Effects of Thermal Treatment on Energy Density and Hardness of Torrefied Wood Pellets

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ABSTRACT:

Three types of wood pellets samples, including two types of commercial pellets and one type of lab-made control pellets were torrefied in a fixed bed unit to study the effect of thermal pretreatment on the quality of wood pellets. The quality of wood pellets was mainly characterized by the pellet density, bulk density, higher heating value, Meyer hardness, saturated moisture uptake, volumetric energy density, and energy yield. Results showed that torrefaction significantly decreased the pellet density, hardness, volumetric energy density, and energy yield. The higher heating value increased and the saturated moisture content decreased after torrefaction. In view of the lower density, lower hardness, lower volumetric energy density, and energy yield of torrefied pellets, it is recommended that biomass should be torrefied and then compressed to make strong pellets of high hydrophobicity and volumetric energy density.

Keywords: Pellets; Torrefaction; Effect; Quality.

1. Introduction

In view of the low energy density, off-gassing, self-heating, poor water-resistance associated with the transportation, storage, and handling of regular wood pellets, thermal pretreatment by torrefaction has been considered as a promising method to make stable wood pellets of higher energy density and hydrophobicity [1-4]. There are at least two pathways to make torrefied pellets: torrefaction followed by densification or densification followed by torrefaction. In the torrefaction-densification process, wood is first torrefied and then followed by grinding, if needed, and densification of torrefied powders into pellets. However, recent researches indicated that torrefied sawdust was more difficult to be compressed into reasonably strong pellets under the same densification conditions as was used to make regular wood pellets [2, 5-10]. The die temperature has to be increased to a higher value ranging from 170 to 230 °C (compared to 70-110 °C for regular pellet compression) or the torrefied sawdust has to be pre-conditioned to a moisture content of around 10% to make dense torrefied pellets, at the expense of increased mechanical energy consumption [8]. To overcome these difficulties in compressing torrefied sawdust into pellets, the densification-torrefaction procedure has also been explored for making torrefied pellets by thermally treating regular wood pellets [11], a method which has been widely practiced in the making of biochar briquettes. The mechanical energy consumption associated with compression of torrefied sawdust into pellets is expected to be reduced, but the pellet density, durability and volumetric energy density may become lower than those made from the torrefaction-densification approach. So far, there has been limited information and no systematic research reported in the literature on the performance of torrefied pellets prepared following the densification-torrefaction pathway. In view of the low weight loss of 20-30% in torrefaction process, compared to more than 60% weight loss in the carbonization process for biochar production, it is important to investigate whether a high quality of torrefied wood pellets can be produced from the thermal treatment of regular wood pellets.

In the present work, two types of commercial wood pellets and one type of control pellets prepared in a laboratory single-die pelleting unit were thermally treated in a fixed bed unit under the torrefaction conditions. Density, heating value, hardness, saturated moisture content, volumetric energy density, and energy yield of those torrefied pellets were then determined. The densification-torrefaction procedure was further evaluated by comparison with the quality of torrefied pellets made from densification of torrefied sawdust.

2. Experimental

2.1. Samples Preparation

White commercial wood pellets from Premium Pellets Ltd., brown commercial wood pellets from Shell Premium Pellets, and pine woodchips from FPInnovation were used in the present work. Pine woodchips were crushed in a hammer mill (Glenmils Inc., U.S.A.; Model: 10HMBL) installed with a 3.18 mm size screen to prepare sawdust. A press machine (Measurement Technology Inc., U.S.A.; Model: MTI 50K) was used for compressing pine sawdust into control wood pellets. For making control wood pellets, the die temperature was maintained at 70 °C with 125 MPa compression pressure and 1 min holding time, and the maximum pressure was set at 156 MPa [8].

Table 1 shows the properties of three wood pellet samples. The single pellet density was calculated from the measured mass and volume of each wood pellet, averaged over 50 pellets. A 1000 ml glass cylinder was used to measure the bulk density of wood pellets. The moisture content was determined by drying the sample at 105 °C for 24 hours inside an oven (Thermol Electron Corporation, U.S.A.; Model: THELCO laboratory PRECISION). The higher heating value (HHV) was measured by a bomb calorimeter (Parr Instrument Company, U.S.A.; Model: 6100 Compensated Calorimeter). The volatile matter, fixed carbon, and ash content were measured by a thermogravimetry analyzer (Shimadzu, Japan; Model: TGA-50). The elemental composition was determined by an elemental analyzer (Fisons, Germany; Model: EA 1108) in the Department of Chemistry at the University of British Columbia. The chemical composition of control wood pellets was measured by FPInnovations using a high-performance liquid chromatography (Dionex Corporation, USA; Model: ICS-3000 Ion Chromatography System) following the ASTM E1758-01 procedure [12]. The chemical composition of two commercial wood pellets was measured by University of Science and Technology Beijing using a liquid chromatography (Shimadzu, Japan; Model: LC-20AT) following the ASTM E1758-01 procedure. From Table 1, it can be seen that the properties of both the control wood pellets and the white commercial wood pellets were very similar. The HHV and the ash content of the brown commercial wood pellets were slightly higher than the white commercial wood pellets and the control wood pellets because of the high bark content in the raw material of the brown commercial wood pellets.

