Effect of Feedstock Moisture Content on Biomass Boiler Operation

by

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Abstract

Burning feedstock with high and constantly varying moisture contents is a challenge in the operation of the stoker-grate type biomass boiler in pulp and paper mills. A fundamental two part study was performed to systematically investigate the effect of moisture content on the combustion behaviour of woody biomass. The first part involved a thermogravimetric combustor controlled at different temperatures, and the second part involved collecting and analyzing operating data of 3 biomass boilers. The laboratory results show that combustion occurs through three stages: time-to-ignition, volatile burning, and char burning and samples containing 40% moisture ignite and burn readily at 800°C, but they take longer to ignite at lower temperatures and do not ignite at 400°C. For the field studies, the moisture content of the feedstock was back calculated by a material and energy balance. The relationship between moisture content and the other operating data was studied. The results suggest that changes in moisture content mainly affect the lower furnace temperature and excess O₂.

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Chapter 1

Introduction

1 Introduction

1.1 Energy Demand in the Pulp and Paper Industry

Pulp and paper mills require high pressure steam and electric power to dry pulp and paper products, heat water and process liquors, concentrate spent cooking liquor (black 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 the energy required is self-supplied by burning concentrated black liquor in recovery boilers. The remaining 30 to 40% is generated by burning biomass in biomass boilers, and by local utility stations. Natural gas and fuel oil are also co-fired in biomass boilers to supplement steam and power as required [1]. Biomass boilers provide pulp and paper mills with a means of addressing rising energy and waste disposal costs in order to remain competitive. There is a need to maximize energy production while minimizing environmental impact in order to meet increasingly stringent regulations.

Figure 1. Overview of pulp making process. (Courtesy: Valmet)

1.2 Biomass Boilers

1.2.1 Summary of Operation

Biomass boilers in pulp and paper mills are often referred to as hog-fuel boilers, bark boilers and power boilers. These boilers can be as large as an eight story tall building and depending on the design and type of boiler, they can produce up to 500 MW of thermal energy [2]. Biomass is fed into the boiler together with excess air for complete combustion to occur. The high temperature lower furnace area is where combustion takes place. The heat released during combustion, heats up the flue gases in the boiler and the flue gases pass through banks of tubes in the super heater area of the boiler which is located at the top levels. The water in the tubes is heated and high pressure steam is produced and passed to the required stages of the process. The flue gases exit at the top of the boiler and are passed through heat exchangers or economizers to heat the inlet air of combustion. At this point, the flue gases have lost most of their heat and can be passed through electrostatic precipitators (ESP) in order for the fly ash and particulates to be captured in the ESP area. After that the flue gases, which are sufficiently cooled and do not contain any fly ash or particulate matter, exit via the stack. The pressure difference between the forced draft fan and the induced draft fan is kept at zero or slightly negative so that the boiler operates under a slight vacuum and the flue gases travel upwards and outwards in the boiler. Figure 2 shows a schematic diagram of a biomass boiler.

Figure 2. Schematic diagram of a biomass boiler (Courtesy: Babcock & Wilcox)

1.2.2 Feedstock Types

The solid fuel that is burned in biomass boilers is known conventionally as hog-fuel, which is a mixture of various types of biomass available at the mill site, such as saw dust coming from the slasher deck, bark falling 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 [3]. Many biomass boilers also burn primary sludge, secondary sludge (bio sludge) and/or deinking sludge generated from various mill processes.

While the main components of biomass on a dry basis are relatively constant, with 45-50 wt% C (carbon), 5-6 wt% H (hydrogen), and 40-44 wt% O (oxygen), the moisture content, ash content and ash composition can vary widely, depending on sources and storage conditions of the feedstock. Bark, for instance, contains more ash, including more Ca (calcium) and K (potassium) than other parts of the tree. Agricultural residues (wheat/rice straw, corn waste, etc.) generally contain more ash, alkali, Cl (chlorine) and S (sulphur) than woody biomass. Rice husk contains a large amount of Si (silicon), while chicken litters contain 20 wt% ash and large amounts of N (nitrogen), P (phosphorus), K, and Ca.

1.2.3 Boiler Types

1.2.3.1 Stoker Grate (SG) Boiler

In stoker-grate (SG) boilers, shown in Figure 3, the biomass is fed into the boiler and piled on a grate and pile burning takes place. Combustion air is introduced from the bottom of the grate and travels through the pinholes to reach the biomass and combustion takes place on the bed. Stoker units are usually equipped with pinhole grates, vibrating grates, traveling grates, or reciprocating grates. If the grate is stationary, grate cleaning needs to take place once or twice daily, where the biomass on the grate is completely burned, and the bottom ash is removed from the grate manually as shown in Figure 4. The design of SG boilers dictates the acceptable properties of the feedstock. The thermal conversion efficiency of these types of boilers decreases significantly if the required properties of the feedstock are not met. The operating window is very narrow and needs to be followed strictly to avoid co-combustion of fossil fuels for a required steam production.

Figure 3. Stoker grate type boiler (Courtesy: Babcock & Wilcox)

Figure 4. Grate cleaning for removal of bottom ash

1.2.3.2 Bubbling Fluidized Bed (BFB) Boiler

Bubbling fluidized bed (BFB) boilers are designed to increase the efficiency of combustion and be able to handle more variations in feedstock properties. In BFB boilers, shown in Figure 5, the biomass is fed in 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 and combustion takes place more efficiently. Also the air required for combustion is fed into the boiler in several locations: primary air at the bottom of the bed, secondary and tertiary higher up in the boiler respectively. The location where the secondary and tertiary combustion air is fed is where the combustion of volatiles takes place. BFB boilers can handle a wider variation in feedstock moisture content and size, and require less fossil fuel co-combustion to maintain the required steam pressure and flow.

Figure 5. Bubbling fluidized bed type boiler (Courtesy: Babcock & Wilcox)

1.2.4 Thermal Performance

A biomass boiler in pulp and paper mills typically converts about 75% of the combustion heat of its feedstock into steam and power. The thermal conversion efficiency of the boiler depends greatly on the moisture content, ash content and ash properties of the biomass, and on the design and operating conditions of the boiler [4]. Modern bubbling fluidized bed (BFB) boilers are generally more efficient and less susceptible to moisture variations than older stoker grate (SG)

boilers [5]. For a given boiler, the boiler efficiency is dictated mainly by the moisture content and the combustion behavior of the feedstock, and the amount and thermal properties of the ash. Understanding the combustion behaviour of the feedstock is of vital importance for predicting the combustion efficiency since the characteristics of the feedstock can vary considerably in type, size, shape and moisture content as shown in Figure 6.

(a)

(b)

(c)

(d)

Figure 6. Different types of feedstock a) conveyor belt to boiler, b) sludge, c) older biomass pile wetted by rain and d) fairly dry biomass pile

1.2.5 Operational Problems

The high variation in feedstock moisture content is an inherent problem in biomass boiler operation. Biomass feedstock typically contains 40 - 50 wt% moisture, but can vary from a few wt% if it has been dried to over 70 wt% for aged feedstock, particularly that has been exposed to rain and/or stored under wet conditions. Wet biomass not only reduces the boiler steam production capacity, but also reduces the boiler's lower furnace temperature, making it more difficult to sustain the fire and to burn the already wet material. More fossil fuels (natural gas or crude oil) will have to be co-fired in order to meet the mill's steam requirement, and this can be costly and is not desirable. On the other hand, if the biomass is too dry, the combustion produces more particulate matter resulting in a high stack opacity problem. It may also increase the furnace temperature excessively leading to problems associated with wall slagging and clinker formation on the furnace grate [6].

Even for a feedstock with the same moisture content other parameters such as size, shape, and type of wood species have a significant effect on the performance of the boiler. Different types of wood species have different combustion behaviors which lead to different operating parameters [7]. All of these factors must be considered when investigating the operation of a biomass boiler.

1.3 Biomass Moisture Content

Moisture content contained in the structure of wood can be chemically bound water, physically bound water or free water. Free water is the apparent moisture content that must be dealt with in order to maintain a constant steam production in biomass boilers. If the biomass is exposed to rain or snow for long periods of time, the fiber saturation point of the wood structure is reached which, depending on the wood type and size, can result in moisture content as high as 80%. High moisture content decreases the heating value of the biomass significantly since some heat is required to evaporate the water and increases the amount of flue gas produced which can drive the ID fan into overdrive and result in tripping the boiler.

On the other hand, if the biomass is exposed to long periods of sunshine, the moisture content can be as low as 0% or reach equilibrium with the humidity of the air resulting in 5-6% moisture

content. In this scenario, the furnace temperature will rise excessively and can lead to clinker or glass formation of the silicone content of the biomass or corrosion of the equipment.

In many mills, bio-sludge from the wastewater treatment section is added in to the feedstock of biomass boilers to avoid regulatory complications and high cost of landfilling. This creates high moisture content in the boiler and decreases the thermal efficiency of the boiler.

