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Torrefaction and densification of different species of softwood residues

J.H. Peng [a], X.T. Bi [a,*], S. Sokhansanj [a,b], C.J. Lim [a]

[a] Clean Energy Research Centre, University of British Columbia, Vancouver, BC, Canada
[b] Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN, USA

HIGHLIGHTS

- Identify optimal torrefaction and densification conditions for torrefied pellet production.
- Quantify increased heating value and decreased moisture uptake for torrefied pellets.
- Quantify increased compression energy consumption and decreased density of torrefied pellets.
- Recommend high die temperature and sample preconditioning for torrefied pellet production.

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ABSTRACT

Torrefaction and densification of British Columbia (BC) softwoods, including pine, fir, spruce, SPF (a mixture of spruce, pine and fir) and pine bark, have been conducted for the production of high quality torrefied wood pellets. A bench-scale fixed bed tubular reactor was used for the torrefaction test at temperatures of 240–340 °C. Densification was conducted in a press machine in order to identify the suitable conditions for making strong torrefied pellets. Results showed that the mass loss of BC softwood mainly depended on the torrefaction temperature and time. The heating value of torrefied sawdust particles had a close relationship with the mass loss, increasing with increasing the severity of torrefaction. It was more difficult to compress torrefied samples into strong pellets than the raw material under the same conditions as used for making the control (regular and non-torrefied) pellets, and either a higher die temperature or adding moisture into torrefied particles could improve the compression process. The moisture content of torrefied pellets prepared in this study was lower than control pellets, and the density of torrefied pellets was slightly lower than control pellets. At the same time, more energy was consumed for compacting torrefied softwood particles into pellets. Increasing torrefaction severity increased the heating value and decreased the moisture uptake of torrefied pellets, but decreased the energy yield and the hardness of torrefied pellets. Considering the quality of torrefied pellets, the optimal torrefaction condition appeared to be around 30% mass loss, which gave a 20% increase in pellet higher heating value and a reasonable low water update rate. The suitable densification conditions for torrefied softwoods corresponded to a die temperature of 170–230 °C for unconditioned samples, or about 110 °C for samples preconditioned to ~10% moisture content.

1. Introduction

Torrefaction is a thermal treatment of wood at the temperature range of 200–300 °C without air or oxygen [1]. The major purpose of torrefaction in the biomass fuel industry is to increase the energy density on the mass basis and to improve the water resistivity of wood. A number of researches have been reported on biomass torrefaction in bench-scale units for different uses, such as co-firing in existing coal-fired power plants [2], gasification [3,4], syngas production [5], and barbeque fuel production [6]. Densification (also called pelletization) enhances the bulk density of wood residues from 40–200 kg/m^3 to 600–1400 kg/m^3 [7], which has been widely practiced in wood pellet plants. Reed and Bryant first considered the combination of torrefaction and pelletization to produce a new type of high energy density and water-resistant pellets [8]. Koukios observed apparent biomass energy densities exceeding 20 GJ/m^3 for torrefied straw, olive kernels and waste wood (softwood) pellets [9]. In Japan, the combined torrefaction and densification has been considered as an effective method to transport biomass from resources in remote areas to major urban centers [10].

The recent rapid growth of wood pellet industry has been mainly driven by the effort to reduce greenhouse gas emissions in Europe and the rising oil and natural gas prices. Bergman proposed and demonstrated a combined torrefaction and pelletization

* Corresponding author. Tel.: +1 604 8224408; fax: +1 604 8226003.
E-mail address: xbi@chbe.ubc.ca (X.T. Bi).

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(TOP) process for the production of high energy density wood pellets [11]. Because of their high energy density and hygroscopicity properties, torrefied pellets are believed to be especially suitable for thermal power plants to replace coal and for export to Europe from North America over long transportation distances [12]. Currently, a number of torrefaction pilot plants have been designed, under construction, or publicly announced [13,14]. In Europe and Canada, two major joint programs have been recently initiated to demonstrate the production of torrefied pellets, with the first demonstration plant to be built in BC of Canada to produce 30,000 tonne/year torrefied pellets by 2015. So far, most researches have been focused on the development of torrefaction kinetics and reactors, with very few studies being conducted on densification of torrefied samples into pellets and combined torrefaction and densification. To build a commercial torrefied wood pellet plant, both torrefaction and densification technologies need to be developed, demonstrated and proved.

We previously developed a two-component first order one-step biomass torrefaction kinetic model based on the mass loss data from a thermogravimetric (TG) analyzer for the BC softwood to establish the relationship among the mass loss, torrefaction temperature and the residence time [15]. We also reported the particle size effect on torrefaction and densification [16], investigated the torrefaction of biomass residues in the presence of low oxygen concentrations [17], and studied the properties of torrefied wood pellets [18]. In this study, a bench-scale tubular reactor has been designed and built to study torrefaction and to produce enough torrefied wood samples for densification tests. A press machine, MTI 50K (Measurement Technology Inc.), was used to make and evaluate torrefied pellets from torrefied softwood samples. The main objective of this study is to identify the optimal conditions for combined torrefaction and densification for the production of high quality torrefied wood pellets.

