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Research article

Experimental study on NO emissions from pulverized char under MILD combustion in an O_2/CO_2 atmosphere preheated by a circulating fluidized bed

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ABSTRACT

This study examined the combustion of pulverized char under an O_2/CO_2 atmosphere to (1) attempt to achieve a moderate or intense low-oxygen dilution (MILD) combustion process and (2) investigate the effects of gas distribution modes on NO emissions. First, fuel was preheated in a circulating fluidized bed (CFB) and then high-temperature preheated fuel from the CFB was burned in a down-fired combustor (DFC). The study was conducted with two secondary gas nozzle positions, three tertiary gas position arrangements, and four secondary oxygen ratios in the DFC. During the test process, the combustion temperature was uniform in the CFB and the CO_2 concentration in the flue gas reached approximately 90%. MILD combustion was achieved when the secondary gas nozzle position was center and the char combustion reaction dispersed into the upper low-oxygen space in the DFC. The obvious flame front disappeared and the temperature profile in the DFC was more uniform which is also one of the important features of MILD combustion. This reduced NO emissions by around half while maintaining high combustion efficiency. NO emissions were further reduced by a particular arrangement of tertiary gas positions, but at the cost of reducing combustion efficiency.

1. Introduction

Coal oxy-fuel combustion is the process of burning coal using a mixture of pure oxygen and recycled flue gas [1,2]. The recycled flue gas mainly consists of CO_2, and is introduced into the burner to mix with O_2 to avoid excessively high temperatures in the combustor. Because N_2 is absent in flue gas, it has a high concentration of CO_2. In most fuel-burning equipment, the highly concentrated CO_2 in the flue gas can be directly compressed and separated without the use of auxiliary equipment. Oxy-fuel combustion has therefore become an attractive means to capture CO_2 in coal combustion, especially in large coal-fired power plants [3–5]. However, the differences in the physical and chemical properties of N_2 and CO_2, such as the diffusion velocity of O_2 in these gases as well as their heat capacities, pose many challenges in practical applications [6]. Furthermore, air pollution, which is primarily caused by nitrogen oxides (NO_x), SO_2, and particulate pollutants, is a major problem associated with coal oxy-fuel combustion. Among these gaseous pollutants, NO_x formation has received the most attention because its oxidation and reduction processes are highly complex. In addition to their contribution to air pollution, NO_x gases have significant effects on the purity of CO_2 during the compression and separation process [7]. Thus, in order to overcome the emission and storage issues in carbon capture systems, NO_x formation during oxy-fuel combustion needs to be understood in detail.

There are already many proven techniques to reduce NO_x, such as air staging, fuel reburning, selective catalytic reduction (SCR), and selective non-catalytic reduction (SNCR) [8–11]. Many promising new techniques have also been proposed in recent years, including high-temperature air combustion [12,13] and flameless combustion [14,16]. All these technologies reduce NO_x by creating a uniform temperature zone in the burning zone and a lower flame temperature to inhibit thermal NO_x formation. Among these new technologies, MILD (moderate or intense low-oxygen dilution) combustion has been the most promising approach for reducing NO_x. To inhibit thermal NO_x formation, MILD combustion works by creating a low-oxygen environment before the fuel comes into contact with oxygen in the combustion zone, causing the combustion reaction to take place in the whole reactor volume. There were originally understood to be two initial requirements to achieve MILD combustion: preheating of air and a high-speed jet of fuel or air [16–18]. Now, the process of preheating the air has been proven to be unnecessary [15,18]. As a result, the flame front and local high temperature point disappears, and NO_x emissions are

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reduced. However, recent research into MILD combustion has mainly focused on gas and liquid fuels [16,19,20] and the air conditions [21,22]. Though there is already some research on solid fuel MILD combustion in the literatures [15,16], there is a lack of research on the new methods to achieve MILD combustion of coal. Investigating this further could help to reduce NO_x emissions from coal burning.

In addition to combustion method, fuel type also has a significant effect on pollution, with low volatility fuels creating much less pollution than higher volatility ones. However, there are currently some barriers to the use of lower-volatility fuels, such as ignition difficulty, low combustion efficiency, and high NO_x emissions [23,24]. Residual char produced from gasification and pyrolysis of low-rank coal is one such low volatility fuel, but its unstable combustion means that using it is inefficient and large amounts of energy are wasted. To respond to this challenge, a promising technique of preheating pulverized coal in a circulating fluidized bed (CFB) has been proposed and developed [25]. In the process, the pulverized coal is first preheated under a low air ratio in a circulating fluidized bed (CFB) and then burned in a down-fired combustor (DFC) under air-staged combustion. This technique stabilizes the combustion of the low-rank fossil fuel despite its lower volatile component. Most importantly, the combustion efficiency is high and NO_x emissions are greatly reduced. The circulating fluidized bed is actually a type of burner used to transport solid fuel to the main combustion region in the down-fired combustor. To meet the needs of larger combustion loads, this CFB could be smaller and the down-fired combustor could be bigger. Both a 0.2 MW boiler and a 2 MW boiler have been operating in China. These are suitable for the direct retrofitting of existing boilers with economy and convenience, making research results valuable to engineering applications.

