International Journal of Technology (2015) 7: 1084-1093
ISSN 2086-9614

EFFECT OF HEATING RATE OF TORREFACTION OF SUGARCANE BAGASSE ON ITS PHYSICAL CHARACTERISTICS

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(Received: June 2015 / Revised: September 2015 / Accepted: September 2015)

ABSTRACT

Torrefaction, which is used to improve the properties of sugarcane bagasse as fuel in pulverised fuel combustion and as carbon feed in gasification, is a low heating rate pyrolysis of biomass carried out at a temperature of 200–300°C, at an atmospheric pressure, and in an inert environment. In the present work, sugarcane bagasse was torrefied at heating rates of 3, 6, and 10°C/minute, respectively, to achieve a final temperature of 275°C and after the final temperature was reached, hold times of 0 and 15 minutes, respectively occurred at a constant temperature of 275°C for a heating rate of 6°C/minute. The physical characteristics of torrefied sugarcane bagasse samples to be determined were a particle size distribution accomplished by grinding, hydrophobicity by allowing the samples to absorb moisture from the ambient air, and pellet hardness of the sample pellets. The torrefaction results show that increasing heating rate and hold time reduced the cellulose content of the sugarcane bagasse to as low as between 5.35% to 10.61% by weight composition, respectively. As the lignin content increased, the sample pellets resulted in better hardness in comparison to that measured on raw sugarcane bagasse. As the hemicellulose content increased, the samples, after grinding and stronger hydrophobicity, produced a higher fraction of smaller particle sizes. The maximum weight fraction of particles in these samples with sizes smaller than 105 µm achieved was 83.43% weight in contrast to 0.62% weight in raw sugarcane bagasse. The maximum water absorption by the samples in 3 hours was 1.28% weight in contrast to 8.02% weight by raw sugarcane bagasse. The results indicate that torrefaction is able to improve sugarcane bagasse physical characteristics, which are favourable for biomass pelletization, storage and transportation.

Keywords: Hardness; Heating rate; Hydrophobicity; Sugarcane bagasse; Torrefaction

1. INTRODUCTION

One of the abundant biomass resources in Indonesia is sugarcane (*Saccharumofficinarum*). In a year, sugarcane millings in Indonesia produce sugarcane bagasse as residue up to 8.5 million tons (Prastowo, 2012). As a source of green energy in pulverized fuel combustion, either sugarcane bagasse or another biomass generates less SO_2, NO_x, and CO_2, (Wang et al., 2012). However, raw biomass has several drawbacks compared to fossil fuel, such as low bulk density, high moisture content, inconsistent particle size, heterogeneous chemical composition, hydrophilic nature, and relatively low calorific value (Arias et al., 2008; Chew & Doshi, 2011). Due to its limitations, raw biomass becomes an expensive fuel to be stored, transported, and handled at large scales. In order to overcome those limitations and make biomass suitable for

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Permalink/DOI: http://dx.doi.org/10.14716/ijtech.v6i7.1771

energy applications, the raw biomass must be pretreated (Tumuluru et al., 2011).

Torrefaction is currently believed to be the most promising pretreatment of biomass for commercial purposes (Deutmeyer et al., 2012). It is a low heating rate pyrolysis process in which raw biomass is heated slowly in an inert atmosphere with an atmospheric pressure at the temperature range of 200–300^{o}C (Zanzi et al., 2002; Chew & Doshi, 2011). Torrefaction allows the conversion of raw biomass into solid fuel suitable for combustion and gasification. Torrefied biomass has better properties, such as higher energy density, more consistent particle size, less hydrophilic nature, lower O/C and H/C atomic ratios, and better grindability, storage and transportation (Arias et al., 2008; Tumuluru et al., 2011).

Biomass basically contains lignocellulosic polymers, such as hemicellulose, cellulose, and lignin in which each has different temperature ranges of decomposition. It has been reported that torrefaction has a significant impact upon hemicellulose, while cellulose and lignin are affected to a certain extent depending on torrefaction temperature and hold time (Chen & Kuo, 2010). Several prior studies have already identified the effects of torrefaction temperature and duration on certain biomass (Wang et al., 2011; Chen et al., 2012; Prins et al., 2006; Bridgeman et al., 2008; Sadaka & Negi, 2009). Those studies concluded that by increasing the torrefaction temperature and hold time significantly, improvement in biomass calorific value, energy density, and grindability would be achieved.