2.2. Pellet Torrefaction

A bench-scale fixed-bed tubular reactor unit was used for the torrefaction (thermal treatment) of three wood pellet samples. The tubular reactor has an inside diameter of 27 mm and is 575 mm in length, located inside an electrically heated furnace. The unit also includes an electrical gas heater with a temperature controller and a power supply (booster) to preheat the nitrogen gas, a cooler and a condensate receiver to remove tar, and a computer for acquiring temperature data [8]. In the present work, five pellets were placed into the tubular reactor and held by a pellet holder.

Table 1

Properties of three wood pellet samples.

	White commercial wood pellets	Brown commercial wood pellets	Control wood pellets
Diameter, mm	6.4	6.0	6.5
Length, mm	16.5	20.2	15.8
Single pellet density, kg/m^3	1190	1230	1150
Bulk density, kg/m^3	650	680	630
Moisture content, %wt	8.9	6.7	9.5
Higher heating value, MJ/kg	18.5	18.9	18.8
Proximate Analysis			
Volatile, %wt	82.8	80.9	82.8
Fixed carbon, %wt	16.9	18.4	16.8
Ash, %wt	0.3	0.7	0.4
Elemental Analysis, %wt			
C	50.3	50.9	50.7
H	6.2	6.0	5.9
O (by difference)	43.2	42.4	43.0
N	<0.1	<0.1	<0.1
Chemical Composition			
Cellulose, %wt	29.1	28.9	36.7
Hemicelluloses, %wt	34.4	29.0	26.3
Lignin, %wt	26.6	27.5	33.6
Extractives, %wt	9.6	13.9	3.0

The optimal torrefaction conditions were found to correspond to a weight loss of around 30% at the reaction temperature, ranging from 250 to 350 °C for a treatment time of 30-60 minutes [1, 4]. Based on our previous studies of the torrefaction kinetics [13], two parameters, temperature and residence time, were selected for investigation. The residence time is defined as the torrefaction reaction time, excluding the time required for pre-heating the sample from room temperature to target temperature. For the two commercial wood pellet samples, the temperature was chosen to be 270, 280, 290, 300, 310, 320, 450 °C with the residence time of 30 min. More torrefaction conditions were tested for the control pellets, with a residence time of both 30 minutes and 52 minutes. For each sample, at least two replicates were tested for each torrefaction condition.

The weight loss (WL, %wt) was determined by measuring the pellet mass (M_o) before torrefaction, the residue mass (M_t) after torrefaction, and the moisture content (MC, %wt) of the untreated wood pellets based on the following equation:

$$WL = 100 \times [1 - \frac{M_t}{M_o} \times (1 + MC)] \quad (1)$$

2.3. Meyer Hardness Measurement

The Meyer hardness of wood pellets was also measured by the MTI 50K press machine. The Meyer hardness (H_M) was applied to characterize the durability of alfalfa cubes with a flat surface [14]. Peng et al. (2013) modified the Meyer hardness for wood pellets that laid horizontally on a flat surface [9]. With a 6.35 mm hemispherical probe on the MTI 50K press machine vertically moving downward at a speed of 1 mm/min, both the force and displacement of the probe were recorded by the MTI 50K press machine control system. The equation for calculating H_M for a hemispherical probe and a cylindrical pellet was given below:

$$H_M = \frac{F}{\pi\sqrt{Dh-h^2}\sqrt{\frac{D_p{}^2}{4}-[\frac{\frac{D_P^2}{2}+\frac{D\cdot D_P}{2}-D\cdot h-D_P\cdot h+h^2}{D+D_P-2h}]^2}} \quad (2)$$

where, F is the maximum force to break the pellet in N, D is the probe diameter in mm, h is the indentation depth corresponding to the piston displacement before the pellet breakage in mm, D_p is the pellet diameter in mm.

2.4. Moisture Uptake Measurement

A humidity chamber (ESPEC CORP, Japan; Model: LHU-113) was used for the measurement of the saturated moisture content of pellets. Before the moisture uptake tests, wood pellets were dried in the THELCO laboratory PRECISION oven at 105 °C for 24 hrs. Then, wood pellets were placed in a Petri glass dish and put into the humidity chamber. During the weight measurement, the Petri dish was covered with a glass cap to reduce the moisture loss. For the saturated moisture content, wood pellets were placed in the chamber at 30 °C and 90% relative humidity for at least 48 hrs [8].

