Effect of feedstock moisture content on biomass boiler operation

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ABSTRACT: Burning feedstock with high and constantly varying moisture content is a challenge in the operation of the stoker-grate type biomass boilers in pulp and paper mills. A fundamental study was performed, using a thermogravimetric combustor controlled at different temperatures, to systematically investigate the effect of moisture content on the combustion behavior of several woody biomasses. The results show that combustion occurred through three stages: drying, devolatilization, and char burning. Increasing the moisture content of the sample above 30% significantly increased the drying time and the time to ignition of the sample. Moisture content, however, had only a small effect on the devolatilization rate and virtually no effect on the char burning rate. Furnace temperature had a great effect on combustion. Samples containing 40% moisture could still ignite and burn readily at 800°C, but they took a much longer time to ignite at 500°C and did not ignite at 400°C. These results imply that in biomass boiler operation, the high moisture content in feedstock delays combustion and causes the furnace temperature to decrease. The low temperature, in turn, suppresses combustion, further decreasing the furnace temperature and causing more delay in combustion. This downward spiral will eventually lead to a boiler blackout unless the biomass feed rate is significantly reduced or the auxiliary fuel (natural gas and fuel oil) flow rate cofired in the boiler is increased to keep the furnace temperature high.

Application: Mills can develop general guidelines for self-sustained biomass boiler operation with minimum need for cocombustion of fossil fuels.

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 23-35 GJ of steam and 700-1000 kW·H of power per air-dried metric ton of pulp produced. About 60%-70% of the energy required is self-supplied by burning concentrated black liquor in recovery boilers. The remaining 30%-40% is generated by burning biomass in biomass boilers and provided by local utility stations. Natural gas and fuel oil are also cofired in biomass boilers to supplement steam and power as required [1]. Biomass boilers provide pulp and paper mills a way to address rising energy and waste disposal costs to remain competitive. There is a need to maximize energy production while minimizing environmental impact to meet increasingly stringent regulations.

Biomass boilers in pulp and paper mills are often referred to as hog-fuel boilers, bark boilers, and power boilers. The solid fuel that is burned in biomass boilers is known as hog fuel, which is a mixture of various types of biomass available at the mill site, such as sawdust coming from the slasher deck, bark falling from the debarking drum, pins and fines from chip screening, wood residue from the woodyard, and rejects generated during chemical pulp treatment and recycled paper processing [2]. Many biomass boilers also burn primary sludge, secondary sludge (biosludge), or deinking sludge generated from various mill processes.

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 the design and operating conditions of the boiler. Modern bubbling fluidized bed boilers are generally more efficient and less susceptible to moisture variations than older stoker grate boilers [3,4]. The boiler efficiency is dictated mainly by the moisture content and the combustion behavior of the feedstock, as well as the amount and thermal properties of the ash. Understanding the combustion behaviors of the feedstock is vital for predicting the combustion efficiency because the characteristics of the feedstock can vary considerably in type, size, shape, and moisture content, as shown in **Fig. 1**.

The high variation in feedstock moisture content is an inherent problem in biomass boiler operation. Biomass feedstock typically contains 40-50 wt% moisture; however, it can vary from a few wt% if it has been dried to over 70 wt% for aged feedstock, particularly feedstock that has been exposed to rain or stored under wet conditions. Wet biomass not only reduces the boiler steam production capacity; it also reduces the lower furnace temperature, making it more difficult to sustain the fire and burn already wet material. Under these conditions,

1. Variety of feedstock for biomass boilers in pulp and paper mills.

more fossil fuels (natural gas or crude oil) will have to be co-fired to meet the mill's stream requirement, which is not desirable and can be costly. On the other hand, if the biomass is too dry the combustion produces more particulate matter and results in a high-stack opacity problem. Also, the furnace temperature may increase excessively and lead to problems with wall slagging and clinker formation on the furnace grate [5].

