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Experimental investigation on ash deposition of a bituminous coal during oxy-fuel combustion in a bench-scale fluidized bed

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ABSTRACT

A bituminous coal was burned in a bench-scale fluidized bed to investigate the associated fly ash depositions under both oxy-fuel and air combustion conditions. The results showed that the highest deposition propensity appeared under 21% O_2/79% CO_2 atmosphere, and only a small difference was observed between 30% O_2/70% CO_2 and air atmosphere. The chemical compositions and micro-morphologies of ash deposits and fly ash were analyzed by inductively coupled plasma-atomic emission spectrometry and by scanning electron microscopy, while particulate matter with an aerodynamic diameter less than 10 μm (PM10) was measured by electrical low pressure impactor. The results showed that there were no obvious differences in the chemical compositions of fly ash and ash deposits between combustion conditions, except for the slight variations in K, Na and S contents. The concentration of PM10 decreased in the order of 30% O_2/70% CO_2 > 21% O_2/79% CO_2 > air.

1. Introduction

Oxy-fuel combustion in circulating fluidized bed (CFB) is regarded as one of the most promising carbon capture and storage (CCS) technologies [1–3]. This technology has the advantage of controlling the bed temperature by the recirculation of cooled ash, thereby, higher O_2 concentrations are allowed in the furnace without the risk of losing control over the furnace temperature. Compared with pulverized coal (PC) systems, oxy-fuel CFB also has the advantages of good fuel flexibility, high boiler efficiency, low NO_x emissions, economical limestone desulfurization and easy load adjustments. Several bench- and pilot-scale CFB units have been built to study the combustion characteristics in furnace [4,5]. In addition, some commercial scale CCS demonstration plants have also been designed to demonstrate the feasibility of applying the advanced technology to fossil fuel power plants. Currently, the 30 MWth CIUDEN oxy-fuel CFB as the largest demonstration has been running successfully since 2011 [6,7]. Fundamental studies of oxy-fuel CFB have also been widely carried out to investigate combustion, heat transfer, and emissions. However, various aspects remain unexplored, such as the effects of recycling flue gas, recarbonation of fly ash and sorbent performance [2,3]. To ensure the reliability, efficiency, and safety of oxy-fuel combustion technology applied to industrial CFB plants, it is vital to obtain more fundamental data from the small scale fluidized bed combustor (FBC) or CFB under well-controlled experimental conditions.

To date, few studies have focused on ash deposition in oxy-fuel fired CFB boilers, even though ash deposition is an important problem in boiler systems and can lead to fouling and agglomeration [8–10]. The mechanism of ash deposition is complex, and the main deposition mechanisms include inertial impaction, thermophoresis, condensation and chemical reaction [11]. The ash deposition process typically involves the coupling of a number of different mechanisms and therefore is affected by many factors, such as coal quality, combustion conditions and deposition environment. Oxy-fuel combustion could have a significant effect on ash deposition behavior [12–16]. In general, two main factors are most likely to affect ash deposition during oxy-fuel combustion: (1) ash properties including unburned carbon, particle size, ash compositions and (2) flue gas physical properties such as temperature, density, viscosity and velocity resulting from varying O_2 concentrations between air and oxy-fuel combustion modes [12]. Li et al. [15] reported major variations in fine ash particle formation and deposition rate during oxy-fuel combustion, since the initial stage of deposition strongly depended on the behavior of fine particles (<10 μm) [17]. Wall et al. [3] pointed out that recarbonation in the back-pass of the boiler could create problems, particularly when burning coal with high Ca contents or when adding limestone for SOx control purposes. Wang et al. [18] conducted a series of tests in a thermogravimetric analyzer (TGA) to study fly ash carbonation under oxy-fuel combustion conditions, and found that the increase in both CO_2 concentration and temperature significantly increases the carbonation ratio. However, there have been no in-depth studies of ash deposition with respect to recarbonation [19]. In addition to the combustion conditions, ash deposition also strongly depends on the coal properties [20]. This effect is difficult to evaluate

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owing to the very wide range of coal types which may be used in boiler systems. In addition, the deposition environment associated with deposit sampling including deposition probe surface temperature, flue gas temperature at the collection port and collection time, is also an important factor which affects ash deposition results [16]. Most literature on ash deposition during oxy-fuel combustion has been based on the use of PC boilers [12–16], such that experimental data concerning ash deposition during oxy-fuel CFB combustion is rare. Our previous experimental results showed that the ash deposition propensity of anthracite burning under 30% O_2/70% CO_2 environment was significantly higher than that obtained under air combustion conditions, a result which was largely related to an elevated concentration of fine particles and a wider particle size distribution (PSD) of the fly ash [21].

In the work reported here, ash deposition of Shuozhou bituminous coal (SBC) was studied to further investigate ash deposition behavior during oxy-fuel combustion in a CFB unit. These detailed ash deposition experiments were carried out in a bench-scale fluidized bed combustor, employing a temperature-controlled ash deposition probe. The concentrations of fine fly ash particles were measured using an electrical low pressure impactor (ELPI) and the results were compared between combustion atmospheres consisting of air, 21% O_2/79% CO_2 and 30% O_2/70% CO_2. The apparatus used here was based on a bubbling fluidized bed that did not include flue gas and ash recycle but still allowed us to obtain suitable operating conditions. No other sorbents were added in experiments.