3. Results and discussion

3.1. Pellet Torrefaction

Figure 1 shows the three torrefied wood pellet samples made from the torrefaction of regular wood pellets. As the torrefaction temperature increased, the darker color and the rougher surface were developed on the torrefied wood pellets. The weight loss of wood pellets after torrefaction is given in Table 2. To reach a weight loss of around 30%wt, a torrefaction temperature ranging from 280 to 290 ºC and a residence time of 30 min were applied. And in all the experiments, the heating rate of the pellets was set at ~15 ºC/min, which was the typical temperature used for biomass torrefaction in laboratory studies. Shang et al. (2012) reported a total weight loss of 41.9%wt for Scots pine pellets with a 9.8% moisture content, torrefied at 270 ºC for 60 min.

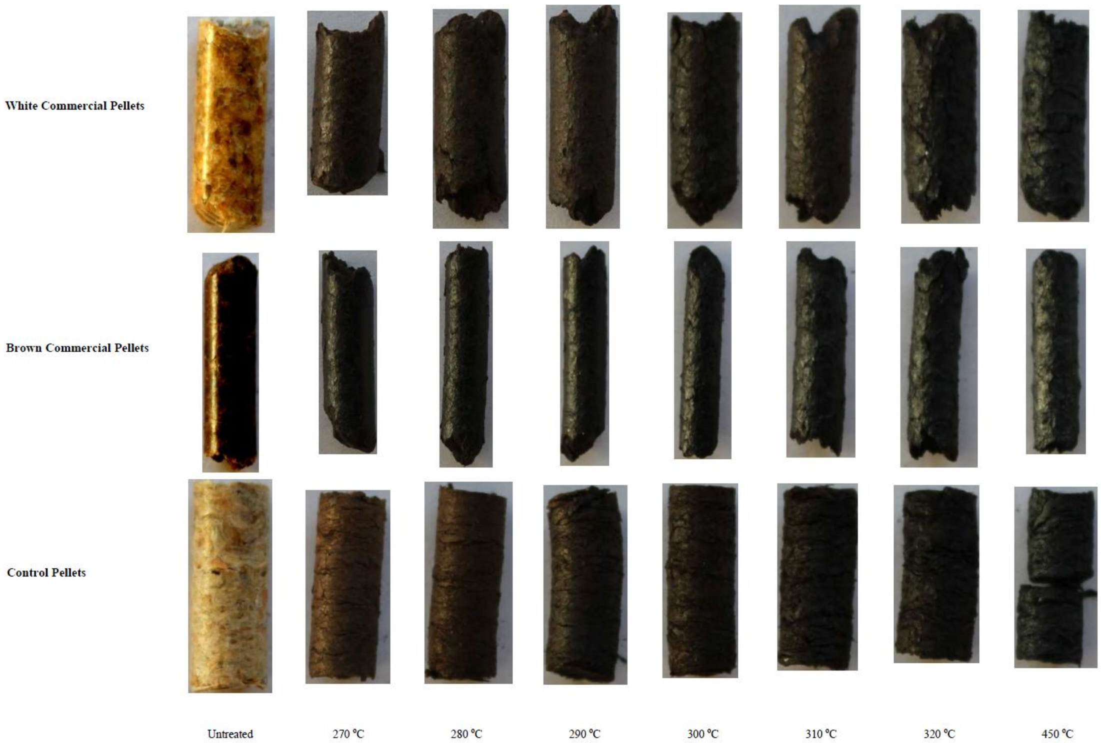

Fig. 1. Photo of torrefied wood pellets made from the torrefaction of wood pellets at different temperatures for 30 min.

Table 2

Weight loss of wood pellets after torrefaction.

Torrefaction condition	White commercial wood pellets	Brown commercial wood pellets	Control wood pellets
270 ºC, 30 min	17.6	17.9	21.6
280 ºC, 30 min	28.4	26.4	31.5
290 ºC, 30 min	29.7	25.6	30.5
300 ºC, 30 min	41.9	35.7	40.4
310 ºC, 30 min	41.0	44.6	58.2
320 ºC, 30 min	54.8	53.7	57.7
450 ºC, 30 min	74.2	72.2	76.4
280 ºC, 52 min			19.9
285 ºC, 52 min			22.5
290 ºC, 52 min			32.9
315 ºC, 30 min			38.2
330 ºC, 30 min			60.5
335 ºC, 30 min			65.6
400 ºC, 30 min			71.9

Figure 2 plots the volume change of single wood pellets after torrefaction. Both the white and brown commercial wood pellets shrank after torrefaction. At a 30% weight loss of torrefaction, the pellet volume of both commercial wood pellets reduced by approximately 15%. At the range of 0-40% weight loss, the volume of control pellets slightly increased in several tests likely because of the expansion of long fibers in woodchips of high cellulose content in those samples (see Table 1) during heat treatment. Note that commercial wood pellets were produced from wood residues rather than woodchips.

