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Torrefaction of sawdust in a fluidized bed reactor

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ABSTRACT

In the present work, stable fluidization of sawdust was achieved in a bench fluidized bed with an inclined orifice distributor without inert bed materials. A solids circulation pattern was established in the bed without the presence of slugging and channeling. The effects of treatment severity and weight loss on the solid product properties were identified. The decomposition of hemicelluloses was found to be responsible for the significant changes of chemical, physical and mechanical properties of the torrefied sawdust, including energy content, particle size distribution and moisture absorption capacity. The hydrophobicity of the torrefied sawdust was improved over the raw sawdust with a reduction of around 40 wt.% in saturated water uptake rate, and enhanced with increasing the treatment severity due to the decomposition of hemicelluloses which are rich in hydroxyl groups. The results in this study provided the basis for torrefaction in fluidized bed reactors.

1. Introduction

Torrefaction is a slow pyrolysis of material in the absence of oxygen, with the aim of maximizing solid yield, thus producing a large fraction of 'biochar' (70–85 wt.%) for use in energy (heat and power), metallurgical (e.g. as a reductant for steel production), fuel and chemical (syngas from gasification) and fertilization applications (Devi et al., 2003; Henriksen et al., 2006; Li, 2001). Apparent energy densities can exceed 20 GJ t^{-1} after torrefaction, reducing transportation volumes of biomass. Torrefaction of biomass also improves grindability, prolongs durability, increases hydrophobicity and slows biological and thermal degradation (Bergman et al., 2005), which can improve the shelf life, storage and transportation. As a result, interest in biomass torrefaction has been growing in recent years, and efforts are being made to scale up and commercialize this technology.

Most previous works on torrefaction (Arias et al., 2008; Bergman et al., 2004; Bergman and Kiel, 2005) have focussed on preparing biomass for further energy conversion processes. As reported by several researchers, the grindability of biomass is improved, while most of the energy is preserved in the solid products after torrefaction. Compared with fresh raw biomass, the energy consumption for grinding torrefied biomass was found to be significantly lower (Chen and Kuo, 2010). Several examples of torrefaction of biomass being used as a pre-treatment for gasification applications have been reported (Acharjee et al., 2011; Couhert et al., 2009; Deng et al., 2009; Yan et al., 2009).

Torrefied biomass has been compacted to produce the 2nd generation biomass pellets to address the problems of low heating value, fast degradation, and high off-gas emissions associated with the current raw biomass pellets. Due to their high heating value and hydrophobicity, torrefied pellets have been considered as premium substitute fuels for existing coal-fired power plants to meet the greenhouse emission reduction targets. Up to now, most studies reported in the literature have focused on the torrefaction of biomass and its optimization, with little work on densification of torrefied biomass into pellets and almost no work on the optimization of combined torrefaction and densification of biomass residues for the production of high quality torrefied pellets (Chen and Kuo, 2011; Phanphanich and Mani, 2011; Pimchuai et al., 2010; Repellin et al., 2010; Rousset et al., 2011).

Meanwhile, fluidized beds have been widely used in the energy conversion field due to their excellent gas–solids heat and mass transfer performance. Most of those applications were focused on the slow-/fast-pyrolysis (Pattiya, 2011), gasification (Hannula and Kurkela, 2010), and combustion (Cummins et al., 2006; Henihan et al., 2003; Rozainee et al., 2008). However, biomass particles, which are irregular in shape and size, are not easily handled in fluidized beds without the use of an inert bed material such as

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sands. The use of inert bed materials in the torrefaction of sawdust will inevitably contaminate the torrefied sawdust due to the introduction of fine broken bed materials, which will increase the ash content of the torrefied sawdust. As a result, to our knowledge, no study has been reported on torrefaction of biomass in fluidized bed reactors.

To take advantage of fast heat and mass transfer rates of fluidized beds and the use of fine particles, it is desirable to carry torrefaction of biomass in fluidized bed reactors in order to shorten the reaction time and improve the heating efficiency. In this paper, we present our recent work on torrefaction of softwood mixtures in a fluidized bed reactor with a novel inclined orifice distributor and the characterization of torrefied sawdust properties, in order to identify suitable torrefaction conditions for the production of high quality and durable torrefied pellets.

