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Co-combustion of anthracite coal and wood pellets: Thermodynamic analysis, combustion efficiency, pollutant emissions and ash slagging☆

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ABSTRACT

This work presents studies on the co-combustion of anthracite coal and wood pellets in fluidized bed. Prior to the fluidized bed combustion, thermogravimetric analysis are performed to investigate the thermodynamic behavior of coal and wood pellets. The results show that the thermal decomposition of blends is divided into four stages. The co-firing of coal and wood pellets can promote the combustion reaction and reduce the emission of gaseous pollutants, such as SO_2 and NO. It is important to choose the proportion of wood pellets during co-combustion due to the low combustion efficiency caused by large pellets with poor fluidization. Wood pellets can inhibit the volatilization of trace elements, especially for Cr, Ni and V. In addition, the slagging ratio of wood pellets ash is reduced by co-firing with coal. The research on combustion of coal and wood pellets is of great significance in engineering.

1. Introduction

The utilization of biomass energy has become an important and urgent issue, due to the depletion of fossil fuels and worsening environmental problems such as greenhouse gases emission (Leckner, 2007; Yousaf et al., 2017). Among the fossil fuels, the carbon emission of coal is highest and the excessive release of potentially toxic elements during coal combustion has the potential to cause severe health hazards (Basu, 2013; Nzihou and Stanmore, 2013). As a green energy resource, biomass is easily slagging and fouling in the process of mono-combustion, because it contains much alkali metals and alkaline-earth metals (Nutalapati et al., 2007). Therefore, the co-combustion of coal and biomass has successfully attracted more and more attentions, because it can not only reduce the emission of pollutants, but also effectively avoid slagging. (Abelha et al., 2008; Lu et al., 2017).

Thermogravimetric analysis was an easy and effective way to observe the combustion profile of fuel (Otero et al., 2002). Varol et al. (2010) found that low rank coal was burned with biomass beneficially using thermogravimetric test and confirmed the ignition temperature of coal was reduced due to the added biomass. Jayaraman et al. (2017) conducted the thermogravimetric analysis of coal and biomass and found that biomass addition increased the maximum mass loss rate and reactivity of the blends. In addition, fluidized-bed combustion, with its excellent heat and mass transfer performance, is steadily increasing in quantity and capacity (Hupa, 2005; McIlveen-Wright et al., 2007).

When coal and biomass are co-firing in a fluidized bed, combustion efficiency is often the object of research, which is used to evaluate comprehensive combustion performance. Armesto et al. (2003) performed a combustion test of coal and foot cake and found that the addition of a small amount of biomass (10–25%) did not affect the combustion efficiency. However, Gayan et al. (2004) demonstrated that the combustion efficiency of coal increased with the increasing pine bark percentage. Generally, coal/biomass combustion can reduce the emission of nitrogen oxides and sulfur oxides, mainly because of low nitrogen and sulfur contents in biomass (Krzywanski et al., 2013; Williams et al., 2001). Wei et al. (2012) found that co-burning could effectively reduce the

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pollutant emissions, and this reduction was mainly related to biomass. Biomass with low contents of nitrogen and sulfur is an ideal fuel to reduce NO_x and SO_2. Sung et al. (2016) revealed that there was a synergistic effect on the NO_x reduction when woody biomass co-firing with coal. Isobe et al. (2005) found that the combustion of coal/biomass briquettes obviously reduced the emission of sulfur dioxide. In addition to gaseous pollutants during co-combustion, there are many studies on the trace elements. The co-utilization of biomass with coal can redistribute trace elements (Yousaf et al., 2017). Zhou et al. (2017) studied the volatilization characteristics of trace elements during coal gangue and biomass combustion and found that the volatilization rate decreased with the increase of biomass ratio. Kalembkiewicz and Chmielarz (2013) pointed out that biomass co-combusted with coal can improve the ash by reduction of the environmental mobility of Pb, Cd and Zn. Ash behavior and ash-related issues, such as slagging and fouling, are the challenges in co-firing technology, which can reduce combustion efficiency and even lead to the failure of the operation (Kupka et al., 2008). Therefore, it is necessary to study the ash composition and the possibility of slagging. Potassium chloride and potassium sulfate are the main substances affecting the ash slagging (Garba et al., 2012). Teixeira et al. (2012) found that there was no obvious slagging and fouling problems during woody biomass burning. Herbaceous and fruit biomass led to slagging and fouling, and this tendency can be alleviated by co-firing with coal. Many studies have proposed evaluation indices to judge the possibility of slagging and provided guidelines for the selection of co-firing fuel (Davidsson et al., 2008; Vamvuka et al., 2008).