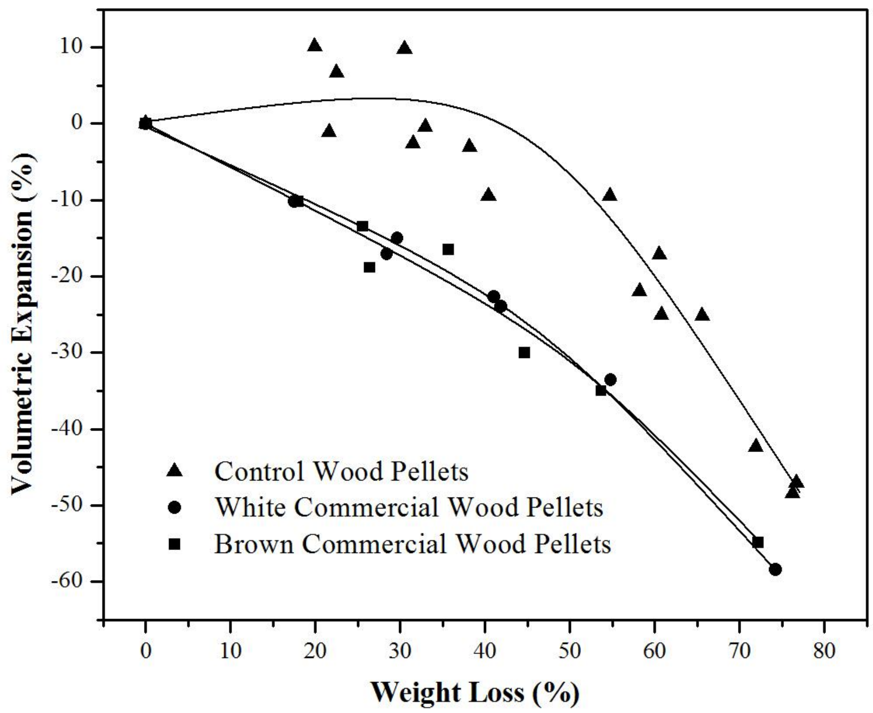

Fig. 2. Single pellet volume change as a function of weight loss for different wood pellet samples.

3.2. Single Pellet Density

Figure 3 shows the single pellet density as a function of torrefaction weight loss for different wood pellet samples. The single pellet density was seen to be significantly reduced after torrefaction. At a 30%wt weight loss, the density of single white commercial wood pellets was reduced to 930 kg/m^3 from 1190 kg/m^3, and the single brown commercial wood pellet density changed from 1230 kg/m^3 to 970 kg/m^3. For control wood pellet sample, the density reduced to 700 kg/m^3 from 1150 kg/m^3 after 30% weight loss by torrefaction, corresponding to the low shrinkage of the pellet volume of those control wood pellets made from pine particles after torrefaction, as shown in Figure 2. Although control pellets were made by a single-die pelleting machine and the commercial pellets were produced by a continuous pelleting machine, both pellets were made at the same die temperature of 70 ^{o}C and compression pressure of 125 MPa.

At the same 30% torrefaction weight loss, Peng et al. (2013) reported that the density of single torrefied pellets compressed from torrefied particles with a die temperature of 230 ^{o}C was 1250 kg/m^3, and the density of single torrefied pellets compressed from torrefied particles pre-conditioned to 10% moisture content under the same compression conditions as used for making regular pellets with raw biomass particles was 1190 kg/m^3 [8]. Since the torrefied particles used to make torrefied pellets were prepared in the same fixed bed unit with the same operating conditions as used for torrefaction of regular pellets, it can be concluded that the density of single torrefied wood pellets made from torrefaction of regular wood pellets has a much lower density than torrefied wood pellets made from the compression of torrefied particle samples.