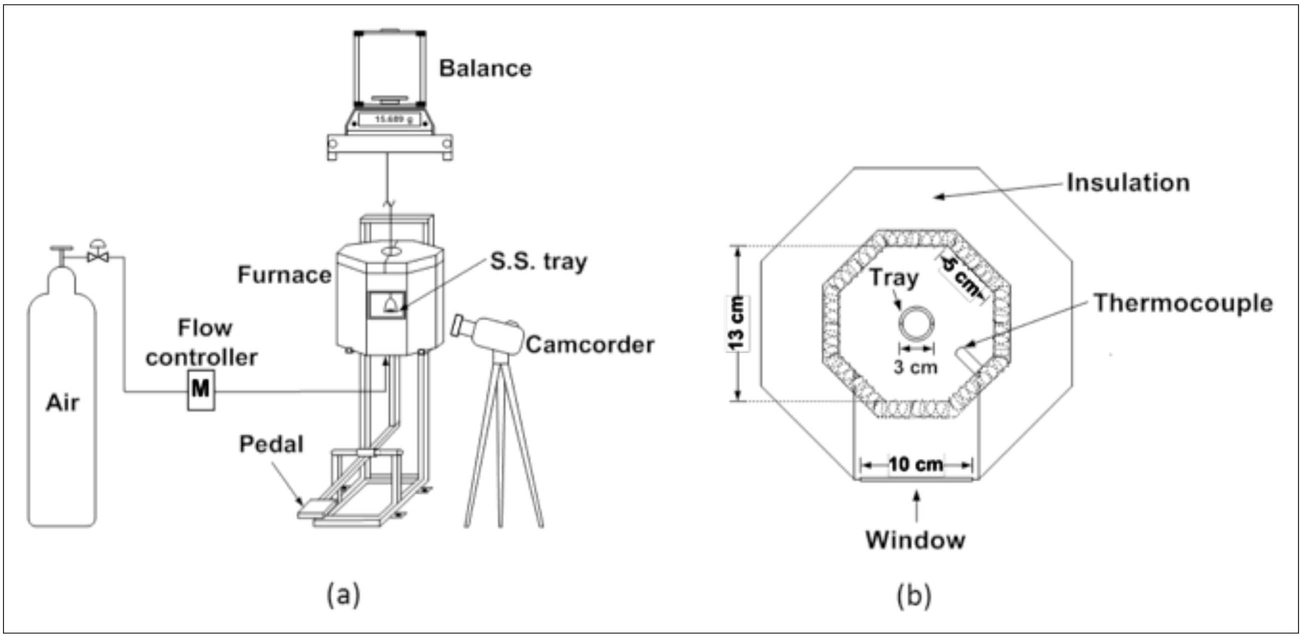
In recent years, a number of studies have been performed on biomass drying, combustion, and ash characteristics by various research groups [3-7]. Their focus, however, has not been on operating issues experienced in biomass boilers, particularly those in pulp and paper mills where hog fuel is the main component of the feedstock. While each pulp and paper mill has its own way of dealing with variations in moisture content and other feedstock characteristics, there is lack of fundamental understanding of how these property changes may affect the combustion behavior of biomass and boiler operation. In this paper, we discuss the results of a systematic laboratory study that we conducted to examine the effect of moisture content on biomass combustion at different temperatures. We also present several key findings for biomass boiler operation.

EXPERIMENTAL

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, the thermogravimetric (TG) combustor (**Fig. 2**) in our laboratory was used. Detailed features and operation procedure of the combustor have been previously described [8].

In this study, samples were prepared from four different wood species: cedar, pine, poplar, oak, and maple. The wood was cut into cuboids of about the same dimension (1.5 cm × 1.2 cm × 1.2 cm). These wood blocks were soaked in water at ambient temperature for 24 h and then dried at 105°C in an oven for different lengths of time to produce samples with different moisture content. The moisture content of each resulting sample was calculated based on the difference in the sample weight before soaking and after drying.

