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Investigation of ash deposition and corrosion during circulating fluidized bed combustion of high-sodium, high-chlorine Xinjiang lignite

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ABSTRACT

A high-sodium, high-chlorine Xinjiang lignite was used as fuel in a 0.4 t/d circulating fluidized bed (CFB) test system to investigate ash deposition and corrosion characteristics using an air-cooled stainless steel probe. Different wall temperatures of the probe, exposed to the similar flue gas environment for 8 h, were achieved by adjusting cooling air flow separately at 1.0 m^3/h, 3.0 m^3/h and 5.0 m^3/h. The probe wall temperature variation was analyzed, and deposited ash was characterized via a series of analytical techniques. Experimental results confirmed the disturbance of ash deposition to the heat flux through the probe, and this disturbance was enhanced due to the faster ash deposition rate at lower wall temperature. The selective deposition of mineral species including Na-, Cl-, K- and Mg-species occurred, resulting in a larger ash deposition amount on the lower-temperature probe. The corrosion caused by NaCl-rich deposited ash was accompanied with the oxidation of metallic matrix. It is found that the antioxidation of metals was in the order of Ni > Cr > Fe. During corrosion, metal chlorides with strong volatility were the main corrosion products, resulting in the presence of voids in deposited ash because of their release. This corrosion was accelerated at high temperatures and had repeatability.

1. Introduction

Worldwide, coal is the second-biggest energy resource after oil. Especially in China, coal still plays an important role in the energy structure due to the small reserve of oil and nature gas. However, the ash deposition, which is primarily related to inorganic minerals in raw coal, needs to be resolved during coal utilization in power plant boilers [1]. Ash deposition on heating surfaces can cause slagging [2–4], fouling [5,6] and corrosion [7,8], which all result in the reduced heat transfer efficiency, increased cost of operation and maintenance, and high accident rate.

Generally, ash deposition was influenced by several factors including reaction temperature, atmosphere, wall temperature, heating surface material and flow field [9–11]. Furthermore, coal type is also believed as one important factor. Actually, more serious ash deposition always happened to the low-rank coals with high contents of Alkali and Alkaline Earth Metal (AAEM) [12–14]. These AAEM species (especially sodium) are primarily present in the coal matrix in water-soluble and ion-exchangeable forms, which are easily released at high temperatures [12]. The released AAEM species, accompanied with droplets, aerosols, solid/molten particles and clusters, usually deposit on heating surfaces resulting in fouling through mechanisms of thermophoresis, condensation, chemical reaction, internal impaction and eddy deposition [5,15,16]. However, for those AAEM species embedded in silicates and aluminosilicates, their low melting points (about 900–1100 °C) are the main reason for the serious slagging on metal surfaces at the high temperature above 1300 °C [17,18]. In addition, during ash deposition process, the corrosion of these metal surfaces frequently occurs under the action of certain special species in deposited ash or flue gas, such as alkali metal chlorines (NaCl or KCl) [8], HCl [19], Cl_2 [20], alkali metal sulfates (Na_2SO_4 or K_2SO_4) [21] and H_2S.

In recent years, several studies have been conducted on ash deposition characteristics of low-rank coals such as Victorian and Xinjiang lignite. Zhou et al. [10,22] measured the effective heat conductivity of ash deposits through the simplified two color method and digital image technique during Zhundong coal combustion in a pilot scale furnace. Based on the digital image technique, it is found that the growth of ash deposits was divided into four stages, which corresponded to the layer structure of the sintering deposits. They found that the measured average effective heat conductivity of ash deposits almost increased linearly with the deposit thickness, which was ascribed to the increasing sintered degree with deposit growth through further analysis

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[22]. In addition, this ash deposition was impacted by wall temperature a lot. In the research of Li et al. [23,24], higher wall temperatures (500 °C, 600 °C and 700 °C) were achieved in a drop tube furnace to simulate the ash deposition behavior of Zhundong coal in the superheaters of supercritical and ultra-supercritical steam cycle boilers. Besides, the mineralogy, morphology and elemental composition of the deposited ash was investigated using an X-ray diffractometer (XRD) and scanning electron microscope with an energy dispersive spectrometer (SEM-EDS). Ja'baz et al. [25] examined the high-temperature tube corrosion upon the interaction with Victorian brown coal fly ash under the oxy-fuel combustion condition, and found the corrosion of low-Cr tubes was more severe, especially under the oxy-firing condition, because of the accelerated corrosion of protective Cr_2O_3 layer caused by sulfates/sulfides. Similar work was also conducted on Xinjiang lignite [11].