Beside torrefaction temperature and hold time, heating rate may improve the properties of torrefied biomass to some extent, as a result of the modification of its lignocellulosic polymer composition. The effects of fast heating rate have been identified in biomass pyrolysis (Azri, 2008). In pyrolysis, a higher heating rate increases the rate of lignocellulosic polymer depolymerization and dehydration into volatiles, so that the char yield is much less. This condition is not desirable in biomass torrefaction, since solid fuel is required as the main product. A low heating rate in torrefaction is expected to produce more of a solid phase. However, there have been no previous studies *per se* related to low heating rate upon sugarcane bagasse torrefaction. The torrefaction has been conducted only to investigate the effect of different constant torrefaction temperatures on moisture and volatile contents, calorific value and fixed carbon composition (Patel et al., 2011) and on grindability (Ribeiro et al., 2013).

The present research investigated the effect of different low heating rates and hold times (heating duration after final temperature has been reached) on the variables of mass yield of solid phase, lignocellulosic contents, particle distribution after grinding, hydrophobicity of torrefied biomass, and hardness of torrefied biomass pellets. This research investigates these last three matters because they are important for solid combustion, storage and transportation of the biomass char. Particle size distribution of biomass particles in combustion is important to control delay of volatiles ignition (Yang et al., 2008), which significantly control radiative heat transfer, and has a major effect on pollutant emissions (Williams et al., 2012). High hydrophobicity and high hardness factors give good implications in storing and transporting particles, due to low moisture capture from surroundings and low brittleness of particles, respectively. Low moisture content is favourable for biomass particle combustion because it is attributed to high heating value. Therefore, the results of the current research are expected to contribute to the improvement of biomass particle handling and combustion, especially those using sugarcane baggase.

2. EXPERIMENTAL SYSTEM

2.1. Raw Material

The experimental system of this experiment is shown in Figure 1. The raw material used in this torrefaction system was sugarcane bagasse. It was taken from a sugar factory in Subang, West

Java. It consists of hemicellulose 31.07%, cellulose 44.20% and lignin 24.73%. It was cut into smaller sizes, i.e.3×0.5 cm (see Figure 2A), and dried until its moisture content reached 10% in an oven set at 105^{o}C which took 45 minutes and 40 seconds. It was then cooled down and stored in a desiccator.

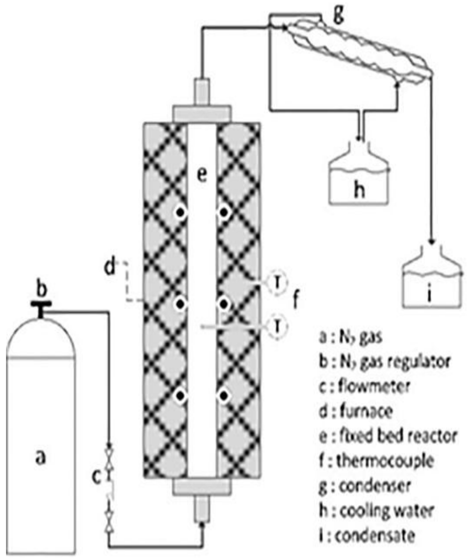

Figure 1 Experimental system of sugarcane bagasse torrefaction

Figure 2 (A) Prepared raw sugarcane bagasse; (B) Torrefied sugarcane bagasse (char) at heating rate and hold time of 6^{o}C/min and 0 minute, respectively; (C) Torrefied sugarcane bagasse at heating rate and hold time of 6^{o}C/min and 15 minutes, respectively

2.2. Reaction System

Sugarcane bagasse torrefaction experiment was carried out in a vertical fixed bed reactor. A pyrex reactor with a diameter of 50 mm and a length of 280 mm was used. This reactor was able to withstand heat up to 400^{o}C. Sugarcane bagasse was placed on glass wool, which was 25 mm above the bottom of the reactor. The upper end of the reactor was sealed with a silicone lid to isolate heat during torrefaction. A nitrogen gas line was connected to the lower end of the reactor that had a conical shape. The nitrogen gas cylinder was equipped with a regulator to adjust the pressure of nitrogen gas flow and its line was also equipped with a flowmeter to adjust the flow rate of nitrogen gas entering the reactor. The reactor outlet pipe was covered with a heating device to ensure that the volatiles temperature was no less than 150^{o}C to prevent condensation of volatiles before entering a condenser.

