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Assessment on oxygen enriched air co-combustion performance of biomass/bituminous coal

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ABSTRACT

The oxygen enriched air combustion performance and ash fusion characteristics of two typical agricultural and wood samples (corncob and hardwood) and bituminous coal were assessed using a thermal analysis technique. The effects of oxygen contents, sample kinds and blending ratios on the combustion performance were revealed, and the effects of sample properties and blending ratios on the ash fusion of samples were also evaluated. Biomasses showed better ignition performance and comprehensive combustion performance than bituminous coal. The ignition and comprehensive performance indices of corncob/coal blends were higher than those of hardwood/coal blends. Apparently, the combustion performances of biomass/coal blends improved with increasing the oxygen contents and blending ratios of biomass. Certain synergistic interactions were detected between Chinese bituminous coal and corncob or hardwood during the co-combustion at 100% and 80% oxygen contents. The ash fusion reactions of corncob, hardwood and bituminous coal mainly occurred in the ranges of 1036–1079 °C, 1046–1289 °C, and 1260–1290 °C, respectively, while the ash fusion reaction of corncob/coal blends occurred in the range of 1096–1289 °C.

1. Introduction

Because there is much abundant corncob supply in the world, a lot of attentions are focused on the new techniques of using corncob as biomass energy source due to much abundant of this material supply in the world [1,2]. Corncob is more suitable for burning as a fuel instead of serving as a fertilizer in comparison with corn stern and leaf [3]. Corncob can be used positively to meet the requirement of thermal output for tobacco drying at low emissions in comparison with lignite [4]. Woody materials have also widely been used as feedstock for energy [5–7]. Wood residues mainly consist of waste from forest harvesting and lumber mills. Generally, hardwood generally has lesser lignin content (23–30%) in comparison to softwood (26–34%), hence hardwood is expected to produce less CO_2 emissions [5]. Burning biomass alone cannot generate high energy output in comparison to coal combustion due to the high moisture content and low calorific value of the former [8]. Co-firing of biomass and coal in existing power plants is a favorable option [9–11]. Muthuraman et al. find that reactivity of coal has been improved by blending with wood [12]. In addition, oxygen-enriched air atmosphere can further improve co-combustion characteristics of biomass and coal [13]. Both techniques are being considered as methods of enhancing the efficiency of CO_2 capture from power plant for subsequent sequestration [11]. The comprehensive performance indices of beetroot/coal blends and switchgrass/coal blends and their parent samples increase with increasing the oxygen content [8]. Quite a few investigations pay attention into the effect of oxygen contents on single coal or biomass particle combustion characteristics in oxygen enriched air atmosphere. An increasing for the oxygen content in oxygen enriched air atmosphere from 21% to 40% reduced the ignition delay of single coal particle [14]. The ignition delay time of single coal particle in O_2/N_2 atmosphere is much shorter than under O_2/CO_2 atmosphere [15]. Increasing the oxygen content in oxygen enriched air for four different coal categories particles (a high-volatile bituminous, a sub-bituminous and two lignites) and a pulverized sugarcane-bagasse, caused flame and char surface temperatures to rise, and caused burnout times to be reduced [16]. Moreover, inorganic species in biomass fuels such as alkali oxides

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and salts can aggravate agglomeration, deposition and corrosion problems on heat transfer surfaces in boilers [17]. The ash fusion characteristics of biomass are mainly dependent on the high-temperature molten material built up of quartz, potassium iron oxide and silicates [18]. Agglomeration characteristics of corncob combustion in a fluidized bed were elsewhere investigated [19], and results revealed that biomass ash characteristics have significant influence on the bed agglomeration. Biomass fuels may significantly lower the ash melting temperature when co-fired with coal [20]. The formation of low temperature eutectic substance is considered as the initiator of agglomerates [21]. Due to the diversity and variable amount of biomass combusted with coal in industrial processes, produced ash has different characteristics and composition compared to coal ash and has not been characterized to date [22]. By blending potassium-rich hazelnut shell with coal in the ratios of 5 and 10 wt.%, it was found that the addition of biomass reduced the sintering temperatures to 919 and 730 °C, respectively, meanwhile, initial deformation temperature dropped to 788 °C in case of the blend of 10 wt.% [23]. Rice straw, pine sawdust and leaf showed serious slagging/fouling due to their high alkali content, and the ash content decreased with the increase in ashing temperature, and the alkali metals were relatively more volatile with the increase in ashing temperature [24]. Addition of straw into coal lowered the viscosity of the produced ash fractions, and the stickiness of the produced ash particles increases at lower temperatures with increasing the percentage of straw in the blends [25]. The properties of ash material formed during combustion of a blend cannot be predicted from the known characteristics of the ash formed from each fuel, and interaction between ashes from different fuels is poorly understood [26].

