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Physical and chemical characteristics of products from the torrefaction of yellow poplar (*Liriodendron tulipifera*)

Young-Hun Kim [a], Soo-Min Lee [b], Hyoung-Woo Lee [a], Jae-Won Lee [a,c,*]

[a] Dept. of Forest Products and Technology, College of Agriculture & Life Sciences, Chonnam National University, Gwang-ju 500-757, Republic of Korea
[b] Div. Wood Chemistry & Microbiology, Dept. Forest Products, Korea Forest Research Institute, Seoul 130-712, Republic of Korea
[c] Bioenergy Research Center, Chonnam National University, Gwangju 500-757, Republic of Korea

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ABSTRACT

We investigated the characteristics of torrefied yellow poplar (*Liriodendron tulipifera*) depending on reaction time (30 min) and temperature (240–280 °C). The thermogravimetric, grindability and calorific value of torrefied biomass were analyzed. As the torrefaction temperature increased, the carbon content of torrefied biomass increased from 49.50% to 54.42%, while the hydrogen and oxygen contents decreased from 6.09% to 5.65% and 28.71% to 26.61%, respectively. The highest calorific value was 1233 kJ/kg when torrefaction was performed at 280 °C for 30 min. An overall increase in energy density and decrease in mass and energy yield was observed with the increase in torrefaction temperature. The analysis of thermal decomposition demonstrated that the hemicelluloses contained in torrefied biomass decreased with increasing torrefaction temperature, whereas cellulose and lignin were only slightly affected. The grindability of torrefied biomass was significantly improved when torrefaction was performed at high temperature. Torrefaction of yellow poplar improved the chemical and physical fuel properties of the biomass.

1. Introduction

The demand for biofuel pellets has increased due to conversion of fossil fuel-based heating systems (Nilsson et al., 2011; Stahl and Berghel, 2011); however, compared to coal, these lignocellulosic pellets have a relatively high moisture content, low energy density, a hydrophilic behavior and are difficult to store (Chen and Kuo, 2011). Furthermore, lignocellulosic biomass pellet do not have consistent calorific values and ash contents because pellet can be produced from various resources.

Torrefaction of lignocellulosic biomass has attracted interest because of its potential to overcome the disadvantages of current biofuel pellets (Chen and Kuo, 2011; Repellin et al., 2010). Torrefaction is a process where raw biomass is heated in an inert or nitrogen atmosphere at a temperature of 200–300 °C. This process produces a hydrophobic material due to the removal of hydroxyl groups during thermal treatment. Therefore, torrefied lignocellulosic biomass is suitable for long distance transportation and long term storage. Additionally, torrefied products have a higher calorific value or energy density, a lower O/C ratio and moisture content, and are easier to grind than untreated biomass. During torrefaction of biomass, most of the volatile compounds are removed from the biomass as vapors, resulting in a higher energy density. Torrefaction temperature is usually within the range of 250–300 °C for lignocellulosic biomass (Prins et al., 2006; Chen et al., 2011; Phanphanich and Mani, 2010). Chen et al. (2011) suggested that biomass torrefied for less than 1 h under light torrefaction (260 °C) was appropriate for producing fuels with desirable energy density. Therefore, the physical and chemical properties of yellow poplar (*Liriodendron tulipifera*) torrefied at 250–300 °C for 30 min were evaluated in the present study.

Yellow poplar has been reported to acclimate well to barren soil or highlands. Its fast growth and high capacity for carbon absorption has led the Korea Forest Service to value this species as a major planting species and it has thus been planted extensively in Korea for the production of woody biomass (Gwak et al., 2009).

2. Methods

2.1. Materials

Yellow poplar chips were provided by the Korea Forest Research Institute. Wood chip were screened to the size of 3–10 and 10–30 mm, using sieves (9.5 and 31.5 mesh) and dried to below 10% moisture content for safe outside storage.

* Corresponding author at: Dept. of Forest Products and Technology, College of Agriculture & Life Sciences, Chonnam National University, Gwang-ju 500-757, Republic of Korea.
E-mail address: ljw43376@chonnam.ac.kr (J.-W. Lee).

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2.2. Torrefaction

The wood chips were dried at 105 °C for 24 h before torrefaction in order to remove the remaining water in the biomass. The dried wood chips of 500 g were placed in a batch reactor (designed by Drying engineering, Korea) equipped with a temperature controller. The wood chips were torrefied at 240, 260, and 280 °C at 30 min reaction time with stirring (30 rpm). Torrefaction was performed under anoxic conditions by providing a nitrogen flow of 2 L/min. The exhaust gas was passed through a series of condensers to collect condensable compounds. The condensed liquid was analyzed by gas chromatography and mass spectrometer (GC/MS, Agilent 6890 and 5973, USA). After torrefaction, the heater was turned off and the reactor was left to cool to room temperature. A schematic diagram of the torrefaction reactor and reaction profile is shown in Figs. 1 and 2.

2.3. Chemical analysis of biomass

The chemical analysis was carried out using TAPPI test methods. Insoluble and soluble lignins (Klason lignin) were determined by sulfuric acid treatment. Acid soluble lignin was determined by UV-spectrometry at 205 nm. Moisture contents (T 207 om-88), holocellulose (TAPPI Useful Method 249, Wise method) and Klason lignin (T 222-om-88) after torrefaction were analyzed.