2.3. Experimental Procedures and Analysis

The prepared sugarcane bagasse was then torrefied until reaching a temperature of 275^{o}C at various heating rates and hold times as shown in Table 1. The temperature of 275^{o}C was chosen as the final torrefaction temperature for this experiment, since a previous study states that it was the optimum temperature of sugarcane bagasse torrefaction to get high yield of char (Aripin, 2013).

Table 1 Operating conditions of sugarcane bagasse torrefaction

Sample Name	Heating Rate (°C/minute)	Hold Time (minute)
A	without torrefaction	
B	3	0
C	6	0
D	10	0
E	6	15

For pellet preparation, the bagasse was firstly ground into powder that had size of 105 μm with a dry mill. Ten drops of polyvinyl alcohol (PVA) as a glue for pelletization that had been diluted in water (5% weight) was added to every 2 grams of sugarcane bagasse powder, and subsequently, the mixture was put into a pellet mold and compressed at a pressure of 9,000 kg/cm^2 for 10 minutes.

Analysis of lignocellulosic content in sugarcane bagasse referred to the Chesson-Datta method. This method basically uses reflux to extract the extractive components, hemicellulose, and cellulose content in biomass and ashing to determine the lignin content (Isroi, 2013).

Analysis of particle size distribution for grindability was conducted by sieving 5 grams of sugarcane bagasse powder that had been ground previously with a dry mill for 60 seconds. Sugarcane bagasse powder was gradually sieved through three sieve sizes, i.e. 250, 177, and 105 μm, respectively. The dry mill used for sugarcane bagasse grinding was a Sharp blender of Type SB-TI181P.

Analysis of hydrophobicity was conducted by letting 5 grams of sugarcane bagasse to absorb moisture in the open air with average relative humidity 65% for 240 minutes. Every 30 minutes, the sugarcane bagasse was weighed and the room temperature and humidity were measured by a thermohygrometer. Analysis of pellet hardness was conducted by using a durometer Shore D, whose procedures refer to ASTM D 2240.

3. RESULTS AND DISCUSSION

3.1. Mass Yield of Torrefied Sugarcane Bagasse

Figure 2 shows the torrefied sugarcane bagasse samples at heating rates of 6°C/minute and hold times of 0 minutes (Sample B) and 15 minutes (Sample C). Sample C is darker than Sample B due to longer heat exposure than the other three sugarcane bagasses. The effect of torrefaction heating rate and hold time on sugarcane bagasse mass yield is shown in Figure 3. Mass yield of sugarcane bagasse was calculated using Equation 1 (Bergman et al., 2005a).

$$mass\ yield = \left(\frac{m_{product}}{m_{feed}}\right) \times 100\% \quad (1)$$

where $m_{product}$ is the mass of torrefied bagasse, m_{feed} the mass of raw bagasse fed for torrefaction. In Figure 3, it can be seen that the increase of heating rate and hold time reduced sugarcane bagasse mass yield. Sugarcane bagasse torrefied at 275°C with heating rates of 3, 6,

10^oC/minute, respectively and the hold time of 15 minutes had a mass yield of 41.22%; 40.54%; 39.82%; and 34.40% respectively.

