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Pretreatment of biomass by torrefaction and carbonization for coal blend used in pulverized coal injection

Shan-Wen Du [a], Wei-Hsin Chen [b,*], John A. Lucas [c]

[a] Iron and Steel Research and Development Department, China Steel Corporation, Kaohsiung 812, Taiwan, ROC
[b] Department of Aeronautics and Astronautics, National Cheng Kung University, Tainan 701, Taiwan, ROC
[c] Department of Chemical Engineering, University of Newcastle, Newcastle, Australia

HIGHLIGHTS

- Biomass is pretreated by torrefaction and carbonization for the use in blast furnace.
- Biomass is pretreated in a rotary furnace to uniformly upgrade solid fuel.
- Fuel ratio, ignition temperature, and burnout of torrefied biomass and biochar are analyzed.
- Carbonization is feasible to improve the energy densities of bamboo and Madagascar almond.
- Biomass torrefied at 300 °C or carbonized below 500 °C can be blended with coal for PCI.

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ABSTRACT

To evaluate the utility potential of pretreated biomass in blast furnaces, the fuel properties, including fuel ratio, ignition temperature, and burnout, of bamboo, oil palm, rice husk, sugarcane bagasse, and Madagascar almond undergoing torrefaction and carbonization in a rotary furnace are analyzed and compared to those of a high-volatile coal and a low-volatile one used in pulverized coal injection (PCI). The energy densities of bamboo and Madagascar almond are improved drastically from carbonization, whereas the increase in the calorific value of rice husk from the pretreatment is not obvious. Intensifying pretreatment extent significantly increases the fuel ratio and ignition temperature of biomass, but decreases burnout. The fuel properties of pretreated biomass materials are superior to those of the low-volatile coal. For biomass torrefied at 300 °C or carbonized at temperatures below 500 °C, the pretreated biomass can be blended with coals for PCI.

1. Introduction

Biomass is able to fix atmospheric carbon while it grows; therefore, biomass is regarded as a carbon-neutral fuel when it is burned. For this reason, using biomass as an alternative fuel to fossil fuels is considered as an effective countermeasure to reduce anthropogenic carbon dioxide emissions into the atmosphere and mitigate global warming (Machado et al., 2010). For example, bioethanol and biodiesel have been extensively employed for power generation in spark ignition engines and compression ignition engines, respectively (Gustavo et al., 2013). In addition to the liquid biofuels, biomass can also be combusted directly to get heat and power. Compared to coals, the energy density of biomass is low and its moisture content is high (Rousset et al., 2011). Moreover, more energy will be consumed to comminute biomass due to its lignocellulosic nature (van der Stelt et al., 2011). These characteristics limit the applications of biomass in industry.

As far as blast furnaces are concerned, coke, produced from metallurgical coal, is an essential reducing agent and provides thermal energy for hot metal production (Du and Chen, 2006). By means of the technique of pulverized coal injection (PCI), non-coking or weakly coking coals are injected into the raceways of blast furnaces to partially replace coke (Chen et al., 2007; Du et al., 2007). On account of mass consumption of coals for coke-making and PCI in blast furnaces, a large amount of CO_2 is emitted from the ironmaking processes (Wang et al., 2009). Solid biomass is a potential substitute to coals and can be partially used for PCI without net carbon dioxide emissions into the atmosphere (Chen and Wu, 2009). However, due to the disadvantages of raw biomass described earlier, the upgrade of raw biomass is necessary for its application in blast furnaces.

* Corresponding author. Tel.: +886 6 2004456; fax: +886 6 2389940.
E-mail address: weihsinchen@gmail.com (W.-H. Chen).

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The upgrade of biomass can be fulfilled via torrefaction and carbonization or pyrolysis where biomass is thermally degraded in an inert or oxygen-free environment. The torrefaction temperature is in the range of 200–300 °C (Peng et al., 2013; Lu et al., 2013; Sabil et al., 2014), whereas carbonization is operated at temperatures of 300–500 °C (Abdullah and Wu, 2009). The biomass materials pretreated from torrefaction and carbonization are called torrefied biomass and biochar, respectively. By virtue of the partial disruption of lignocellulosic structure in biomass from the two methods, biomass grindability is improved greatly (Arias et al., 2008). Grinding coal for PCI is an energy-intensive process. Therefore, the energy for grinding coal can be saved if torrefied biomass and biochar are used for PCI (Abdullah and Wu, 2009; Phanphanich and Mani, 2010). Torrefaction and carbonization lead to the release of volatile matter from biomass and change the hygroscopic material to hydrophobic one. This transformation improves the reactivity of solid biomass. Bridgeman et al. (2008) studied raw and torrefied willow exposed to a methane–air flame, and found that the latter was ignited more quickly than the former. Pimchuai et al. (2010) investigated rice husk reaction in a spout-fluid bed combustor, and reported that torrefied rice husk ignited faster and raised the bed temperature to a higher level when compared to raw rice husk. These ignition observations were very likely due to the low moisture content in the torrefied willow and rice husk.

