular and non-uniform shapes. Cubic samples were modelled in this work, however the size change and drag coefficient variation for particles with higher aspect ratios still need to be studied and validated.

The entrainment model presented here does not take into account temperature variations. The temperature distribution on the grate as well as the area immediately above it may have an impact on the density of the flue gas and therefore on the results of the entrainment model. Particle interactions were also not considered in this work, as well as temperature differences along the boiler. To account for these changes, a CFD model of a biomass boiler would be needed, which would include the density change of the particle modelled in this work.

The online application of the PLS model needs to be verified by field studies. The models presented in this work were created based on data received from mills after the fact. Creating the PLS model beforehand and validating with online operating parameters would be beneficial in determining the accuracy and applicability of the model.

Apart from work directly related to this research, another topic related to biomass boilers with growing applications is the impact of adding sludge to biomass boiler feedstock. The impact on combustion behaviour, entrainment, emissions and ash properties needs to be investigated in detail.
References


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Appendices

Appendix A: Kinetic constant calculations

The kinetic constants for devolatilization ($k_b$) and char formation ($k_{c1}$) were determined experimentally from experiments done in the TG combustor. Cubic particles from different wood species were prepared and burned at 800°C and density change during combustion was calculated based on weight measurements from the balance and volume measurements from the physical appearance of the particle captured by the camcorder during combustion. To determine the devolatilization constant, the change in density during the devolatilization stage (first few minutes of combustion where a flame is present) were used. Equation (29) was used to calculate the density at any given time during combustion; this calculated value was subtracted from the measured value, and squared. This was done for all density measurements available and the squared errors were added (SSE). The final $k_b$ value was determined by minimizing the value of SSE using Generalized Reduced Gradient in nonlinear optimization.

\[
SSE = \sum (\rho_b(t) - e^{-k_b t})^2
\]  \hspace{1cm} (A1)

Once the value of $k_b$ was found from using density values from the devolatilization stage only, the same optimization algorithm was used now for the entire combustion duration using the obtained $k_b$ value from the previous step and $k_{c2}$ value of $1.9 \times 10^{-3}$ (1/s) which is widely used in literature for char burning.

\[
SSE = \sum (\rho_s(t) - \rho_0( \frac{k_{c1} + k_{c2} - k_b}{k_{c2} - k_b} e^{-k_b t} - \frac{k_{c1}}{k_{c2} - k_b} e^{-k_{c2} t} ) )^2
\]  \hspace{1cm} (A2)
Appendix B: Density models for all wood species studied

In this appendix, the results for density change during combustion of all wood species studied are presented. Each figure includes the density model results as well as experimental results for cubic samples of varying sizes.

![Graph showing density change comparison]

**Figure B 1.** Density change comparison of model results and experiments for combustion of different sample weights for poplar
Figure B 2. Density change comparison of model results and experiments for combustion of different sample weights for aspen

Figure B 3. Density change comparison of model results and experiments for combustion of different sample weights for cedar
Appendix C: Oxygen diffusion through the ash layer

In the shrinking core model, oxygen diffusion through the ash layer is the rate limiting step. The total amount of oxygen diffusing into the ash layer per unit time, is the same as the total amount of oxygen reacting on the particle surface and at any intermediate location, the total quantity of oxygen diffusing per unit time is the same, i.e. change in the number of moles of oxygen with time is constant and is equal to the oxygen diffusion rate:

$$\frac{-dN}{dt} = D \frac{\partial C}{\partial l} 6l = \text{constant}$$

(C1)

Where N is number of moles of oxygen, D is the diffusivity coefficient, C is the concentration of oxygen and l is the length of the cube. Since the change in number of moles with time is constant, equation C1 can be integrated with respect to the length.
Both sides of equation C2 are integrated with the limits shown:

\[
\int_{C_{\text{surface}}}^{C_{\text{ash}}} 6D \, dC = \int_{t_c}^{t_L} \frac{1}{l} \left( -\frac{dN}{dt} \right)
\]  

(C2)

\[
\frac{-dN}{dt} = \frac{6D}{\left( \frac{1}{t_c} - \frac{1}{L} \right)} \left( C_{\text{ash}} - C_{\text{surface}} \right)
\]  

