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Experimental study on NO_x generation characteristics of Zhundong coal in cyclone air-staging combustion

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ABSTRACT

The cyclone-fired boilers are very suitable for burning high-alkali content coal due to high slag capture rate and low flue gas dust content. However, NO_x generation in cyclone-fired boilers is higher than that in other boiler types. In this work, the NO_x generation characteristic of cyclone combustion was studied in a 100 kW cyclone combustion test bench. The results show that a strong reducing atmosphere is formed in cyclone barrel, and NO_x generation is greatly inhibited in cyclone air-staging combustion. In cyclone barrel, NO_x generation is high in the near-wall zone and low in the central zone. The central zone is the core region of NO_x reduction. After the over fire air (OFA) injects into the burnout furnace, an obvious increase in NO_x concentration is observed, which may be due to oxidation of char-N residue in char in burnout furnace.

Keywords: cyclone combustion, NO_x generation, air-staging combustion.

1. INTRODUCTION

In China, the primary energy structure determines that coal power will remain the main force to ensure the stable supply of electricity for a long time. Large-scale coal resources have been discovered in Xinjiang, with a total reserves of 2.19 trillion tons, of which the most suitable for development and utilization is the Zhundong coalfield. However, the content of alkali metal in Zhundong coal is generally high, which gives rise to sediment pollution problems during combustion and has severely affected the safe and economic operation of power plant boilers[1].

Slag tapping cyclone combustion is a kind of combustion method with high combustion intensity and slag capture rate. It can reduce the degree of heat surface contamination and ash accumulation in the furnace to a certain extent. Since 70% to 90% of the coal ash is discharged from the bottom of the boiler in the form of liquid slag[2], cyclone combustion can greatly reduce the amount of fly ash in flue gas. The slag tapping cyclone combustion can effectively alleviate the problem of surface contamination in the utilization of Zhundong coal. However, NO_x formation in cyclone-fired boilers is higher than that in other boiler types, which limits the application of cyclone-fired boilers to full-fired Zhundong coal. Therefore, it is necessary to develop low NO_x cyclone combustion technology.

Air staging technology has become the widely-accepted and effective method to reduce NO_x [3, 4]. Air staging technology can significantly reduce NO_x generation by creating a reductive atmosphere in the main combustion zone. Bai et al.[5] found that if the high temperature condition can be created on the basis of the reducing atmosphere (i.e. high temperature and strong reducing atmosphere condition), the production of NO_x can be further reduced. It is speculated that the high temperature and strong reducing atmosphere condition is easier to achieve in cyclone boiler, and can effectively alleviate the problem of high generating of NO_x in traditional cyclone boiler. However, the research on air staging combustion technology is only carried out in the drop-tube furnace at present[5, 6], which is much different from the cyclone combustion. There is less research on cyclone air-staging combustion.

In this paper, a 100 kW cyclone combustion test bench is set up to explore the generation characteristics of NO_x under cyclone air-staging combustion.

2. EXPERIMENT

2.1 Coal preparation

The coal species selected for the experiment is Hongshaquan (HSQ) Coal, which is a representative high alkali coal species in the Zhundong coalfield. The proximate and ultimate analyses of coal samples are shown in Table 1. Before the experiment, the coal was ground and sealed for storage. The particle size of coal was measured by laser particle size analyzer. The average particle size of coal is 49.13 μm and d90 is 110.4 μm.

