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Effect of ash preparation method on the sintering characteristics of ashes from combustion of coal and biomass blends

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HIGHLIGHTS

- Effect of ash preparation methods on ash sintering systematically studied.
- Sintering temperatures were lowest for low temperature ashes.
- Sintering temperatures were highest for high temperature ashes.
- Biomass addition in coal significantly reduced ash sintering temperature.
- K- and Ca-bearing minerals played a key role in determining sintering temperatures.

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ABSTRACT

Sintering behaviour of ashes from combustion of coal and biomass blends was experimentally investigated with a focus on the effect of ash preparation method. Blends of a Chinese anthracite, Jincheng coal, and two biomass materials, a wheat straw and a pine sawdust, respectively, were subjected to three different ash preparation procedures, namely, a low temperature oxygen plasma ashing device operating at ca 150 °C, combustion in a Muffle furnace at 815 °C and in a drop tube furnace at 1500 °C. The resulting ash samples were then subjected to the sintering temperature measurement using a pressure-drop sintering device, morphological and mineralogical characterisation using scanning electron microscope (SEM) fitted with X-ray energy dispersive spectroscopy (EDS) and X-ray diffractometry analyser (XRD), respectively. For the same coal and biomass blends but different ash preparation methods, the sintering temperatures were always the lowest for the ash samples from the plasma ashing device and the highest from drop tube furnace. SEM imaging showed that the texture of ash samples from the plasma ashing device was irregular, loose and more fibrous, indicating little interactions among the different mineral and inorganic constituents in the individual fuels. The muffle furnace and drop tube furnace ashes were denser and more uniform in shape as the mineral matter and inorganics became fused together. In addition, the drop tube furnace ashes were mostly in spherical-shape, indicating ash melting had occurred during combustion. The XRD analysis revealed that different minerals were present in the ash samples due to different ash preparation temperatures, with high temperature minerals present in the drop tube furnace ash. Biomass addition in the blends lowered the sintering temperature of corresponding ash; the higher the proportion of biomass in the blend, the lower the ash sintering temperature regardless the ashing method. At the same biomass addition ratio, the ash sintering temperature of the blend with the wheat straw addition was lower than that with the pine sawdust addition, because the wheat straw had a higher K and Cl content but lower Ca than the pine sawdust. The EDS and XRD analyses confirmed that the ashes of coal/wheat straw blends contained more K-bearing minerals, while the ashes of the coal/pine sawdust contained more Ca and K-bearing minerals. Both Ca and K-bearing minerals reacted with other minerals in the ash to form low temperature eutectics, leading to the reduction of sintering temperatures of the coal and biomass blends. However, the melting points of the K-containing minerals are higher than the Ca-containing minerals, therefore, the sintering temperatures of ash with the wheat straw addition were lower than those with the pine sawdust addition.

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1. Introduction

Co-firing of coal and biomass has in recent years attracted substantial interest from the utility industry due to its potential to offset carbon dioxide emission and utilise a large quantity of biomass waste, and relative low investment cost required [1–3]. However, co-firing of coal and biomass has also brought about some ash related operation challenges, such as severe ash deposition, slagging and fouling, due to the high content of alkali and alkali-earth species present in many biomass materials. As such, the direct co-firing of coal and biomass blends under various combustion conditions [4–8] and the behaviour of ash formation and deposition have been subjected to many academic and industrial studies [2,9–13].

Kupka et al. [9] studied the co-firing of blends of a South African bituminous 'Middleburg' coal and a sawdust in a slagging combustor to examine the effect of the added sawdust on the slagging propensity of the blends. Two ceramic deposition probes were used to investigate the initial stages of slagging at furnace 1300 °C and 1200 °C at particle residence times of 0.5 s and 2 s, respectively. The addition of the sawdust to the coal was shown to enhance ash deposition and alter the deposit structure of the mixture to become loose and easily removable. Abreu et al. [14] investigated the ash deposition characteristics of a bituminous coal, a pine sawdust and their blends with the pine sawdust proportions being 10% and 50%. The results showed that adding the pine sawdust into the coal decreased the ash deposition rate and the ash deposition rate decreased with increasing the blending ratio of the pine sawdust as higher pine sawdust ratio in the blends yielded the ash deposits with higher levels of silicon and aluminium that had lower capacity to adhere to the surfaces. Wang et al. [15] investigated the fusion characteristics and mineralogy of ash deposits from co-firing of blends of a coal and a wheat straw and found that the ashing processes of the blends were influenced by the coupling reactions of the minerals present in the straw and coal. The literature findings seems to be mixed and sometimes contradicting, suggesting that the addition of biomass affects the ash formation during co-firing and the characteristics of ashes of the blends vary with the nature of the coal and biomass and the ash forming conditions such as combustion temperature and reducing or oxidising nature of the combustion atmosphere [16].