To date, most studies about corrosion have been focused on the biomass-fired or biomass/coal-fired boilers [15,19], while few studies are conducted on the high-sodium, high-chlorine coal. Moreover, for this kind of coal, ash deposition and corrosion should not be separated as the individual object of study, but studied as a whole due to their deep symbiosis. Although some studies on the ash deposition of Xinjiang lignite partly involved corrosion caused by alkali metal salts [12,23], these studies paid more attentions to the ash deposition rather than corrosion. Besides, the conventional research method of corrosion on metal heating surfaces through a metal probe coated with synthetic or real ash in thermostatic tube furnace was lack of convincingness because of the big difference with actual boiler metal heating surfaces [8,26].

In this study, a high-chlorine, high-sodium Xinjiang low-rank coal was used as fuel in a 0.4 t/d CFB test system to investigate its ash deposition and corrosion characteristics during combustion. In order to study the influence of wall temperature on ash deposition, the air-cooled stainless steel probes were temperature-controlled through adjusting cooling air flow, which will serve as an extension of our previous works on fouling characteristics under different cooling-media conditions [27]. The probe wall temperature variation was analyzed to assess the heat transfer characteristics during ash deposition process. Besides, the deposited ash was mounted in epoxy and characterized by the thermal field emission scanning electron microscope with an energy dispersive spectrometer (TFSEM-EDS), which was expected to reveal the relationship between ash deposition and corrosion. The aim of this study was to further verify the feasibility of the special Xinjiang lignite during CFB combustion and obtain some useful and new conclusions for its successful industrial applications.

2. Experimental section

2.1. Materials

The used coal was mined from Shaerhu region, Xinjiang province, China. Its properties according to Chinese standards (GB/T212-2008, GB/T476-2008, etc) are listed in Table 1. In particular, the coal contains only 0.12% sulfur but as high as 1.279% chlorine. Besides, Na_2O content is up to 4.38%. The XRD analysis indicates chlorine and sodium mainly exist in the form of halite (NaCl) [28].

Here, quartz sand with SiO_2 as the primary component was used as the bed material. During the preparation process, quartz sand was crushed and sieved in a size range of 0.18–0.71 mm. The used coal was in the size range of 0.1–1.0 mm.

2.2. Test system

The experiments were conducted in a 0.4 t/d CFB test system, as illustrated in Fig. 1. The test system mainly consists of a riser, a cyclone and a loop seal. Thermocouple points (T1 ~ T16) as well as ash sampling points (P1 ~ P16) were located along the gas flow direction. The points of P5 ~ P8, P10, P11 and P13 were set for ash deposition probes to investigate slagging and fouling characteristics of different fuels. More detailed description about this test system can be found in our previous studies [27,29].

Table 1
Properties of the experimental coal.

Proximate analysis (%, air dry basis)	
Fixed carbon	43.86
Volatile	30.46
Ash	14.66
Water	11.02
LHV(MJ/kg)	17.93
Ultimate analysis (%, dry basis)	
C	57.92
H	2.65
O	22.17
N	0.65
S	0.12
Cl	1.279
Ash compositions (%)	
SiO_2	41.98
Al_2O_3	17.59
Fe_2O_3	6.76
CaO	19.39
MgO	2.49
TiO_2	1.08
SO_3	1.82
P_2O_3	0.18
K_2O	0.66
Na_2O	4.38

In these experiments, the ash deposition probe in P7 was used to investigate the ash deposition behavior on it. The probe was cooled by compressed air to simulate heating surfaces in actual boilers. As exhibited in Fig.2, two thermocouples were set for measuring the internal and external wall temperatures of the probe top, which are separately labelled as T_i and T_o. To some degree, the average of the two temperatures can be considered as the wall temperature of the probe. The probe is composed of stainless steel 06Cr25Ni20 named according to GB/T20878-2007, of which chemical components are given in Table 2.

2.3. Test conditions

To investigate the ash deposition and corrosion characteristics of the high-sodium, high-chlorine Zhundong coal, we conducted three tests (labelled as Test I, II and III) in the 0.4 t/d CFB test system. Test conditions were pre-designed. The working temperature (the highest temperature along the riser) was set at 950 °C (± 10 °C). To fluidize ash particle well, we controlled the fluidized velocity in the riser above 3.00 m/s. During the experiments, the air equivalence ratio (ER, the ratio between the actual air flow and the theoretical air flow for fuel just complete combustion) was designed at 1.20. Actually, the measured O_2 concentrations in flue gas by the ZrO oxygen analyzer were 3.73%, 2.49% and 3.25%, corresponding to the ER of 1.21, 1.13 and 1.18, respectively. Besides, the wall temperature of the probe in P7 was controllable through the adjustment of cooling air flow, which was separately fixed at 1.0 m^3/h, 3.0 m^3/h and 5.0 m^3/h for the three tests. For each experiment, the steady working condition lasted for 8 h. The test conditions are listed in Table 3.

2.4. Analysis

After experiments, the main focus was on the wall temperature variation and the property of deposited ash collected from the probe. Based on the wall temperature variation, the influence of ash deposition