Table 1 The proximate and ultimate analyses of coal

Coal	Proximate analysis（wt%，ar）				
	w(V)	*w*(A)	*w*(FC)	*w*(M)	
HSQ	29.79	7.78	45.69	16.74	
	Ultimate analysis（wt%，ar）				
Coal	*w*(C)	*w*(H)	*w*(N)	*w*(S)	*w*(O^a)
HSQ	59.50	2.70	0.64	0.28	12.36

w(O) ^{a}=100- *w*(A)- *w*(C)- *w*(H)- *w*(N)- *w*(S)

2.2 Experimental setup

A 100 kW cyclone combustion test bench for staged combustion is demonstrated in Fig 1. The test bench consists of a cyclone barrel and a burnout furnace, which are connected by a transition channel in the middle. The internal chamber of the cyclone barrel is 280 mm in diameter and the effective length is 1150 mm. The top of the cyclone barrel is equipped with a burner, from where the primary air carries coal into the furnace. Four pairs of secondary air ports are evenly arranged along the cyclone barrel, and each pair of them is tangentially arranged. Five sampling ports are arranged on the axis of the cyclone barrel to sample and analyze the flue gas. There is a slag discharge port at the bottom of cyclone barrel, where liquid slag flows out of the test bench. At the end of slag discharge port, a sludge pool filled with water is equipped, which can seal the test bench and quickly cool the liquid slag. In addition, there are also four pairs of over fire air ports arranged on the burnout furnace.

Along the direction of flue gas flow, S_1, S_2, S_3 and S_4 ports are selected to sample and measure the components of flue gas, and T_1, T_2, T_3 and T_4 ports are selected to monitor the flue gas temperature. The concentrations of NO and O_2 are analyzed by Testo 335 gas analyzer, and the CO concentration is analyzed by FTIR gas analyzer. The B-type thermocouple is employed to detect the temperature of flue gas in cyclone barrel, with a temperature range of 0-1800 °C. The S-type thermocouple is equipped in burnout furnace, with a temperature range of 0-1600 °C.

2.3 Experimental methods

Before the experiment, the test bench was preheated by burning propane, and the temperature curve of flue gas in cyclone barrel is displayed in fig 2. When propane started to burn, the flue gas temperature increased continuously. As the gas temperature increased to 1170 °C, the rise of temperature tended to slow down. At this time, the gas supply was stopped and the coal feeder was turned on. After the coal burned smoothly, the flue gas temperature rose rapidly until the flue gas temperature stabilized at 1420 °C, at which point the flue gas sampling work began.

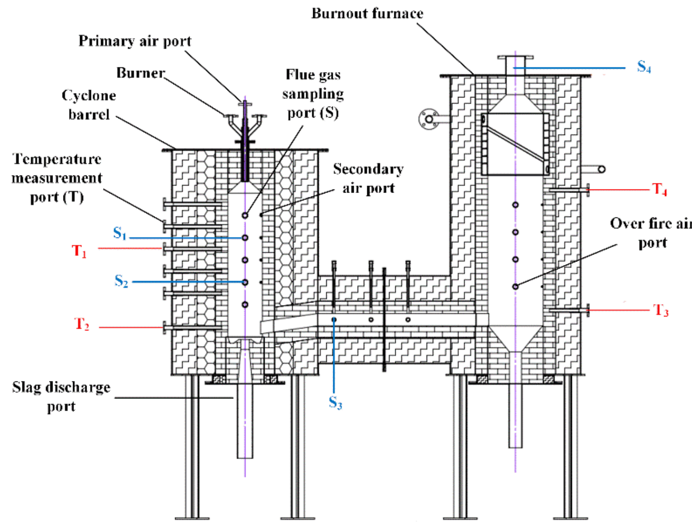

Fig 1 Schematic diagram of experimental setup

During the experiment, the coal feed rate was stably maintained at 20 kg·h^{-1} and the total air volume was controlled at 123 m^3·h^{-1}. The primary air rate was kept at 0.3, and the stoichiometric ratio (SR) of the cyclone barrel was adjusted by changing the secondary air rate. In this experiment, the SR of cyclone barrel was 0.8, and the total SR of the test bench was 1.1. During operation, the pressure in the furnace was adjusted by the air pump and induced draft fan, and the pressure of the cyclone barrel was controlled within -100 Pa.

