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Interactions of coal gangue and pine sawdust during combustion of their blends studied using differential thermogravimetric analysis

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HIGHLIGHTS

- Pine sawdust and coal gangue exhibited very different combustion behaviour.
- Combustion rate of coal gangue was enhanced by blending with pine sawdust.
- Various interactions within the blends were observed during combustion.
- The interactions within blends were dominated by thermal effect of the materials.
- Oxygen concentration and heating rate affect the extent of the interactions.

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ABSTRACT

The interactions between coal gangue and pine sawdust during the combustion process were studied using thermogravimetric analysis. The effect of the blending ratio, oxygen concentration and heating rate on the weight loss (TG) and differential thermogravimetric (TGA) profiles was examined. The TG and DTG curves of the blends were not additives of those of the individual materials, suggesting that interactions between coal gangue and pine sawdust had occurred during the combustion, especially in the temperature range of 400–600 °C. Kinetic analysis confirmed that the combustion of coal gangue, pine sawdust and their blends was chemical reaction controlled. Further analysis revealed that the interactions between coal gangue and pine sawdust were primarily due to thermal effects rather than structural changes, with the thermal inertia of coal gangue dominating over the behaviour of the blends. The interactions decreased with decreasing the coal gangue ratio in the blend, oxygen concentration and heating rate.

1. Introduction

Coal gangue is an undesired but inevitable by-product of coal mining (Zhou et al., 2012). In China, coal gangue accounts for approximately 10–15% of the total amount of coal produced (Liu and Liu, 2010). Coal gangue disposal occupies a tremendous amount of land and results in a range of serious environmental problems (Querol et al., 2008). Among several strategies, efficient and clean utilisation for power generation is perhaps the most effective means to contain the adverse impacts of coal gangue (Zhang, 2013). With the fuel flexibility advantage of circulating fluidized bed combustion (CFBC) technology and increasing demand for electricity, coal gangue is widely used in CFBC power plants firing low heating value fuels, including biomass and other wastes, in China (Guo et al., 2014). Co-firing of coal gangue and biomass is considered as an alternative, effective method for coal gangue utilisation and pollution control. Since biomass has lower nitrogen and sulphur contents than coal gangue, it can help to limit the discharge of air pollutants such as SO_x and NO_x (Aboyade et al., 2013). In addition, the co-firing with biomass can also off-set carbon dioxide emissions (Lu et al., 2013). Furthermore, biomass also has higher volatile matter and lower ash contents compared to coal gangue (Vassilev et al., 2013), the co-firing of coal gangue with biomass would also provide stable combustion and improve the thermal behaviour of CFBC (Wang et al., 2009; Gil et al., 2010). Note that in operation practices good quality coals are sometimes added to promote the combustion performance by compensating the high ash content and low heating value characteristics of coal gangue (Xiao et al., 2010). Therefore, co-firing of coal gangue and biomass

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not only facilitates the clean utilisation of solid wastes but also increase the combustion efficiency.

The combustion process of biomass is more complicated than that of coal gangue and the fundamental knowledge of combustion of coal gangue and biomass blends is lacking (Meng et al., 2013; Ren et al., 2014; Zhang et al., 2015). Zhou et al. (2015, 2014) pointed out that the addition of biomass (soybean stalk, pine sawdust, peanut shell, and wheat straw) could improve ignition and combustion characteristics of coal gangue and concluded that there were no interactions between coal gangue and biomass during the combustion process of their blends. Although, there have been a number of studies on the synergistic effects between coal and biomass during combustion, some reported that no obvious interactions occur (Gil et al., 2010; Idris et al., 2012; Zhang et al., 1992; Zhang and Wall, 1994) while others noted significant interactions (Vamvuka and Sfakiotakis, 2011; Liu et al., 2012; Moon et al., 2013; Liu and Balasubramanian, 2013). It is also evident that the interactions between coal and biomass were complex and the detailed mechanisms were unclear. However, there has been little work in the literature regarding the mechanisms of interactions and possible synergistic effects between coal gangue and biomass, which is extremely important to the understanding of the combustion processes of coal gangue and pine sawdust blends. Therefore, further understanding of the combustion characteristics of coal gangue and biomass blends and their interactions is still essential.

In the present contribution, the combustion behaviours of a coal gangue and a pine sawdust and their blends were studied by using a thermogravimetric analysis (TGA) technique. The interactions between the coal gangue and pine sawdust during combustion were also investigated under different conditions including the coal gangue blending ratio (CBRs: 80%, 60%, 40%, 20%), oxygen concentration (21% O_2, 7% O_2, 2% O_2) and heating rate (2 °C min^{-1}, 10 °C min^{-1}, 90 °C min^{-1}). The outcomes of this study has been shown to enhance the understanding of the combustion characteristics of coal gangue and pine sawdust blends, providing a useful reference for applications of co-firing coal gangue and biomass in power stations.