1.4 Motivation and Objective

In recent years extensive studies on biomass drying, combustion and ash characteristics and on the thermal conversion of biomass into bio-oil/biogas via pyrolysis and gasification have been performed by various research groups around the world [3-5, 8-32]. In the field of biomass combustion, the main studies have been on low moisture content samples (less than 20% [8] [9]), developing kinetic model [5] [10], drying methods [11] [12], and combustion of kitchen waste material [13]. The focus, however, has not been placed on operating issues in biomass boilers, particularly those in pulp and paper mills where hog-fuel with high and constantly varying moisture content is the main component. While each pulp and paper mill has its own way of dealing with variations in moisture content and other feedstock characteristics, there is a lack of fundamental understanding of how these property changes may affect the combustion behaviour of biomass and their impact on boiler operation. The purpose of this study is to systematically investigate these effects, leading to the development of fundamental data for biomass combustion and boiler operation.

The objective of this study is achieved in two parts: laboratory experiments, where biomass combustion of single particles are investigated in a thermogravimetric combustor controlled at different temperatures, and field studies, where data analysis of 3 biomass boilers is carried out to help better understand the impact of moisture content fluctuations on the operation of biomass boilers in pulp and paper mills.

Chapter 2 Literature Review

2 Literature Review

As discussed in the introduction section, the effect of moisture content on the operation of biomass boilers at pulp mills has not been systematically studied, however the effect of moisture content on combustion has been sporadically studied, and some of the relevant research is presented here.

2.1 Biomass Combustion

Combustion is the oldest and most efficient method of utilizing the energy content of biomass. Temperatures higher than 300°C and ample amounts of oxygen are required for combustion to start. First the volatile content of the biomass need to reach volatilization temperature which varies from 250°C -300°C, at this point they are emitted from the structure of the wood, and if the surrounding temperature is high enough, a flame will form. After all the volatile content of the biomass have emitted, oxygen will penetrate into the remaining fixed carbon content of the biomass and carbon oxidization will take place. If the oxygen penetrating into the biomass structure is not the stoichiometric ratio, incomplete combustion will take place which can have byproducts such as carbon monoxide [7].

Since the elemental composition of different types of biomass is relatively constant, the heating value and combustion behaviour of biomass depends on its moisture and ash content. The main reactions taking place during combustion are the oxidization of carbon and hydrogen.

From the above reactions, the amount of theoretical oxygen required can be calculated and excess amounts of the required oxygen can be made available for complete combustion to take place.

2.2 Combustion of High Moisture Content Material

The effect of water content on waste material combustion has been studied by Saito et al. [13] where balsa wood was used as sample material which is representative of the physical properties of the waste material. Their results suggested that drying and devolatilization stages of combustion overlap for high moisture content and the volatile burning rate drastically decreased with increasing moisture content.

Shanmukharadhya and Sudhakar [8] studied the effect of moisture content on combustion in bagasse fired furnaces. Their results showed that moisture content caused a significant delay in the start of combustion and ignition. They also reported that the combination of particle size and moisture content played an important role in the stability of the furnace operation.

Suksankraisorn et al. [9] reported that waste material with moisture content higher than 20% did not ignite at a furnace temperature of 600°C. For lower moisture contents optimum carbon combustion efficiency was reached with 10% moisture content. Diego et al. [14] developed a model for the devolatilization of wet pine wood particles in fluidized beds. They observed that the devolatilization times increased with increasing moisture content and their model predicted the same trend. Their model however, only predicted combustion behaviour for samples with moisture content up to 50% and did not include the char burning stage of combustion.

Incineration of bio-sludge has been investigated by different researchers since it is a safer alternative to landfilling or use as fertilizer which have potential hazards and risks. Nevertheless, the formation of hazardous by-products is still a concern. In addition to environmental issues, the high moisture content of sludge, both free and bound water, causes problems for sludge dewaterability as well as combustion. The effect of moisture content on bio-sludge combustion has been studied by Shin et al. [15] both in a batch type combustor and cyclone circulating fluidized bed. They concluded that the optimum combustion of carbon can be reached with 35% water content in the sludge. The combustion characteristics of wet sewage sludge (80% moisture content) in a fluidized bed have been studied by Ogada and Werther [16]. Their results showed that there is significant overlap between drying, devolatilization, and char combustion stages to the extent that the three stages could be thought to occur simultaneously.

2.3 Fixed Bed Combustion

Biomass combustion in stoker-grate type boilers is one type of fixed bed combustion, which has been studied extensively. Shin and Choi [18] proposed a mechanism for the combustion of waste particles in a fixed bed. They identified two distinct reaction modes based on the availability of oxygen: the oxygen limited mode and the reaction limited mode. The flame disappearance is caused by the increase in flow rate of air which results in excessive cooling by convection. From the heat and mass transfer mechanisms, radiative heat transfer in the bed was found to be important in initiating the flame front and in transferring heat to the cold bed.

Yang et al. [19] studied the effect of fuel moisture content for modelling waste combustion in grate furnaces. Their model predicted that wetter fuels take a longer time to ignite and the average burning rate in the bed decreases with an increase in moisture content of the fuel.

Another important parameter in fixed bed combustion is the fuel particle size. Yang et al [20] studied the fuel size effect on combustion of pinewood cubes ranging in size from 5 to 35 mm. Their research showed that the smaller particles ignited more quickly and had higher burning rates, whereas larger particles created more distinctive combustion stages with less overlap, and produced a higher flame temperature

Bruch et al. [21] developed a computer model for the conversion of wood under packed-bed conditions with particle sizes ranging from 5 to 25mm. Their single-particle model considered each particle undergoing heating, drying, pyrolysis, gasification, and combustion. They also conducted experiments to validate the single particle model for beech wood conversion during pyrolysis and char burning and the agreement between the model and the experiments were satisfactory with the exception of wet wood with 67% moisture content where the pyrolysis rates were not accurately estimated.

2.4 Biomass Boilers in Pulp and Paper Mills

The high and constantly varying moisture content of the feedstock has been an ongoing challenge from the perspective of pulp mills. McDermott et al. [21] investigated the effect of wet feedstock from the boiler operators' experience and came to the conclusion that the maximum moisture content of the feedstock is 55% for stable combustion using 50% excess air preheated to 200°C. Their findings however, were not confirmed by systematic experimental data and were only based on the experience at different mills.

Linderoth [22] studied the advantages of drying the feedstock and demonstrated theoretical calculations for changes in boiler efficiency, grate heat release, adiabatic combustion temperature, excess air ratio and steam generation with fuel moisture levels. The theoretical boiler efficiency decreases from 80% to 70% for increase in moisture content from 20% to 40% and for moisture contents higher than 60%, the efficiency drops below 55%. For this study, even though theoretical values are discussed, the findings are not supported by experimental observations and a fundamental understanding of the effect of changes in moisture content on the combustion characteristics in biomass boilers is not presented.

In summary, the combustion characteristics of different biomass material has been investigated by other researchers, however the emphasis has not been on the feedstock of biomass boilers at pulp mills with constantly varying properties such as moisture content. Moreover, the focus of most studies has been on modelling of combustion, either as a single particle or in boilers with continuous feed, but the findings have not been supported by experimental observations. Therefore, there is a need for fundamental understanding and systematic study of biomass combustion characteristics related to biomass boilers in pulp and paper mills which is the main objective of this work.

Part I: Laboratory Experiments

In order to investigate the effect of moisture content on biomass combustion, laboratory experiments with two setups were carried out. First, the water absorption of different types of wood species was studied by soaking biomass samples in water and measuring changes in weight. Second, a thermogravimetric combustor was used to run biomass combustion experiments with different sample properties and furnace temperatures.

Chapter 3

Water Absorption Experiments

3 Water Absorption Experiments

Changes in moisture content of woody biomass were studied to find the effect of biomass type, cut orientation and duration of water exposure.

3.1 Methodology

Depending on the cut surface of the wood particle, the directions can be transverse, tangential or radial as shown in Figure7. In order to better understand the effect of moisture content and the behaviour of water inside the wood particle, a series of experiments was carried out to first determine the water absorption characteristics of different surfaces of the wood particle.

Figure 7. Wood structure cut surfaces [21]

Figure 8. Setup for water absorption experiments

3.1.1 Sample Preparation

Untreated maple and cedar wood panels were purchased from the Home Depot and cut into cuboids with $1.2\text{cm} \times 1.2\text{cm} \times 1.2\text{cm}$ dimensions. The transverse, tangential and radial surfaces were identified and all surfaces were covered with aluminum type tape except for the surface which would be exposed to water. In order to have one sample from each surface exposed, 3 samples from each wood species were prepared.

3.1.2 Test Procedure

Three samples each exposing different wood surfaces were prepared (Figure 9a). The initial dry weight of the samples was measured. The samples were inserted in water from the exposed surface at the same time as shown in Figure 9b and the change in weight after specific time intervals was measured.