In summary, extensive research on co-firing of coal and different biomass materials such as wheat straw, rice husk, pine sawdust and olive oil residues, has been carried out recently. However, these biomass materials are often in the traditional form, which means they have low energy density, unstable combustion rate, and cannot be used directly in combustion engineering (Karkania et al., 2012). Biomass pelleting technology can increase the particle density, improve the combustion efficiency and reduce the transportation and storage costs, which is considered as an effective method to solve the barrier hindering large-scale application of biomass (Nunes et al., 2014a; b). With the rapid growth of the market, the application of biomass pellets is becoming more and more widely and the majority of pellets are produced from wood. Global wood pellet market has significant growth in the past four years, from about 19.5 million metric tons in 2012 to about 28 million metric tons in 2015 (William Strauss, 2017). In addition, some additives are often added in in the molding process to ensure that the pellets can fulfill some commercial standards. The addition of these additives to more or less changes the nature of the woody biomass (Berghel et al., 2013; Kuokkanen et al., 2011). Therefore, it is necessary and important to study wood pellets. However, to the best our knowledge, there are few studies on the co-combustion of coal and wood pellets in experimental large-scale fluidized bed.

Considering the above factors, the main objective of this paper is to investigate co-combustion of coal and wood pellets. Thermogravimetric analysis was applied to research the combustion behavior of coal and wood pellets. Combustion efficiency, gaseous emissions and trace elements behaviors in fluidized bed were studied. Lastly, the potential risk of ash slagging was also evaluated. These conclusions will provide a theoretical reference for the co-combustion of coal and wood pellets in engineering applications.

2. Materials and methods

2.1. Materials prepare and analysis

Coal in the study is Xuzhou anthracite in China, which is widely used in power plants. Wood pellets are purchased from the biomass pellet manufacturer (Yuejin biomass company, Nanjing). Coal particles were ground to <1 mm and wood pellets were selected at one uniform size (L = 10 mm, D = 8 mm). Prior to fluidized bed experiments, coal particles and wood pellets were dried at room temperature, and prepared for thermogravimetric testing. Proximate analysis was based on the standard procedures of Chinese standard (GB/T 212–2008). Elemental analysis was performed by elemental analyzer (vario EL III, Germany). Heating value was carried out using bomb calorimeter (GB/T 213–2008). Ash sample was prepared in muffle furnace and the compositions were determined by X-Ray Fluorescence (XRF-18000, Shimadzu). The characteristics of coal and wood pellets are listed in Table S1.

2.2. Thermodynamic analysis

Thermogravimetric (TG) and differential thermogravimetric (DTG) analyses of anthracite coal, wood pellets and their blends were performed by TG 209 cell (Thermal Instruments). The samples were heated from ambient temperature to 1000 °C at 100 mL/min (air flow rate) and 20 °C/min (heating rate). Each test was repeated three times to ensure the accuracy of the test results.

2.3. Fluidized bed combustion and analysis

Combustion experiments were performed using fluidized bed, which is illustrated schematically in Fig. 1. The fluidized bed reactor is made of stainless steel with diameter of 100 mm and height of 4.5 m. The combustion system consists of four parts: air supply, feeding device, combustion reactor, and gas purification. Coal and wood pellets are fed into combustion reactor (3–1) through hopper (2–2) by a screw feeder (2–3), which is controlled by electromotor (2–1). Besides, water cooling jacket (2–4) protects the screw feeder during combustion. Inlet air has to go through the preheater (3–4) before entering the reactor. The heat of the whole combustion process comes from the diesel combustor (3–5). The heating jacket (3–2) on the reactor surface ensures the temperature required for the combustion. Fly ash is separated and collected by cyclone separator (4–1). Flue gas was discharged after purified by a fabric filter (4–2). Moreover, in order to keep micro-negative pressure in reactor, induced draft fan (4–3) is operated.

The main influence factors in fluidized bed include combustion temperature, feeding material and air coefficient, etc (Basu, 1999). According to previous researches (Prompubess et al., 2007; Wang et al., 2017), the temperature range for coal/biomass combustion is usually 800–1000 °C. During the experiment, it is found that the temperature error is ±30 °C, which means the temperature adjustment should be large enough (>30 °C). Therefore, the different temperatures (780, 840, 880 and 940 °C) are selected for our research. Excess air coefficient remained steady at about 1.2. As our previous published papers have shown that wood pellets can be fluidized with coal particles (Guo et al., 2017). However, excessive pellets were not conducive to the mixing of two-component materials in fluidized bed. Therefore, it is important to select the appropriate wood pellets ratio. Previous experimental results indicated that the wood pellets percentage should be no more than 20% in fluidized bed (Guo et al., 2017). During the co-combustion test, the feeding rate is 9–10 kg/h (20% wood pellets and 80% coal sample). SO_2 and NO were simultaneously measured by a flue gas analyzer (MGA5, MRU). Measurement parameters of flue gas analyzer are listed in Table S2. The collected bottom ashes from fluidized bed were put into the Teflon crucible and cold digestion for 12 h (HNO_3:$HClO_4$:HF = 3:2:1), then arranged on electric heating board for digestion (120 °C for 2 h + 180 °C for 1 h + 220 °C for 1 h). After completely digestion, the solution was diluted by