2. Methods

2.1. Experimental materials and analyses

The sawdust sample, obtained from RONA furniture store in Vancouver, is a mixture of spruce and fir, with spruce as the main component (see Table 1). The sample was separated into six size fractions, 0–250, 250–355, 355–425, 425–500, 500–600 and 600–710 μm. All fractions were used in the cold model tests, but only the 250–355 μm size fraction was used in the torrefaction test in this study. The higher heating value (HHV) of the samples was measured with a Parr 6100 bomb calorimeter. The particle density was measured with a multipycnometer (Quantachrome Instruments). The size distribution was determined using a Ro-Tap RX94 sieving device. The SEM images of raw and torrefied sawdust were obtained with a Hitachi H7600 TEM.

The moisture absorption rates of raw and torrefied sawdust samples were measured using a controlled humidity chamber (ESPEC CORP, LHU-113, Japan), in which the samples resided 48 h at 30 °C and 90% relative humidity. Before the test, all the raw samples were first dried in a convection oven at 103 °C for 24 h. These dry samples were then stored in a desiccator before use. The torrefied sawdust samples collected at the end of each torrefaction experiment were kept inside closed glass bottles. In each case, two replicates were used for raw sawdust and torrefied samples. The Petri dishes containing the samples were quickly covered with a glass cap to prevent moisture loss as they are removed from the humidity chamber, and weighted quickly using an ALC-80.4 analytical balance with 0.1 mg accuracy (Acculab, Edgewood, NY). After weighing, the samples were returned to the controlled humidity chamber. Each sample weight was measured every 20 min for the first 4 h and every 60 min afterward.

2.2. Fluidized bed reactor

The batch fluidized bed reactor is made of stainless steel, 1.5 m tall and 50 mm in diameter, as shown in Fig. 1. Thermocouples were used to measure temperatures of the inlet gas, the fluidized bed and the reactor wall. The pressure drops through the system and across the fluidized bed were measured with differential pressure transducers.

A gas distributor with angled orifices was designed to achieve good fluidization of irregularly shaped sawdust powders. In total there are 14 holes of 0.6 mm in diameter on the distributor, with 12 located around the peripheral region and 2 in the central region. All the holes were inclined vertically with an angle of 30°. The angle of inclination of the 12 holes in the outer region was opposite to that in the center, in order to create a vortex motion of particles in the bed.

The fluidization behavior of seven size-fractions of sawdust particles with sizes of 0–250, 250–355, 355–425, 425–500, 500–600, 600–710, and 710–850 μm was first investigated in a Plexiglas unit with the same dimensions as the hot unit. The sample of 0–250 μm could not be properly fluidized because of channeling, while the fluidization of the sample of 710–850 μm was associated with slugging. The other samples could be fluidized stably with a different gas flow rate. It was observed that as the bed became fluidized, a high gas velocity region is produced close to the distributor, due to the inclined orifices around the periphery of the distributor. The gas flows through those inclined orifices causing a sweeping pattern near the reactor wall in the form of a vortex. As a result, a solids circulation pattern is established with sawdust particles rising in the center, passing through a fountain region and then moving down slowly along the wall, keeping the entire bed of particles in motion.

In the torrefaction tests, the sample of 250–355 μm was used to minimize the internal heat and mass transfer. In order to operate the fluidized bed reactor fully fluidized during the hot test, a minimum stable operating gas velocity (0.26, 0.29 and 0.32 m s^{-1} corresponding to gas flow rates of 1.83, 2.05 and 2.26 m^3 h^{-1}, for sawdust loads of 10, 15 and 20 g, respectively) was determined from the cold unit experiments. During the hot model test, the temperature of gas flow in the empty fluidized bed was heated up to the desired temperature with the preheater, heating tape and reactor furnace. Weighted sawdust sample was fed from the top of the reactor. After then, the sample was fluidized by nitrogen with a predetermined flow and a desired residence time. When the test was finished, the furnace jackets were opened to have the reactor cooled down by a fan, followed by the discharge of the solid product from the bottom of the reactor into a collecting container.