(a)

(b)

Figure 9. Water absorption experiment a) cedar sample with all surfaces covered except for radial surface b) radial surface of cedar sample inserted in water

3.2 Results and Discussions

3.2.1 Water Absorption and Wood Orientation

Figure 10 shows the results of water absorption from different surfaces for cedar. It was observed that for softwoods, the highest rate of water absorption was on the transverse surface, this can be explained by the empty structure of the vessels which are exposed on the transverse surface. For hardwoods on the other hand, the water absorption of the different surfaces were very similar and the tangential surface had a slightly higher absorption rate, as shown in Figure 11. This can be explained by the dense structure and compaction of hardwood species where the different cut surfaces do not have varying amounts of empty space for water to penetrate into the structure.

Figure 10. Water absorption for softwood (cedar)

Figure 11. Water absorption for hardwood (maple)

Comparing Figure 10 with Figure 11, it is clear that the rate of water absorption is faster for softwoods and after 40 minutes of exposure to water, the moisture content of softwoods reaches almost 40% whereas the moisture content of hardwoods reaches only 15%. This difference in rate of water absorption can also be explained by the difference in wood structure and density between hardwoods and softwoods. For samples with equal volume, the softwood structure has more empty spaces for water penetration and absorption, whereas for hardwoods, the compact structure allows less water penetration and therefore, a slower increase in moisture content.

3.2.2 Maximum Moisture Content

For studying the effect of moisture content on combustion, samples with different moisture contents were prepared from different wood species. It was observed that, depending on the wood type, the maximum moisture content reached after 4 weeks of water exposure, was different. Table 1 shows the maximum moisture content achieved for different wood types when left in water for 4 weeks. It shows that for increasing wood density, the maximum moisture content decreases. Also for saw dust with particle sizes ranging from 0.42 mm to 1.12 mm, the maximum moisture content reached was 80% which was higher than that of wood chips suggesting that due to the smaller size of sawdust, the collective surface area of the sample was higher, and therefore the maximum moisture content reached was also higher.

Table 1. Maximum moisture content possible for different wood species up to 4 weeks of water exposure

	Wood Species	Sample Size	Density (g/cm ³)	Maximum Moisture Content (%)
Mix	Saw Dust	0.42 mm-1.12 mm	0.15	80
Softwood	Cedar	1.5cm×1.2cm×1.2cm	0.33	62
	Pine Bark		0.37	59
	Pine		0.39	60
Hardwood	Poplar		0.56	44
	Oak		0.62	46
	Maple		0.76	43

Chapter 4 Combustion Experiments

4 Combustion Experiments

In order to systematically study the effect of moisture content on combustion, the thermogravimetric combustor at our laboratory was used which not only continuously records the weight change of the sample, but also allows for monitoring of the physical appearance of the combustion process.

4.1 Experimental Setup

4.1.1 Thermogravimetric Combustor

In order to fairly 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 that can handle various types of samples and provide more quantitative insight into the combustion process.

Figure 12a 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 12b). It has a 10 cm $\times$ 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 gas control system regulates compressed air and passes it through an air distributor at the bottom of the furnace.

(a)

(b)

Figure 12. a) Thermogravimetric (TG) combustor and b) Cross section of the electrical furnace

4.1.2 Sample Preparation

In this study, samples were prepared from 5 different wood species purchased from the Home Depot: cedar, pine, poplar, oak, and maple. They were cut into cuboids with the desired dimensions for each set of experiments. These wood blocks were soaked in water at ambient temperature for 24 hours, and then dried at 105°C in an oven for different lengths of time to produce samples with different moisture contents. The moisture content of each resulting sample was calculated based on the difference in the sample weight before soaking it in water and after drying it in the oven, and according to the following formula:

$$MC\% = \frac{\text{original weight} - \text{oven dried weight}}{\text{original weight}} \times 100$$

4.1.3 Test Procedure

The furnace temperature was controlled and monitored using a K-type thermocouple placed near the test sample (Figure 12b). In order to allow combustion air to be well distributed from all sides of the sample, the sample was placed on a stainless steel type 316 mesh tray (3 cm O.D.) and hung on a hook underneath the balance. After the sample weight was appropriately tared and the tray became stable, the camcorder was turned on. The furnace was subsequently pushed up to quickly lower the sample tray into the middle of the furnace. The sample appearance was recorded by the camcorder through the glass window, while the sample weight was continuously recorded by the balance. During the test, the air flow was controlled at 1L/min. The time required for each combustion stage was determined based on video images recorded by the camcorder and the weight loss registered by the balance.

4.2 Results and Discussions

4.2.1 Combustion Behaviour

Figure 13 shows, as an example, still images of the combustion of a 1.34 g cube of oak (1.5cm×1.2cm×1.2cm) with 20% moisture content at 800°C. The time (minutes: seconds) at which the image was taken is displayed at the bottom right corner of each frame. The first frame (00:00) is the appearance of the sample at the instance it was inserted into the furnace. For the first few seconds, only slight blackening or charring was observed around the edges of the sample. This suggests that the sample surface temperature was sufficiently high for the water to dry and for the volatiles to release, but was not sufficient for the volatiles to ignite. A yellow flame appeared after 4 seconds (00:04), indicating the beginning of the volatile burning stage in which the volatile content of the sample was emitted and the temperature of the surrounding was high enough for the volatiles to ignite and form a flame. As the combustion heat further transferred into the sample interior, volatile burning became more intense, producing a larger flame. The flame fully enveloped the sample at (00:15), but its intensity appeared to slowly diminish with time. The flame eventually disappeared at (01:05) indicating the end of the volatile burning stage and the beginning of the char burning stage. As the char continued to burn, it glowed brighter (01:05), further illuminating the surrounding of the sample (comparing (01:30) and (02:00)). At the end, char burning stopped and a small amount of ash was left over (05:11). These video images confirmed that drying and volatile burning are fast (about 1 minute) and overlap with each other due to the non-uniform temperature distribution within the sample. Char burning is much slower, and it requires more than 5 minutes to complete.

Figure 13. Combustion of a 1.34 g oak sample with 20% moisture content at 800°C (time displayed in mm:ss)

4.2.2 Combustion Stages

From the combustion video of a biomass sample, there are four distinct times that may be used to characterize the combustion behaviour of the sample. In the case shown in Figure 13, for example, Time ‘A’ was the moment the sample was inserted into the furnace (00:00), Time ‘B’ was when the sample caught fire as a result of volatile burning (00:04), Time ‘C’ was when the flame disappeared indicating the end of the volatile burning stage (01:05), and Time ‘D’ was when the char no longer glowed indicating the end of the char burning stage (05:11). Based on these times, the combustion stages were defined as:

- Time-to-Ignition (from A to B)
- Volatile Burning (from B to C)
- Char Burning (from C to D)

Combustion tests were performed on over 300 samples of different wood species and moisture contents. Figure 14 shows the duration of the combustion stages for all of the samples which were tested in the thermogravimetric combustor at 800°C. In this figure, the time-to-ignition or drying duration is shown with diamond shaped markers, volatile burning duration is shown with triangles, and char burning duration is shown with squares. It is evident that the drying duration is much shorter than the volatile burning or the char burning for all samples. As the moisture content increases, the drying duration also increases but compared to the overall combustion duration, this increase is not significant up to 30%. For moisture contents higher than 30%, on the other hand, the increase in drying time or time-to-ignition increases exponentially. The volatile burning duration also shows an increasing trend with moisture content. The results shown here in Figure 14 are from different samples with different compositions and sizes. Therefore the differences in the volatile content, fixed carbon content and ash content have an effect on the combustion stages. This is why the values for the char burning duration shown in Figure 14 do not show a specific trend and vary from 2 minutes to more than 6 minutes. The effect of moisture content on different types of wood species is discussed in detail in the following sections.

Figure 14. Combustion stages of biomass samples (1.5cm×1.2cm×1.2cm) burned at 800°C

Figure 15 shows an example of a weight change profile during the combustion of oak at 800°C. Drying (vaporization of water) and volatile burning are thermal processes that occur rapidly at low temperatures (100°C for water evaporation and 250-300°C for biomass pyrolysis). Due to the uneven temperature distribution across the sample, drying and volatile burning are often overlapped, making it difficult to distinguish them. As a result, the moisture content and the volatile content of the sample are lumped together as the total weight loss from A to C on the graph.

On the other hand, since char burning is a relatively slow solid-gas reaction that occurs at a much higher temperature (> 600°C) compared to volatile burning, there is no overlap between volatile burning and char burning. The weight loss from C to D is the same as the char content and the remaining weight (D onward) is the same as the ash content.

Figure 15. Weight change profile for combustion of oak at 800°C (1.34 g dry sample, 40% moisture content)

From the weight change profile of each sample, the volatile content, fixed carbon content and ash content can be determined in weight percentages. If the moisture content of the sample is known, the weight change during volatile burning, during which a flame is present, is the volatile content, and the weight change during char burning is the fixed carbon content of the biomass sample. It is also evident from the weight change profile, that even though the volatile content of the biomass sample is almost 80% of the total weight, the volatile burning duration is shorter than the char burning duration. Therefore, the rate determining step for the overall combustion is the char burning stage.