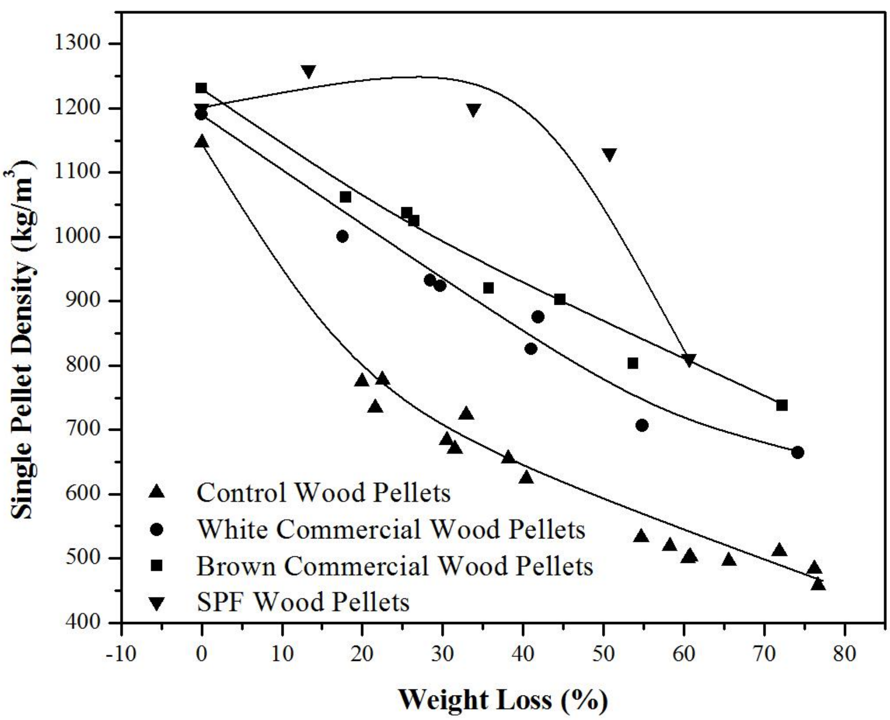

Fig. 3. Single pellet density as a function of torrefaction weight loss for different wood pellet samples. SPF wood pellet data were from Peng et al. (2013) made from compression of torrefied 1.1 mm SFP sawdust sample in the same MTI 50K press machine [8].

The difference in single pellet density between pellets made from torrefaction of three wood pellet samples and compression of torrefied SPF sawdust (a mixture of spruce pine and fir with more than 80% pine) is also shown in Figure 3. The SPF wood pellet data were from Peng et al. (2013) who prepared torrefied pellets in the same MTI 50K press machine from the compression of torrefied SPF sawdust of 1.1 mm in mean particle size at a die temperature of 230 ºC [8]. Since the white commercial wood pellets are usually made from SPF residues, the results can be directly compared to the laboratory SPF wood pellet sample. Furthermore, the compression force in the MTI 50K press machine was adjusted so as to make the density of regular SPF pellets close to that of untreated white commercial pellets at about 1200 kg/m^3, as seen in Figure 3. After torrefaction, the density of torrefied pellets made from torrefaction of commercial wood pellets decreased significantly, while the torrefied sawdust could still be compressed into pellets with a density similar to the regular pellets. At a 30% torrefaction weight loss, the density of single torrefied pellets from densification of torrefied sawdust was around 1250 kg/m^3, compared to 930 kg/m^3 for the torrefied white commercial wood pellets.

3.3. Heating Value

Figure 4 plots the higher heating value of different wood pellet samples as a function of weight loss after torrefaction, which revealed a strong correlation with little dependence on the types of samples. The higher heating value of wood pellets increased with the increase of torrefaction weight loss, reaching 29 MJ/kg at a weight loss of 75%wt. At a 30%wt weight loss, the higher heating value increased to 22.7 MJ/kg for white commercial wood pellets, 23.1 MJ/kg for brown commercial wood pellets, and 22.5 MJ/kg for the control wood pellets, representing about 20% increase in HHV from untreated pellets. The result is consistent with torrefied SPF pellets made from the compression of torrefied sawdust [9], as shown in Figure 4, and Shang et al. (2012) who reported that the higher heating value of Scots pine wood pellets increased by 25% at a weight loss of 41.9% achieved by torrefaction at a temperature of 270 ºC for 60 min [11]. One can conclude that the higher heating value of torrefied pellets is almost independent of whether they are made from torrefaction of regular wood pellets or densification of torrefied sawdust.

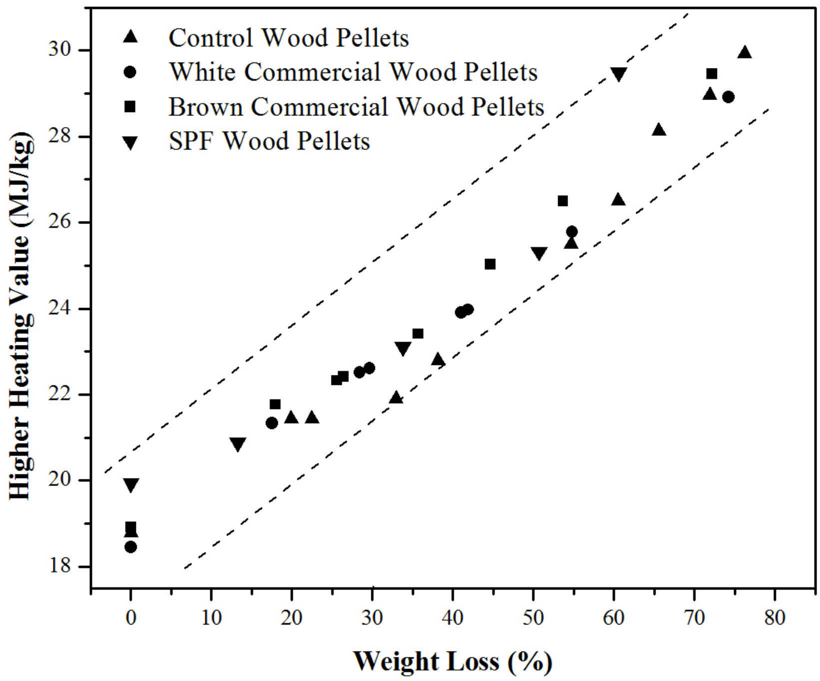

Fig. 4. HHV of wood pellets as a function of torrefaction weight loss for different wood pellet samples. SPF wood pellet data were from Peng et al. (2013) made from compression of torrefied 1.1 mm SFP sawdust sample in the same MTI 50K press machine [8].