Ash sintering is an early step in the processes of ash fouling and slagging and the knowledge of the sintering characteristics of ashes can help understanding the subsequent ash deposition, fouling and slagging [17]. However, there has been little research on the sintering behaviour and mechanism of ashes from co-firing of coal with biomass. Therefore, a systematic research effort is still needed to understand the mechanisms, especially the interactions between coal and biomass minerals under different ash forming conditions and how the ash fouling and deposition characteristics are impacted upon.

The present research was aimed to investigate the effect of ash sample preparation method on the sintering behaviour of the ashes from coal and biomass blends. The ashes were prepared using three ash preparation methods, namely the low temperature oxygen plasma ashing, combustion in a muffle furnace and a drop tube furnace, respectively. The sintering temperatures of the ashes were measured using a pressure-drop sintering device [18–22] and the effect of biomass blending ratio on the sintering temperature of ashes prepared from the different ashing methods was discussed. The morphology, mineralogy and chemical composition of the ashes prepared were analysed as well in order to understand the transformation and interactions of minerals during the ash formation processes.

2. Experimental

2.1. Preparation of samples

Jincheng coal, an anthracite from Shanxi Province, China, and two biomass materials, a wheat straw and a pine sawdust, were chosen for this study. The as-received coal sample was air-dried, and then crushed and sieved to a size fraction of <100 μm. The as-received wheat straw and pine sawdust were air-dried and then ground in a Waring blender (W-800S, Waring Torrington, CT) and then sieved to a size fraction of <0.8 mm. The sieved coal and biomass samples were dried in an electric oven at 105 °C for 24 h. Coal and biomass blends, with 5%, 10% and 25% addition by mass of each of the two biomass samples, respectively, were prepared. The proximate and ultimate analysis data of the coal and two biomass samples as well as their ash chemistry obtained using an X-ray fluorescence (XRF) analyser are presented in Table 1.

The ash samples were prepared using three different methods, namely, a low temperature oxygen plasma ashing device, combustion in a Muffle furnace and in a drop tube furnace. The low temperature ashes (LTA) were prepared using a low temperature plasma ashing device (EMITECH: K1050X). As reported elsewhere, approximately 1 g of a sample was weighed and placed in a sample cell in the plasma oxidation chamber. Oxygen was passed through the chamber at a flow rate of 27.3 mL min^{-1}. The sample was inspected both visually and by weighing the mass approximately every three hours, until the colour and mass of the sample showed no further change. Typically, the temperature of the plasma chamber was ca. 140–150 °C during the ashing. At this low ashing temperature, the nature of the minerals and inorganic matter in the coal and biomass blends was not significantly affected during the ashing process. Hence, the LTA was prepared to provide the information of the minerals and inorganic matter as present in the coal and biomass samples.

The preparation of ashes of the individual coal, biomass and coal/biomass blends by combustion in a muffle furnace followed the Australian Standard AS 2434.8 (1993). Approximately 0.5 g of each sample was thinly spread on a ceramic tray and then placed in the muffle furnace already preheated to 815 °C. After ashing for 2 h, the muffle furnace was switched off and the ash sample was cooled naturally to room temperature and collected. The ashes thus prepared were denoted as MFA.

In order to simulate the co-firing of the coal and biomass blends, high temperature ashes (HTA) were also prepared using a drop tube furnace operating at temperature of 1500 °C. The drop tube furnace facility consisted of an electrically heated furnace (55 mm I.D. and 800 mm in length) housing a vertical mullite tube (50 mm I.D., 800 mm in length), a vibration screw feeder at the top and an ash collector at the bottom. The length of the isothermal zone was approximately 500 mm and the residence time of the burning particles was approximately 1 s. In a typical combustion experiment, the drop tube furnace was first preheated to 1500 °C and then the sample was fed from a hopper into the furnace through the vibration screw feeder at a feeding rate of 0.1 g s^{-1}. Combustion air was supplied from an air cylinder at a flow rate of 15 L min^{-1} and preheated to 200 °C before entering the furnace. Preliminary experiments confirmed that complete combustion was achieved under such conditions. The ash collected in the ash collector was analysed for unburnt carbon content and the LOI (loss on ignition) was always less than 0.5%.

2.2. Sintering temperature measurement

A pressure-drop sintering temperature measurement technique [19,21–24] was used to determine the sintering temperatures of