



Torrefaction of cedarwood in a pilot scale rotary kiln and the influence of industrial flue gas



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HIGHLIGHTS

- Torrefaction was performed in a pilot-scale rotary kiln.
- The temperature of flue gas torrefaction for cedarwood should not higher than 260 °C.
- The flue gas had a greater influence on the properties of the torrefied biomass.
- The torrefied samples had similar combustion characteristics to lignite.

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ABSTRACT

Torrefaction of cedarwood was performed in a pilot-scale rotary kiln at various temperatures (200, 230, 260 and 290 °C). The torrefaction properties, the influence on the grindability and hydroscopicity of the torrefied biomass were investigated in detail as well as the combustion performance. It turned out that, compared with raw biomass, the grindability and the hydrophobicity of the torrefied biomass were significantly improved, and the increasing torrefaction temperature resulted in a decrease in grinding energy consumption and an increase in the proportion of smaller-sized particles. The use of industrial flue gas had a significant influence on the behavior of cedarwood during torrefaction and the properties of the resultant solid products. To optimize the energy density and energy yield, the temperature of torrefaction using flue gas should be controlled within 260 °C. Additionally, the combustion of torrefied samples was mainly the combustion of chars, with similar combustion characteristics to lignite.

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1. Introduction

Biomass was the only renewable energy source that could be converted into chemicals and fuels through biochemical and thermochemical processes (Zheng et al., 2012). However, it had some fatal weaknesses such as being difficult to store, transport and grind, possessing a high moisture content and low energy density, all of which limited the large-scale application of biomass (Chen and Kuo, 2011). To surmount these disadvantages, a new pretreatment process called torrefaction had been developed (Chen and Kuo, 2011; Park et al., 2012).

Torrefaction was a mild thermal pretreatment process that occurred below 300 °C in a reduced or oxygen-free environment (Prins et al., 2006). Dehydration, dehydroxylation and decarboxylation reactions occurred during torrefaction, resulting in a lower O/C ratio and H/C ratio compared to the original biomass, in turn resulting in a higher energy density (Arias et al., 2008; Chew and Doshi, 2011; Van der Stelt et al., 2011). The removal of the hydroxyl group during thermal treatment also led the biomass to a hydrophobic condition (Bourgeois et al., 1989; Kim et al., 2012; Kobayashi et al., 2008). Acharjee et al. (Acharjee et al., 2011) measured the equilibrium moisture content (EMC) of raw and torrefied biomass at relative humidities ranging from 11% to 97% at a constant temperature of 30 °C. The results showed that the EMC of pretreated biomass was much lower than that of raw biomass, indicating that pretreated biomass possessed a greater hydrophobicity. Arias et al. (Arias et al., 2008) and Deng et al.

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(Deng et al., 2009) confirmed that torrefaction could improve the grindability of biomass, and the energy consumption during milling was three to seven times lower than that of raw materials. Torrefied samples were therefore more advantageous than raw biomass in terms of grinding, transportation, storage and feeding. Fisher et al. (Fisher et al., 2012) discussed the combustion characteristics of chars from raw and torrefied biomass, and determined that torrefaction was an attractive pretreatment technology prior to combustion. Nevertheless, most recent researches were based on the laboratory-scale torrefaction in an inert atmosphere.

It was well accepted that new processes or technologies needed to be trialed at the pilot scale before industrial application, however the large-scale use of inert gas was neither realistic nor economical, and thus many researchers had attempted to find an effective substitute. Uemura et al. (Uemura et al., 2013) pointed out that if it were possible to use flue gas from burners as a carrier gas and heat source, the process of torrefaction would become more economically viable. As the source of waste heat, the temperature of flue gas fluctuated in the range of 160–350 °C (Zhou et al., 2013). Because of this encompasses the temperature range of torrefaction it would be suitable as a heat source for the process, however, the amount of oxygen in flue gas ranged from 2% to 6% (Haryanto and Hong, 2011), and whether the presence of oxygen was suitable for torrefaction or not was still in question. Wang et al. (Wang et al., 2013) investigated the oxidative torrefaction of sawdust with a carrier gas containing 3–6% O₂ in a TGA and a fluidized bed reactor, and concluded that using oxygen-laden combustion flue gases as carrier gases for the torrefaction of biomass was feasible. Despite this, only a few studies had attempted to analyze the properties of the products of torrefaction performed under oxygenated conditions (Chen et al., 2013; Rousset et al., 2012; Tapasvi et al., 2013; Uemura et al., 2013; Wang et al., 2013), and no literature had investigated pilot-scale torrefaction using flue gas. In this context, torrefaction in both flue gas and N₂ atmospheres was conducted in a pilot scale rotary kiln. In addition, the mass yield, energy yield, grindability, hydroscopicity and combustion performance of torrefied cedarwood at four temperatures of 200, 230, 260, 290 °C were investigated.