2.4. Elemental analysis and calorific value of biomass

The moisture content of torrefied biomass was determined by the oven-dry method (Korea Forest Service, 2009). The gross calorific value at constant volume based on dry weight was determined with samples weighing from 0.5 to 0.6 g and combustion was performed by calorimeter (6400 Automatic Isoperibol calorimeter, Parr Instrument Inc., Moline, Illinois). The ash content was determined by burning 1 g samples oven-dried for 30 min in a platinum crucible in a muffle furnace model at 575 ± 25 °C. The nitrogen content of torrefied biomass was measured by direct combustion and thermal conductivity detection with an elemental analyzer (Thermo EA 1112A, USA). Briefly, the sample was dropped into a hot furnace and flushed with pure oxygen for very rapid combustion, and the products of combustion (CO_2, H_2O, NO_x and N_2) were passed through the furnace filter and thermoelectric cooler for collection in a ballast apparatus. The collected gases in the ballast were mixed, and a small amount was used for further conversion of the gases. The remaining gas mixture was reduced and the nitrogen content was determined by the thermal conductivity measurements (Korea Forest Service, 2009).

Inorganic compounds were determined with an ICP-ES (inductively coupled plasma emission spectrometer). Exactly weighed samples of 0.5 g were digested with 10 ml of HNO_2:HCl:H_2O_2 (8:1:1 v/v) using a microwave apparatus (Multiwave 3000, Anton Parr). After digestion, samples were diluted with distilled water to 50 ml and filtered with Whatman No. 42 filter paper. The filtrates were analyzed using an ICPS-1000IV instrument (Shimadzu, Japan). All experiments were performed according to the quality standards for wood pellets (Korea Forest Service, 2009) and repeated in triplicate and a mean value is reported.

2.5. Thermogravimetric analysis (TGA)

The pyrolysis and torrefaction characteristics of biomass were analyzed with a DTA/TGA analyzer (TA Instruments, USA) at a temperate range of 25–700 °C at a heating rate of 10 °C/min. In each test, the biomass was tested under nitrogen gas flow of 100 ml/min. Both thermogravimetric and differential temperature measurements were recorded during combustion.

2.6. Grinding characteristic

The torrefied biomass was placed into a four-blade grinder (Grinder AL-540, Hibell, Korea). Grinding was performed at 24,000 rpm for 1 min. The ground biomass was passed through three different sieves (100, 200 and 325 mesh), resulting in the accumulation of four differently sized particle collections.

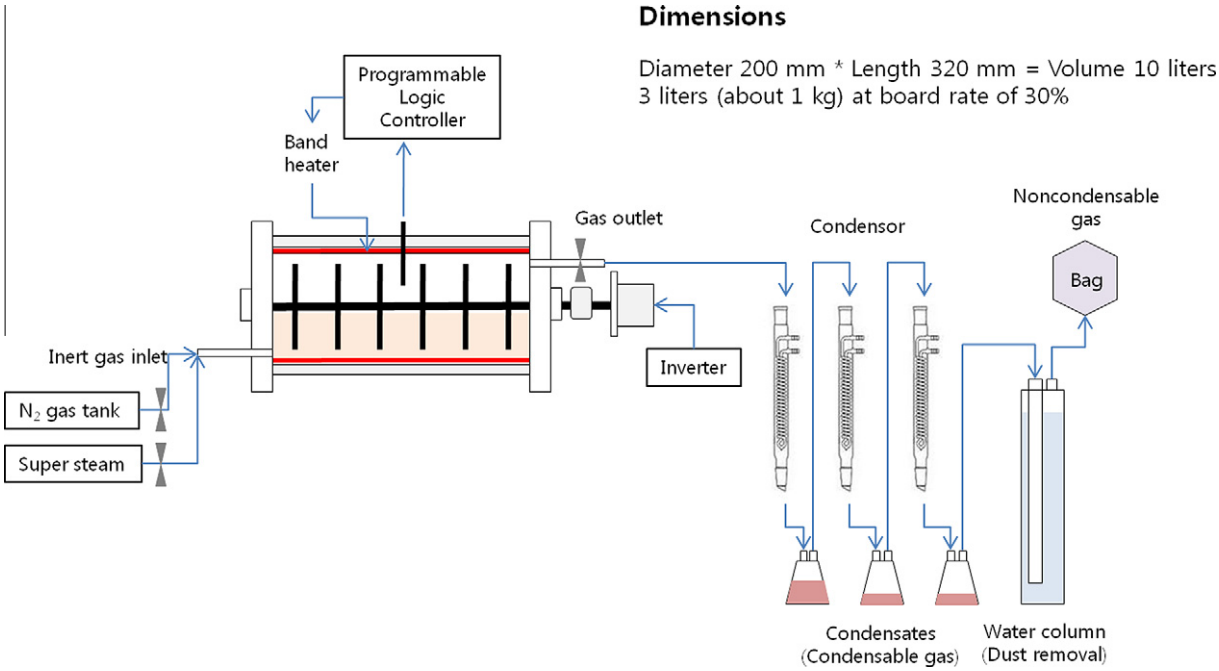

Fig. 1. Design of torrefaction reactor used in this study.