2.3. Sawdust TGA results

The weight loss characteristics of the sawdust samples were first investigated in a TGA analyzer (Shimadzu, TA-60WS) at different temperatures in order to identify suitable ranges of temperature and residence time for the fluidized bed torrefaction experiments. In a typical TGA test, a dried sample was first heated up to a temperature of 105 °C, which was held for 10 min. Then, the temperature was increased to the desired test temperature at a heating rate of 50 °C/min, and kept constant for 8 h. At the end, the sample was heated up to 800 °C to complete the conversion process. The entire TGA test took place under an inert atmosphere of nitrogen with a flow rate of 50 mL/min.

Table 2 presents the TGA test results for sawdust particles with a size of 0–250 μm, chosen to minimize the internal heat and mass transfer. It is seen that residence times between 15 and 440 min are required to reach a targeted weight loss of 10–30 wt.% at

Table 1
Raw sawdust chemical analyses (wt.%, dry basis).

	Chemical analysis			Proximate analysis			Elemental analysis			
	Cellulose	Hemicellulose	Lignin	Volatile	Fixed carbon	Ash	C	H	N	O[a]
Sawdust	19.64	27.20	51.48	80.49	19.42	0.24	48.34	6.21	1.50	43.95

[a] By difference.

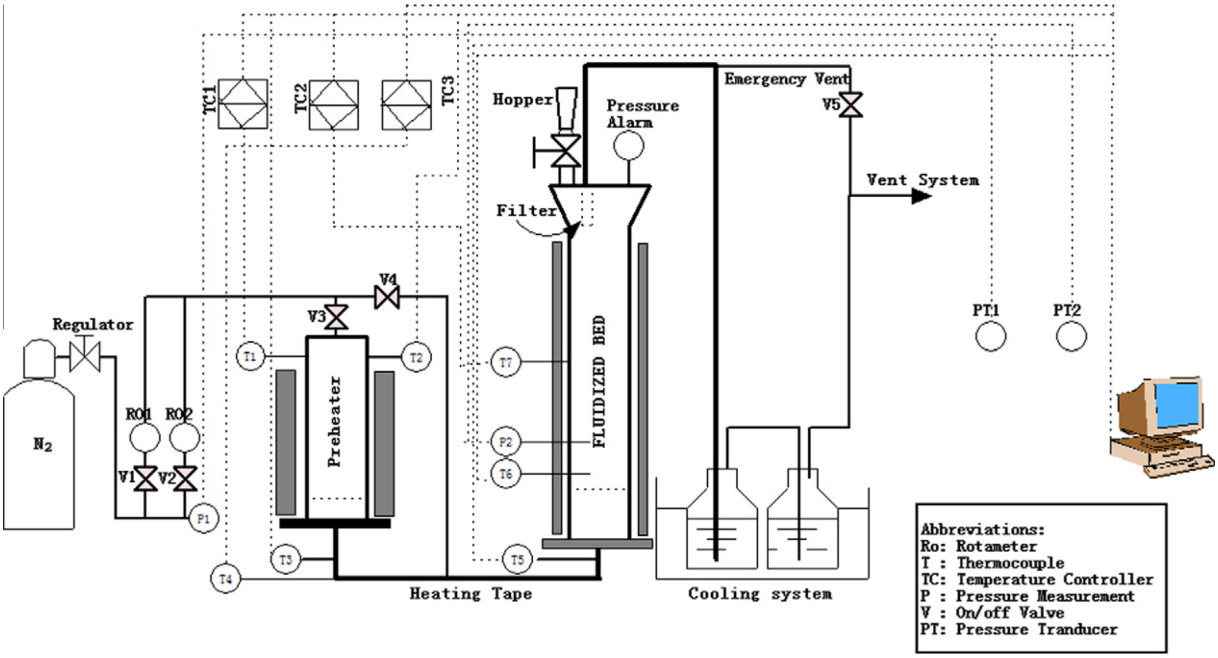

Fig. 1. Schematic of fluidized bed torrefaction unit.