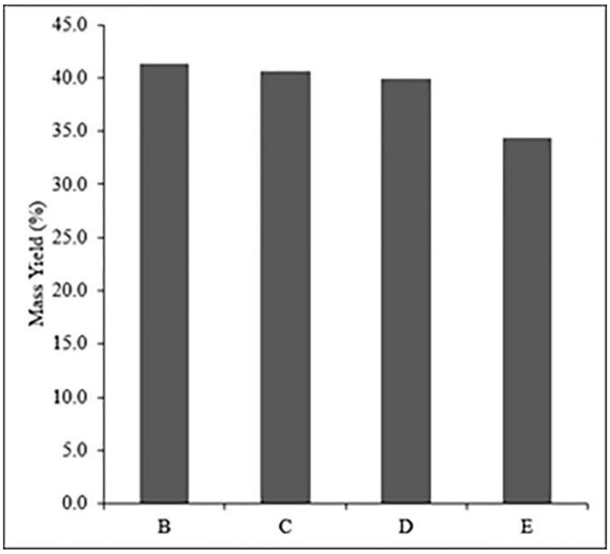

Figure 3 Mass yield distributions of torrefied sugarcane bagasse at various torrefaction heating rates and hold times, (B) at 3^oC/min, 0 minute; (C) at 6^oC/min, 0 minute; (D) at 10^oC/min, 0 minute; and (E) at 6^oC/min, 15 minutes, respectively

The torrefaction heating rate has been expected to give a significant effect on lignocellulosic polymers cracking, thereby determining the mass yield and torrefied products composition. When sugarcane bagasse is torrefied at lower heating rate, the released condensable volatiles are trapped much longer in the reactor. The slow removal of volatiles from the reactor facilitates secondary reactions between volatiles and char, which favour the formation of secondary char (Azri, 2008). Thus, the lower heating rate produces more char. Otherwise, more condensable volatiles are produced.

Torrefaction hold time may also affect the thermal degradation of sugarcane bagasse, thereby determining the mass yield and torrefied products composition. Sugarcane bagasse torrefied for a longer hold time experiences greater lignocellulosic polymers devolatilization. Because of that, more volatiles are released during torrefaction and the char yield was less. Thus, the longer hold time produces more volatiles, so that the char yield obtained from the torrefaction is less, (Sadaka & Negi, 2009; Pach et al., 2002).

3.2. Lignocellulosic Content of Raw and Torrefied Sugarcane Bagasse

The most susceptible lignocellulosic polymer to thermal degradation is hemicellulose, which is then followed by cellulose and lignin (Yang et al., 2007, Basu, 2013). Compared to hemicellulose, the crystalline structure of cellulose makes it harder to depolymerize (Tumuluru et al., 2011). Lignin, which has a phenolic structure and wraps the polysaccharides of biomass cell wall, acts as a strong composite and is resistant to thermal degradation and even enzymatic degradation (Yang et al., 2007). So, the main constituent of torrefied sugarcane bagasse was lignin. At a lower heating rate, sugarcane bagasse experiences dehydration, decarboxylation, and carbonization, so it produces more solid product or char. At higher heating rate, cellulose has less time to dehydrate, so it experiences more depolymerization and produces less solid product (Basu, 2013).

By comparing B, C, and D bars in Figure 6, it can be seen that the increase of the heating rate reduced the cellulose content in the sugarcane bagasse. For sugarcane bagasse torrefied at 275^{o}C with heating rates of 3, 6, and 10^{o}C/minute, respectively, the cellulose content was reduced to 11.89%; 11.77%; and 10.61%, respectively. It is known that torrefaction mainly affects the cellulose degradation, however its effect on hemicellulose and lignin are also alike, (Pach et al., 2002). At a lower heating rate, sugarcane bagasse experiences dehydration, decarboxylation, and carbonization, so it produces more solid product or char. At a higher heating rate, cellulose has less time to dehydrate, so it experiences more depolymerization and produces less solid product.