The furnace temperature was controlled and monitored using a K-type thermocouple placed near the test sample (Fig. 2b). The sample was placed on a 3-cm outside diameter circular tray made of stainless steel type 316 wire screen mesh to maximize its exposure to the combustion air fed into the



2. (a) Thermogravimetric (TG) combustor and (b) cross-section of the electrical furnace.

combustor from below. The tray was hung on a stainless steel 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 so that the sample tray was placed quickly in 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 1 L/min. The time required for each combustion stage was determined based on the video images recorded by the camcorder and the weight loss registered by the balance.

RESULTS AND DISCUSSION

Combustion behavior

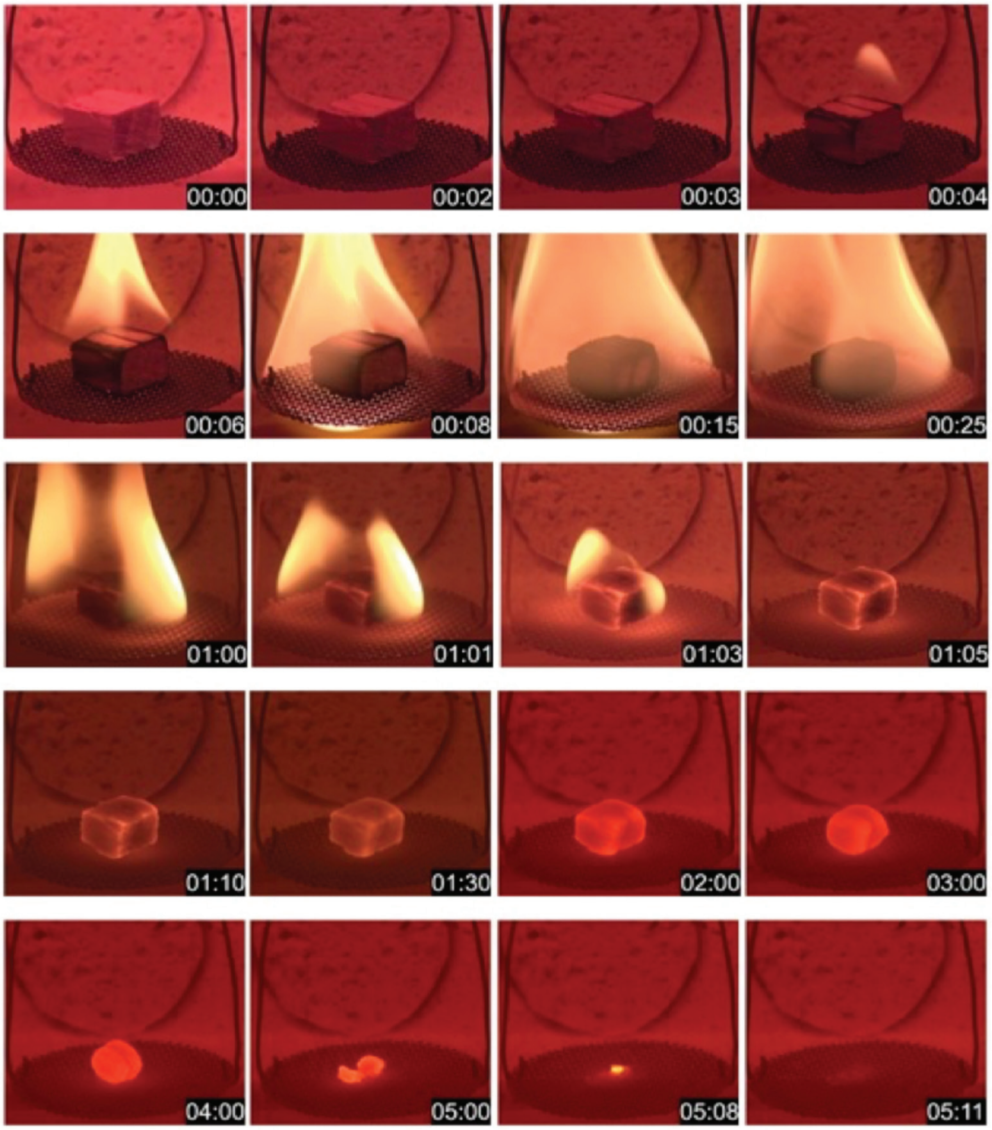
Figure 3 shows an example of still images of the combustion of a 1-g cube of oak with 40% moisture content at 800°C. The time (in minutes:seconds) at which the image was taken is displayed at the bottom right corner of each frame. The first frame (00:00) is the appearance of the sample when it was inserted 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 s (00:04), indicating the beginning of the devolatilization stage in which the volatile content of the sample was emitted and the temperature of the surrounding air was high enough for the volatiles to ignite and form a flame. As the combustion heat further transferred into the sample interior, devolatilization 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 devolatilization 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 devolatilization are fast (about 1 min) and are overlapped due to the non-uniform temperature distribution within the sample. Char burning is much slower, requiring more than 5 min to complete.