4.2.3 Effect of Surface Area

One of the characteristics of the feedstock that needs to be studied thoroughly is the shape and size of the biomass. Dry sawdust, for instance, can burn up instantly as it is blown into the boiler, whereas large clumps of wood may take a much longer time to burn, and the combustion is much less intense. Understanding these effects would provide design guideline on the extent of pulverization and the extent of drying; it would also provide the required correlation to predict and then optimize the boiler operation, minimizing the emission of pollutant, and improving the overall efficiencies while maintaining the optimum operating air-to-fuel ratio. As a first step towards understanding the effect of shape for a fixed sample weight, experiments were carried out in the thermogravimetric combustor on samples with varying surface area.

Table 2 shows the sample sizes used for studying the effect of surface area on combustion. It can be seen from the shape of the samples, increasing the surface area for a fixed volume and weight, creates samples that are longer and thinner where samples with lower surface areas tend to be bulkier and have a more cubic-like form.

Table 2. Poplar sample sizes with different surface areas (1.21 g dry sample)

Shape	Length (cm)	Width (cm)	Height (cm)	Surface Area (cm ²)
1.4	1.3	1.2	10.6
2.0	1.2	1.0	11.2
2.6	1.1	0.9	12.1
3.7	0.9	0.8	13.5

The combustion results are shown in Figure 16 where the weight change profile of all the samples is shown. It can be seen that for samples with higher surface area, the slope of the volatile burning section of the curve is steeper, and moving to the samples with lower surface area, the volatile burning rate decreases. The same trend can be seen for char burning with a less obvious difference for changes in surface area. This is an indication that thinner samples seem to burn faster since a higher surface area means more surface is available for heat penetration in the volatile burning stage, and higher oxygen penetration during char burning stage. Therefore the sample burns more readily.

Figure 16. Combustion of poplar at 800°C

Figure 17 shows the duration of combustion stages for poplar samples with different surface area and shape. The time-to-ignition, volatile burning and char burning all show a slight decrease with increase in surface area which suggest that for higher surface area, the overall combustion duration is shorter. Similar results obtained for oak and pine can be found in Appendix 1.

Figure 17. Combustion stages for poplar during combustion at 800°C

4.2.4 Effect of Moisture Content

4.2.4.1 Moisture Content Comparison

Figure 18 shows the weight change profiles of pine with different moisture contents during combustion at 800°C. The y-axis shows the normalized weight of the sample with its dry weight. Therefore the starting point for 0% moisture content is 1g/ g dry. For 44% moisture content the total initial weight of the sample is 1.4 g (0.8 g dry + 0.6 g water) and normalized with the initial dry weight, the starting point of the weight change profile is 1.7 g/g dry.

From the weight change profile, the combustion stages for different moisture contents can be compared. Since the time-to-ignition stage is much shorter compared to volatile and char burning, it is difficult to see the differences from the weight change profile and comparisons can be made from the duration of this stage which is discussed below. For volatile burning on the

other hand, the difference in slope is clear with change in moisture content. For lower moisture contents the slope of the volatile burning stage seems to be steeper indicating a higher rate. Towards the end of the volatile burning stage, the similarities in the slope of the weight change profile suggests that once all the water content has evaporated from the sample, the volatile burning rate becomes the same for samples burnt at the same furnace temperature.

For the char burning stage, the slope for all moisture contents is almost the same. For lower moisture contents, the change in slope indicating the onset of the char burning stage occurs earlier, however, once the char burning stage starts, all the samples seem to have the same slope and therefore the same char burning rate.

Figure 18. Effect of moisture content on the weight change profiles of pine during combustion at 800°C. (All samples have an initial dry weight of 0.8 g).

Figure 19 shows the change in duration for all combustion stages with moisture content. The char burning and volatile burning durations can be read from the primary axis, whereas the time-to-ignition is shown on the secondary axis which only displays the first 30 seconds of combustion. The effect of moisture content on time-to-ignition is more evident, due to the

presence of water that needs to evaporate before volatile burning can start. There is also a slight increase in the volatile burning time as the moisture content increases. Moisture content, however, does not have an effect on the char burning time. This is understandable, since at the onset of char burning, there is no more water or volatile matter present.

Figure 19. Combustion stages for pine during combustion at 800°C.

4.2.4.2 Comparison of Different Wood Species

A series of experiments was conducted to find the effect of wood species and moisture content on combustion. Cubic samples with a constant volume of 2.2 cm^3 ($1.5\text{cm} \times 1.2\text{cm} \times 1.2\text{cm}$) were prepared from different wood species. As summarized in Table 3, the results indicate that the combustion behaviour of biomass is highly dependent on the density of the wood species. Hardwood samples have a higher density, thus taking a longer time to burn than softwood. The different combustion behaviour of hardwoods and softwoods is more evident for samples with higher moisture contents. When comparing the weight profile of different wood species with

40% moisture content, the decrease in the volatile burning rate is greater for the low density softwood (from 19.3 to 13.8 mg/s in the case of cedar), compared to that for the high density hardwood (from 7.7 mg/s to 6.3 mg/s in the case of maple). This can be explained by the dense structure of hardwoods where water vapour has less room to escape. Since the water vapour takes longer to exit the sample, the heat will also take longer to penetrate into the sample. Therefore lower volatile burning rates are observed for high moisture contents specially for higher density biomass samples. The weight change profiles and combustion stages information for the data shown in Table 3 can be found in Appendix 2.

Table 3. Combustion rate of different wood species

Wood Species		Density (g/cm3)	Combustion Stage Rate (mg/s)					
			Time-to-ignition		Volatile Burning		Char Burning	
			Moisture Content					
			0%	40%	0%	40%	0%	40%
Softwood	Cedar	0.33	0	33.1	19.3	13.8	0.720	0.677
	Pine	0.39	0	27.1	16.0	12.4	0.545	0.582
Hardwood	Poplar	0.56	0	17.8	9.72	8.12	0.420	0.439
	Oak	0.62	0	15.1	8.89	6.75	0.305	0.356
	Maple	0.76	0	12.7	7.73	6.29	0.286	0.339

4.2.4.3 Saw Dust Combustion

Saw dust is a common feedstock for biomass boilers in the pulp and paper industry. For this reason the effect of moisture content on saw dust combustion with particle size range 0.42 mm to 1.12 mm was studied. The results were similar to that of wood chips: increasing the moisture

content has a significant effect on time to ignition or drying, since the water contained in the sample needs to evaporate in order for the sample to reach a minimum temperature of 250°-300°C and for combustion to start. As discussed in Section 3.2.2, the maximum moisture content for saw dust samples was 80% which was higher than the other samples tested in this study. It was discussed previously that for pine wood chips, the time-to-ignition showed an exponential increase with increasing the moisture content up to 40% which is similar to that of saw dust as shown in Figure 20 and 21. Moreover, for saw dust samples with more than 40% moisture content, the time-to-ignition continues to increase exponentially. Volatile burning did not increase as much for moisture contents higher than 50%. It seemed that for a furnace temperature of 800°C, once volatile burning starts, the duration of the flame for increasing moisture contents increases slightly. This is understandable since the volatile content of the samples were equal and therefore at the commencement of combustion, all these volatiles exit in form of a flame.

Figure 20. Weight change profile for saw dust combustion at 800°C (0.2 g dry sample)

Figure 21. Combustion stages for saw dust combustion at 800°C (0.2 g dry sample)

4.2.5 Water Vapor Exit during Combustion

Since water is stored in the vessels of the cellular structure of the wood (Figure 22), during drying, it vapourizes and escapes through the vessel openings on the transverse surface more readily than through vessel walls on the radial and tangential surfaces which was discussed in detail in Chapter 3. Thus, per surface area, wood dries more readily from the cross-section than from the side of the trunk or branch. This preferential release of water from the transverse surface of wood was observed in all combustion tests in this study.

An example of this is shown in Figure 23 which compares the combustion behaviours between softwood and hardwood samples containing 40% moisture. Thirty seconds (00:30) after the softwood sample was loaded into the TG combustor at 800°C, the tangential and radial surfaces of the softwood sample turned black with yellow flames around them. The transverse surface, however, appeared to remain intact, still showing its original woody texture. The sample at this

point appeared to resemble the cross section of a coffee crisp bar that had been split in half. This “coffee-crisp” effect was presumably caused by the continuous release of water vapour from the transverse surface keeping the surface temperature below the ignition point of the volatiles. As the rate of water vapour release decreased with time, the transverse surfaces became darker and eventually ignited into yellow flames after one minute (1:00), while the yellow flame on the tangential/radial surfaces were weakening. After 1.5 minutes (01:30), flames were observed only on the transverse surfaces. Similar results were observed for the hardwood sample, except that the “coffee crisp” effect was not as clear as that observed in the softwood sample. This is understandable since hardwood is denser and contains less water in its vessels than softwood.