Table 2
Residence time (min) required for different targeted weight losses at different temperatures (°C) from TGA curves (particle size 250–355 μm).

Weight loss (wt.%)	240	250	260	270	280	290	300
10	21.9	17.5	16.3	15.7	15.6	15.5	15.4
20	110.3	52.2	33.7	24.5	19.0	17.2	16.6
30	364.6	168.2	87.2	50.8	30.2	24.1	19.9
40	–	439.1	212.1	113.2	55.9	38.1	27.5

temperatures between 240 and 300 °C. For the fluidized bed experiments, the targeted weight loss was selected to be approximately 30 wt.%, which was considered to be suitable for achieving an auto-thermal or self-energy sustained torrefaction based on energy balance.

3. Results and discussion

3.1. Weight loss of solid product

Fig. 2 shows the weight loss of sawdust as a function of torrefaction time and reactor temperature. To guide the selection of torrefaction conditions, Fig. 2 has been constructed as a weight loss map for the fine sawdust tested in relation to temperature and residence time. Overall, weight losses obtained during the fluidized bed torrefaction experiments were consistently higher than those obtained in the TGA apparatus. It appears that the fluidized bed environment, which provides more intense conditions in terms of particle heat and mass transfer rates, yields a higher conversion than the fixed bed TGA at similar temperature and residence time conditions. Fig. 2 shows that the weight loss increased with increasing the residence time at a given reactor temperature. The weight loss increased more significantly in the first 30 min, and approached a steady value beyond 30 min. This can be explained by the pyrolysis of two major wood constituents in the torrefaction process. During torrefaction, dehydration and decarboxylation reactions cause a mass loss of the wood (Prins et al., 2006), mostly related to the degradation of the hemicelluloses. The lower thermal stability of hemicelluloses compared to that of cellulose is usually explained by its lack of crystallinity (Windeisen et al., 2007; Yildiz et al., 2006). The decomposition of hemicelluloses is fast and typically finishes in the first 30 min or so, leading to a fast weight loss. The decomposition of lignin and cellulose is slower, which contributes to the slow but steady weight loss after 30 min.

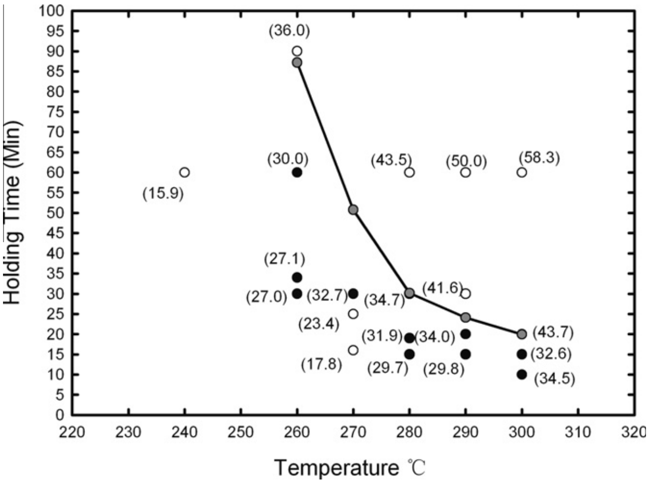

Fig. 2. Map of percentage weight loss (shown in the brackets) as a function of temperature and residence time (30 wt.% weight loss from TGA shown as a solid line).

As shown in Fig. 2, a different combination of temperature and residence time may be used to achieve the same degree of weight loss during torrefaction. The optimal condition, therefore, needs to be selected based on the ease of densification to the torrefied pellets and the pellet quality, which will be investigated and reported separately.