(C3)

Appendix D: Flue gas velocity calculations for the fixed bed biomass combustor

To calculate flue gas velocity, first the total volumetric flow rate of the flue gas \( V_{\text{Total}} \) (m\(^3\)/h) is calculated:

\[
V_{\text{Total}} = \sum_{i = \text{CO}_2, \text{H}_2\text{O}, \text{SO}_2, \text{N}_2, \text{O}_2} V_i = \sum \left( \frac{F_i}{\text{MW}_i} \times 22.4 \, \frac{\text{L}}{\text{mol}} \times \frac{T}{298 \, \text{K}} \right)
\]

(D1)

Where \( i \) represents each compound in the flue gas, \( V \) (m\(^3\)/h) is the volumetric flow rate of each combustion product, \( F_i \) (kg/h) is obtained from the mass balance as described in Section 3.3, and MW is the molecular weight of each compound, and \( T \) (K) is the temperature of the flue gas.

Then the flue gas velocity \( v_{FG} \) (m/s) is calculated by dividing the total volumetric flow rate of the flue gas by the cross-sectional area of the combustor \( A \) (m\(^2\)):

\[
v_{FG} = \frac{V_{\text{Total}}}{A}
\]

(D2)
Appendix E: Normalization of thermal performance for all mills

Overall the thermal performance of 7 biomass boilers were studied. The steam produced by each biomass boiler had different temperature and pressure, therefore different enthalpies. In order for the thermal performance comparison between boilers to be meaningful, the steam production rates were normalized to one temperature and pressure.

All TP values were normalized to mill G steam properties:

\[
TP_{\text{normalized}} = TP \times \frac{H_{TP}}{H_{400\degree C, 4.4\, MPa}}
\]

Table E1. Superheated steam properties for the mills studied

<table>
<thead>
<tr>
<th>Mill ID</th>
<th>Superheated Steam Enthalpy kJ/kg ( (H_s) )</th>
<th>Superheated Steam Temperature ( ^\circ C ) ( (T_s) )</th>
<th>Superheated Steam Pressure MPa ( (P_s) )</th>
<th>Total number of data points</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3268</td>
<td>438</td>
<td>6.2</td>
<td>1269</td>
</tr>
<tr>
<td>B</td>
<td>3276</td>
<td>442</td>
<td>6.3</td>
<td>9648</td>
</tr>
<tr>
<td>C</td>
<td>3188</td>
<td>393</td>
<td>4.5</td>
<td>503</td>
</tr>
<tr>
<td>D</td>
<td>3310</td>
<td>466</td>
<td>8.1</td>
<td>365</td>
</tr>
<tr>
<td>E</td>
<td>3314</td>
<td>454</td>
<td>5.9</td>
<td>2299</td>
</tr>
<tr>
<td>F</td>
<td>3271</td>
<td>441</td>
<td>6.4</td>
<td>2763</td>
</tr>
<tr>
<td>G</td>
<td>3203</td>
<td>400</td>
<td>4.4</td>
<td>603</td>
</tr>
</tbody>
</table>
Where \( H_{T,P} \) (kJ/kg) is the specific enthalpy of the superheated steam at temperature \( T \) (°C) and pressure \( P \) (MPa).

For example, for mill A:

\[
TP_{\text{normalized}} = TP \times \frac{3268 \text{kJ/kg}}{3203 \text{kJ/kg}}
\]

**Appendix F: Soft sensor calculations**

**Mill E Case Study: Sample Calculation and Data**

In order to calculate the moisture content of the feedstock based on other operating parameters, first the elemental composition of the hog fuel is needed. It should be noted that one of the challenges of using this soft sensor is the fact that the elemental composition of the hog fuel will not be the same over time. Therefore, for best results, the elemental analysis of the hog fuel should be determined periodically. The elemental analysis for Mill E hog fuel is shown in the following table:

<table>
<thead>
<tr>
<th>Table F 1. Elemental composition of mill E hog fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
</tr>
<tr>
<td>Carbon</td>
</tr>
<tr>
<td>Hydrogen</td>
</tr>
<tr>
<td>Sulfur</td>
</tr>
<tr>
<td>Nitrogen</td>
</tr>
<tr>
<td>Oxygen</td>
</tr>
<tr>
<td>Chlorine</td>
</tr>
<tr>
<td>Ash</td>
</tr>
<tr>
<td>Total Dry Mass</td>
</tr>
</tbody>
</table>
For Mill E, samples were taken from the hog fuel conveyor feeding into the boiler and oven dried to determine their actual moisture content. The operating data from the same time frame was used to calculate the moisture content of the feed based on heat and mass balance.
**Table F 2. Operating parameters for day 1 and 2 of soft sensor case study at Mill E**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Variable Description (Units)</th>
<th>Day 1</th>
<th>Day 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>6AM</td>
<td>8AM</td>
</tr>
<tr>
<td>$F_S$</td>
<td>Steam Flow (klb/h)</td>
<td>368</td>
<td>293</td>
</tr>
<tr>
<td>$P_S$</td>
<td>Steam Pressure (psi)</td>
<td>857</td>
<td>845</td>
</tr>
<tr>
<td>$T_S$</td>
<td>Steam Temperature (°F)</td>
<td>833</td>
<td>838</td>
</tr>
<tr>
<td>$F_{NG}$</td>
<td>Natural Gas Flow (ft³/h)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$F_{air}$</td>
<td>Total Air Flow rate (klb/h)</td>
<td>494</td>
<td>445</td>
</tr>
<tr>
<td>$T_{air}$</td>
<td>Tubular Air Heater Inlet Temperature (°F)</td>
<td>130</td>
<td>129</td>
</tr>
<tr>
<td>$T_{FG}$</td>
<td>Economizer Outlet Temperature (°F)</td>
<td>337</td>
<td>328</td>
</tr>
<tr>
<td>$P_w$</td>
<td>Feed Water Supply Temperature (°F)</td>
<td>272</td>
<td>272</td>
</tr>
<tr>
<td>$F_B$</td>
<td>Bark Feed Conveyor Scale (ton/h)</td>
<td>47</td>
<td>46</td>
</tr>
<tr>
<td>$X_{CO}$</td>
<td>Boiler Stack CO (ppm)</td>
<td>257</td>
<td>249</td>
</tr>
<tr>
<td>$X_{O2}$</td>
<td>Boiler Stack O₂ (%)</td>
<td>6.2</td>
<td>8.3</td>
</tr>
<tr>
<td>$F_{B1}$</td>
<td>Continuous Blowdown Flow (klb/h)</td>
<td>8.8</td>
<td>6.1</td>
</tr>
<tr>
<td>$P_{B1}$</td>
<td>Steam Drum Pressure (psig)</td>
<td>963</td>
<td>897</td>
</tr>
<tr>
<td>$F_{w}$</td>
<td>Feed Water Flow Rate (klb/h)</td>
<td>370</td>
<td>373</td>
</tr>
</tbody>
</table>
Table F 3. Operating parameters for day 3 and 4 of soft sensor case study at Mill E

<table>
<thead>
<tr>
<th>Variable</th>
<th>Variable Description (Units)</th>
<th>Day 3</th>
<th>Day 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>6AM</td>
<td>8AM</td>
</tr>
<tr>
<td>$F_s$</td>
<td>Steam Flow (klb/h)</td>
<td>412</td>
<td>419</td>
</tr>
<tr>
<td>$P_s$</td>
<td>Steam Pressure (psi)</td>
<td>856</td>
<td>859</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Steam Temperature ($^\circ$ F)</td>
<td>850</td>
<td>849</td>
</tr>
<tr>
<td>$F_{NG}$</td>
<td>Natural Gas Flow (ft $^3$/h)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$F_{air}$</td>
<td>Total Air Flow rate (klb/h)</td>
<td>547</td>
<td>550</td>
</tr>
<tr>
<td>$T_{air}$</td>
<td>Tubular Air Heater Inlet Temperature ($^\circ$ F)</td>
<td>131</td>
<td>116</td>
</tr>
<tr>
<td>$T_{FG}$</td>
<td>Economizer Outlet Temperature ($^\circ$ F)</td>
<td>347</td>
<td>348</td>
</tr>
<tr>
<td>$P_w$</td>
<td>Feed Water Supply Temperature ($^\circ$ F)</td>
<td>272</td>
<td>272</td>
</tr>
<tr>
<td>$F_B$</td>
<td>Bark Feed Conveyor Scale (ton/h)</td>
<td>46</td>
<td>52</td>
</tr>
<tr>
<td>$X_{CO}$</td>
<td>Boiler Stack CO (ppm)</td>
<td>272</td>
<td>399</td>
</tr>
<tr>
<td>$X_{O_2}$</td>
<td>Boiler Stack $O_2$ (%)</td>
<td>5.0</td>
<td>4.9</td>
</tr>
<tr>
<td>$F_{Bl}$</td>
<td>Continuous Blowdown Flow (klb/h)</td>
<td>8.4</td>
<td>7.9</td>
</tr>
<tr>
<td>$P_{Bl}$</td>
<td>Steam Drum Pressure (psig)</td>
<td>941</td>
<td>942</td>
</tr>
<tr>
<td>$F_w$</td>
<td>Feed Water Flow Rate (klb/h)</td>
<td>368</td>
<td>370</td>
</tr>
</tbody>
</table>
The calculations for the first sample taken on May 10, 2016 at 6 AM are shown below.