2. Methods

2.1. Materials

The raw material, cedarwood, was acquired from central China. The moisture content was 18.6 wt% (as received basis). The cedarwood was ground without drying by a commercial wood grinder (HJF800, Huijie Machine Corp., China) with a power of 37 kW, and the maximum size of the ground powder was 20 mm in nominal diameter. It was then used for the torrefaction experiment in

the pilot scale rotary kiln. The proximate and ultimate analyses and the gross calorific value were shown in Table 1.

2.2. Torrefaction experiment

A pilot-scale rotary kiln was used for the torrefaction as shown in Fig. 1. It consisted of a ceramic tube (190 mm ID and 1.5 m long) with an electrical heater. The tube was heated up to the preset temperatures (200, 230, 260 or 290 °C), and when the temperature was stable, the ground sample was fed into the tube by the auger feeder, then the sample was tumbled and heated with the rotation of the kiln. The feeding rate (FR) and the residence time (RT) were controlled by the rotate speed of auger and kiln respectively. In this experiment, the FR was set as 3 kg h⁻¹ and the RT was 50 min. Flue gas (FG) was synthesized by a mixture of 6 vol.% O₂, 10 vol.% CO₂ and 84 vol.% N₂, which provided the oxygenated atmosphere for torrefaction. Before the samples were delivered into the reactor, FG or N₂ would be applied to the tube for 30 min at 5 LPM to purge the air out and create the stable torrefaction atmosphere (flue gas or N₂).

2.3. Sample analysis and torrefaction yields

2.3.1. Sample analysis

The raw and torrefied materials were analyzed through proximate, ultimate and calorific analyses. The proximate analysis was performed in accordance with the standard procedure of the American Society for Testing and Materials (ASTM). The ultimate analysis was carried out by using an EL-2 CHN elemental analyzer (Vario, Germany), and the oxygen content was obtained by difference. The higher calorific values of samples were measured with a bomb calorimeter (Parr 6300, America). Combustion of biomass samples (including the raw sample and eight torrefied samples) was performed in a thermogravimetric analyzer (STA449F3, NETZSCH). 10 mg of sample (<425 μm) was placed in an Al₂O₃ ceramic pan, and heated from room temperature to 900 °C at 15 °C min⁻¹ under an air flow rate of 100 ml min⁻¹.

2.3.2. Torrefaction yields

To measure the yield of torrefaction, the mass and energy yields were calculated on a dry basis (d), and defined by Eqs. (1) and (2) respectively (Bridgeman et al., 2008).

$$\text{Mass yield } (Y_m) = \frac{\text{Mass (d) of torrefaction biomass}}{\text{Mass (d) of raw biomass}} \times 100\% \quad (1)$$

$$\text{Energy yield } (Y_e) = \frac{\text{Higher calorific value (d) of torrefaction biomass}}{\text{Higher calorific value (d) of raw biomass}} \times Y_m \quad (2)$$

Table 1
Proximate analysis and ultimate analysis of raw and torrefied cedarwood. (Raw, N₂-200, FG-200 represent the unprocessed sample and torrefied samples under atmospheres of nitrogen (N₂) and flue gas (FG) at 200 °C respectively.)

Samples	Proximate analysis/d%			Ultimate analysis/d%					HHV d / (MJ/kg)
	V	A	FC	C	H	N	S	O ^a	
Raw	85.49	1.72	12.79	45.14	6.34	0.26	0.29	46.25	18.13
N ₂ -200	84.63	1.64	13.73	47.66	5.68	0.5	0.31	44.21	19.02
N ₂ -230	83.04	1.87	15.09	48.82	5.49	0.48	0.37	42.97	19.35
N ₂ -260	81.26	1.58	17.16	52.17	5.21	0.7	0.41	39.93	20.56
N ₂ -290	74.60	2.38	23.02	54.30	4.99	0.83	0.43	37.07	21.25
FG-200	69.71	1.96	28.33	53.74	4.48	0.31	0.45	39.06	20.66
FG-230	66.13	1.42	32.45	55.28	4.12	0.57	0.41	38.20	20.96
FG-260	58.48	1.69	39.83	56.13	4.01	0.48	0.42	37.27	21.14
FG-290	57.75	2.24	40.01	56.55	3.97	0.55	0.37	36.32	22.25

^a The oxygen content was calculated by difference.

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