3.4. Hardness

The Meyer hardness of both untreated wood pellets and torrefied wood pellets made from the torrefaction of wood pellets was measured. The Meyer hardness was 12 N/mm^2 for untreated control wood pellets, 24 N/mm^2 for untreated white commercial wood pellets, and 22 N/mm^2 for untreated brown commercial wood pellets. To visualize the impact of torrefaction on pellet hardness, a relative hardness was calculated as the ratio of the Meyer hardness for torrefied wood pellets over the untreated wood pellets, and shown in Figure 5 as a function of torrefaction weight loss for different wood pellet samples. It can be seen in Figure 5 that the hardness of torrefied wood pellets made from the torrefaction of wood pellets was significantly reduced. At a 30% weight loss, the relative hardness of torrefied wood pellets made from the torrefaction of wood pellets decreased by more than 40%. Shang et al. (2012) studied the change of pellet strength after torrefaction, and reported that the strength of torrefied wood pellets decreased by 90% after torrefaction at a temperature of 270 °C for 60 min with a weight loss of 41.9%wt

[11]. Wood pellets after torrefaction also became brittle, which, in combination with lowered hardness, made the torrefied pellets prone to easy breakage and dust generation during handling, storage and transportation. As a result, in order to make stronger torrefied pellets, it is better to torrefy the sawdust prior to compressing it to pellets at a higher densification temperature of 170 to 230 °C [8] or 20-30 °C below the torrefaction temperature [6], as shown in Figure 5.

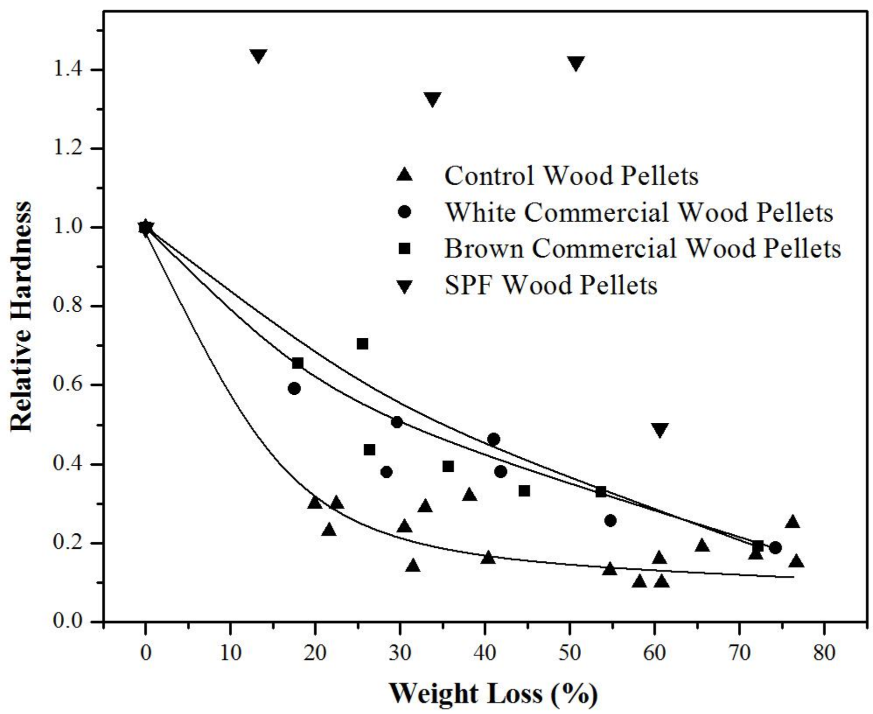

Fig. 5. Relative hardness as a function of torrefaction weight loss for different wood pellet samples (untreated control wood pellet Meyer hardness: 12 N/mm^2; untreated white commercial wood pellet Meyer hardness: 24 N/mm^2; untreated brown commercial wood pellet Meyer hardness: 22 N/mm^2; regular SPF wood pellet Meyer hardness: 9 N/mm^2). SPF wood pellet data were from Peng et al. (2013) made from compression of torrefied 1.1 mm SFP sawdust sample in the same MTI 50K press machine [8].

3.5. Moisture Uptake

The moisture uptake of torrefied wood pellets was examined in the humidity chamber with air at 90% relative humidity and 30 °C. Figure 6 plots the saturated moisture content of torrefied pellets as a function of weight loss for different pellets samples. The results show that the saturated moisture content of torrefied wood pellets mainly depended on the torrefaction condition. At a 30%wt weight loss, the saturated moisture content of torrefied wood pellets was less than 10%, which was about 40% lower than that of the untreated wood pellets. Peng et al. (2013) reported that the saturated moisture content of pellets made from the compression of torrefied sawdust was around 10% at a 34%wt weight loss [8].