Combustion stages

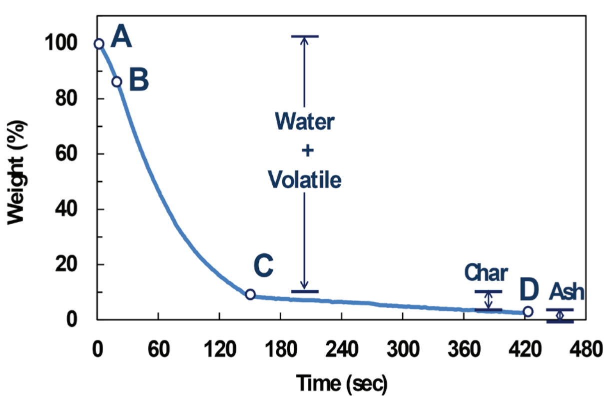
From the combustion video of a biomass sample, there are four distinct times that may be used to characterize the combustion behavior of the sample. As shown in Fig. 3, for example, time A was the moment the sample was submerged into the furnace (00:00); time B was when the sample caught fire as a result of volatile burning (00:04), time C was when the flame was out indicating the end of volatile burning (01:05), and time D was when the char no longer glowed, indicating the end of the char burning stage (05:11). On the basis of 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 content. **Figure 4** shows an example of a weight change profile during the combustion of oak at 800°C. The drying stage (vaporization of water) and the devolatilization stage are thermal processes that occur rapidly at low temperatures (100°C for water evaporation and be-



3. Combustion of a 1-g oak sample with 20% moisture content at 800°C (time displayed in minutes:seconds).



4. Weight change profile for combustion of oak at 800°C.

tween 250°C and 300°C for biomass pyrolysis). These stages are overlapped somewhat, making it difficult to distinguish them. The weight loss from A to C is the sum of the moisture content and the volatile content. On the other hand, there is no overlap between devolatilization and char burning. This is because char burning occurs at a much higher temperature (> 600°C) than devolatilization, and it is limited by oxygen diffusion. 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, which is less than 1% for biomass and could not be accurately measured with the setup of this experiment.