First Sample_May 10, 2016 6 AM:

\[ \text{MC}_{\text{measured}} = 47 \% \]

In order to calculate moisture content of the feedstock, the mass balance for oxygen is set up as shown in the following equation:

\[
x_{O_2} = \left( \frac{32}{16} F_B x_O + 0.23 F_{\text{air}} - \left( \frac{32}{12} F_B x_C + \frac{32}{4} F_B x_H + F_B x_S \right) \times \left( 1 - \frac{M_B}{100} \right) \right) / \\
\left( \frac{44}{12} F_B x_C \times \left( 1 - \frac{M_B}{100} \right) + \frac{36}{4} F_B x_H \times \left( 1 - \frac{M_B}{100} \right) + \left( F_B M_F + F_{\text{air}} M_{\text{air}} \right) + \\
\frac{28}{14} F_B x_N \times \left( 1 - \frac{M_B}{100} \right) + 0.77 F_{\text{air}} + \frac{32}{16} F_B x_O \times \left( 1 - \frac{M_B}{100} \right) + 0.23 F_{\text{air}} - \\
\left( \frac{32}{12} F_B x_C + \frac{32}{4} F_B x_H + F_B x_S \right) \times \left( 1 - \frac{M_B}{100} \right) \right)
\]

The values for the elemental composition of the hog fuel and the operating parameters from May 10, 2016 at 6AM are plugged into the mass balance for oxygen:
\[
0.0616 = \left( \frac{32}{16} \times 0.4512 \, F_B \times \left(1 - \frac{MC_B}{100}\right) \right) + \left( 0.23 \times 494.16 \, \frac{\text{klb}}{h} \right) \\
- \left( \frac{32}{12} \times 0.44 \, F_B \times \left(1 - \frac{MC_B}{100}\right) \right) \\
\left. + \left( \frac{32}{4} \times 0.05 \, F_B \times \left(1 - \frac{MC_B}{100}\right) \right) \right) \\
/ \left( \frac{44}{12} \times 0.44 \times F_B \times \left(1 - \frac{MC_B}{100}\right) \right) \\
\left. + \left( \frac{36}{4} \times 0.05 \, F_B \times \left(1 - \frac{MC_B}{100}\right) \right) \right) \\
\left. + \left( F_B MC_B + \left( 494.16 \, \frac{\text{klb}}{h} \times 0.05 \right) \right) \right) \\
\left. + \left( \frac{28}{14} \times 0.0038 \, F_B \times \left(1 - \frac{MC_B}{100}\right) \right) + \left( 0.77 \times 494.16 \, \frac{\text{klb}}{h} \right) \right) \\
\left. + \left( \frac{32}{16} \times 0.4512 \, F_B \times \left(1 - \frac{MC_B}{100}\right) \right) + \left( 0.23 \times 494.16 \, \frac{\text{klb}}{h} \right) \right) \\
\left. - \left( \frac{32}{12} \times 0.44 \, F_B \times \left(1 - \frac{MC_B}{100}\right) \right) \right) \\
\left. + \left( \frac{32}{4} \times 0.05 \, F_B \times \left(1 - \frac{MC_B}{100}\right) \right) \right) \\
\right)
\]

(F1)

Since there are two unknowns in the above equation, another equation is needed to solve for both hog fuel flow rate and moisture content.