In summary, this paper aims to improve the understanding of integrating preheating combustion technology and oxy-fuel combustion technology. Due to the potential advantages of applying preheating combustion technology to establish char MILD combustion, the aims of this study are to (1) identify the most efficient gas-solid mixing conditions to achieve MILD combustion of pulverized char in a down-fired combustor under an O_2/CO_2 atmosphere and (2) identify the effects of gas distribution mode (secondary gas nozzle positions, tertiary gas distribution mode, and secondary oxygen ratio) in such a system on NO emissions.

2. Experimental section

2.1. Apparatus and method

The combustion experiments of pulverized coal were conducted on a test platform (Fig. 1) consisting of a CFB, a DFC, and an auxiliary system. The CFB riser was 78 mm in diameter and 1500 mm in height. The DFC was 260 mm in inner diameter and 3000 mm in height. The heat power of this test platform was 30 kW during normal operation.

The primary gas provided 30–50% of the stoichiometric oxygen requirement. It was used to establish the circulation and provide oxygen for partial coal gasification and combustion to hold an operating temperature of around 850 °C in the CFB. High-temperature gas and preheated char particles entered the DFC through a flue duct of 500 mm length and 48 mm diameter. There were two different secondary gas nozzle positions, as shown in Fig. 2. One, defined as structure-A, was installed in the center position, which is surrounded by preheated fuel (⌀ 14 mm). Structure-B was installed in the ring position consisting of four spouts (⌀ 9 mm). Three flame viewing-windows (⌀ 100 mm) were installed at distances of 100, 300, and 1800 mm below the top to observe the form of the flame. The tertiary gas was imported at 600 or 1200 mm below the top to ensure fuel burnout.

There were four Ni-Cr/Ni-Si thermocouples placed in the CFB, three of which were located above the gas distributor at distances of 100, 500, and 1450 mm, while the fourth was located at the return leg. In addition, there were two Ni-Cr/Ni-Si thermocouples, one placed in the flue duct between the CFB and DFC and one in the inner-circle space of the secondary gas nozzle. There were five Pt/Pt-Rh thermocouples placed in the DFC, which were located 100, 400, 900, 1400, and 2400 mm below the top of the DFC. There were eight sampling ports set as follows: one placed at the CFB outlet for sampling preheated fuel from the CFB; one at the bag filter outlet for sampling fly ash; and the other six ports at 100, 400, 900, 1400, 2400, and 3000 mm below the top of the DFC. The coal gas was analyzed at the CFB outlet with a gas chromatographic analyzer and a Testo-310 analyzer, the gas in the DFC was measured by a Gasmet FTIR DX-4000 analyzer, and the oxygen concentration in the flue gas was measured by a Zirconia oxygen analyzer. The uncertainties of species concentrations and temperatures were estimated to be ± 2% and ± 5 °C, respectively. The data presented in this study are intended to show trends rather than absolute values.

2.2. Fuel characteristics

Shenmu char was used to study combustion and NO emissions characteristics. The characteristics of the fuel derived from proximate and ultimate analyses are listed in Table 1. The size of char particles ranged from 0.1–0.355 mm. The single point adsorption total pore volume of the char was 0.026 cm^3/g, and its bulk density was 827 kg/m^3.

2.3. Experimental conditions

The experiments included changing the secondary gas nozzle positions, secondary oxygen ratio, and tertiary gas nozzle positions. Table 2 lists the conditions of all experiments. The oxygen ratio in the CFB furnace is expressed by λ_{CFB}; the oxygen ratio in the secondary gas nozzle by λ_{Se}; and the tertiary oxygen ratio by λ_{Te}. These variables were calculated as follows:

$$\lambda_{CFB} = \frac{A_{Pr}}{A_{Stoic}} \tag{1}$$

$$\lambda_{Se} = \frac{A_{Se}}{A_{Stoic}} \tag{2}$$

$$\lambda_{Te600} = \frac{A_{Te600}}{A_{Stoic}} \tag{3}$$

$$\lambda_{Te1200} = \frac{A_{Te1200}}{A_{Stoic}} \tag{4}$$

where A_{Stoic} (Nm^3/h) is the total volumetric flow rate of oxygen during the operation process; A_{Pr} is the volumetric flow rate of oxygen supplied to the CFB; A_{Se} is the volumetric flow rate of secondary oxygen supplied to the DFC by the nozzles; and A_{Te600} and A_{Te1200} are the volumetric flow rates of tertiary oxygen supplied to the DFC at the positions 600 or 1200 mm below the top.

During the experiment, λ_{CFB} was fixed at 0.355, i.e. 35.5% of the total oxygen was supplied to the CFB. During the experiment, the oxygen contents of CFB gas, secondary gas, and tertiary gas were around 31.5%, 35%, and 29%, respectively. The total oxygen concentration was adjusted to around 32%, and the oxygen content of flue gas was fixed at 6–8% under the O_2/CO_2 atmosphere. Cases 1 and 2 were used to investigate the effects of secondary gas nozzle positions on NO emissions. Cases 1, 3, and 4 were used to study the effects of the tertiary gas distribution mode on NO emissions. Cases 4, 5, 6, and 7 had the purpose of investigating the effects of secondary oxygen ratio on NO emissions.