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Investigating combustion behaviors of bamboo, torrefied bamboo, coal and their respective blends by thermogravimetric analysis

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ABSTRACT

To investigate co-combustion behavior of bamboo/coal blends, thermogravimetric analysis (TGA) was used to determine combustion characteristics of bamboo, torrefied bamboo, coal and their respective blends with five mixing ratios and three air flows. The results indicated that torrefaction was an effective way to improve physical properties of bamboo materials. The combustion process of bamboo and torrefied bamboo included drying, oxidative pyrolysis and char combustion. Torrefied bamboo had a lower reactivity compared to bamboo. The ignition and burnout temperature of torrefied bamboo also shifted to higher temperature. The char combustion of torrefied bamboo and coal coincided. The presence of bamboo and torrefied bamboo improved the thermo-chemical reactivity of blends. Air flow could also enhance the combustion reaction and strengthen combustion efficiency of blends. It was better potential for the co-combustion of torrefied bamboo and coal blends in existing coal-fired power plants. The results from this research will be very important and helpful to promote bamboo resources as a blend fuel for co-firing application with coal.

1. Introduction

Biomass is an important renewable source of energy, currently accounted for 15% of primary energy consumption worldwide. Biomass has gained considerable interest because of the widespread availability of biomass materials and the low environmental impacts [1]. Direct co-firing is the simplest, cheapest and most common option for biomass energy utilization. Compared to direct combustion of biomass alone, biomass/coal co-firing in existing coal-fired boilers can accommodate varying amounts of available biomass and does not require large investments in new, standalone biomass plants [2]. Luschen and Madlener investigated the economic potential of biomass co-firing in hard coal power plants in Germany and identified suitable biomass input fuels, investment and operating costs [3]. Biomass/coal co-combustion is also one of the promising short term alternatives for the use of renewable fuels with the aim of reducing of CO_2 emission [4]. Extensive researches related to biomass/coal co-firing were carried out over the years [5–7]. Muthuraman et al. investigated the co-combustion characteristics of wood and municipal solid waste with Indian coal. They found significant interaction between wood and Indian coal, and reactivity of coal was improved upon blending with wood [8]. Kwong et al. investigated co-combustion performance of coal with rice husks and bamboo. The combustion temperature and energy output from the co-firing process decreased due to the lower heating value of biomass materials. Gaseous pollutant emissions including carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x) and sulfur dioxide (SO_2) also decreased and minimum energy-based emission factors were found in the range of 10–30% blending ratio of biomass and coal [9]. Atimtay and Kaynak investigated co-combustion of peach and apricot stone with coal in a bubbling fluidized bed. It was found that peach and apricot stones were potential fuels that could be utilized for clean energy production in small-scale fruit juice industries. The percentage of peach stones or apricot stones in the fuel mixture was suggested to be below 50%. During the design of bubbling fluidized bed combustor, the volatile matter content of the biomass had to take care [10].

It is well known that co-combustion behavior of biomass/coal depends on biomass characteristics. The diversity in physical and chemical properties of biomass materials makes difficulties and challenges encountered when handling raw biomass for fuel or energy [11]. To efficiently use biomass materials for bioenergy products, a variety of pretreating methods of biomass have been

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developed. One of the methods is torrefaction, where raw biomass is heated in a non-oxidizing atmosphere with the temperatures of 200–300 °C [12]. Torrefaction yields a solid uniform product with lower moisture content and higher energy content compared to those in the biomass feedstock. Furthermore, completely torrefied biomass has lost its original fiber structure which makes it very suitable to be pulverized in coal mills. This also gives the opportunity for a further increase of the biomass/coal-ratio in power plants [13]. Chen et al. evaluated biomass property for solid fuel through torrefaction. It was found when torrefaction temperature was relatively low such as 230 and 260 °C, the weight loss of biomass depended significantly on the temperature. Once torrefaction temperature was up to 290 °C, weight loss of biomass materials tend to become uniform. The O/C ratio decreased and gross calorific value increased during torrefaction process of biomass [14]. Wen et al. evaluated the characteristics of torrefied bamboo at diverse temperatures (200–300 °C) by elemental analysis, XRD, and CP-MAS 13C NMR methodologies. They found that chemical reactions of the native bamboo lignin towards severe torrefaction treatments occurred, such as depolymerization, demethoxylation, bond cleavage, and condensation reactions. Aryl-ether bonds (b–O–4) and p-coumaric ester in lignin were cleaved during the torrefaction process at mild conditions. The severe treatments of bamboo (275 and 300 °C) induced a dramatic enrichment in lignin content together with the almost complete disappearance of b–O–4, b–b, and b–5 linkages [15].

