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Comparison of particulate formation and ash deposition under oxy-fuel and conventional pulverized coal combustions

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HIGHLIGHTS

- ▶ Comparison between conventional and oxy-coal modes was done in a self- sustained coal combustor.
- ▶ Oxy-fuel mode causes more submicron particles and finer bulk ash particles.
- ▶ Aerodynamic factor determines the difference in ash deposition behavior of two modes.
- ▶ The data of a self-sustained combustor differ from those of drop tube rectors.

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ABSTRACT

The characteristics of both particulate formation and ash deposition play an important role in retrofitting the conventional air-fired coal power plant into the recycled oxy-fuel plant. In this paper, an intensively comparative study was performed with a 25 kW quasi one-dimensional down-fired pulverized coal combustor for clarifying the differences between air combustion and recycled oxy-fuel combustion of bituminous coal. In oxy-fuel mode, the volume recycle ratio of flue gas (dry basis) was kept at 77.8%, and then the oxygen concentration at 30% to provide a similar heat flux output to the air mode. A nitrogen-aspirated, isokinetic particulate sampling probe, followed by either electric low-pressure impactor (ELPI) or scanning mobility particle spectroscopy (SMPS), was introduced to measure fine particulates, while an air-cooled deposition probe was designed to collect ash deposit samples. The results indicated that, under similar furnace temperature profiles, the oxy-fuel combustion leads to the higher fine particulate formation, finer bulk ash particle formation and lower ash deposition. The aerodynamic factor, instead of the chemical composition related to fine particulates, determines the difference in the ash deposition behavior in two combustion modes.

1. Introduction

Oxy-fuel combustion, firstly proposed to provide CO_2 rich flue gas for enhanced oil recovery [1], is now becoming one of the most convincing technologies to reduce greenhouse gas CO_2. Since coal will remain one of the biggest energy resources in the foreseeable future, the oxy-coal combustion is receiving considerable attention. In this mode pure oxygen is supplied as an oxidizer and the high CO_2 concentration flue gas is recycled back to the furnace to control temperature. It makes a biggest difference from the conventional combustion by replacing N_2 in furnace by CO_2. As the molar heat capacity, oxygen diffusion rate and other physical properties of CO_2 are quite different from that of N_2, the combustion characteristics and other related issues will be different in the oxy-fuel combustion mode [2].

In order to support the retrofitting process from conventional combustion to oxy-fuel combustion, numerous studies have been conducted on several issues including ignition [2,3], flame stability, coal pyrolysis, char burnout [4,5], NO_x emission [6–8], sulfur chemistry [7,8], radiation [9], fly-ash formation and deposition [10–14] for comparison between conventional combustion and oxy-coal combustion. More recently, some review papers can be found [15–17]. Despite the differences between these two modes, most believe the gap between them can be made up by proper adjustments like input O_2 ratio, recycle ratio or other operating parameters. For instance, similar combustion characteristics can be achieved in oxy-fuel combustion by using higher O_2 concentrations, typically around 30% (in contrast to 21% in air), which suggests that about 60% of the flue gases must be recycled [15].

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However, this elevated oxygen concentration can increase the surface combustion temperature of coal particles, and this will affect the submicron ash formation because of the different evaporation of the metals. Furthermore, the difference in submicron ash formation between oxy-fuel and conventional combustion may impact ash deposition, which ultimately affects fouling and slagging and thus boiler operation. At present, research to bridge particulate formation and ash deposition is limited.

As for particulate formation in both oxy-fuel and conventional combustions is concerned, past researches have mainly focused on combustion in drop tube furnaces (DTFs), where the coal flames are supported by external power, as opposed to a self-sustained coal flame [10,11]. Under conditions of the same O_2 concentration, DTF studies [10] have shown that the total amount and mean size of the submicron particles in oxy-coal combustion are reduced from that of the conventional mode. However, as the O_2/CO_2 ratio increases, these differences become smaller [10]. This can be partially attributed to changes in the particle surface temperature, which determines the metal vaporization during coal combustion [18]. When it comes to ash deposition characteristics in oxy-coal combustion, there are a few works available and these have contradictory conclusions. For instance, some of the literatures report that there are no apparent differences in ash deposition between oxy-fuel and conventional combustions [19,20], while others emphasized a significant difference between them, and then attributed this to the physical and aerodynamic properties of the flue gas and ash particles, instead of the chemical properties of fly ash [12–14]. Also, the existing studies of ash deposition in the oxy-fuel mode were mostly performed in DTF, where heating rates and combustion characteristics differ from those in practical coal combustion devices [10–14]. In oxy-fuel combustion, the experiments in DTF were mainly operated as a once-through system where the CO_2 flow was supplied from gas cylinders instead of recycled flue-gas. So the effects of the recycled H_2O, O_2, SO_2, NO_x and ash particles cannot be accounted for [14]. In addition, the deposition mechanism of ash particles in DTF differs significantly from that in real pulverized coal combustors because of the different aerodynamic characteristics. Therefore, in order to simultaneously examine both particulate formation and ash deposition, it is essential to conduct the experiment in a self-sustained coal flame system with mass feed rates at the kg/h level.