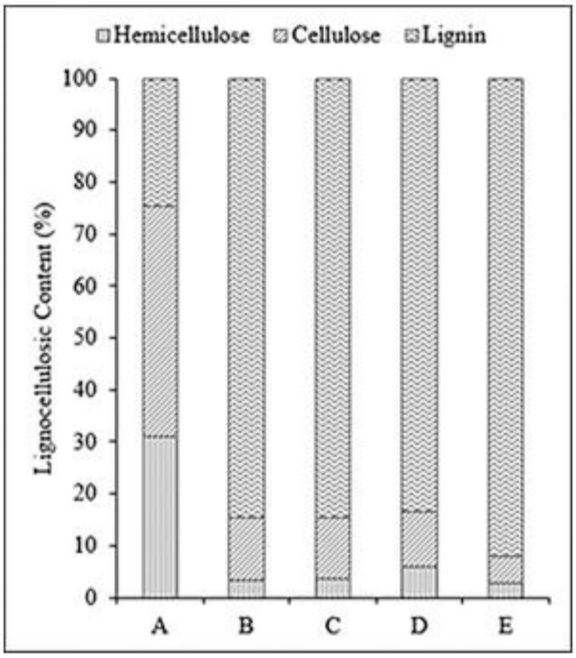

Figure 4 Lignocellulosic contents of raw and torrefied sugarcane bagasse at various torrefaction heating rates and hold times, (A) raw bagasse; (B) torrified bagasse at 3^{o}C/min, 0 minute; (C) at 6^{o}C/min, 0 minute; (D) at 10^{o}C/min, 0 minute; and (E) at 6^{o}C/min, 15 minutes

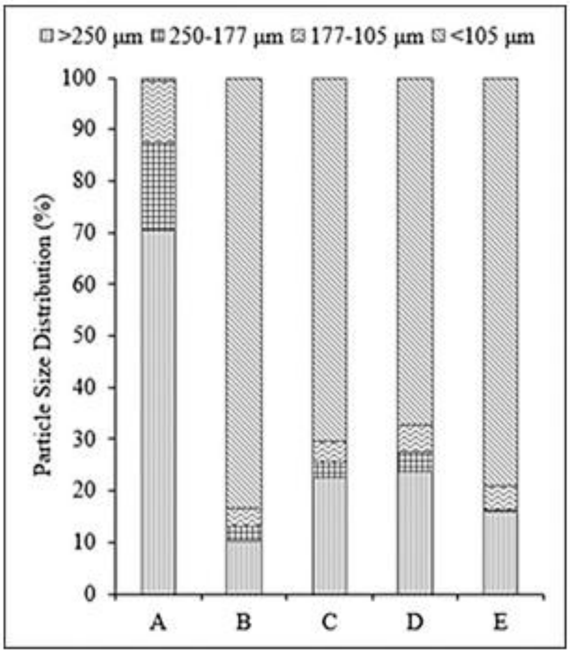

Figure 5 Particle size distributions of raw and torrefied sugarcane bagasse at various torrefaction heating rates and hold times. Symbols refer to Figure 4

By comparing C and E bars in Figure 4, it can be seen that the increase of hold time reduced the hemicellulose and cellulose content in the sugarcane bagasse. With hold times of 0 and 15 minutes, the hemicellulose content reduced to 3.67 and 2.74%, while the cellulose content was reduced to 11.77 and 5.35%. It is known that in a longer hold time, hemicellulose and cellulose releases more volatiles, so they experience more cracking and produce less solid product, (Tumuluru et al., 2011).

3.3. Particle Size Distribution of Ground Raw and Torrefied Sugarcane Bagasse

Figure 5 shows the particle size distributions of raw and torrefied sugarcane bagasse. This figure shows that for raw sugarcane bagasse, only 0.62% of the particles had sizes smaller than 105 μm, while 70.58% of the particles had sizes bigger than 250 μm. After being torrefied at 275^{o}C with heating rates of 3, 6, 10^{o}C/minute, and a hold time of 15 minutes, the amount of particles smaller than 105 μm increased significantly to 83.43%; 70.55%; 67.29%; and 79.14%, respectively. The particle size distribution of sugarcane bagasse was inversely proportional to its hemicellulose content. By comparing Figure 4 and 5, it is clearly seen that the amount of sugarcane bagasse particles smaller than 105 μm increased as hemicellulose content bagasse decreased.

The lignocellulosic polymers in sugarcane bagasse, especially hemicellulose, contribute to its fibrous and tenacious nature (Arias et al., 2008). Hemicellulose acts as a binding agent of lignocellulosic polymers, thus they tend to have strong particle bonds. Because of that, more grinding energy is required to grind raw sugarcane bagasse into small particle sizes. Moreover, the grinding of raw sugarcane bagasse still produces large and heterogeneous particle size distribution.

The degradation of hemicellulose, cellulose, and lignin in sugarcane bagasse during torrefaction causes shortening of polymer chains. Therefore, the sugarcane bagasse cell wall crushes and its properties change. The changes of sugarcane bagasse properties into less fibrous, soft, and brittle is mainly caused by the degradation of hemicellulose and cellulose. Thus, torrefaction reduces the amount of grinding energy required to grind sugarcane bagasse into certain particle size (Phanphanich & Mani, 2011). Moreover, the grinding of torrefied sugarcane bagasse produces smaller particle size and homogeneous particle size distribution (Arias et al., 2008).