Figure 22. Wood cellular structure [22]

Figure 23. Flame distribution of softwood and hardwood during volatile burning (Furnace temperature = 800°C)

The surface of the sample must reach about 300°C in order for volatile burning to occur. As volatiles burn, the surface temperature of the sample increases, the heat continues to transfer to the interior of the particle, further increasing its temperature, and causing volatile burning. Due to the large temperature gradient between the sample surface and interior, particularly for samples with high moisture contents, drying and volatile burning often overlap [17]. While volatile burning occurred on the radial and tangential surfaces, drying continued to occur in the middle of the sample and on the transverse surface, keeping its temperature low. In other words, while one part of the sample is drying, the other part has already undergone volatile burning. This means that overall, drying and volatile burning can occur simultaneously, particularly for samples with high moisture contents.

4.2.6 Effect of Furnace Temperature

4.2.6.1 Oakwood Chips

In biomass boilers, the combustion heat is sustained by continuously burning the biomass feedstock. Burning feedstock with high moisture contents will inevitably lower the furnace temperature, significantly reducing combustion and steam production efficiencies of the boiler. In this study, only a fixed amount of the sample was used and the combustion was carried out in the TG combustor where the temperature was well controlled by electrical heaters. The results obtained, therefore, may not be applicable to the actual boiler environment. In order to simulate the effect of temperature fluctuations in biomass boilers, a set of experiments was carried out to examine the effect of moisture content on combustion at different furnace temperatures. The results are summarized in Figure 24.

At all temperatures examined, the time-to-ignition appeared to exponentially increase with an increase in moisture content (Figure 24a). The increase, however, was more dramatic at a lower furnace temperature, particularly at 500°C. The volatile burning time (flame duration) also increased as the furnace temperature decreased. Note however that the volatile burning time at 500°C was longer than that at 700°C and 800°C, but was shorter than that at 600°C (Figure 24b). This shorter volatile burning time is possible, since at 500°C, the temperature was sufficiently low that during the time-to-ignition stage, some volatiles might have been released without burning. Similar to the results shown in Figure 19 and Figure 21, the char burning duration was not affected by the moisture content. However, char burning lasted longer as the furnace temperature decreased (Figure 24c).

For dry samples (0% moisture content) and at furnace temperatures higher than 500°C, the heat provided by the combustion is sufficient to produce similar weight loss profiles (Figure 25). However, for samples with 40% moisture content, drying and volatile burning are clearly influenced by the surrounding temperature (Figure 26). The weight loss profile undergoes a change in slope the moment the sample ignites (point A on the 600°C curve, for example). The lower the surrounding temperature, the longer it takes the sample to ignite, or for this break point to appear on the curve. Beyond this point, the slope of the curve is almost the same. This is likely because the ignition and the subsequent burning of the volatile matter resulted in the same

temperature at the sample surface, despite the difference in the surrounding furnace temperature. At 400°C, the change in slope occurs after 4 minutes from the insertion of the sample into the furnace. This is an indication that the combination of low furnace temperature and high moisture content causes the surface temperature of the sample to reach the auto-ignition temperature of biomass (approximately 250°C-300°C) when most of the volatile content has already escaped from the sample and due to the dilution of the vapor phase with water, there is simply not enough fuel for ignition to occur and for a flame to form. Therefore at this furnace temperature, no flame is formed for samples with 40% moisture content. The still-images for combustion experiments related to Figures 25 and 26 can be found in Appendix 3.

Figure 24. Effect of moisture content and furnace temperature on combustion of oak (1.34 g dry sample)

Figure 25. Weight profile for combustion of oak with 0% moisture content (1.34g dry)

Figure 26. Weight profile for combustion of oak with 40% moisture content (1.34g dry)

4.2.6.2 Freshly Cut Branches

The combustion of freshly cut maple branches at different furnace temperatures was studied and the moisture content of fresh maple branches was found to be 30%. The results shown in Figure 27 and tests were performed at 800°C, 600°C, and 400°C. The weight change profiles indicate similar behaviour to wood chips discussed in the previous section.

The main driving force for the initiation of combustion in the experiments is the temperature gradient between the surface of the sample and the surrounding. Therefore, when the furnace temperature is set at a higher value, combustion takes place faster due to the higher temperature gradient between the sample and the surrounding and with a stronger driving force.

Figure 27. Combustion of freshly cut maple branch (30% moisture content)

4.2.6.3 Pine Bark

In industrial biomass boilers, the feedstock usually consists of wastewood or bark. To study the differences between combustion of wood and bark, a series of experiments was conducted for combustion of jack pine bark with different moisture contents at different furnace temperatures and compared with pine wood chips. Table 4 shows the differences in composition of pine bark and pine wood calculated from the weight change profile at different combustion stages and it shows that bark has less volatiles and more ash and fixed carbon compared to pine wood.

Table 4. Composition of pine bark and wood

Proximate Analysis	Pine Bark	Pine Wood
Ash content (wt %)	1.6	0.2
Volatile matter (wt %)	72.0	88.9
Fixed carbon (wt %)	26.4	10.9

Figure 28 shows time lapse images for combustion of bark with 40% moisture content at 800°C. the time interval between each frame is not constant to show the onset of different combustion stages. It can be seen that the time-to-ignition stage takes 15 seconds(00:00 to 00:15), the volatile burning stage takes almost one minute (00:15 to 1:20) and the char burning stage lasts almost 5 minutes (1:20 to 6:00). In frames (00:16) , (00:25) and (00:30) small pecies are seen flying out of the sample in form of sparks. This is the main difference observed between pinewood and pine bark combustion. Due to the layered structure of the bark, as combustion progresses, the layers expand and ocassionaly sparks fly out of the sample which can cause the sample to shift and fall off the crucible. The expansion of the layers can be seen by comparing frame (00:00) with frame (00:20) during volatile burning or frame (2:01) during char burning where the edge of each layer seems to be glowing brighter than the rest of the sample.

Figure 28. Combustion of pine bark with 40% moisture content at 800 °C

The effect of moisture content and surrounding temperature on combustion of bark is very similar to that of wood as discussed in the previous section. That is when the moisture content is higher than 40% and the furnace temperature is lower than 500 °C, the flame duration is shorter which suggests that the volatiles escape without burning. Figure 29 shows the effect of furnace temperature and moisture content on combustion stages. As seen in Figure 29a, with the decrease of furnace temperature and increase in moisture content, the time to ignition stage increases

exponentially. In Figure 29b, the changes in volatile burning can be seen where for 500°C, the volatile burning duration decreases indicating “loss” of volatiles without burning. In Figure 29c, it can be seen that char burning is not affected by changes in moisture content. Figure 30 and 31 show the weight change profiles for different furnace temperatures which is similar to Figures 25 and 26 for combustion of wood chips.

Figure 29. Effect of moisture content and furnace temperature on combustion of pine bark (1g dry sample)

Figure 30. Weight profile for combustion of pine bark with 0% moisture content (1g dry)

Figure 31. Weight profile for combustion of pine bark with 40% moisture content (1g dry)

4.2.7 Implication

The average moisture content of the feedstock burned in biomass boilers in pulp mills is typically about 40-50% and the average furnace temperature is about 800°C. Results obtained from this study imply that in biomass boiler operation, if the moisture content of the feedstock suddenly increases due to rain, or due to its mixing with wetter feedstock piles (old wood waste, biosludge etc.), the furnace temperature will decrease. This, in turn, will suppress the combustion of the wet feedstock, further decreasing the furnace temperature. The downward spiral effect will lower the steam production capacity of the boiler, and lead eventually to a boiler blackout, unless the biomass feed rate is significantly reduced, the wet feedstock is mixed with drier piles of feedstock to reduce the moisture content, and/or the auxiliary fuel (natural gas and fuel oil) flow rate is increased to keep the furnace temperature high and to maintain the steam production on target.

It was discussed in previous sections that for a decrease in furnace temperature, the volatile burning duration increased. For samples that contained 40% moisture however, the volatile burning time at 500°C was found to be shorter than that at 600°C (Figure 24b). This shorter volatile burning time implies that some volatiles might have “escaped” without burning during the time-to-ignition stage. The unburnt volatile organic compounds (VOC) would travel up the boiler and exit via the stack. This implies that the combined effect of the high moisture content in feedstock and the low furnace temperature can result in increased concentrations of combustibles and volatile organic compound (VOC) in the biomass boiler flue gas which results in loss of the net energy released from combustion of biomass. As a result of less heat being released, the furnace temperature would decrease further as described above and the operation of the biomass boiler would not be self-sustained.