2. Experimental

2.1. Samples

Pine and spruce chips from FPInnovations, fir and SPF (a mixture of spruce, pine and fir) chips from Fiberco, pine bark and SPF shavings from Wood Pellet Association of Canada, were used as biomass samples in this study. Woodchips and bark were prepared by drying with a THELCO laboratory PRECISION oven (Thermo Electron Corporation) at 105 °C for 24 h and crushing in a hammer mill (Glenmills Inc., USA; Model: 10HMBL) installed with different size screens. SPF shavings after milled with 4 mm opening screen were used for the study of temperature and residence time effects on torrefaction and densification. Spruce, fir, SPF, and pine bark sawdust samples were prepared using a hammer mill installed with a 0.79 mm opening screen, and then used for studying the effect of different BC softwood species on torrefaction and densification.

Table 1 shows the properties of BC softwood residues (ground materials). The volatile matter, fixed carbon, and ash content were measured by a TG analyzer (SHIMADZU, Japan; Model: TGA-50). The chemical composition 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 [19]. 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 results in Table 1 show that the pine bark sample has a lower volatile mater content and a higher content in fixed carbon, ash, lignin and extractives than spruce, pine, fir and SPF samples. The elemental contents of spruce, pine, fir and SPF, on the other hand, were very close, but different from pine bark.

Table 1
Properties of BC softwood residues (bone dry material).

	Spruce	Pine	Fir	SPF	Pine bark	SPF shavings
Volatile matter (%)	80.5	82.8	82.9	84.4	75.8	85.1
Fixed carbon (%)	19.4	16.8	17.0	15.3	21.6	14.7
Ash (%)	0.1	0.4	0.1	0.3	2.6	0.2
Chemical composition						
Cellulose (%)	42.4	36.7	37.1	NA	26.1	NA
Hemicelluloses (%)	20.0	26.3	25.0	NA	17.9	NA
Lignin (%)	35.1	33.6	35.0	NA	41.0	NA
Extractives (%)	2.4	3.0	2.8	NA	12.4	NA
Elemental analysis (%)						
C	51.2	51.2	50.0	50.3	53.2	49.5
H	6.0	6.0	6.1	6.1	6.0	6.2
O (by difference)	42.6	42.2	43.6	43.2	37.7	43.9
N	0.1	0.1	0.2	0.1	0.5	0.2

Note: chemical composition of SPF is not measured because it depends on different fractions of spruce, pine and fir.

A THELCO laboratory PRECISION oven (Thermo Electron Corporation) was used to evaluate the moisture content for all biomass samples. A 25 ml glass cylinder was used to determine the bulk density [20]. A multipycnometer (Quantachrome Instruments, USA) was used to measure the particle density. The higher heating value was measured by a calorimeter (Parr 6100, USA). Particle size distributions were determined using a Ro-Tap sieve shaker (Tyler Industrial Products, USA). For the ground SPF shaving sample, the following sieves were used: 5, 7, 10, 14, 18, 25, 35, 45, 60, 80, 100, and 120 mesh (corresponding to 4.00, 2.80, 2.00, 1.41, 1.00, 0.707, 0.500, 0.354, 0.250, 0.177, 0.149, and 0.125 mm). For other samples, the following sieves were used: 18, 25, 35, 45, 60, 80, 100, 120, 170 and 230 mesh (corresponding to 1.00, 0.707, 0.500, 0.354, 0.250, 0.177, 0.149, 0.125, 0.088 and 0.063 mm). Sieving time was set at 5 min for each test run. The mass retained on each sieve was weighed to obtain the particle size distribution of the sample. In total, two replicates were measured for each sample. Fig. 1 shows the measured particle size distributions of different BC softwood species prepared with a grinder installed with a 0.79 mm size screen and a 4.00 mm size screen. From Fig. 1a, it is seen that the particle size distributions of prepared spruce, pine, fir and SPF samples were very close to each other, but different from the pine bark sample. Table 2 shows the properties of those samples. The particle density for all samples was around 1400 kg/m^3. The pine bark had a higher heating value than other samples. The mean sizes of spruce, pine, fir and SPF particles were very close to each other, but different from the pine bark sample. Those results indicated that the grinding behavior of pine bark could quite different from wood samples.

2.2. Torrefaction apparatus

A bench-scale fixed bed reactor was used for torrefaction tests. The unit includes a tubular reactor, an electrical gas pre-heater with a temperature controller and a power supply, a cooler, a condensate receiver, and a computer data acquisition system. The reactor has a inside diameter of 27 mm and a length of 575 mm, made from stainless steel. The reactor is located inside an electrically heated furnace with a reaction zone of ~100 mm in length. The biomass sample loaded into the reactor was heated up by both the preheated hot nitrogen gas flow and the electrical furnace. The hot nitrogen gas flows into the reactor from the top to the bottom. The temperature of the reactor zone was controlled by regulating the electric power via a temperature controller. The raw sample