2. Experimental

2.1. Materials and methods

A bituminous coal gangue (CG) provided by Pingshuo Power Plant, Shanxi Province in China and a pine sawdust (PS) representing woody biomass were chosen for this study. The CG and PS samples were separately air-dried, milled and sieved into a particle size fraction of 53–75 μm. The samples were then dried in an oven in air at 105 ± 2 °C for 24 h and then stored in sealed plastic bags before use in experimentation. The proximate, ultimate and ash composition analyses of the CG and PS samples were performed according to GB/T 212 2008, GB/T 31391 2015 and GB/T 1574 2007, respectively, and the results are shown in Table 1. It is clear that compared to the coal gangue, the pine sawdust had higher contents of volatile matter and oxygen while lower contents of nitrogen, sulphur and ash. Six CG and PS blends were prepared by vigorously mixing the CG and PS samples in proportions according to the following per cents of CG by mass in the blends, termed as coal gangue blending ratios (CBRs): 0%, 20%, 40%, 60%, 80%, 100%. When CBR was equal to 100%, it means that the coal gangue was tested alone; when CBR was 0%, it means that only the pine sawdust was tested.

2.2. Experimental procedure

A simultaneous thermogravimetry (TG) and differential scanning calorimetry (DSC) instrument (SDT-Q600, TA instruments, USA) was used to study the combustion behaviour of coal gangue, pine sawdust, and their blends. Each sample (around 5 mg) was loaded into a ceramic crucible and placed into the thermogravimetric apparatus. A typical experimental run involved the following steps: (1) heating the TGA from room temperature to 105 °C at a constant heating rate of 20 °C min^{-1}; (2) keeping it isothermal at this temperature for 10 min so as to complete the removal of free moisture; (3) heating TGA to a preset temperature at a certain heating rate (2 °C min^{-1}, 10 °C min^{-1}, 90 °C min^{-1}). During the TGA runs, a constant gas flow rate of 100 ml min^{-1} was used for each of the different atmospheres (21% O_2/79% N_2, 7% O_2/93% N_2, 2% O_2/98% N_2, N_2) employed. Each test was repeated at least twice to assure the repeatability of the experimental results.

3. Results and discussion

3.1. Combustion characteristics of individual samples

The experimental TG, DTG and DSC profiles of the CG and PS samples as a function of temperature at a heating rate of 10 °C min^{-1} in air and nitrogen atmospheres, respectively, are presented in Fig. 1. As shown in Fig. 1(a-1), no obvious weight loss was observed before ca. 300 °C. Possible devolatilization of a small amount of adsorbed gases and very light hydrocarbons might have occurred below 300 °C. A net weight gain was evident before 300 °C according to the TG curves, which may be attributed to the chemisorption of oxygen molecules on the coal gangue surface (Zhou et al., 2012; Zhang et al., 2015). The obvious weight loss of coal gangue in air started from 300 °C and completed at around 600 °C, between which only one peak with the maximum weight loss rate of 3.5% min^{-1} and the maximum heat release rate of 33 mW at 481 °C was seen. When temperature was higher than 600 °C, the mass became invariant, indicating the completion of the combustion of the coal gangue. From Fig. 1(a-2), it can be seen that pyrolysis of the coal gangue took place over a broader temperature range with relatively lower weight loss rates compared to

Table 1
Proximate and ultimate analysis and ash chemistry of coal gangue and pine sawdust used in this study.

Samples	Proximate analysis, ad (wt%)				Ultimate analysis, ad (wt%)					
	M	VM	A	FC	C	H	O[b]	N	S	
CG	1.03	19.06	60.58	19.33	26.65	2.34	6.71	0.46	2.23	
PS	10.09	76.83	0.71	12.37	49.61	5.7	33.69	0.19	0.01	
	Ash chemistry composition (wt%)									
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	SO_3	K_2O	Na_2O	P_2O_5
CG	52.02	33.82	6.01	1.72	0.76	2.29	0.50	0.94	0.65	0.15
PS	12.68	2.74	2.46	35.91	12.66	0.24	3.24	21.39	2.93	5.09

Abbreviations: CG, Pingshuo coal gangue; PS, pine sawdust; ad, air dry basis; M, moisture; VM, volatile matter; A, ash yield; FC, fixed carbon.
Note: b: by difference.