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Hydrothermal carbonization of coniferous biomass: Effect of process parameters on mass and energy yields

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ABSTRACT

Hydrothermal carbonization of biomass presents a promising way to improve fuel characteristics of biomass without preliminary drying. In this process, feedstock is subjected to heating with water at temperatures between 180 and 250 °C during a certain period of time. This paper investigates the effect of process conditions (temperature, time, and the ratio between biomass and water) on the hydrothermal carbonization of coniferous biomass. Three sets of experiments were carried out with coniferous wood chips. Mass and energy yields together with proximate analysis measurements were used for the carbonization process evaluation. Dependencies of hydrochar mass and energy yields from the operation parameters could be described with mathematical correlations.

1. Introduction

The use of biomass fuels is currently quite intensively promoted as one way of reducing carbon dioxide emissions. Wood and other forms of biomass present a perspective source to substitute conventional fossil fuels with zero net CO_2 emissions [1,2]. Using biomass as fuel is associated with certain difficulties, however, the heterogeneity of properties, low density, poor grindability, relatively high moisture content, and hydrophilic behavior – all these factors increase the cost of biomass applications [2–7].

Hydrothermal carbonization (HTC) is a relatively recent technology that offers the benefits of converting the biomass into homogenous lignite-like material. In this process, biomass in a mixture with water is kept during a certain period of time in a closed vessel in the temperature range of 180–250 °C (pressure corresponding saturated values) [2,8–12]. The reaction temperature, residence time, and water-to-biomass (w/b) mass ratio are reported to be the main factors to determine the rate of wood components decomposition [2,11,12]. Several reaction mechanisms are involved in biomass decomposition during HTC, such as hydrolysis, dehydration, decarboxylation, polymerization, and aromatization. Components of lignocellulosic biomass (lignin, hemicellulose, and cellulose) become less stable with the presence of water under saturated conditions [2,4,13].

Solids (hydrochar), aqueous solution, and some amount of gases (about 10% by mass of feedstock) are generated during the HTC process. Hydrochar presents the main product of the process. In comparison with the feedstock, hydrochar is charactarized by the increased carbon content [4,7,8,10], higher homogeneity, better grindability, and hydrophobic behavior [4,5,11,14]. These improved product characteristics together with the independence from feedstock moisture make the HTC process a promising technology for enhancing biomass fuel properties. Besides the utilization for heat and power production, hydrochar may find other potential applications: for example, soil fertilizer, catalyst, energy storage, or absorbent [13,15].

Recent studies mostly report on HTC activities with decidous wood (beech [14], poplar [11,16], bamboo [6]), herbaceous biomass (agricultural residues [17], sunflower stem [2], wheat [18], and barley straw [10]) as well as with non-lignocellulosic materials (algae [12,19], MSW [20], packaging materials [21], and digestate [18]). So far, the results on the hydrothermal carbonization of coniferous biomass are limited to experiments with loblolly pine [4,19] and white fir/Jeffrey pine (Tahoe mix) [5].

Coniferous and deciduous wood have certain differences in the chemical composition and amount of lignocellulosic components [22,23]. During hydrothermal carbonization, hemicellulose as the most reactive wood cell fraction is mainly affected. At the same time, previous research indicated that in coniferous wood, this component is mannan-based, while deciduous species are rich with more reactive xylan-containing fractions. For this reason, the reactivity of hemicelluloses and decomposition character together with distribution and characteristics of resulting products noticeably

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Fig. 1. Milled wood chips for experiments.

differ between coniferous and deciduous wood [9,22,23]. Therefore, previously published results on the deciduous wood decomposition during HTC could not be directly applied for coniferous species. The main objective of this work was to gather more experimental data on the hydrothermal carbonization of coniferous wood. Wood chips and hydrochar samples were characterized by proximate analysis measurements. The influence of process parameters (temperature, time, and water-to-biomass ratio) on hydrochar mass and energy yields was evaluated and described with mathematical correlations.

2. Materials and methods

2.1. Feedstock material

Wood chips from coniferous species presented by pine and different logging residues were collected locally (Lappeenranta, Finland) and used for experiments. The material was milled to the particle size of 1 cm in length on average and air dried. Before the experiments, biomass was kept in plastic bags at room temperature. Fig. 1 presents an example of feedstock material.

2.2. HTC reactor

Hydrothermal carbonization was performed in a batch reactor designed and constructed at Lappeenranta University of Technology (Lappeenranta, Finland). The 1 l reactor is comprised of a stainless steel tube with a flange connection at the top part and screw closing at the bottom (Fig. 2). Heat to the process was provided by a controllable 10 kW electric heater coil surrounding the reactor tube. The experimental unit was covered by a thick insulation layer and outer steel sheet.