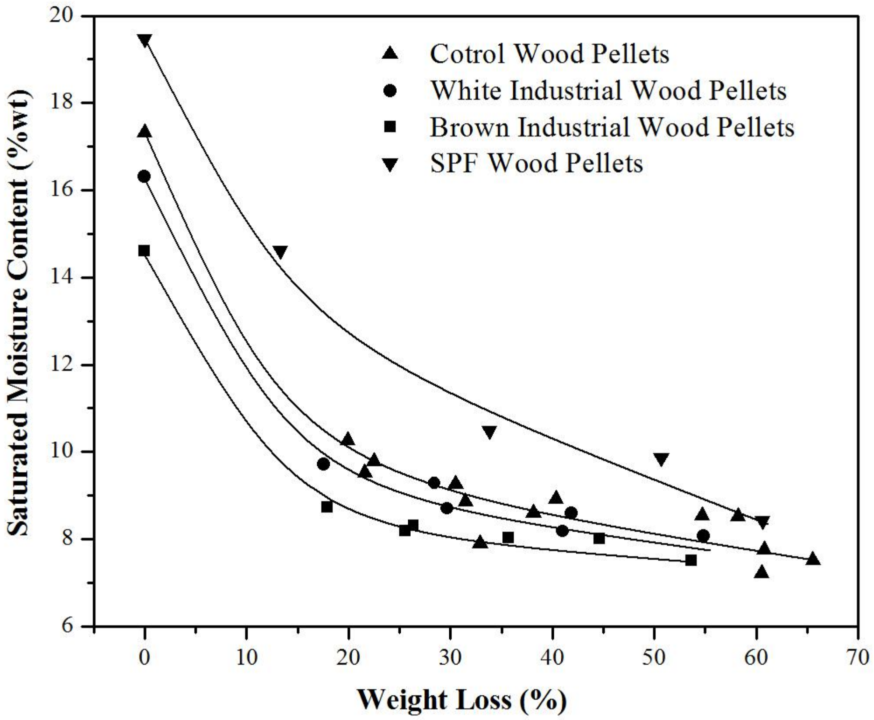

Fig. 6. Saturated moisture content of torrefied wood pellets as a function of weight loss for different wood pellet samples measured in a humidity chamber with air at 90% relative humidity and 30 °C over 48 hours. SPF wood pellet data were from Peng et al. (2013) made from compression of torrefied 1.1 mm SFP sawdust sample in the same MTI 50K press machine [8].

Figure 6 also compared the saturated moisture content of torrefied pellets and pellets made from compression of torrefied SPF sawdust, with data from Peng et al. (2013) [8]. It can be seen that at the same weight loss of torrefaction the saturated moisture content of torrefied wood pellets was slightly lower than pellets made from the compression of torrefied sawdust. This can be partly explained by the difference in the surface properties. For torrefied wood pellets, the surface of pellets may be carbonized more severely than the interior because of the temperature gradient in wood particles resulting from its low thermal conductivity. On the other hand, the pellets made from torrefied sawdust were carbonized more or less homogeneously. As a result, even at the same average weight loss of the two types of torrefied pellets, the torrefied pellets from torrefied sawdust tend to be more water resistant because of a more hydrophobic surface than pellets made from torrefied sawdust.

3.6. Energy Yield

Figure 7 plots the energy yield of torrefied pellets, defined as (initial energy content of biomass - energy loss during torrefaction)/ (initial energy content of biomass), as a function of weight loss for different pellet samples. The results show that the energy yield mainly depended on the torrefaction condition, with little dependence on the types of samples. At a 30%wt weight loss, the energy yield of torrefied wood pellets was around 80%.