Bamboo is a vital component of plant and forest resources in the world, including over 70 genera and 1200 species. There are totally 2,20,000 km^2 of bamboo resources and the annual production of bamboo is estimated to be 15–20 million tons [16]. With the outstanding characteristics of short rotation, high economic value and advantage for sustainable management, bamboo has become one of the most important non-timber forest products in China. Currently, bamboo resources are very abundant and the total area of bamboo is about six million hectares. Bamboo has been used to produce bamboo house, bamboo panels or composites, bamboo mat, bamboo chopsticks, bamboo sticker, bamboo charcoal or active carbon, bamboo pulp and papermaking, etc. Bamboo is also a promising biomass for future energy production in China [17]. Liu et al. investigated pellet properties from mixture of bamboo and rice straw [18] and compared the properties of bamboo and pine pellets as biomass solid fuel [19]. Liu et al. investigated combustion characteristics of torrefied bamboo, with a temperature range from 200 to 300 °C. It was found that torrefied bamboo had better combustion characteristics compared to bamboo, such as a lower content of moisture and volatiles, a higher energy density, heat release rate and the average effective heat of combustion, a lower H/C and O/C ratios and a shorter ignition time [20]. Fryda et al. analyzed the combustion behavior of the bamboo species *Guadua angustifolia Kunth*, virgin as well as torrefied, in blends with coal or pure, comparing with other biomass feedstocks such as wood and herbaceous biomass. Based on combustion and co-firing data, bamboo showed behavior closer to herbaceous biomass. Dry torrefaction improved its physical properties by increasing the density and grindability without improving significantly its fouling behavior while the fouling behavior of wet torrefied bamboo was similar to woody biomass [21]. Rousset et al. evaluated the effects of torrefaction on the main energy properties of *Bambusa vulgaris* and compared elemental characteristics of lignite, coal and torrefied bamboo. The characteristics of bamboo tended toward those of low rank coals. The loadings plot indicated that the bamboo samples underwent chemical changes related to carbonyl groups, mostly present in hemicelluloses, and aromatic groups present in lignin [22]. Despite these previous researches are very helpful in understanding fuel characteristics of bamboo, Phyllostachys praecox *(CV.Ventricousinternode)* is a different type of bamboo resource. Phyllostachys praecox has been widely cultivated in Zejiang Province of China. Currently, these bamboo resources are very abundant and are mainly used to make toothpicks. During this process, there are a lot of wastes, which have great potential as a bioenergy resource of the future. In this research, Phyllostachys praecox was therefore torrefied with a temperature of 300 °C and a residue time of 2.0 h in the nitrogen environment [21]. Blends of bamboo and torrefied bamboo with coal were prepared in the blend ratios of 10%, 20%, 30%, 40% and 50%, respectively. The combustion behaviors of bamboo, torrefied bamboo, coal and their respective blends were determined by thermogravimetric analysis (TGA) under 20 ml/min, 40 ml/min, 60 ml/min of air flows. The results from this research will be very important and helpful to promote bamboo resources as a blend fuel for co-firing application with coal.

2. Materials and methods

2.1. Materials

Phyllostachys praecox was used in this study. Bamboo materials aging with 4 years were taken from a bamboo plantation located in Zejiang Province, China. The initial moisture content was about 8.1%. Bamboo materials were sawed to bamboo tube with the length of 200 mm (longitudinal) and dried at temperature 105 °C until their mass stabilized.

Bamboo were torrefied using a digitally controlled XD-1200N muffle furnace, made by Aremco Products, Inc. Torrefaction process was carried out in the nitrogen environment with a torrefaction temperature of 300 °C and a residue time of 2.0 h [20]. Then, they were immediately cooled in the desiccator to room temperature.

Coal used for the present study was standard rank originated from China coal research institute. All samples including bamboo, torrefied bamboo and coal were pulverised with a Wiley mill and sieved to desired particle size of 250–425um, respectively. They were dried at temperature 105 °C until their mass stabilized. Then, they were transferred to separate Ziploc bags and sealed tightly.

2.2. Testing combustion characteristics

Combustion characteristics was analyzed in terms of global mass loss though TA Instrument, TGA Q 500 thermogravimetric analyzer (TA Instrument, USA). Samples were evenly and loosely distributed in an open pan with an initial weight of about 5–8 mg. Temperature variation was controlled from room temperature (30 ± 5 °C) to 800 °C with heating rate of 20 °C/min. In this investigation, air was used as reactive gas at constant flows of 20 ml/min, 40 ml/min, 60 ml/min. Weight loss of the samples was continuously recorded during the process. Three replicates of each TGA experiment were performed. The experiment data could be directly obtained though TGA Q 500 thermogravimetric analyzer, and were analyzed using universal analysis software from TA Instruments and origin 8.0 software.

3. Results and discussion

3.1. Thermal decomposition of bamboo and torrefied bamboo

The pyrolysis of lignocellulosic materials plays an important role as the first chemical step in their combustion process because a large part of the original biomass is converted to volatile products. Fig. 1 showed the pyrolysis process of bamboo, torrefied bamboo at a heating rate of 20 °C/min in the nitrogen environment. The characteristic peaks of DTG located in 250 °C indicated moisture