When fuel particles are injected into blast furnaces, they proceed from blowpipes, tuyeres, and then to raceways, and experience rapid heating, devolatilization, gas-phase combustion, char combustion, and gasification (Hutny et al., 1991; Shen et al., 2009; Wijayanta et al., 2014). Devolatilization and gas-phase combustion correspond to the mass transfer and reactions of volatile matter from fuel particles, while char combustion and gasification account for the reactions of fixed carbon. Accordingly, particle reactions are highly related to the volatile matter and fixed carbon contents in the fuels. The ignition temperature of volatile is much lower than that of char. Therefore, the first stage of fuel particle reactions is triggered by volatile ignition, while char combustibility is subject to its residence time in the reactor and the surrounding temperature (Du et al., 2010). However, after biomass is torrefied or pyrolyzed, part of the volatiles are liberated from the material and relatively more fixed carbon is retained (Chen et al., 2012). This may lower the ignition temperature of biomass in the gas phase.

Coals with high fuel ratios are frequently blended with low fuel-ratio coals to increase the flexibility of PCI operation (Du et al., 2010). When biomass is used as an alternative fuel to coals for PCI, its utility can be evaluated through a number of properties, such as fuel ratio, ignition temperature, and burnout (Gao and Bian, 2013; Li et al., 2014). To the authors' knowledge, the pretreatment of biomass simultaneously covers torrefaction and carbonization has not been studied yet. The purposes of the present study are to examine the fuel properties of biomass pretreated by torrefaction and carbonization and compare to those of a high-volatile coal and a low-volatile coal. Particular emphasis will be paid to the applications of upgraded biomass, from the viewpoint of coal blend used in PCI.

2. Experimental

2.1. Materials and preparation

Five different biomass materials were studied in the present work; they are bamboo, oil palm, rice husk, sugarcane bagasse (abbreviated by bagasse), and Madagascar almond. The bamboo, rice husk, bagasse, and Madagascar almond were obtained in Taiwan. The oil palm was the fiber fraction left after the nut was removed in a Malaysia oil extraction mill. Oil palm is an important economic crop in some countries, especially in Malaysia. Oil palm fibers are abundant wastes from palm oil fruit harvest and oil extraction processing. The fibers are considered as a potential renewable energy source due to its high calorific value and quantity (Shuit et al., 2009). Therefore, oil palm fiber is adopted and studied in the present study.

Meanwhile, a high-volatile bituminous coal (Coal A) and a low-volatile coal (Coal B) for PCI operation at China Steel Corporation (CSC) were tested for comparison. The basic properties of the coals and biomass materials, such as proximate, elemental, fiber, and calorific analyses, are given in Table 1. The proximate analysis was performed in accordance with the standard procedure of the American Society for Testing and Materials (ASTM E870-82). The elemental analysis was carried out by use of an elemental analyzer (Vario EL III). The fiber contents (hemicellulose, cellulose, and lignin) in biomass were analyzed through the measurements of neutral detergent fiber, acid detergent fiber, and ash (Chen et al., 2010). The higher heating values (HHVs) of samples were detected

Table 1
Proximate, elemental, fiber, and calorific analyses of two coals and raw biomass materials.

	Coal A	Coal B	Bamboo	Oil palm	Rice husk	Bagasse	Madagascar almond
Proximate analysis (wt%)							
Moisture	13.92	1.09	5.76	7.20	8.00	7.03	10.17
VM	44.09	14.67	78.76	67.25	73.18	75.03	70.38
FC	40.47	76.35	14.40	19.03	9.27	13.61	18.62
Ash	1.52	7.89	1.08	6.52	9.55	4.33	0.83
Elemental analysis (wt%)							
C	63.72	83.24	48.64	44.81	43.40	46.38	47.68
H	4.40	3.78	5.64	4.10	4.33	4.68	4.31
N	0.67	1,62	0.52	2.10	0.65	0.50	0.50
S	0.10	0.52	0.03	0.24	0	0	0
O*	29.59	1.86	44.09	42.23	42.07	44.11	46.68
Fiber analysis (wt%)							
Hemicellulose			20.38	34.00	21.34	30.59	18.23
Cellulose			39.82	26.78	36.06	45.66	41.86
Lignin			12.16	16.08	21.16	19.38	16.17
Others			27.64	23.14	41.44	5.37	23.74
Higher heating value (MJ kg^{-1})	23.99	31.01	18.95	17.12	17.46	18.31	17.32

* By difference.