3.4. Hydrophobicity of Raw and Torrefied Sugarcane Bagasse

Percentage of water absorption by sugarcane bagasse char was calculated by comparing the mass increase of baggase to the initial mass when exposed for 240 minutes in the ambient air with relative humidity about 40%. Figure 6 shows the water absorption of raw and torrefied sugarcane bagasse.

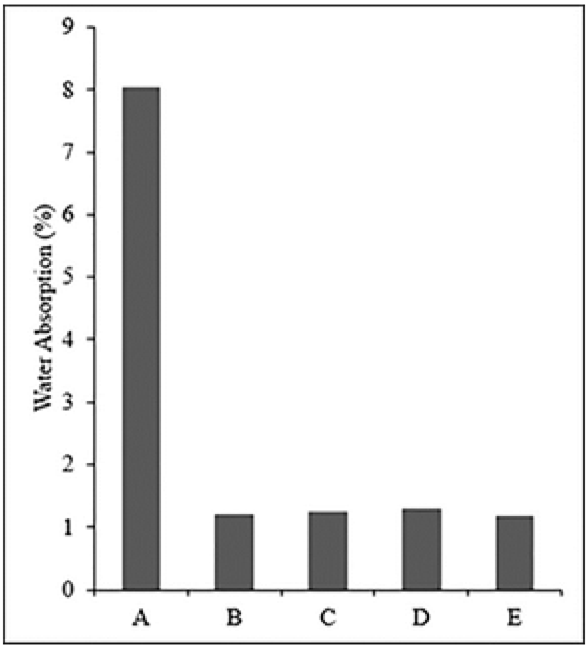

Figure 6 Water absorption of raw and torrefied sugarcane bagasse at various torrefaction heating rates and hold times. Symbols refer to Figure 4

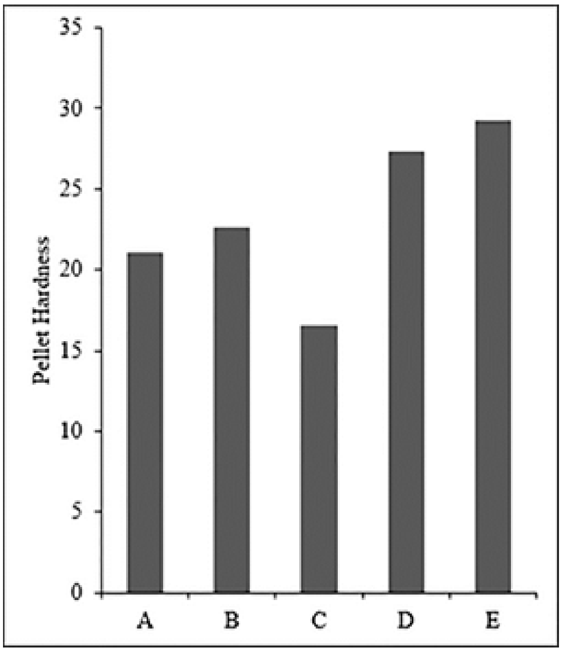

Figure 7 Pellet hardness of raw and torrefied sugarcane bagasse at various torrefaction heating rates and hold times. Symbols refer to Figure 4

Figure 6 shows that raw sugarcane bagasse absorbed quite a lot of water in 240 minutes, which was about 8.02% of sugarcane bagasse original mass. After being torrefied, the amount of water absorbed by sugarcane bagasse reduced significantly. For sugarcane bagasse torrefied at 275^{o}C with heating rates of 3, 6, 10^{o}C/minute, and a hold time of 15 minutes, the water absorption in 240 minutes reduced to 1.21%; 1.26%; 1.28%; and 1.17% of the sugarcane bagasse original mass. The water absorption of sugarcane bagasse was directly proportional to its hemicellulose content. By comparing Figure 4 andFigure 6, it is clearly seen that the amount of water absorbed by sugarcane bagasse increased when its hemicellulose content increased.