Effect of moisture content

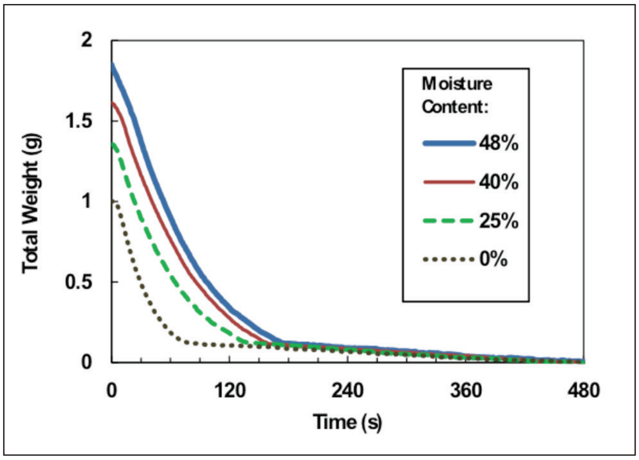
Figure 5 shows the weight change profiles of oak with different moisture content during combustion at 800°C. An increase in moisture content causes a longer drying time, a slightly longer devolatilization time, and no change in the char burning time. The results are in agreement with results reported elsewhere for the combustion of high-moisture waste material [9].

Figure 6 shows the change in 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 that is magnified for the first 30 s of combustion. The effect of moisture content on combustion stages is more evident on time to ignition, which is due to the presence of more water that needs to be dried first for devolatilization to start. There is also a slight increase in devolatilization time. The moisture content, however, does not have an effect on the char burning duration. This is understandable, since at the onset of char burning no more water or volatile matter is present.

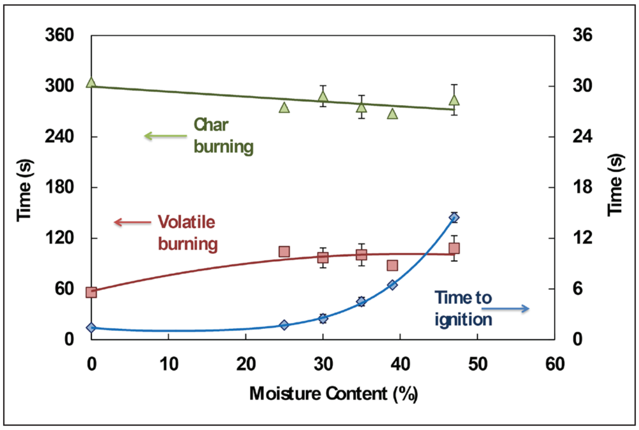
Comparison of different wood species

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 cm × 1.2 cm × 1.2 cm) were prepared from different wood species.

As summarized in **Table I**, the results indicate that combustion behavior of biomass is highly dependent on the density of the wood species. Hardwood samples have higher density, thus taking longer to burn than softwood samples. The different combustion behavior of hardwoods and softwoods is more evident for samples with higher moisture content. When comparing the weight profile of different wood species with 40% moisture content, the decrease in the devolatilization rate is greater for the low-density softwood (from 19.3 to 13.8 mg/s in the case of cedar) than 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 in which water vapor has less space to move out. Because the water vapor 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 content, especially for higher-density biomass samples.



5. Effect of moisture content on weight change profiles of oak during combustion at 800°C. (All samples have an initial dry weight of 1 g.)



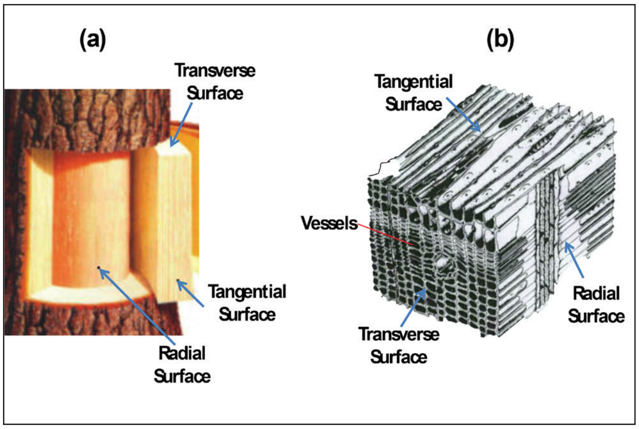
6. Combustion stages for oak combustion at 800°C.