3.2. Heating values of torrefied sawdust and energy yield

Fig. 3a shows that the higher heating value of the torrefied sawdust increased with increasing torrefaction temperature at a

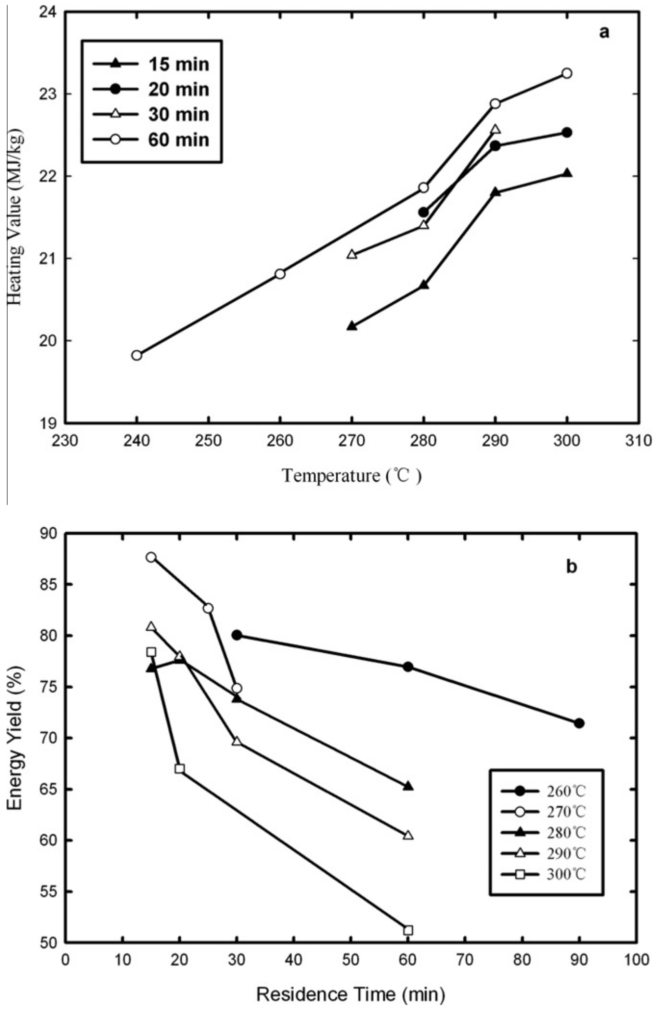

Fig. 3. (a) Higher heating value and (b) energy yield as a function of reactor temperature and residence time.

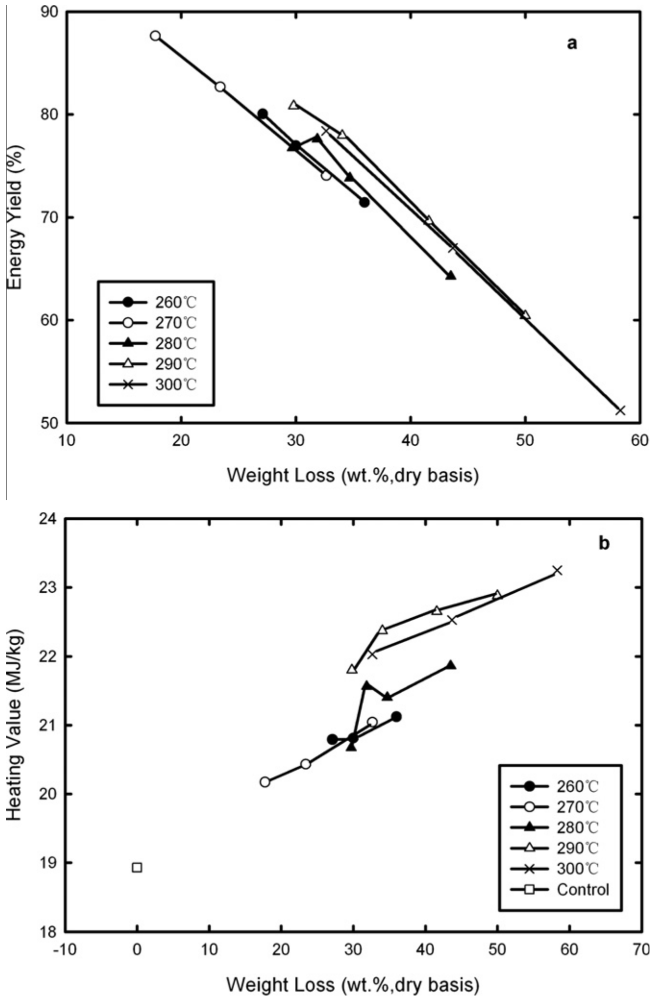

Fig. 4. (a) Energy yield and (b) higher heating value as a function of weight loss.