Sugarcane bagasse is a hydrophilic compound, so it will always absorb water even though it has been dried beforehand (Chew & Doshi, 2011). The hydrophilic nature of sugarcane bagasse is mainly due to the high content of hemicellulose. Hemicellulose polymers have many hydroxyl groups (–OH) which drive sugarcane bagasse to be polar and to make easily hydrogen bonds with water molecules (Tumuluru et al., 2011).

Hemicellulose degradation during torrefaction causes the loss of hydroxyl groups in sugarcane bagasse, (Tumuluru et al., 2011). Thus, torrefied sugarcane bagasse loses its hydrophilic nature, since there are no hydroxyl groups, which tend to be polar and easily make hydrogen bonds with water molecules. In addition, the changes of lignocellulosic polymers during torrefaction lead to the formation of unsaturated non-polar structures in sugarcane bagasse. The non-polar structure is caused by a partial condensation of tar on the torrefaction solid product, which then prevents the condensation of moisture in sugarcane bagasse pores (Felfli et al., 2005).

3.5. Hardness of Raw and Torrefied Sugarcane Bagasse Pellets

The pellets had a diameter of 25 mm and a height of 4 mm. If torrefied sugarcane bagasse is densified without any heating, then the lack of hemicellulose and water content hardly causes lignin to bind with other lignocellulose polymers. Thus, torrefied sugarcane bagasse densification will consume higher energy than raw sugarcane bagasse (Li et al., 2012). Since the sugarcane bagasse densification was carried out at a relatively low pressure and without any heating, PVA was added to torrefied sugarcane bagasse in which it acted as an additive binding agent. However, PVA was not added to raw sugarcane bagasse, since the addition of PVA turned out to wet the powder and made it hard to solidify.

Figure 7 shows the pellet hardness distributions of raw and torrefied sugarcane bagasse. This figure shows that torrefaction was able to increase sugarcane bagasse pellet hardness. The pellet hardness of raw sugarcane bagasse was only 21 on a durometer Shore D scale. For sugarcane bagasse torrefied at 275^{o}C with heating rates of 3 and 10^{o}C/minute, respectively and a hold time of 15 minutes, the pellet hardness increased to 22.58; 27.26; and 29.22, respectively on the durometer Shore D scale. However, there was a deviation of pellet hardness data for torrefied sugarcane bagasse at 6^{o}C/minute. This sugarcane bagasse pellet had a hardness value of 16.54, which meant it was more brittle than the raw sugarcane bagasse pellet. The data deviation of torrefied sugarcane bagasse pellet at 6^{o}C/minute might occur because of different densification treatment procedures, in which the compression pressure was lower and could not be stably maintained at 9,000 kg/cm^2 for 10 minutes.

Lignin is a natural binding agent in sugarcane bagasse, thus the mechanical strength or hardness of sugarcane bagasse pellets is evaluated by its lignin content (Tumuluru et al., 2011). The heating and compression process during sugarcane bagasse pellets densification softens the lignin, so the lignin will then harden and bind with other lignocellulosic polymers. As a thermochemical pretreatment, torrefaction improves sugarcane bagasse pellet hardness. During torrefaction, hemicellulose degrades and forms unsaturated structures, so that more active lignin sites are opened. Because of the increase of lignin content and its active sites, torrefaction improves lignin ability as a natural binding agent so that the pellets have better hardness, (Bergman, 2005).

4. CONCLUSION

The effects of torrefaction heating rates and hold times on physical characteristics of sugarcane bagasse have been determined by its lignocelullosic content, particle size distribution, hydrophobicity, and pellet hardness. Some conclusions arising from this sugarcane bagasse torrefaction experiment are that the increasing heating rate and hold time of the torrefaction further reduce mass yield of the torrefied bagasse in which high heating rate significantly degrades cellulose, but improves hemicellulose content, while hold time greatly degrades hemicellulose and cellulose contents in the torrefied bagasse. Consequently, by % composition, this degradation increases lignin content in the torrefied bagasse. The increase of lignin composition in torrefied sugarcane bagasse improves its pellet hardness. The degradation of hemicellulose in sugarcane bagasse makes the bagasse more brittle and easy to grind. This degradation improves the torrefied bagasse hydrophobic tendency.

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