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Thermochemical and trace element behavior of coal gangue, agricultural biomass and their blends during co-combustion

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HIGHLIGHTS

- The thermal characterization of coal gangue and biomass were studied.
- The kinetic profiles and optimum conditions of the blends were evaluated.
- The partition behavior of trace element was analyzed.

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ABSTRACT

The thermal decomposition behavior of coal gangue, peanut shell, wheat straw and their blends during combustion were determined via thermogravimetric analysis. The coal gangue/agricultural biomass blends were prepared in four weight ratios and oxidized under dynamic conditions from room temperature to 1000 °C by various heating rates. Kinetic models were carried out to evaluate the thermal reactivity. The overall mass balance was performed to assess the partition behavior of coal gangue, peanut shell and their blends during combustion in a fixed bed reactor. The decomposition processes of agricultural biomass included evaporation, release of volatile matter and combustion as well as char oxidation. The thermal reactivity of coal gangue could be improved through the addition of agricultural biomass in suitable proportion and subsequent appropriate heating rate during combustion. In combination with the heating value and base/acid ratio limitations, a blending ratio of 30% agricultural biomass is conservatively selected as optimum blending.

1. Introduction

Current awareness of fossil energy shortage and environment pollution has resulted in an obvious shift to the exploitation of sustainable and renewable energy. Agricultural biomass is considered to be a clean energy with enormous renewable potentiality, which can contribute to the reduction of CO_2 and SO_x emissions (Demirbas, 2005). Numerous studies have addressed on the various applications with biomass, such as combustion, gasification, pyrolysis (Wang et al., 2009; Idris et al., 2010, 2012; Vassilev et al., 2013; Zhang et al., 2013). Thereinto, co-combustion with coal is one of the promising alternatives for the utilization of biomass fuels. There have been intensive investigations into the co-combustion characteristics of biomass with lignite, bituminous and anthracite coal, which have confirmed that the co-combustion of coal/biomass blends can not only relieve the rapid consumption of the limited fossil fuels, but also can improve the combustion processes (Idris et al., 2010; Li et al., 2011). However, reports on the co-combustion behaviors of biomass with coal gangue are limited so far (Sadhukhan et al., 2008).

Coal gangue is the unexpected residues produced during coal production (about 10–15% of coal production), which contains high ash content, low carbon composition and low calorific value. Nevertheless, with the effective heat and mass transfer potentiality, circulating fluidized bed combustion technology developed for coal gangue combustion has been increasing gradually in both capacity and quantity (Font et al., 2012). Due to the low calorific value and volatile matter of coal gangue, it is necessary to improve its ignition property and combustion process by addition of high calorific value coal when combusted. It is well known that agricultural biomass is a

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material which is characterized by high volatile matter and low ignition temperature. The co-combustion of agricultural biomass with coal gangue may provide a stable flame, improve its combustion characteristic, and enhance the utilization of biomass energy (Biagini et al., 2002). It was reported that the ash deposition and fouling problems encountered in the combustion of biomass may be reduced or eliminated drastically by the combustion of coal/biomass blends (Gil et al., 2010). In addition, the existed circulated fluidized bed combustion devices may be carried out directly with imperceptible modifications (Biagini et al., 2002). Due to the significant difference in the properties of volatile matter, fixed carbon and ash composition, the thermochemical characterization of coal gangue and biomass is completely distinctive. The combustion behaviors and performance of blends, e.g., ignition temperature, heat transfer behavior, gaseous pollutant emissions, fouling, could be affected by the additive amount of biomass (Williams et al., 2012). Therefore, it is extremely significant to investigate the co-combustion behaviors of the coal gangue/agricultural biomass blends.

Trace elements play an important role in the various practices of the renewable biomass energy (Suarez-Garcia et al., 2002). Trace elements are sometimes of great biochemical enrichment, which depends on the plant species, growing site, and age of the agricultural biomass (Kalac et al., 2004). The trace elements' concentrations and transformation behaviors are not only relation with the efficiency of collection and removal devices, but also influence the utilization of biomass highly (Demirbas, 2005). Therefore, the study on partition behaviors of trace elements during co-combustion of biomass together with coal gangue is of great importance.

The main objectives of the present study are to determine (a) the thermal decomposition characterization of coal gangue/biomass blends via thermogravimetric analysis, (b) the reactivity properties of co-combustion of coal gangue and agricultural biomass and the optimum blending ratio and (c) the partition behaviors of trace elements during co-combustion of the blends. The outcome of this study is expected to provide a useful basis for the utilization of biomass rationally.