2. Materials and method

2.1. Fuel and bed materials

SBC from the Shuozhou mine in China was selected and sieved. The ultimate and proximate analysis for SBC and the chemical compositions of its ash are provided in Tables 1 and 2, respectively. The particle size in SBC ranged from 0 to 2.36 mm with a mean diameter of 0.767 mm, and the PSD is presented in Fig. 1. Quartz sand with a particle size range from 0.18 to 0.55 mm and a mean particle diameter of 0.235 mm was used as the bed material. An initial amount of approximately 200 g was loaded to form the bed prior to heating.

2.2. FBC apparatus and operating conditions

A bench-scale fluidized bed apparatus was built to allow the desired experimental combustion and deposition trials to be performed. The body of the combustor consisted of a preheating section, a furnace section (including both dense phase and dilute phase sections), a convective section, a cyclone and a filter bag. The total height of the combustor was 3.5 m; the height of the preheating, dense and dilute phase sections was 385, 315 and 2800 mm, respectively. The inner diameters of the dense and dilute sections were 51 and 83 mm, respectively, between which there was a cone transition section with a slope of 11°. The convective section was 850 mm in length and 56 mm in ID. Three ports were located along this section, for flue gas, fly ash and deposit ash sampling, respectively. The important dimensions of other components of the combustor are also illustrated in Fig. 2a.

To maintain a stable bed temperature, the combustor was equipped with electric heating wires along its vertical structure. All the experimental trials reported in this paper were performed using the same fluidization gas velocity so as to eliminate the variations in the flue gas velocity between oxy-fuel and air combustion modes on deposition. A list of experimental trials is provided in Table 3. The FBC temperature profiles along the flue gas flow direction for the three combustion conditions are presented in Fig. 3. It can be observed that there was an obvious temperature drop near 3.5 m distance in the direction of flue gas flow. This was because this position did not have electric heaters near the outlet of furnace. This temperature drop may lead to the condensation of some gaseous alkali metals in flue gas [22], which will then affect the property of fly ash and subsequent ash deposition. However, considering that the sample coal had a low content of alkali metals, there should be very limited quantity of gaseous alkali metals in the flue gas. Therefore, the influence of temperature drop can be ignored. Before the collection of ash sampling, the central bed temperatures in the dense and dilute phase sections were kept at 750 °C and 850 °C, respectively. As soon as coal samples were introduced into the furnace, the bed temperature of the dense phase section would firstly increase rapidly, but it could be kept at some stable values by adjusting the temperature of preheating gas. However, the adjusted furnace temperature range by this method was still limited. In our experiment conditions, bed temperatures in the dense and dilute phase sections in all trials reached ~870 °C and ~850 °C, respectively. The pressure drop of the dilute phase sections was also monitored by a U-shaped manometer. In the stable experimental condition, the pressure drop was around 1.5 KPa.

The flue gas components, including O_2, CO, CO_2, SO_2, NO_X and H_2O, were measured by an online Fourier transform infrared (FTIR) gas analyzer (GASMET-DX4000, Finland). The linearity measurement deviation for every gas component was lower than 2% of measuring range. The gas components obtained from each of the three combustion cases are given in Table 4. It was observed that the O_2 concentration in the flue gas during air combustion was slightly lower than that obtained during oxy-fuel combustion. The SO_2 and NO_X emissions increased in the order of 21% O_2/79% CO_2 < air < 30% O_2/70% CO_2. In the case of CO, the concentration increased in the order of 30% O_2/70% CO_2 < air < 21% O_2/79% CO_2.

2.3. Ash sampling and analysis

The concentration of PM10 in flue gas was measured by (ELPI, Dekati Ltd., Finland) as shown in Fig. 2b. The ELPI can measure airborne particle size distributions of aerosol particles in the size range of 0.03–10 μm. There were 12 channels with 13 stages with 50% aerodynamic cut-off

Table 1
Proximate and ultimate analyses of the SBC samples (wt.% air dry basis).

Proximate analysis				Ultimate analysis					LHV (MJ·kg^{-1})
M	A	V	FC	C	H	O[a]	N	S	Q_{net}
2.4	29.5	24.4	43.7	57.1	3.83	4.15	1.14	1.88	20.48

M—moisture; A—ash content; V—volatile; FC—fixed carbon; LHV—lower heating value.
Notes: O[a] is obtained by assuming the total weight percentage of C, H, O[a], N and S is 100%.

Table 2
Chemical compositions of the resulting ash for SBC.

	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	Fe_2O_3
Composition (wt.%)	0.47	0.06	40.92	45.81	0.11	4.65	0.04	0.12	0.98

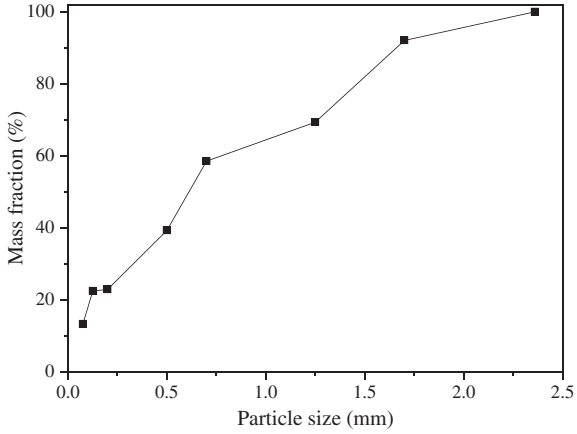

Fig. 1. PSD of SBC.