The heat balance equation is setup:
\[ F_B \left(1 - \frac{MC_B}{100}\right)HHV_B + F_{NG}HHV_{NG} + F_{oil}HHV_{oil} + F_{w}H_{T,w}p_w + F_{air}C_{P_{air}}T_{air} \]

\[ = F_{Bl}H_{P_{Bl}} + F_{s}H_{T_s}p_s + F_{FG}C_{P_{FG}}T_{FG} + F_{ash}C_{P_{ash}}T_{ash} \]

The operating parameters for May 10, 2016 at 6AM are plugged into the heat balance equation:
Equations F1 and F2, are a system of two equations with two unknowns which can be algebraically solved to find the two unknowns $F_B$ and $MC_B$. For this particular example, the values are:
\[ F_B = 111.2 \, \text{klb/h} = 55.66 \, \text{ton/h} \]

\[ MC_B = 42 \% \]

The calculated moisture content is 42\%, the measured moisture content from the oven dried method was reported by the mill as 47\%. Therefore, the calculation error is 11\%.

**Mill F Case Study Data:**

Samples of hog fuel were taken from the conveyor feeding into the BFB boiler at Mill F, the samples were oven dried to determine their actual moisture content. The operating data from the same time period was used to calculate the moisture content from the heat and mass balances.
Table F 4. Operating parameters for soft sensor case study at Mill F

<table>
<thead>
<tr>
<th>Variable (units)</th>
<th>Day 1</th>
<th>Day 2</th>
<th>Day 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6AM 10AM 12PM 2PM</td>
<td>6AM 10AM 12PM 2PM</td>
<td>6AM 10AM 12PM 2PM</td>
</tr>
<tr>
<td>Steam Flow (t/h)</td>
<td>105 101 104 107 100</td>
<td>108 105 105 108 106</td>
<td>106 105 105 107 105</td>
</tr>
<tr>
<td>Steam Pressure (MPa)</td>
<td>6.5 6.5 6.6 6.4 6.4</td>
<td>6.5 6.4 6.4 6.4 6.4</td>
<td>6.4 6.5 6.4 6.5 6.4</td>
</tr>
<tr>
<td>Steam Temperature (°C)</td>
<td>440 440 441 440 441</td>
<td>440 440 440 440 440</td>
<td>440 440 439 440 440</td>
</tr>
<tr>
<td>Economizer Inlet Water Temperature (°C)</td>
<td>154 155 155 155 155</td>
<td>154 154 154 154 154</td>
<td>154 154 154 154 154</td>
</tr>
<tr>
<td>Blowdown Pressure (MPa)</td>
<td>10 10 10 10 10</td>
<td>10 10 10 10 10</td>
<td>10 10 10 10 10</td>
</tr>
<tr>
<td>Total Oil Flow Rate (kg/h)</td>
<td>426 421 411 418 418</td>
<td>476 475 475 473 471</td>
<td>466 461 460 463 467</td>
</tr>
<tr>
<td>Air inlet Temperature (°C)</td>
<td>34 39 40 35 39</td>
<td>27 29 31 32 32</td>
<td>27 30 29 31 31</td>
</tr>
<tr>
<td>Outlet CO (ppm)</td>
<td>210 181 231 191 214</td>
<td>300 254 241 252 267</td>
<td>260 317 371 218 210</td>
</tr>
<tr>
<td>Total Air Flow Rate (m³/s)</td>
<td>33 33 33 33 33</td>
<td>33 33 33 33 33</td>
<td>33 33 33 34 33</td>
</tr>
<tr>
<td>Total Hog Fuel Feed Rate (t/h)</td>
<td>37 46 44 40 37</td>
<td>43 48 38 41 40</td>
<td>39 42 44 42 42</td>
</tr>
<tr>
<td>Blowdown (t/h)</td>
<td>1.5 1.2 1.6 1.6 1.6</td>
<td>1.6 1.6 1.5 1.6 1.6</td>
<td>1.6 1.6 1.6 1.6 1.6</td>
</tr>
<tr>
<td>Flue gas Temperature (°C)</td>
<td>202 203 203 201 202</td>
<td>204 204 200 203 200</td>
<td>203 200 200 204 205</td>
</tr>
</tbody>
</table>
Mill A Case Study: Sample Calculation and Data

For the case study at mill A, the measured water vapor in the flue gas was used to calculate moisture content as described below. This value was compared to the actual moisture content of the feed determined based on the oven dry method.