Figure 32 demonstrates the spiral cycle leading to boiler blackout. The high moisture content feedstock requires a longer drying time which needs more heat for evaporation of water, this leads to less heat being available in the furnace area and therefore a decrease in the furnace temperature. Once the furnace temperature drops, the operator would increase the feed rate to compensate and keep the steam production on target. Since the feedstock already has a high

moisture content, more of the wet material is introduced into the boiler which requires more heat for drying. This will further decrease the furnace temperature and therefore the steam production and the operator will once again increase the feed rate to compensate. This will continue until the temperature of the furnace is not high enough for the volatile content to burn off completely and release their energy content. Therefore VOCs are formed and exit with the flue gases and the temperature of the furnace will further decrease until the fire is completely out and the boiler needs to be started up again with the help of fossil fuel burners.

Figure 32. Spiral effect leading to boiler blackout

Part II: Field Studies

The results of the laboratory experiments demonstrate the effect of moisture content on the combustion of a single particle in a closed system. Biomass boilers at pulp mills however, operate on a continuous basis. Therefore the effect of moisture content needs to be looked at from a wider perspective.

The main purpose of this study is to better understand the effect of changes in moisture content on the operation of biomass boilers and to develop viable detection and control strategies for maintaining a stable boiler operation and steam production. For this purpose, the results of the laboratory experiments needed to be paired with field studies and data analysis of industrial scale biomass boilers and together relevant conclusions can be made.

The field studies were carried out for biomass boilers at three different pulp mills. With the help of process engineers at each mill, the operation of each boiler was investigated and 2 years of data for the relevant operating parameters were collected and analyzed.

Chapter 5 Mill Visits

5 Mill Visits

(a)

(b)

Figure 33. Mill visits a) Mill A and b) Mill B

5.1.1 Mill A

The biomass boiler at mill A is a Babcock & Wilcox boiler built in 1984. The grate is a pinhole vibrating grate. The boiler has four burners which run on either natural gas or fuel oil when necessary. The boiler can produce up to 102 T/h of 6205 kPa steam. On average 30 T/h of bark are fed to the boiler. The undergrate air has two sections on the north and south sides, each of which is divided into three sections to allow adjustment of the undergrate air for maximum combustion and distribution on the grate. The lower furnace temperature is 600°-800°C. Figure 34 shows a schematic of the biomass boiler at mill A.

The types of biomass burnt in the boiler are a mixture of the piles of biomass stored outside which are divided into two piles, old and new. The old bark is almost 40 years old (heritage pile) and the new bark is purchased on a regular basis. It is also mixed with the knotter rejects coming from the uncooked chips in the digester and the chip rejects from the screens before the digester.

In the winter time, the smaller particle sizes for the bark feed tend to freeze together and create plugging problems in the fuel chute and a high moisture content in the boiler. One indication of high moisture content in the boiler is fluctuations of the lower furnace temperature, or the ID fan outlet temperature or the stack temperature.

Figure 34. Schematic diagram of biomass boiler at mill A

5.1.2 Mill B

The biomass boiler at Mill B is very similar to that of Mill A. It is also a stoker grate type boiler with pinhole grates in order to allow the distribution of combustion air on the grate. The biomass boiler at mill B produces an average of 120 T/h steam with a temperature of 442 °C and pressure of 6400 kPa.

5.1.3 Mill C

The stoker grate type boiler at Mill C has a sloping grate for drying the feedstock in the boiler. The wood waste enters the boiler and is piled on the drying slope of the grate and then moves to the flat area of the grate where combustion takes place. Also, mill C injects secondary and tertiary air into the boiler at locations above the grate in order for the volatiles to burn off completely. The average steam production is 130 T/h with a temperature of 400°C and pressure of 4500 kPa. Mill C is the only mill which measures the moisture content of the feedstock and these data were used to double check the calculations in the data analysis section.

5.1.4 Total Heat Release Calculations

Table 5 shows the effect of moisture content on the total heat released from biomass combustion. The calculations are done for 1 g of dry biomass sample with moisture content ranging from 0% to 83%. For higher moisture content values, the heat required for drying is higher than the heat released from combustion resulting in a negative net heat release. The second column of the table shows the total weight of biomass sample which includes the dry biomass weight as well as the weight of water and the third column shows the amount of water only. The fourth column shows the sensible heat of water which is the amount of heat required to raise the temperature of the water inside the biomass sample from ambient temperature, assumed to be 25°C, to the evaporation temperature of water, which is 100°C at atmospheric pressure. The heat capacity of liquid water used for the calculation of the sensible heat is 4.19 kJ/kg K. The fifth column of the table shows the latent heat of evaporation for water to undergo a change from liquid state to vapor state. The specific latent heat of water used here is 2270 kJ/kg. The sensible heat of water

vapor is the amount of heat required to raise the temperature of water vapor from 100°C to 800°C which is the furnace temperature, and the specific heat capacity of water vapor at 800°C is 1.996 kJ/kg K. For calculating the total heat released, the heating value of the biomass is set at 20,000 kJ/kg and the heat required to raise the temperature of the biomass sample from ambient temperature to the auto-ignition temperature of biomass which is 300°C, is set at 687.5 kJ/kg. Therefore when the sample is dry, the net heat released is 19.31 kJ and for different values of moisture content, the total heat required for drying is subtracted from the total heat released from combustion.

Table 5. Effect of moisture content on net heat release from biomass combustion

Moisture Content (%)	Total Weight (g)	Water (g)	Sensible Heat of Water (kJ)	Latent Heat of Evaporation (kJ)	Sensible Heat of Water Vapor (kJ)	Total Heat for Drying (kJ)	Net Heat Release (kJ)
0	1.00	0.00	0.00	0.00	0.00	0.00	19.31
10	1.11	0.11	0.03	0.25	0.16	0.44	18.87
20	1.25	0.25	0.08	0.57	0.35	1.00	18.32
30	1.43	0.43	0.13	0.97	0.60	1.71	17.61
40	1.67	0.67	0.21	1.51	0.93	2.65	16.66
50	2.00	1.00	0.31	2.27	1.40	3.98	15.33
60	2.50	1.50	0.47	3.41	2.10	5.97	13.34
70	3.33	2.33	0.73	5.30	3.26	9.29	10.02
80	5.00	4.00	1.26	9.08	5.59	15.93	3.39
83	5.88	4.88	1.53	11.08	6.82	19.44	-0.13

5.1.5 Data Analysis

For each mill, the operation of their biomass boiler was reviewed over a two year period and the data for the pertinent operating parameters was collected as daily averages and the changes of different operating parameters with respect to one another were studied. The moisture content of the feedstock was not measured on a regular basis at all mills. Therefore, in order to be able to study the effect of moisture content on other operating parameters, an energy and material balance was constructed for each biomass boiler and the average daily moisture content was back calculated. Figure 35 shows a simplified box diagram of a biomass boiler and the different heat components (Q) used in the energy balance.

Figure 35. Biomass boiler box diagram

$$Q_{in} = Q_{biomass} + Q_{fossil\ fuel}$$

$$Q_{loss} = Q_{flue\ gas} + Q_{air} + Q_{MC} + Q_{radiation} + Q_{ash} + Q_{unaccounted}$$

$$Q_{steam} = Q_{in} - Q_{loss}$$

Table 6 shows a summary of the input and output variables for one set of data, where the average daily values of the operating parameters are used to calculate the average moisture content of the feedstock for that particular day, the same calculations have been carried out using a macro

based spreadsheet to calculate the average daily moisture content for two years of data. For the output variables, the measured and calculated values for the excess O₂ of the stack are used to verify the accuracy of the calculations as shown in Appendix 4.

Table 6. Summary of input and output variables for one set of data for Mill A used to calculate moisture content

Input Variables	
Biomass Feed Rate	25.9 T/h
Air Flow Rate	207 T/h
Inlet Air Temperature	18°C
Natural Gas Flow Rate	462 m ³ /h
Fuel Oil Flow Rate	2.0 T/h
Flue Gas Temperature	200°C
Steam Flow Rate	92 T/h
Steam Temperature	438°C
Steam Pressure	6205 kPa
Output Variables	
Moisture Content	45%
Excess O ₂ (calculated)	7.7%
Excess O ₂ (measured)	8.1%

The main objective of this was to find which parameters could be used to detect variations in moisture content and which parameters could be used to minimize the fluctuation in the operation due to the variations in moisture content before the need to co-combust fossil fuels. After calculating moisture content for each set of data, all the operating parameters were compared to the calculated value of the moisture content to find which parameter is impacted by changes in moisture content. The changes of all the operating parameters with moisture content are listed in Appendix 4. Of all the operating parameters, it was found that lower furnace temperature, excess O₂ and undergrate air have the most direct relationship with moisture content.

Figures 36, 37 and 38 show the main findings from data analysis. Lower furnace temperature, excess O₂ and undergrate air are plotted respectively on the left hand axis with moisture content on the right hand axis to show the relationship between each operating parameter and moisture content. For comparison purposes, moving averages of each value is plotted in the figures.

The results suggest that moisture content and furnace temperature have an inverse relationship and excess O₂ and undergrate air have a direct relationship with moisture content.