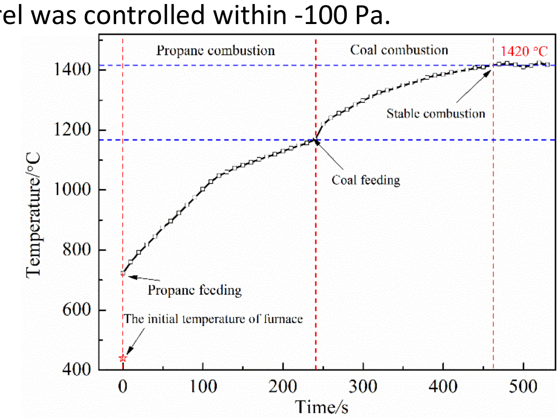

Fig 2 Temperature changes of flue gas in cyclone barrel

2.4 Calculation

For the convenience of comparing with previous studies, the NO concentration (μL·L^{-1}) in the flue gas measured by Testo335 has been converted to the mass concentration of NO_2 (mg·m^{-3}), which is computed by

$$NO_2\text{(mg}\cdot\text{m}^{-3}\text{)} = C_{NO} \times 2.05$$

where, C_{NO} is the concentration of NO in flue gas (μL·L^{-1}).

2.5 Uncertainty analysis

For this experiment, the accuracy of the experiment depends on the accuracy and stable of the coal feeder, the accuracy of the flow meter and the measurement accuracy of the flue gas analyzer. Before the experiment, the coal feeder was strictly calibrated, and the feeding rate error is less than 2%. The high-precision vortex shedding flow meter was employed to measure the flow rate of air, the error of which is less than 0.5%. The NO_x and O_2 concentration were analyzed Testo 335 gas analyzer, and the estimated uncertainty limits are ±2%. The CO concentration was analyzed by the gas analyzer (GASMET FTIR DX4000), and the estimated uncertainty limits are ±2%. For each experiment, the measurement was recorded for at least 10 min after the flue gas concentration is stabilized, and the average value is obtained. For all experiments, the uncertainties of NO_x are less than 5%, and the uncertainties of CO are within ±3%. For instance, at the upper of cyclone barrel, the NO_x concentration is 775±35 mg·m^{-3}, and the CO concentration is 6.03±0.15%. At the exit of cyclone barrel, the NO_x concentration is 246±10 mg·m^{-3}, and the CO concentration is 9.91±0.18%.

3. RESULTS

3.1 The distribution of flue gas components along the direction of flue gas flow.

The changes of NO_x, O_2 and CO concentrations along the direction of flue gas flow in cyclone air-staging combustion are shown in Fig3. The results suggest that a drastic decrease in NO_x concentration occurs along the direction of flue gas flow in the cyclone, and the initial NO_x concentration in the flue gas is relatively high. At the outlet of cyclone barrel, the NO_x concentration drops by 44% than that in the flue gas sampled at S_1 port. This can be attributed that at the upper of cyclone barrel, the oxygen supply is abundant due to the injections of primary air and secondary air. In such an oxygen-sufficient environment, NH_3 and HCN produced by coal pyrolysis are rapidly oxidized. Although local high oxygen concentration leads to an increase in NO_x generation, the overall oxygen supply in the cyclone is insufficient. With the coal burning, the oxygen in the flue gas is gradually consumed. As shown in Fig 3, the oxygen concentration gradually decreases in the cyclone barrel, while a dramatic increase can be observed in CO concentration. At the outlet of cyclone, the oxygen concentration is only 0.15%, and the CO concentration can reach 9.91%. A reducing atmosphere condition is formed, which promotes the reduction of NO_x. The consumption of oxygen greatly inhibits the oxidation of nitrogen-containing substances and in the reducing atmosphere, the reduction reaction of NO_x is the dominant reaction. Moreover, as the consumption of oxygen, the heterogeneous conversion of coal is mainly based on gasification reaction, which significantly facilitates the generation of CO. High concentration of CO can promote the Char-NO_x-CO reduction reaction, effectively reducing the formation of NO_x under staging condition. To sum up, NO_x generation in cyclone barrel can be significantly inhibited under air-staging condition. But the NO_x concentration in the flue gas at the outlet of cyclone can still reach 246 mg·m^{-3}, this may be due to the high initial generation of NO_x at the upper of cyclone barrel. To further reduce the NO_x generation in cyclone barrel, the local high oxygen concentration should be avoided, and a staging secondary injection method maybe alleviate this problem.