The elemental composition of the hog fuel from mill A is shown in the following table:

<table>
<thead>
<tr>
<th>Composition</th>
<th>(% dry basis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>52</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>6.5</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.31</td>
</tr>
<tr>
<td>Oxygen</td>
<td>37.7</td>
</tr>
<tr>
<td>Chlorine</td>
<td>0.01</td>
</tr>
<tr>
<td>Ash</td>
<td>3.5</td>
</tr>
<tr>
<td>Total Dry Mass</td>
<td>100</td>
</tr>
</tbody>
</table>

The table below shows the trial data as well as the operating data for the same time period:
<table>
<thead>
<tr>
<th>Trial Data</th>
<th>Mill A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial #</td>
<td>1 2 3 4</td>
</tr>
<tr>
<td>Flue gas volume (L)</td>
<td>59.5 55.3 69.5 58</td>
</tr>
<tr>
<td>Boiler house temperature (°C)</td>
<td>36 36 35 37</td>
</tr>
<tr>
<td>Dry flue gas standard volume (L)</td>
<td>52.6 48.9 61.6 51.2</td>
</tr>
<tr>
<td>Water collected (g)</td>
<td>8.7 7.3 8.2 7.5</td>
</tr>
<tr>
<td>Water collected (L)</td>
<td>10.8 9.1 10.2 9.3</td>
</tr>
<tr>
<td>Water vapor (vol%)</td>
<td>17.2 15.7 14.2 15.4</td>
</tr>
<tr>
<td>Water vapor (wt%)</td>
<td>10.9 9.96 8.95 9.76</td>
</tr>
<tr>
<td>Operating Data</td>
<td></td>
</tr>
<tr>
<td>Feed flow rate (ton/h)</td>
<td>29.6 28.2 24.9 26.2</td>
</tr>
<tr>
<td>Total air flow rate (klb/h)</td>
<td>360 387 374 370</td>
</tr>
<tr>
<td>Calculated moisture content (%)</td>
<td>47.0 49.5 44.3 50.6</td>
</tr>
<tr>
<td>Oven Dry Method</td>
<td></td>
</tr>
<tr>
<td>Measured moisture content (%)</td>
<td>45.6 52.0 42.5 51.2</td>
</tr>
<tr>
<td>Measurement error (%)</td>
<td>3.1 4.8 4.2 1.1</td>
</tr>
<tr>
<td>Squared error</td>
<td>1.96 6.25 3.24 0.325</td>
</tr>
</tbody>
</table>

In order to calculate moisture content of the feedstock from the water vapor in the flue gas, the mass balance for water explained in chapter 3 is used, ignoring the water content of the air due to humidity:
\[ x_{H_2O} = \frac{36}{4} F_B x_H (1 - \frac{MC_B}{100}) + (F_B \frac{MC_B}{100})/ (\frac{44}{12} F_B x_C \times (1 - \frac{MC_B}{100}) + \frac{36}{4} F_B x_H \times (1 - \frac{MC_B}{100}) + 
(F_B MC_B) + \frac{28}{14} F_B x_N \times (1 - \frac{MC_B}{100}) + 0.77 F_{air} + \frac{32}{16} F_B x_O \times (1 - \frac{MC_B}{100}) + 0.23 F_{air} - \left( \frac{32}{12} F_B x_C + \frac{32}{4} F_B x_H + F_B x_S \right) \times (1 - \frac{MC_B}{100}) \]

