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Combustion performance and slagging characteristics during co-combustion of Zhundong coal and sludge

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ABSTRACT

Zhundong coal (ZDc) with a very large reserve is faced with severe problems of slagging and fouling during combustion in boilers because of the high-Na content. Sludge, the by-product of urban sewage treatment, is also faced with the problem in utilization. In this study, the co-combustion of ZDc and sludge was investigated in a laboratory-scale experimental apparatus before further studies in larger-scale setups. The experimental results confirm an interaction between ZDc and sludge during co-combustion, which was mainly caused by the Na catalytic action and improved the combustion performance of the co-fuels. The catalytic effect was particularly significant at low sludge mixing ratios. The reactions between Na-based compounds in ZDc and Si/Al/P-rich minerals in sludge, forming high-melting-point phosphates and aluminosilicates, not only increased Na retention in residual ash reducing the risk of fouling on tail-heating surfaces in boilers, but also raised the ash fusibility of the co-fuels avoiding low-temperature sintering. Even so, to prevent slagging, the high combustion temperature above 900 °C should be avoided during co-combustion because of the high Na retention in residual ash. Moreover, the high heavy metal retention in residual ash decreased the pollution caused by heavy metal volatilization during sludge combustion.

1. Introduction

Zhundong coalfield, the largest integrated coalfield in China, has an estimated coal reserve of 390 Gt, which satisfies more than 100 years of coal consumption in China [1]. Zhundong coal is a clean fuel due to low contents of ash, sulfur and nitrogen. However, the coal-forming time and local conditions cause the higher Na content in Zhundong coal than other coals in China. The high Na content would induce severe slagging and fouling during Zhundong coal combustion in boilers, which largely limited the utilization of Zhundong coal [2,3]. In addition, the high alkali metal contents in fuel would corrode the metal surfaces of boilers [4–7].

Na in Zhundong coal mainly exists in the soluble form [8,9]. The soluble Na is reactive at high temperature and easily reacts with other minerals to form low-melting-point eutectics, which cause slagging easily [10]. In a fluidized bed, such reaction will form a sticky coating layer on the surface of bed material, leading to agglomeration or even defluidization of the whole bed [9,11,12]. Besides, the release of Na starts at 400 °C [8]. Na vapors condense on low-temperature heating surfaces to form an initial deposition layer, or condense/agglomerate on surfaces of fine ash particles to form a sticky coating layer, which enhances ash deposition [10]. For the high-Na coal, the high Na content in the initial deposition layer is the main cause of deposition. Moreover, sodium sulfates resulting from the reaction between the Na in the initial deposition layer and the S in ash or flue gas would corrode metal surfaces [13]. In addition, the NaCl-caused corrosion is more common under Cl-rich conditions [4–7].

To date, there have been many studies on Zhundong coal, but no effective solutions. Temperature is the dominant factor limiting the utilization of Zhundong coal. Slagging of Zhundong coal occurred when the temperature in the furnace was above 1250 °C [14]. Combustion experiments of Zhundong coal in a 25 kW drop tube furnace [10] and a 30 MWth pulverized coal furnace [15] showed that slagging occurred near the high-temperature burner. If the wall temperature of tail-heating surfaces was not controlled well, ash particles would heavily

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deposit on these surfaces [13,16]. Ash deposition experiments of Zhundong coal showed that the deposits on the ash deposition probe were not sintered when wall temperature was controlled below 400 °C [16]. As a summary, a low reaction temperature might be the effective solution to these ash-related problems of Zhundong coal. Thus, the application of Zhundong coal in circulating fluidized bed (CFB) with a reaction temperature range of 850–950 °C is a new trend [9,17,18]. However, no reliable low-cost bed material has been found for this application. Although co-combustion with other low-Na coals [2] or with a proportion of certain additive [19] may also reduce slagging and fouling, these schemes raise the costs.