Figure 36. Changes of furnace temperature and moisture content with time

Figure 37. Changes of undergrate air flow rate and moisture content with time

Figure 38. Changes of excess O₂ and moisture content with time

The changes in the lower furnace temperature or the stack temperature with moisture content variations can be explained as follows: when the moisture content of the feedstock increases, more heat is required to dry the biomass in order for devolatilization to start, for this reason the net heat release from combustion decreases resulting in the lower furnace temperature to decrease and eventually the stack flue temperature decreases as well.

The undergrate air is changed by the operator in order to maintain a set amount of pressure in the steam header. The data analysis results suggest that the undergrate air is used as a control parameter for high moisture content: the operator increases the undergrate air when high moisture content is suspected in order to speed up the drying process. The increase in excess O₂ with moisture content on the other hand, can be due to this increase of undergrate air or due to the overall increase in flue gas amount with increasing moisture content.

After considering all the operating parameters collected for each biomass boiler, it was concluded that furnace temperature or stack temperature and excess O₂ can be used to indicate variations in moisture content. Undergrate air can be the control parameter for maintaining a constant steam flow when changes in moisture content are detected. Also the material and energy balance can be used as a tool for measuring the moisture content of the feedstock at any given time.

5.1.6 Thermal Performance

The average values for the operating parameters which were used for the purposes of data analysis are shown in Table 7. The auxiliary fuels burnt in all three boilers are natural gas and only Mill A burns fuel oil as well. Therefore the average natural gas flow rate is lower for mill A since two types of auxiliary fuels are burnt to compensate for steam production.

Table 7. Average values for operating parameters of mills A, B, and C

Average Operating Parameters	Mill A	Mill B	Mill C
Biomass Feed Rate (T/h)	26.3	26.8	56.0
Air Flow Rate (T/h)	209	139	266
Undergrate Air Flow Rate (T/h)	80.3	77.1	72.2
Inlet Air Temperature (°C)	89	145	176
Natural Gas Flow Rate (m ³ /h)	843	3504	3501
Fuel Oil Flow Rate (T/h)	1.0	-	-
Flue Gas Temperature (°C)	214	171	179
Steam Flow Rate (T/h)	97	120	129
Steam Temperature (°C)	438	442	392
Steam Pressure (kPa)	6205	6310	4494
Moisture Content (%)	38	40	58
Excess O ₂ (%)	7.7	5.5	7.3

For each biomass boiler studied, thermal performance was compared to theoretical values which were calculated from the material and energy balance as discussed previously. The results are shown in Figure 39 where the thermal performance is defined as follows:

$$\text{Thermal Performance} = \frac{\text{Steam produced from biomass}}{\text{Amount of dry biomass}}$$

Figure 39. Thermal performance of mills A, B and C

The results show that the thermal performance of mill A is very close to theoretical values for a range of moisture contents from 30% to 50%. This is an indication that mill A does not operate with very high moisture contents at the expense of co-combusting fossil fuels. Rather it seems that the different piles of biomass are mixed before entering the boiler in order to achieve moderate moisture contents and relatively constant steam production. Similarly, the thermal performance of Mill C is very close to theoretical values for moisture contents ranging from 40% to 60%. Again this is an indication that for higher moisture contents, either the biomass feed is shut off completely and only fossil fuels combusted in the boiler, or that the moisture content of the entering feedstock is controlled and monitored to stay well below 60%. On the other hand, the results from Mill B show much higher thermal performance values even for high moisture contents. This could be due to many factors, for example it is not clear whether the amount of steam used in soot blowing of the tube banks in the super heater area is included in the total steam measurements or not. Another significant issue in the calculations is the assumed heating value of the feedstock. As discussed previously, the feedstock of biomass boilers in pulp and paper mills can come from many different sources and are often the rejects or wastes produced in

other parts of the process. This makes a constantly varying, non-homogenous mixture for the feedstock. For this reason, it is almost impossible to classify the different types of wood species entering the boiler at any given time as it is made from different mixtures. Considering this issue for calculation purposes, it can be seen that the moisture and ash content, and therefore the heating value, of the feedstock is unknown and an average or typical value is considered for calculation purposes. This can be the source of the discrepancies observed between the thermal performance of the biomass boilers and theoretical values calculated from energy and material balances.

Chapter 6

Conclusions and Recommendations

6 Conclusions and Recommendations

6.1 Conclusions

A two part fundamental study was performed to systematically investigate the effect of moisture content on the combustion behaviour of several wood species, first using a thermogravimetric combustor controlled at different temperatures, and second by conducting field studies and data analysis. The results show that:

- Combustion occurs through three stages: time-to-ignition (mostly drying), volatile burning, and char burning;
- Drying occurs more readily on the transverse surface of the biomass sample than on tangential and radial surfaces;
- Increasing the moisture content of the sample significantly increases the drying time and hence, the time-to-ignition. It has only a small effect on the volatile burning time and virtually no effect on the char burning time;
- Furnace temperature has a significant effect on combustion. Samples containing 40% moisture can ignite and burn readily at 800°C, but take a much longer time to ignite and to burn at 500°C, and do not ignite at all at 400°C;
- Of the wood species tested, softwood, due to its lower density (higher porosity), dries faster, catches fire sooner, and burns more readily than hardwood.
- Effects of moisture content and furnace temperature on jack pine bark combustion are similar to those of jack pine wood. The main difference is that bark burns at a slightly higher volatile burning rate and tends to produce fire sparks during combustion.

- The results from field studies and data analysis suggest that the combination of excess O₂ and furnace temperature could be used as detection parameters for changes in moisture content and change in undergrate air can be the first control strategy to deal with variations in moisture content before co-combusting fossil fuels.
- The thermal performance of three boilers indicated that the average moisture content of the feedstock is 30% to 60%. For mills A and B, the thermal performance is close to theoretical values, whereas the thermal performance of mill C was higher than theoretical values, nevertheless the rate of decrease in thermal performance with increase in moisture content was similar for the three boilers studied.
- The combined adverse effect of high moisture content in feedstock and low furnace temperature on combustion will eventually lead to a boiler blackout, unless the biomass feed rate is significantly reduced, a drier feedstock is used, and/or the auxiliary fuel (natural gas and fuel oil) flow rate is increased to maintain the furnace temperature. Also, it will likely result in increased combustibles and volatile organic compound (VOC) concentrations in the biomass boiler flue gas.

6.2 Recommendations

For the continuation of this work, the following issues can be considered:

- The thermogravimetric combustor is a batch like process where continuous feed is not possible; therefore it would be beneficial if moisture content experiments are carried out in a continuous way in order to monitor the changes in temperature and composition of flue gases during combustion.
- The combination of optimum moisture content and size need to be considered.
- Trial runs could give insight to how moisture content affects the actual operation of a boiler and which parameters are affected most.
- The energy balance used here could be tailored to each individual boiler for real time moisture content measurement.

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Appendices

Appendix 1. Effect of shape

Table A- 1. Physical properties of pine samples

Shape	Length (cm)	Width (cm)	Height (cm)	Surface Area (cm ²)
1.4	1.3	1.2	10.6
2.1	1.2	1.0	11.6
3.0	0.9	0.9	12.2
3.5	0.9	0.9	13

Figure A- 1. Weight change profile for combustion of pine at 800°C

Figure A- 2. Combustion stages for pine at 800°C

Table A- 2. Physical properties of oak samples

Shape	Length (cm)	Width (cm)	Height (cm)	Surface Area (cm2)
1.4	1.3	1.2	10.6
1.9	1.2	1.1	11.5
3.0	1.0	0.8	12.0
3.5	0.9	0.8	13.1

Figure A- 3. Weight change profile for combustion of oak at 800°C

Figure A- 4. Combustion stages for oak at 800°C

Appendix 2. Effect of moisture content and wood species

Wood Species: Cedar

Furnace Temperature: 800°C

Dry Weight: 0.82 g

Sample Size: 1.5cm×1.2cm×1.2cm

Figure A- 5. Weight change profile for combustion of cedar at 800°C (0.82 g dry weight)

Figure A- 6. Combustion stages for cedar at 800°C (0.82 g dry weight)

Wood Species: Poplar

Furnace Temperature: 800°C

Dry Weight: 1.21 g

Sample Size: 1.5cm×1.2cm×1.2cm

Figure A- 7. Weight change profile for combustion of poplar at 800°C (1.21 g dry weight)

Figure A- 8. Combustion stages for poplar at 800°C (1.21 g dry weight)

Wood Species: Oak

Furnace Temperature: 800°C

Dry Weight: 1.34 g

Sample Size: 1.5cm×1.2cm×1.2cm

Figure A- 9. Weight change profile for combustion of oak at 800°C (1.34 g dry weight)

Figure A- 10. Combustion stages for oak at 800°C (1.34 g dry weight)

Wood Species: Maple

Furnace Temperature: 800°C

Dry Weight: 1.75 g

Sample Size: 1.5cm×1.2cm×1.2cm

Figure A- 11. Weight change profile for combustion of maple at 800°C (1.75 g dry weight)