Water movement versus wood orientation

Figure 7 shows the cut surfaces and cellular structure of wood [10]. Depending on how a piece of wood is cut, the cut surface can be transverse, tangential, or radial (Fig. 7a). Because water is stored in the vessels of the cellular structure (Fig. 7b), during drying it vaporizes and escapes through the vessel openings on the transverse surface more readily than

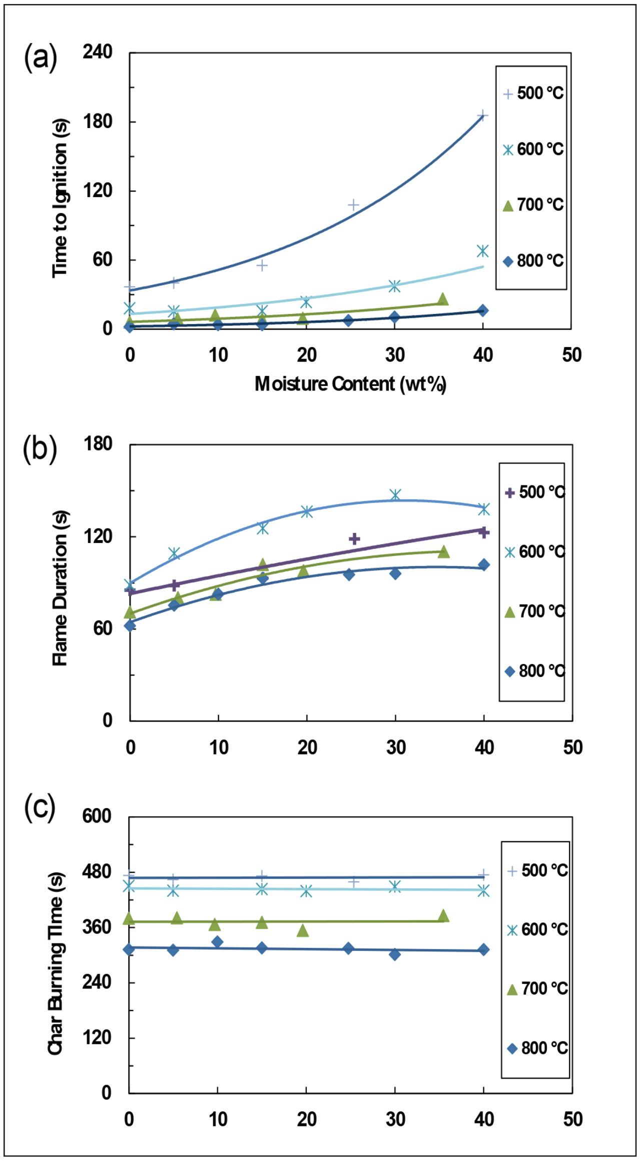
Wood Species		Density, g/cm^3	Combustion Stage Rate, mg/s					
			Time to Ignition		Devolatilization		Char Burning	
			Moisture Content		Moisture Content		Moisture Content	
			0%	40%	0%	40%	0%	40%
Softwood	Cedar	0.33	0	33.1	19.3	13.8	0.720	0.677
	Pine	0.39	0	27.1	16.0	12.4	0.545	0.582
Hardwood	Poplar	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