With the accelerated urbanization in China, the urban sewage discharge is increased rapidly. Sludge is the major challenge of sewage treatment. Since sludge is the breeding ground for a large number of pathogens and parasites, sludge treatments such as drainage to seas and landfill are banned [21,22]. Combustion is the best way to deal with sludge [23]. The fluidized bed incineration technology is an important way and research hotspot of sludge utilization [24–26]. Combustion not only eliminates pathogens and other harmful substances in the sludge, but also facilitates the recycle of sludge energy. However, the combustion of sludge is limited by the low calorific value, indicating sludge should be added with auxiliary fuels (e.g. coal). Co-combustion with coal can effectively improve the sludge combustion and eliminate conventional pollutants (e.g. NO_x) and dioxin in flue gas [27,28]. Another issue regarding the combustion of urban sludge is the volatilization of heavy metals, which is a secondary pollution of sewage sludge [23,29,30]. The contents of heavy metals in ash during sludge incineration are different among sampling positions [31], which indicates the existence of heavy metal migration and transformation during this process and further increases the difficulty of processing the problem. To date, the capture or solidification of heavy metals by solid additives has been the main solution to this problem. As reported, solid additives such as limestone, alumina and kaolin were added into the sludge effectively removing heavy metal vapors from the flue gas [32,33]. Adding coal into sludge also contributed to the solidification of heavy metals in incineration ash [34]. Moreover, during the sludge-biomass co-combustion in a fluidized bed, sludge could retain alkali metals in residual ash in the form of high-melting-point aluminosilicates and phosphates, effectively restraining defluidization [35]. Although the above studies indicate that both Zhundong coal and sludge are faced with problems of utilization, the co-combustion between these two fuels might be their new application solution. However, it is important to realize that a low reaction temperature is still the key to a successful co-combustion.

In this paper, sludge was considered as a potential auxiliary fuel to solve the ash-related problems of Zhundong coal. Based on the above discussion, it is expected that combining the low reaction temperature (such as CFB technology) with the co-combustion of the two fuels could result in an ideal effect without ash problems by retaining more Na in bottom ash in forms of high-melting-point aluminosilicates and phosphates. Since there are no relevant reports about this co-combustion, many works during this co-combustion including Na release and transformation, combustion performance, slagging and fouling characteristics, heavy metal problems because of volatilization, dioxin and other pollutants emission, etc, need to be studied. Therefore, some mechanistic studies about the co-combustion should be first conducted on laboratory-scale experiment platforms as early-stage preparations for their utilization in CFB. In this paper, Zhundong coal with different sludge mixing ratios were tested to investigate the influence of mixing ratio on the co-combustion. By doing this, we also aim to obtain the optimal mixing ratio. In addition, the feasibility of the co-combustion was verified by the co-combustion performance, the release and transformation of Na and slagging characteristics. Some quantitative data, which provided some useful suggestions for the safe operation of co-combustion in larger-scale test system, could be obtained from this paper.

2. Experimental

2.1. Materials

The experimental Zhundong coal (ZDc) was collected from Zhundong coalfield in Xinjiang of China. The experimental sludge in the drying-grained form was sampled from a sewage treatment plant. During preparations, the two fuels were broken and sieved to the size below 0.2 mm. Both fuels were oven-dried at 105 °C for 2 h and sealed as the standby.

Properties of ZDc and sludge are shown in Table 1. ZDc contains only 3.69% ash, but the ash contains up to 7.28% Na_2O, indicating that ZDc is a typical low-rank high-sodium coal. The sludge has only 9.09% carbon and a calorific value only 13.67 MJ/kg. Thus, the sludge is not suitable for combustion alone. In this study, ZDc was mixed with sludge. Sludge mixing ratios were 25%, 50% and 75%, and the corresponding mixtures were referred to as ZS(25%), ZS(50%) and ZS(75%), respectively.

Heavy metal contents in the sewage sludge are shown in Table 2. Common and harmful heavy metals mainly include Cd, Pb, Cu, Zn, Cr, As and Hg. Four major elements in sludge are Zn, Cu, Cr and Pb. Thus, these four heavy metals in residual ash were the focus during the co-combustion of ZDc-sludge. For ZDc, the heavy metal contents are very low. Among the above heavy metals, the content of Cu is the highest, less than 0.2 mg/kg, and the others are even not detected in ZDc. Thus, the heavy metal in ZDc could be ignored.

2.2. Thermogravimetric (TG) experiment

The co-combustion performance of ZDc and sludge was tested in a PE thermogravimetric analyzer (TG/DTA, 6300). TG curves and first derivative of TG curve (DTG) were determined according to the weightlessness of samples during heating. Differential thermal analysis (DTA) curves between the crucible and the reference were also plotted. In this experiment, 15 mg of a sample was put into an Al_2O_3 crucible, which was heated from room temperature (~20 °C) to 1000 °C at a rate of 20 °C/min. Then the temperature was maintained at 1000 °C for 1 h. Due to heat dissipation, the actual highest temperature in the furnace was about 960 °C (Fig. 1). The air atmosphere of the co-combustion was simulated by mixing 21% O_2 with 79% N_2.

2.3. Co-combustion experiment

Co-combustion experiments were conducted in a tube furnace, which had an inner diameter of 30 mm and a total heating length of 300 mm (Fig. 2). The reaction temperature was measured by a thermocouple over the sample. Before each experiment, 3 g mixing sample was loaded in the alumina boat. Then the alumina boat was placed into the reactor. After that, the reactor was heated from the room

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