Plugging in the elemental composition, operating parameters, and measured water vapor for the first trial into the water mass balance, moisture content can be calculated. First the biomass feed flow rate and air flow rate should be converted to kg/h:

\[ F_B = 26,852 \text{ kg/h} \]

\[ F_{air} = 163,293 \text{ kg/h} \]

\[ 0.109 = \left( \left( \frac{36}{4} \times 26852 \times 0.065 \times \left(1 - \frac{MC_B}{100}\right) \right) + \left( 26852 \times \frac{MC_B}{100} \right) \right) \]

\[ \left/ \left( \left( \frac{44}{12} \times 26852 \times 0.52 \times \left(1 - \frac{MC_B}{100}\right) \right) \right) \right. \]

\[ + \frac{36}{4} \times 26852 \times 0.065 \times \left(1 - \frac{MC_B}{100}\right) + (26852 \times MC_B) \]

\[ + \frac{28}{14} \times 26852 \times 0.0031 \times \left(1 - \frac{MC_B}{100}\right) + 0.77 \times 163293 \]

\[ + \left( \frac{32}{16} \times 26852 \times 0.377 \times \left(1 - \frac{MC_B}{100}\right) \right) + (0.23 \times 163293) \]

\[ - \left( \left( \frac{32}{12} \times 26852 \times 0.52 \right) + \left( \frac{32}{4} \times 26852 \times 0.065 \right) \right) \times \left(1 - \frac{MC_B}{100}\right) \]
Solving the above equation moisture content of the feedstock is calculated $MC_B = 47\%$, the measured moisture content from the oven dry method was 45.6%.

**Mill H Case Study Data**

For the case study at mill H, the water vapor in the flue gas was measured and used to calculate the moisture content of the feedstock, this value was compared to the actual moisture content of the feed measured by the oven dry method. The following table shows the elemental composition of the hog fuel:

<table>
<thead>
<tr>
<th>Composition</th>
<th>(%) dry basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>48.4</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>6.4</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.08</td>
</tr>
<tr>
<td>Oxygen</td>
<td>43.6</td>
</tr>
<tr>
<td>Chlorine</td>
<td>0.01</td>
</tr>
<tr>
<td>Ash</td>
<td>1.5</td>
</tr>
<tr>
<td><strong>Total Dry Mass</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

The trial data for measuring the water vapor in the flue gas, as well as operating data from the same time period as the trials are shown in the following table:
**Table F 8. Case study data for mill H**

<table>
<thead>
<tr>
<th></th>
<th>Mill H</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trial #</strong></td>
<td>1  2  3</td>
</tr>
<tr>
<td><strong>Trial Data</strong></td>
<td></td>
</tr>
<tr>
<td>Flue gas volume (L)</td>
<td>64.5  53.2  60.3</td>
</tr>
<tr>
<td>Boiler house temperature (°C)</td>
<td>10  10  10</td>
</tr>
<tr>
<td>Dry flue gas standard volume (L)</td>
<td>62.2  51.3  58.2</td>
</tr>
<tr>
<td>Water collected (g)</td>
<td>10.5  8  12</td>
</tr>
<tr>
<td>Water collected (L)</td>
<td>13.1  10.0  14.9</td>
</tr>
<tr>
<td>Water vapor (vol%)</td>
<td>17.4  16.2  20.4</td>
</tr>
<tr>
<td>Water vapor (wt%)</td>
<td>11.7  10.9  13.9</td>
</tr>
<tr>
<td><strong>Operating Data</strong></td>
<td></td>
</tr>
<tr>
<td>Feed flow rate (ton/h)</td>
<td>20.8  20.5  23.3</td>
</tr>
<tr>
<td>Total air flow rate (klb/h)</td>
<td>258  265  251</td>
</tr>
<tr>
<td>Calculated Moisture content (%)</td>
<td>50.5  42.0  61.4</td>
</tr>
<tr>
<td><strong>Oven Dry Method</strong></td>
<td></td>
</tr>
<tr>
<td>Measured Moisture content (%)</td>
<td>47.4  41.2  64.3</td>
</tr>
<tr>
<td>Measurement error (%)</td>
<td>6.5  1.9  4.5</td>
</tr>
<tr>
<td>Squared Error</td>
<td>9.61  0.64  8.352</td>
</tr>
</tbody>
</table>