Two thermocouples were used to monitor the temperatures at the lower and upper zones of the reactor (at 245 mm and 645 mm from the top). Pressure sensor and pressure relief valve were set at the top of the unit. The required temperature level inside the reactor during the desired period of time was maintained with a proportional-integral-derivative (PID) controller. Data from the temperature and pressure sensors was recorded automatically every 2 s.

2.3. Experimental procedure

In the current work, three sets of HTC experiments were performed. Water-to-biomass mass ratios of 6:1 (approximately 50 g of fuel and 300 ml of water) and 8:1 (approximately 50 g of wood and 400 ml of water) were tested. Residence times of three and six hours were used in the experiments. The reaction temperature was varied in the range of 180–250 °C. The principle biomass components became more reactive under the saturated conditions within this temperature range: not only hemicellulose that is completely decomposed around 230 °C, but also typically more stable cellulose and lignin reacted partially at this temperature [7,9].

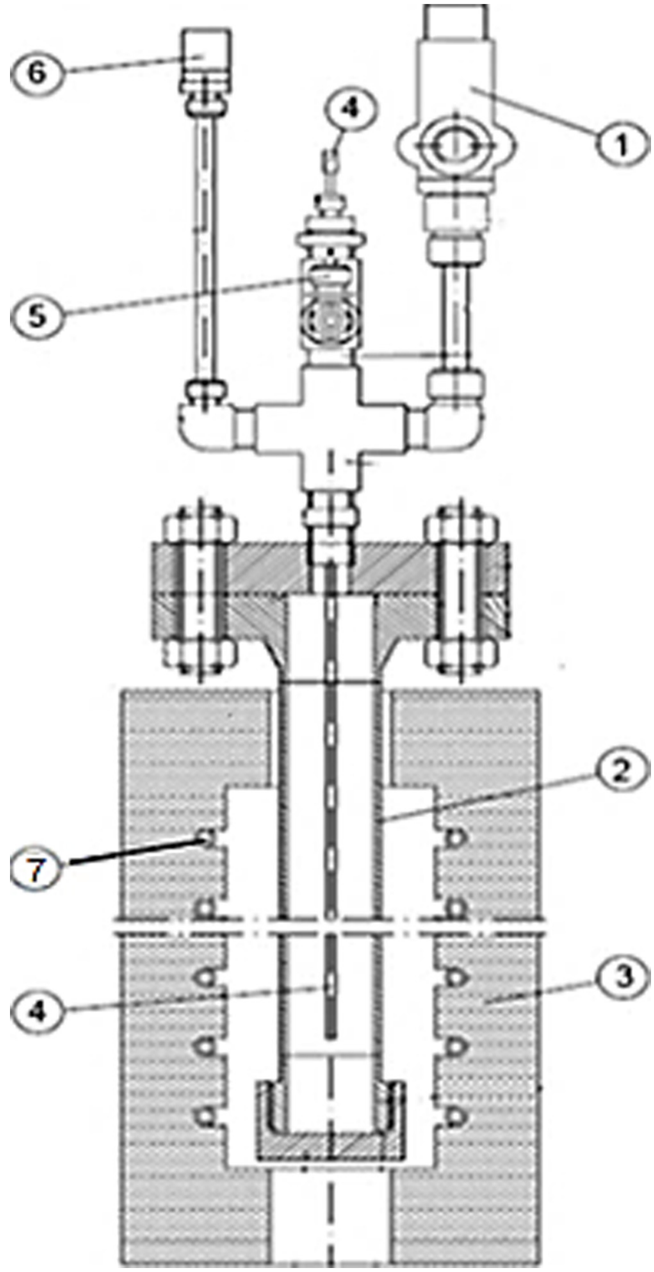

Fig. 2. HTC experimental unit, where (1) safety valve (set point pressure 40 bar, maximum temperature 300 °C); (2) reactor tube; (3) insulation; (4) thermocouples; (5) sampling valve (maximum temperature 315 °C, maximum pressure 215 bar); (6) pressure sensor; (7) heater.

For each experiment, a pre-weighted sample of biomass was dispersed in water and stirred manually. At the end of the experiment, the carbonized wood and liquid products were collected and then separated by vacuum filtration using the Büchner funnel with a Whatman glass microfiber filter paper (grade GF/A). Hydrochar was subsequently dried overnight in the oven at a temperature of 105 ± 2 °C. All tests were performed at least twice, and the average values were chosen. Liquid and gaseous product analysis was not included in the scope of the current work.

Hydrochar samples were named in accordance with the operation parameters as HTC-*t*-*r*, where *t* denotes the reaction time and *r* denotes the w/b ratio.