I. Combustion rate of different wood species of a constant cubic volume of 2.2 cm^3.



7. Wood structure: (a) cut surfaces and (b) cellular structure.

8. Flame distribution of softwood and hardwood during devolatilization (furnace temperature = 800°C).

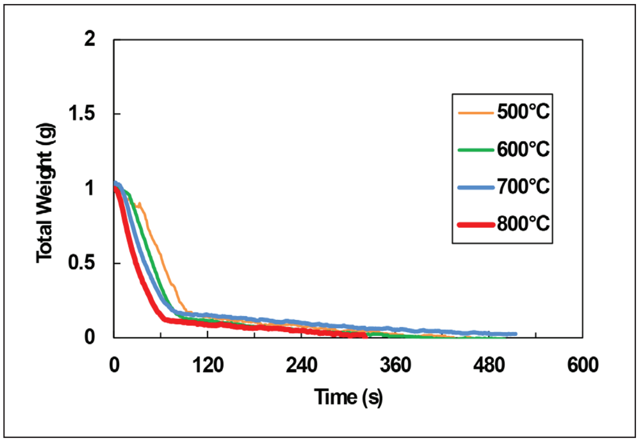


9. Effect of moisture content and furnace temperature on combustion of oak (1-g dry sample).

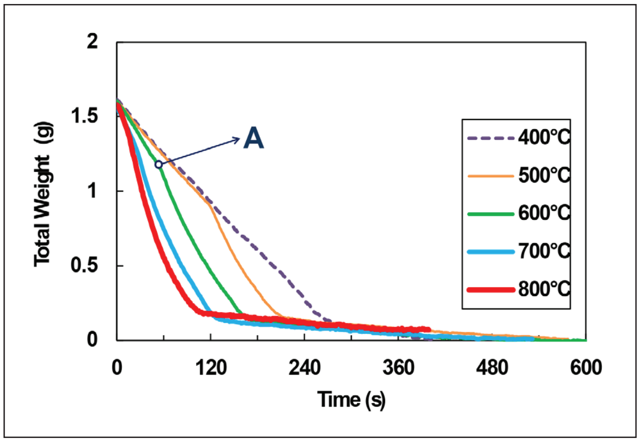
through vessel walls on the radial and tangential surfaces. Thus, per surface area, wood dries more readily from the cross-section than from the side of the trunk or branch. This preferential release of water from the transverse surface of wood was observed in all combustion tests in this study.

An example of this is shown in **Fig. 8**, which compares the combustion behavior of softwood and hardwood samples containing 40% moisture. At 00:30, or 30 s 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 burning 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 has been split in half. This so-called coffee-crisp effect was presumably caused by the continuous release of water vapor from the transverse surface that kept the surface temperature below the ignition point of the volatiles. As the rate of water vapor release decreased with time, the transverse surfaces became darker and darker and eventually burst into yellow flames at 01:00, while the tangential and radial surfaces were covered with increasingly weaker flames. At 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 because hardwood is denser and contains less water in its vessels than softwood.

The surface of the sample must reach about 300°C for devolatilization to occur. As the volatile burns the surface sample temperature increases and the heat continues to transfer to the interior of the particle, further increasing its temperature and causing devolatilization. Because of the large temperature gradient between the sample surface and interior, particu-



10. Weight profile for combustion of oak with 0% moisture content (1-g dry sample).



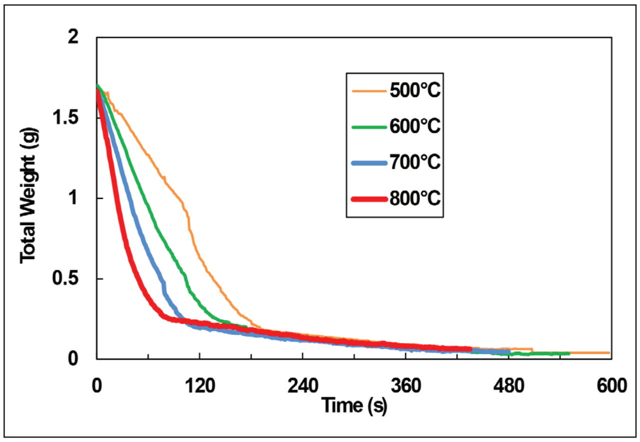
11. Weight profile for combustion of oak with 40% moisture content (1-g dry sample).

larly for samples with high moisture content, drying and devolatilization often overlap [11]. While devolatilization 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 already undergoes devolatilization. This means that as a whole, drying and devolatilization can occur simultaneously, particularly for samples with high moisture content.