In this paper, aiming to clarify the effect of oxy-fuel combustion on particulate formation as well as ash deposition, both oxy-coal and conventional combustion experiments were conducted in a 25 kW one-dimensional down-fired combustion with self-sustained coal flames. The oxy-coal mode was conducted with flue-gas recycling. A nitrogen-aspirated, isokinetic particulate sampling probe and an air-cooled, temperature-controlled deposit probe, reported in our previous work [21,22], were introduced to obtain particulate matter and ash deposit samples, respectively. In the sampling probe, a high dilution ratio of 65 was used to prevent the fine ash particle nucleation and coagulation in the probe. On the basis of these two kinds of samples, the results and discussion were performed in order to obtain an understanding of ash-related problems associated with oxy-coal combustion.

2. Experimental methods and coal properties

2.1. Air and oxy-coal combustion in a one-dimensional down-fired system

The experiments were performed in a 25 kW one-dimensional, self-sustained, down-fired coal combustor, with 150 mm ID and 3.4 m height. A detailed description of the set-up as well as the procedure of conventional air mode can be found in literature [21]. Fig. 1 is a schematic of the oxy-coal combustion system. A flue-gas recycle system, as opposed to a once-through system, was employed, where the flue gases, after passing through a precipitator and water condenser, were recycled back to the furnace through both primary and secondary "air" inlet tubes. The coal particles were fed through the primary "air" tube, and pure oxygen was only added into the secondary "air" tube. The burner system is a co-annular flow system. From inside to outside, the first flow is gas fuel flow, then the second one is primary air with pulverized coal powders, the flow outer primary air is secondary air with guide vanes (14° between exit velocity direction and vertical direction) to get low swirl flow. Primary air and secondary air flow rates under conventional combustion are 8 N m^3/h and 16 N m^3/h, respectively. Primary "air" and secondary "air" flow rates under oxy-coal combustion are 7.5 N m^3/h and 10 N m^3/h, separately. Reynolds numbers inside furnace body tube near burner are 5100 and 4100, separately for air and oxy mode combustions. In oxy-coal combustion, the recycle ratio is defined as the mass fraction of recycled flue gas to the total amount of flue gas, which is about 77.8% (dry basis) for this work. In order to reduce the effect of air leakage and minimize other external effects to the system operation stability, an auto-supply of pure CO_2 was added into the flue gas, as shown in Fig. 1. The amount of make-up CO_2 is less than 10% of the total flue gas volume. Along the furnace height, there are a dozen thermocouples to monitor temperature profiles and several sampling ports. Here, both the particulate and ash deposit probes were inserted at the port marked "P4" (Fig. 1), which corresponds to the char burnout zone of coal combustion according to the prediction of residence time. For all experimental runs, the gas compositions of O_2, CO_2, CO, SO_2 and NO_x were monitored and recorded by a gas analyzer (MGA-5).

2.2. Coal properties and operating conditions

Here, we used one typical Chinese bituminous coal, Shenhua coal produced from Shanxi Province. The proximate, ultimate and LTA analyses are shown in Table 1. The air dry basis moisture content is about 3%. The 90% volume fraction of this coal is smaller than 76.7 μm. For both in the air and oxy-coal combustion modes, the coal feeding rates were both kept at 3.52 kg/h (air dry basis). The secondary air (flue gas mixed with pure oxygen under oxy-coal mode) was preheated to 640 K before entering into the burner. At start-up, the furnace was heated by liquid petroleum gas. Then, the furnace was switched to a self-sustained coal combustion mode for all the experiments. Under oxy-coal combustion, the O_2/CO_2 ratio into the burner was particularly chosen as 30:70 on a volume basis, which enables a similar furnace temperature profile to the conventional air combustion mode. The furnace temperature profiles of the two different combustion modes are shown in Fig. 2. The gaseous temperatures are measured by S-type thermocouples. The thermocouple bead is covered by a ceramic tube to prevent damages from flying ash particles as well as to reduce radiation loss due to furnace wall. Within the range of experimental error, they are very close, indicating no temperature effect during the data comparison. More importantly, the similar temperature profile meets the retrofitting requirement from conventional combustion to oxy-combustion which ensures similar energy output to heat exchangers. The flue gas compositions, residence time in sampling position and char burnout are presented in Table 2, the O_2 and CO_2 concentrations are presented as volume fraction, and the CO, SO_2 and NO_x concentrations are presented both in ppm and the mass concentration in the stack gas per unit of energy input to the furnace. In this work, the CO_2 concentration in flue gas was always kept at around 80–85%. The SO_2 and NO_x emissions through the stack in oxy-coal mode were much lower than that in air mode. From Table 2, it is noted that the flue gas oxygen concentration