given residence time. During heat treatment of sawdust, the formation of CO was attributed to the decarbonylation reactions, while CO_2 was formed from the cleavage of the acetyl groups from the xylan chain (Ponder and Richards, 1991; Shen et al., 2010). Meanwhile, CO_2 reacts with char produced from the decomposition of sawdust at higher reaction temperatures to produce CO (Pan and Richards, 1989). The release of CO_2 and CO removes oxygen from the solid fraction, resulting in an increase in the higher heating value of the solid product.

The energy yield, which is defined as the fraction of the original energy content of the raw material that is retained in the final solids product after torrefaction, was calculated for each condition and reported in Fig. 3b. The results show that as the higher heating value increases with increasing the residence time as a result of more oxygen and more material being consumed from the raw sawdust, the energy yield decreases. Similar results were reported by Arias et al. (2008). The significant decrease of energy yield during the first 30 min is associated with the rapid decomposition of hemicellulose fractions.

Fig. 4a and b plots the higher heating value and energy yields, respectively, as a function of weight loss, showing a strong correlation between the higher heating value, energy yields and the weight loss. At the same weight loss, both the higher heating value and the energy yield of the torrefied sawdust prepared at higher temperatures are only slightly higher, likely related to a higher degree of decomposition of hemicelluloses with more oxygen and hydrogen removal at higher torrefaction temperatures. The results suggest that higher heating value and energy yield are primarily determined by the net weight loss from torrefaction, regardless of the different combinations of torrefaction temperature and residence time used to produce that weight loss. At a typical weight loss of 30 wt.%, the higher heating values from the tests were in the range of 21–22 MJ kg^{-1}, and the energy yield was 75–80%.

3.3. Physical properties of torrefied sawdust

The size distribution of raw and torrefied sawdust was also measured in a Ro-Tap RX94 sieving device with six fractions (0–63, 63–125, 125–180, 180–212, 212–250 and 250–355 μm). Comparing with raw sawdust, about 50 wt.% of particles still remained in this range after torrefaction, with the rest distributed to smaller size fractions with 25–30 wt.% at 212–250 μm, 6–15 wt.% at 180–212 μm, 3–12 wt.% at 125–180 μm and 0.9–5 wt.% at 63–125 μm (see Table 3). For torrefaction in fluidized beds, large particles may shrink slightly due to the material loss. At the same time, fine particles may be generated from the attrition of original particles due to the particle–particle and particle–wall collisions. Results in Table 3 show that particles smaller than 63 μm were not found in most experiments, except those conducted for 60 min residence time at 300 and 280 °C. This may be explained by the high conversion that was obtained during these two

Table 3
Size distribution of torrefied sawdust with different temperatures (°C) and residence times (min).

Temperature	Time	Size (μm)					
		250–355	212–250	180–212	125–180	63–125	0–63
Raw sawdust		93.10	3.81	2.37	0.56	0.16	
280	60	38.82%	25.81%	14.63%	11.18%	4.88%	1.22%
300	60	50.83%	27.50%	10.56%	7.22%	2.50%	1.11%
260	30	55.35%	29.97%	7.95%	4.74%	1.38%	
270	30	60.93%	28.33%	6.11%	3.52%	1.11%	
280	20	55.62%	29.73%	7.25%	4.41%	1.14%	
290	20	56.25%	27.76%	8.46%	5.15%	1.84%	
300	20	58.56%	26.98%	8.62%	4.08%	0.91%	
290	15	54.28%	30.79%	8.09%	4.51%	1.56%	
300	15	53.01%	30.73%	8.94%	4.72%	2.11%	