Effect of furnace temperature

In biomass boilers, the combustion heat is sustained by continuously burning the biomass feedstock. Burning feedstock with high moisture content 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 environment. 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 **Fig. 9**.

At all temperatures examined, the time to ignition increases with an increase in moisture content (Fig. 9a). The increase, however, was more dramatic as the furnace temperatures decreased, particularly at 500°C. The flame duration (or the volatile burning time) also increased as the furnace temperature decreased. However, the flame duration at 500°C was longer than that at 700°C and 800°C but shorter than that at 600°C (Fig. 9b). This shorter flame duration is possible because at 500°C, the temperature was sufficiently low that during the time to ignition stage some volatiles might have released without burning. Similar to the results shown in Fig. 6, the char burning duration was not affected by the moisture content. However, it became longer as the furnace temperature decreased (Fig. 9c).



12. Weight profile for combustion of pine bark with 40% moisture content (1-g dry sample).

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 (**Fig. 10**). However, for samples with 40% moisture content, drying and devolatilization stages are clearly influenced by the surrounding temperature (**Fig. 11**). The weight loss profile undergoes a change in slope the moment the sample ignites (e.g., point A on the 600°C curve). The lower the surrounding temperature, the longer it takes the sample to ignite, or for this breakpoint 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 result in the same temperature at the sample surface, despite the difference in surrounding furnace temperature. At 400°C, the temperature is too low for the ignition to occur; thus, no appreciable change in slope was observed.

Combustion of bark

In biomass boilers, the feedstock usually contains a large amount of wastewood or bark. To study the difference between the combustion behaviors of wood and bark, a series of experiments was conducted using jack pine bark with different moisture content and at different furnace temperature and comparing the results with those obtained using pine wood chips. The results are shown in **Fig. 12**. The devolatilization rate of jack pine bark was slightly higher than that of pine wood (Fig. 11). This was probably due to the layered and porous structure of the bark. The effects of moisture content and surrounding temperature on combustion of bark were similar to those of wood, as discussed in the previous section.

CONCLUSIONS

The average moisture content in 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 (e.g., old wood waste, biosludge), the furnace temperature will decrease. This, in turn, will suppress the combustion and lower the steam production capacity of the boiler. The downward spiral will eventually lead to a boiler blackout, unless the biomass feed rate is significantly reduced or the auxiliary fuel (natural gas and fuel oil) flow rate is increased to keep the furnace temperature high.

Study results show that 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 the time to ignition of the sample. Increased moisture had only a small effect on the devolatilization rate and virtually no effect on the char burning rate. Furnace temperature also has a significant effect on combustion. Samples containing 40% moisture can ignite and burn readily at 800°C, but they take a much longer time to ignite and to burn at 500°C and do not ignite at 400°C. Softwood has lower density (higher porosity), and hence greater drying, devolatilization, and char burning rates than hardwood. Effects of moisture content and furnace temperature on jack pine bark combustion are similar to those of jack pine wood. However, bark burns at a slightly higher devolatilization rate and tends to produce fire sparks during combustion. **TJ**

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ABOUT THE AUTHORS

Understanding the effect of moisture content on biomass combustion would help pulp and paper mills develop viable strategies for optimizing their biomass boiler operation. This research complements previous research by other groups. However, our focus is mainly on the understanding of how moisture content may affect combustion characteristics of biomass.

The most difficult aspect of this research was determining how to translate the results obtained in the laboratory into useful information that pulp and paper mills can use. We addressed the issue by visiting mills to learn how biomass boilers are operated and what the issues are. While biomass combustion has been known to mankind for tens of thousands of years, there are still mysteries to unravel. The most interesting discovery was the coffee-crisp effect observed during the combustion of samples with high moisture content.

Mills may use the results obtained from this work to develop general guidelines for self-sustained biomass boiler operation with minimum need for co-combustion of fossil fuels. The next step is to conduct this study in a bench-scale combustor with a continuous feeding system to simulate the operation of biomass boilers more closely.


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