Many investigations are usually conducted on co-combustion of biomass/coal under air atmosphere; however, there is a real shortage of published data on assessment of oxygen enriched air co-combustion performance of biomass/coal. Many works are focused on ash fusion characteristics of pure biomass and pure coal. Comparison of oxygen enriched air co-combustion indices and ash fusion behavior between herbaceous or woody biomass and bituminous coal are still scarce.

This paper assesses oxygen-enriched air co-combustion performance and ash fusion characteristics of two typical herbaceous and woody biomass samples (corncob and hardwood) and bituminous coal for a wide range of oxygen contents and blending ratios. The main purpose of the current study is to assess basic understanding of the combustion performance (ignition index and comprehensive performance index) of these solid fuels over the entire possible range of oxygen enhancement, above and beyond the oxygen content of air and possible blending ratio. In addition, the ash fusion behaviors of biomass, bituminous coal and their blends are also evaluated. The comprehensive performance indices are analyzed to assess if there are any synergistic interactions between biomass and coal.

2. Methods

2.1. Experimental facility and test samples

A thermogravimetric analyzer (TGA/SDTA851, Mettler Toledo) with a precision of 0.001 mg was used to conduct the combustion experiments. The corncob and hardwood samples were provided by University of Oakland, and Chinese pulverized bituminous coal were selected, then the biomass samples were crushed and sieved to 0.2–0.6 mm using 80 mesh size. The corncob/bituminous coal and hardwood/bituminous coal blends were shaken thoroughly in a box with biomass mass percentages of 20, 40, 60 and 80%. The initial mass of each sample was maintained at 10 mg ± 0.5 mg, and the total flow of nitrogen and oxygen was set at 100 ml min^{-1}, in which oxygen flow was taken as 21, 40, 60, 80, 100 ml min^{-1}, corresponding to the 21, 40, 60, 80 and 100% oxygen content, respectively. A temperature range of 50–800 °C was set for the combustion processes which were performed at a heating rate of 40 °C min^{-1}. The sample was placed into a platinum crucible. The proximate analyses of the individuals were also tested. The detailed method has been published in our previous work [8]. To examine ash fusion behavior, the samples were dried at 50 °C and crushed into powder with diameters less than 0.2 mm. Then, ash was formed in a muffle furnace by placing 1 g sample in a corundum crucible below 100 °C, and it was heated up to the final temperature (600 °C) at 10 °C min^{-1}. Finally, the samples were maintained at 600 °C for 4 h to ensure complete ashing, and the residual ash was respectively milled to smaller particles (<0.1 mm) by using an agate mortar. Furthermore, corncob/coal ash blends were prepared and homogenized with biomass ash with mass percentages of 20%, 40%, 60% and 80%. TG/DTG/DSC experiments were carried out by a synchronous thermal analyzer (SDT-Q600, TA) with a precision of ±2%. The samples were heated in nitrogen (80 ml/min) in a Pt crucible (using Al_2O_3 as a reference material), in the temperature range between 30 and 1300 °C, with a heating rate of 20 °C min^{-1}. To ensure reproducibility, the experiments were repeated three times. The results indicated that a good reproducibility was maintained for each run because the relative deviation was generally within ±1.0%.

The uncertainties of the measurement in the experiment are dependent on the experimental conditions and the measurement instruments. The uncertainties of the measured parameters were estimated by using the method in Refs. [27–29].

$$\text{The uncertainty of temperature}: \pm\frac{\delta T}{T} = \pm\frac{0.01/2\sqrt{3}}{30} = \pm 0.01\%$$

$$\text{The uncertainty of mass}: \pm\frac{\delta m}{m} = \pm\frac{0.001/2\sqrt{3}}{10} = \pm 0.003\%$$

2.2. Characterizations of combustion performance

The ignition index (D_i) and the comprehensive performance index (D_c) are often applied to evaluate combustion performance of different fuels.

D_i represents the ignition performance of fuels, which reflects how difficult or easy and how fast or slow the fuel gets ignited. It is expressed Eq. (1) as below [30,31].

$$D_i = \frac{DTG_\text{max}}{T_\text{i} T_p} \tag{1}$$

where, DTG_max is the maximum combustion rate (mg min^{-1}), T_p the corresponding temperature of maximum combustion rate DTG_max (°C), T_i the ignition temperature (°C).

D_c represents the comprehensive characteristics. It can be determined by Eq. (2) as follow [8,32–36]:

$$D_c = DTG_\text{max} DTG_\text{m} \Big/ \left(T_\text{i}^2 T_\text{b}\right) \tag{2}$$

where, DTG_m is the average combustion rate (mg min^{-1}), T_b the burnout temperature (°C). It can be deduced that the higher the D_c value is, the better the comprehensive performance.