2. Methods

2.1. Materials

Coal gangue samples (CG) were collected from the floor of No. 7 coal seam of Guqiao Coal Mine, Huainan, China. The samples were collected by cutting channels downwards in order to be representative within a coal seam studies. The agricultural biomass i.e., peanut shell (PS) and wheat straw (WS) originated from Huainan were selected for the co-combustion study. After being collected, these selected samples were stored immediately in sealed plastic bags to prevent contamination. Both the agricultural biomass and coal gangue were air-dried and pulverized to pass through a 200-mesh sieve to eliminate heat transfer limitations. The proximate and ultimate analyses together with the heating values determination of the selected samples were performed and results were summarized in Table 1. Blended samples were prepared with coal gangue and agricultural biomass with ratios of 90:10, 80:20, 70:30 and 50:50, respectively. The coal gangue/biomass blends were mixed in described appropriate proportion and homogenized manually.

The possible chemical functional groups present in coal gangue and agricultural biomass were determined by FTIR analysis (Thermo Nicolet 8700 spectrometer) in the range of 4000–40 cm^{-1} frequency.

2.2. Thermogravimetric analysis

The thermogravimetric analysis carried out in a SDT Q600 thermal analysis system, was performed to determine the combustion characteristics of coal gangue, agricultural biomass and the blends. Experimental conditions of these samples are illustrated as below: 20 mg sample for each analysis, air flow of 100 ml/min and linear heating rates ($H = dT/dt$) of 15 and 60 °C/min, respectively. The combustion temperature was raised from room temperature to 1000 °C. Simultaneous weigh loss (TG) and the rate of weight loss (DTG) reflecting the function of temperature were recorded continuously under dynamic conditions. For each sample and two different heating rates, TG analysis was conducted in triplicates to ensure the reproducibility of the results.

2.3. Trace element analysis

In order to evaluate the partition behavior of trace element during combustion, coal gangue, peanut shell and the blends were fitted within a fixed bed reactor. The fixed bed reactor consists of a cylindrical stainless steel reactor tube and an electric heater of 4 kW to allow the reactor being heated to desired temperatures. The selected samples were fed into the reactor and heated to the desired temperature (1000 °C) under constant air flow. After combustion, fly ash captured at the fabric filter and bottom ash samples were collected for the subsequent elemental analysis. The unburned samples and their ashes were acid digested using an acid solution ($HCl:HNO_3:HF$) with ratio of 3:3:2 in a microwave oven. After digestion, the concentration of selected trace elements (As, Cd, Cr, Cu, Ni, Pb, V and Zn) in these samples was determined by inductively coupled plasma mass spectrometry (ICP-MS). The accuracy of the trace element analysis was calibrated by standard reference material NIST 1632b (coal) and GBW07406 (GSS-6). The precision is within ±5% for the selected trace elements.

3. Results and discussion

3.1. Physical and chemical characteristics

A comparison of calorific value, proximate and ultimate, trace element analysis of coal gangue and agricultural biomass is shown in Table 1. The selected biomass samples PS and WS have much higher moisture content than coal gangue, whereas lower in calorific value and fixed carbon content. Furthermore, biomass samples contain higher volatile matter and volatile fuel ratio [VM/(VM + FC)] than coal gangue, which are significant factors involved in the ignition during combustion (Gil et al., 2010). In addition, biomass samples also have higher proportion of hydrogen and oxygen when comparing with coal gangue, indicating that agricultural biomass has higher thermal reactivity and easier to achieve the ignition. Thus it is expected that the blending of agricultural biomass and coal gangue would enhance the ignition property. The proximate and ultimate analysis of the selected biomass samples are similar to other common biomass that reported in previous studies (Wang et al., 2009; Idris et al., 2010).

For the ash analysis, it is notable that the main chemical components in agricultural biomass are alkali and alkali-earth oxides including CaO, K_2O, Na_2O and MgO other than SiO_2, which are different from that in the coal gangue ash. It was reported that the high concentration of alkali and alkali-earth oxides could lower the melting temperature and emerge agglomeration problems during combustion (Teixeira et al., 2012). The SO_3 and P_2O_5 in biomass samples are also higher than that in the coal gangue ash. During biomass combustion, for the high concentration of alkali and alkali-earth oxides, the sulfide or phosphide can react with these metals and form sulphate or phosphate, and finally retain in residues. Comparison between the trace element concentration in agricultural biomass and coal gangue, the selected