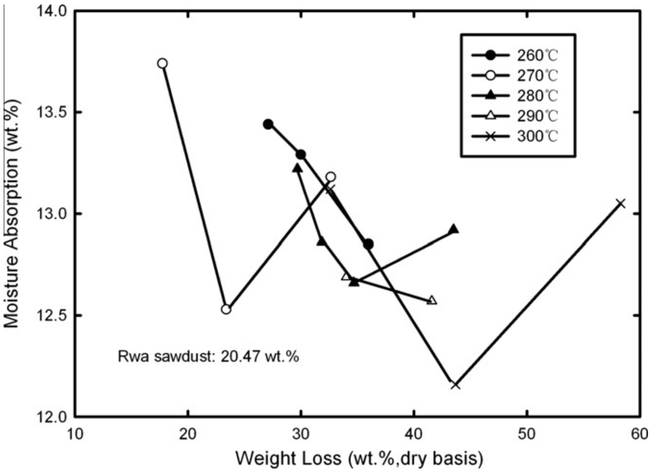

Fig. 5. Saturated moisture absorption rate of torrefied sawdust as a function of weight loss at different torrefaction temperatures and residence times.

experiments, with weight losses of 58.3 and 43.5 wt.% respectively. The particles were more brittle, and consequently broke into fine particles due to grinding in the fluidized bed reactor.

During torrefaction, fine particles are produced from the decomposition and grinding process in the fluidized bed. Those fine particles may be entrained and leave the reactor with the exiting gases. As a result, higher weight loss values may be computed from the experimental results than what is actually occurring due to torrefaction. This may explain part of the consistently higher weight loss values obtained in the fluidized bed reactor than in the TGA under similar conditions.

The fine particles generated during torrefaction are linked to the structural changes during the decomposition of lignocelluloses. SEM images of raw and torrefied sawdust particles were taken and compared. It is found that the structure of sawdust particles torrefied at 260 °C for 30 min was similar to that of the raw sawdust particles, corresponding to a low conversion with a weight loss of only 27 wt.%. However, a significantly different structure of sawdust particles torrefied at 300 °C for 20 min can be observed in the SEM picture. The image shows those particles to be more porous with several branches, which indicates higher conversion under those torrefaction conditions. During torrefaction and sieving analyses, those branches may be removed from the particles, resulting in finer particles that can be entrained from the reactor.

The moisture absorption rate, which is defined as the weight of water uptake divided by the original weight of the dry sample, was measured by placing samples in a controlled humidity chamber over a 48 h period. The moisture absorption rate was measured in triplicate for each sample and the results are presented in Fig. 5. The moisture absorption rates of the torrefied sawdust were significantly lower than the absorption rate of raw sawdust. For example, the absorption rate of the torrefied sawdust prepared at 280 °C over 30 min is 12.9 wt.%, while the value for untreated sawdust is 20.5 wt.%, a reduction of about 40 wt.%. The moisture absorbability of the torrefied sawdust also decreased steadily with increasing weight loss. For the same weight loss, moisture uptake is slightly higher for the torrefied sawdust samples produced at higher temperatures. Of the three primary components of lignocellulosic biomass, hemicelluloses have the highest capacity for water sorption, while lignin has the lowest capacity (Bjork and Rasmuson, 1995). During torrefaction, most hemicelluloses in the sawdust are decomposed, leading to the increase of hydrophobicity of the torrefied sawdust. At a typical weight loss of 30 wt.%, the moisture update of the torrefied sawdust is expected to be reduced by 30–40 wt.% compared to the raw sawdust. The improvement in the hydrophobicity for the torrefied pellets, however, will be investigated and reported in another paper separately.

4. Conclusions

Stable fluidization of sawdust was first achieved in a fluidized bed with an inclined orifice distributor. The higher heating values of solid products increased but the energy yields decreased with the increase in the severity of torrefaction. The hydrophobicity of the torrefied sawdust was enhanced with increasing the severity of treatment. The performance of the proposed fluidized bed reactor under continuous solids feed and withdrawal operation needs to be investigated in the future. The quality of the torrefied wood pellets from the torrefied sawdust needs to be examined to optimize the performance of the fluidized torrefaction reactor.

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