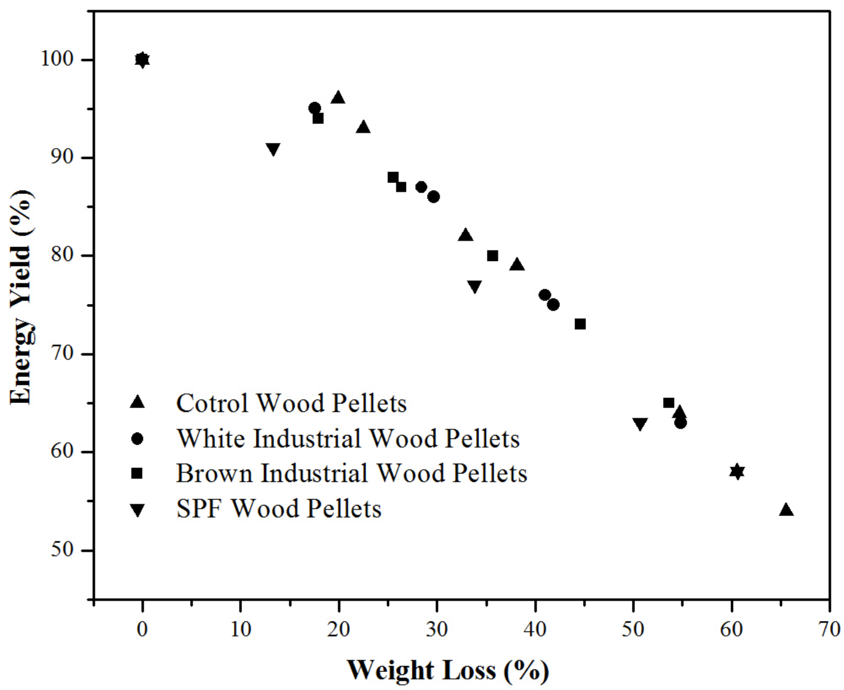

Fig. 7. Energy yield of wood pellets as a function of torrefaction weight loss for different wood pellet samples. SPF wood pellet data were from Peng et al. (2013) made from compression of torrefied 1.1 mm SFP sawdust sample in the same MTI 50K press machine [8].

3.7. Comparison of regular pellets, torrefied pellets from regular pellets and from torrefied sawdust

Pertinent properties of the regular wood pellets, torrefied wood pellets and pellets from torrefied sawdust from the current study and previous studies are compared in Table 3. The volumetric energy density was calculated from the measured higher heating value and the bulk density of pellets. It is seen from Table 3 that the higher heating value and hydrophobicity, as reflected by saturated moisture content, are all improved after torrefaction for both pellets made from torrefaction of wood pellets or densification of torrefied sawdust, and there is little difference between the types of torrefied pellets at a given weight loss or degree of carbonization. However, the bulk density, single pellet density and hardness decreased significantly for wood pellets after torrefaction treatment, leading to poor quality of torrefied pellets. On the other hand, the bulk density, single pellet density and hardness could be controlled to be at the same level as the regular pellets when torrefied sawdust was compressed into pellets under properly selected die temperature and moisture content of torrefied sawdust. Although the higher heating value is increased after torrefaction, the volumetric energy density of torrefied wood pellets remained more or less the same as the regular pellets because of the reduced bulk density. For pellets made from torrefied sawdust, the volumetric energy density can be 20-25% higher than the regular pellets because of their comparable bulk density. All results in Table 3 suggest that torrefied wood pellets made from torrefaction of wood pellets are not suitable for storage and long distance transportation because of their low strength and low volumetric energy density. To make strong and durable torrefied pellets of high volumetric energy density, biomass needs to be torrefied before compressed into pellets at carefully selected die temperature and compression pressure with pre-conditioned torrefied sawdust.

Table 3

Pertinent properties of torrefied pellets and pellets made from torrefied sawdust at 30%wt weight loss (SPF) compared to regular wood pellets.

	White Pellets		Brown Pellets		Control Pellets		**SPF Pellets**	
Properties	Untreated	Torrefied	Untreated	Torrefied	Untreated	Torrefied	**Untreated**	**From torrefied sawdust**
HHV, MJ/kg	18.5	22.7	18.9	23.1	18.8	22.5	**19.9**	**22.5**
Bulk density, kg/m^3	650	530	680	540	630	380	**650**	**700**
Single pellet density, kg/m^3	1190	930	1230	970	1150	700	**1200**	**1250**
Meyer hardness, N/mm^2	24	12	22	12	12	3	**9**	**11**
Saturated water uptake, %wt	16	9	15	8	17	9	**19**	**11**

Volumetric energy density, GJ/m^3	12.0	12.0	12.9	12.5	11.8	8.5	**12.9**	**15.9**
Energy yield, %	100	83	100	82	100	83	**100**	**78**

4. Conclusions

The heating value, saturated moisture content, and energy yield of torrefied wood pellets were almost the same as pellets made from the compression of torrefied sawdust. The single pellet density and the hardness of torrefied wood pellets decreased significantly with increasing the degree of torrefaction or the weight loss. The decrease in single pellet density counteracts the increase in higher heating value for torrefied pellets, leading to a slightly lower volumetric energy density for torrefied pellets, which may increase the storage and transportation costs. The low strength or hardness of torrefied pellets may also impose difficulties in safe handling of torrefied pellets because of dust generation. In comparison, Pellets made from compression of torrefied sawdust could have similar density and strength as regular pellets, as well as higher volumetric energy density than regular pellets, making them suitable for storage and long distance transportation. Therefore, it is recommended that torrefied pellets should not be made from the torrefaction of wood pellets; instead, research and development on torrefied pellets should be focused on optimizing the die design and operating temperature and pressure to compress torrefied sawdust into strong and durable pellets at a low energy consumption, or choosing some binders and optimizing the content of some binders.

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