Figure A- 12. Combustion stages for maple at 800°C (1.34g dry weight)

Appendix 3. Effect of furnace temperature

Furnace Temperature: 800°C

Figure A- 13. Weight change profile for combustion of oak at 800°C (1.34 g dry weight)

Furnace Temperature: 750°C

Figure A- 14. Weight change profile for combustion of oak at 750°C (1.34 g dry weight)

Furnace Temperature: 700°C

Figure A- 15. Weight change profile for combustion of oak at 700°C (1.34 g dry weight)

Furnace Temperature: 650°C

Figure A- 16. Weight change profile for combustion of oak at 650°C (1.34 g dry weight)

Furnace Temperature: 600°C

Figure A- 17. Weight change profile for combustion of oak at 600°C (1.34 g dry weight)

Furnace Temperature: 550°C

Figure A- 18. Weight change profile for combustion of oak at 550°C (1.34 g dry weight)

Furnace Temperature: 500°C

Figure A- 19. Weight change profile for combustion of oak at 500°C (1.34 g dry weight)

Figure A- 20. Effect of furnace temperature and moisture content on time-to-ignition (1.34 g dry sample)

Figure A- 21. Effect of furnace temperature and moisture content on volatile burning time (1.34 g dry sample)

Figure A- 22. Effect of furnace temperature and moisture content on char burning time (1.34 g dry sample)

Wood Species: Oak

Moisture Content: 0% (wet basis)

Dry Weight: 1.34 g

Sample Size: 1.5cm×1.2cm×1.2cm

Figure A- 23. Combustion of oak with 0% moisture content at difference furnace temperatures (1.34 g dry sample)

Wood Species: Oak

Moisture Content: 40% (wet basis)

Dry Weight: 1.34 g

Sample Size: 1.5cm×1.2cm×1.2cm

Figure A- 24. Combustion of oak with 40% moisture content at different furnace temperatures (1.34 g dry sample)

Appendix 4. Field studies

Input and output summary for material and energy balance

Input Variables				
Basis (tonnes/hr)	28.50			
Moisture Content (% dry basis)	80.71	MC wet basis%	44.66	
Air Flow klb	455.88			
Natural Gas Flow kscf	16.30	Air Flow klb	0	
Fuel Oil Flow klb/hr	4.40	Air Flow klb	0.00	
Waste Oil Flow L/min	0.00			
Heated Air	Inlet Temperature (°F)	63.82	Outlet Temperature (°F)	392.16
Gas Product	Outlet Temperature (°F)	392.16		
Steam	Inlet Temperature (°F)	63.82	Outlet Temperature (°F)	819.88
Steam Flow klb	203.54			
Output Summary				
Total Air	455.88			
Excess Air Volume %	119.18	Excess O2	7.69	
Steam Flow klb	203.54			

Figure A- 25. Summary of material and energy balance

1. $Q_{in} = Q_{biomass} + Q_{fossil\ fuel}$
2. $Q_{loss} = Q_{flue\ gas} + Q_{air} + Q_{MC} + Q_{radiation} + Q_{ash} + Q_{unaccounted}$
3. $Q_{steam} = Q_{in} - Q_{loss}$

Substituting equation 1 and 2 into equation 3 and expanding all the terms:

$$\begin{aligned}
& m_{steam} \left(C_{latent} + C_{p\ steam}(T_{Final} - 100) + C_{p\ water}(100 - T_{initial}) \right) + \\
& m_{flue\ gas} C_{p\ flue\ gas} (T_{final} - T_{initial}) = \\
& \left(m_{biomass} q_{biomass} + m_{fossil\ fuel} C_{p\ fossil\ fuel} \right) - \left(m_{air} C_{p\ air} (T_{final} - T_{initial}) \right) + \\
& MC\ m_{biomass} C_{p\ water} (T_{final} - 100) + MC\ m_{biomass} C_{latent} + \\
& MC\ m_{biomass} C_{p\ water} (100 - T_{initial}) + 0.12\ Q_{total\ input}
\end{aligned}$$

For the values shown in the summary above, the following calculations were done to find the moisture content value:

Table A- 3. Material balance for biomass combustion

Composition	(% dry basis)	Amount (kg/hr)	Required Oxygen (kg/hr)
Carbon	52.00	7439.85	19839.59
Hydrogen	6.50	929.98	7439.85
Sulfur	0.00	0.00	0.00
Nitrogen	0.31	44.35	0.00
Oxygen	37.68	5391.03	0.00
Chlorine	0.01	1.43	
Ash	3.50	500.76	
Total Dry Mass	100.00	14307.40	27279.44

Table A- 4. Calculations for amount of required oxygen and air

Oxygen Required		kg/kg feed	1.53
Air Required		kg air/kg dry biomass	6.59
Excess Air volume %	119.18	kg air/kg dry biomass	14.45
Excess Oxygen		kg O2/kg dry biomass	3.35

Table A- 5. Calculations for flue gas composition

Product	Amount (kg/hr)	%	Volume (m3)	%
CO2	27279.44	11.74	14809.69	7.57%
H2O	19917.20	8.57	24772.64	12.66%
SO2	0.00	0.00	0.00	0.00%
N2	159270.47	68.55	136712.85	69.85%
O2	25861.33	11.13	19430.00	9.93%
Total	232328.44	100.00	195725.18	100.00%
kg Flue gas/kg feed	16.24		100619	

Table A- 6. Calculation for heat of formation

	Heat of formation (kJ/mol)	Heat of formation (kJ/kg)	Heat of formation (MJ)
C + O2 => CO2 (12 kg C)+(32 kg O) => (44 kg CO2)	393.50	32791.67	243964.99
2 H2 + O2 => 2 H2O (4 kg H)+(32 kg O) => (36 kg H2O)	285.82	142910.00	132903.57
S + O2 => SO2 (32 kg S) + (32 kg O) => (64 kg SO2)	296.70	9271.88	0.00

Table A- 7. Energy inputs for heat balance

Energy Input		
	Heat Input (MJ)	% Total Heat Input
Biomass	364670.31	76.62
Natural Gas	21504.50	4.52
Fuel Oil	89757.63	18.86
Total	475932.44	100.00

Table A- 8. Energy loss for heat balance

Energy Loss		
	Heat Loss (MJ)	% Total Heat Input
Heated Air	45415.21	9.54
Moisture Content of Biomass		
Sensible Heat	3626.16	0.76
Latent Heat	26212.54	5.51
Radiation Heat Loss	4759.32	1.00
Fly Ash	149.25	0.03
Bottom Ash	112.84	0.02
Unaccounted	47593.24	10.00
Total	127868.57	26.87

Table A- 9. Energy output for heat balance

Energy Output		
	Heat Output (MJ)	% Total Heat Input
Total	348063.87	73.13
Gas Product Heat	44426.24	9.33
Sensible Heat of Water in Tube Banks	31823.26	6.69
Latent Heat of Water in Tube Banks	209580.28	44.04
Heat Available for Steam Production	303637.62	63.80
SET STEAM TEMPERATURE: Final Temperature (°C)	437.71	
Amount of Steam kg	92326.11	
klb	203.54	
kg steam/kg feed	6.45

Figure A- 26.Changes of bark feed rate and moisture content with time for Mill A

Figure A- 27. Changes of outside air temperature and moisture content with time for Mill A

Figure A- 28. Changes of oil flow rate and moisture content with time for Mill A

Figure A- 29. Changes of natural gas flow rate and moisture content with time for Mill A

Figure A- 30. Changes of windbox air damper control and moisture content with time for Mill A

Figure A- 31. Changes of north undergrate air and moisture content with time for Mill A

Figure A- 32. Changes of south undergrate air and moisture content with time for Mill A

Figure A- 33. Changes of arch air flow and moisture content with time for Mill A

Figure A- 34. Changes of windswept air flow and moisture content with time for Mill A

Figure A- 35. Changes of burner air flow and moisture content with time for Mill A

Figure A- 36. Changes of total air flow and moisture content with time for Mill A

Figure A- 37. Changes of tubular air heater outlet temperature and moisture content with time for Mill A

Figure A- 38. Changes of steam flow and moisture content with time for Mill A

Figure A- 39. Changes of steam from bark and moisture content with time for Mill A

Figure A- 40. Changes of steam from oil and moisture content with time for Mill A

Figure A- 41. Changes of steam from natural gas and moisture content with time for Mill A

Figure A- 42. Changes of economizer inlet gas temperature and moisture content with time for Mill A

Figure A- 43. Changes of tubular air heater inlet gas temperature and moisture content with time for Mill A

Figure A- 44. Changes of ID fan outlet temperature and moisture content with time for Mill A

Figure A- 45. Changes of lower furnace temperature and moisture content with time for Mill A

Figure A- 46. Total precipitation and changes of moisture content with time for Mill A

Figure A- 47. Changes of incline amperage and moisture content with time for Mill A

Figure A- 48. Verification of calculations by comparisong measured and calculated excess O₂