After the over fire air (OFA) injects into the burnout furnace, the CO in the flue gas is consumed rapidly, and an obvious increase is observed in NO_x concentration. According to previous study[7], this phenomenon may be caused by oxidation of char-N residue in char. To minimize the increase of NO_x in burnout furnace, the residence time of coal particle should be extended and the slag capture rate can be raised by adjusting the operating parameters.

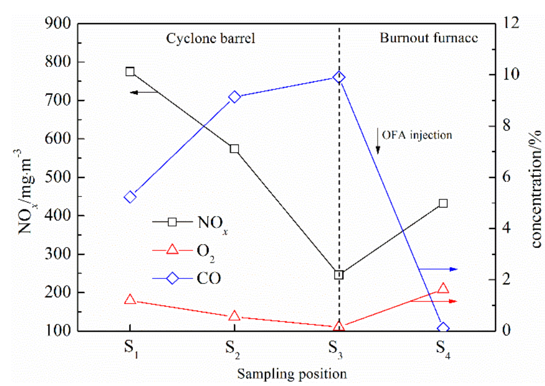

Fig 3. The distribution of flue gas components along the direction of flue gas flow

3.2 The distribution of flue gas components in the radial direction of the cyclone barrel.

For cyclone boiler, coal particles are burnt in the cyclone barrel with a strong rotation. The coal particles are carried by the primary air through the swirl vanes of burner into the cyclone barrel and mix with the secondary air. Then, driven by a rotating secondary air, the coal particles move to the cyclone barrel wall and burn violently near the wall. The composition of flue gas varies significantly in the radial direction of the cyclone barrel. Therefore, it is essential to explore the distribution characteristics of NO_x in the radial direction of cyclone barrel to reveal the characteristics of NO_x generation in cyclone combustion.

The distribution of NO_x, CO and O_2 concentration in the radial direction of cyclone barrel is shown Fig 4. The results suggest that the NO_x distribution presents the characteristics: NO_x generation is higher near the wall and lower in the central zone. Along the wall to center in cyclone barrel, oxygen concentration decreased significantly and CO concentration gradually increased. This may be attributed that tangential injection of secondary air mainly gathers in the annular zone near the wall, which causes that oxygen concentration is relatively high in this region, promoting the generation of NO_x.

While in the central zone of cyclone barrel, oxygen supply in this zone is insufficient. When the small size coal particles burn in this region, there is not enough oxygen to ensure the full combustion of them. Thus, a strong reducing atmosphere is formed in this region. In such an environment of high CO concentration and low oxygen concentration, the generation of NO_x is inhibited and NO_x diffused from near-wall region can be also effectively reduced. Therefore, the central zone is the core area of NO_x reduction. In order to reduce the total generation of NO_x in cyclone barrel, the ratio of primary air to secondary air can be adjusted to minimize the area of high oxygen concentration area in near-wall region.

4. CONCLUSIONS

The main following conclusions that can be drawn from this paper:

(1) The strong reducing atmosphere condition can be formed in cyclone barrel in cyclone air-staging combustion, and NO_x generation is reduced dramatically under air-staging condition.

(2) After OFA injects into the burnout furnace, the NO_x increases, this phenomenon may be due to the oxidation of char-N residue in char. To minimize the increase of NO_x in burnout furnace, the residence time of coal particle should be extended and the slag capture rate can be raised by adjusting the operating parameters.

(3) NO_x distribution in the radial direction of cyclone barrel presents the characteristics: NO_x generation is higher near the wall and lower in the central zone. The central zone is the core region of NO_x reduction.

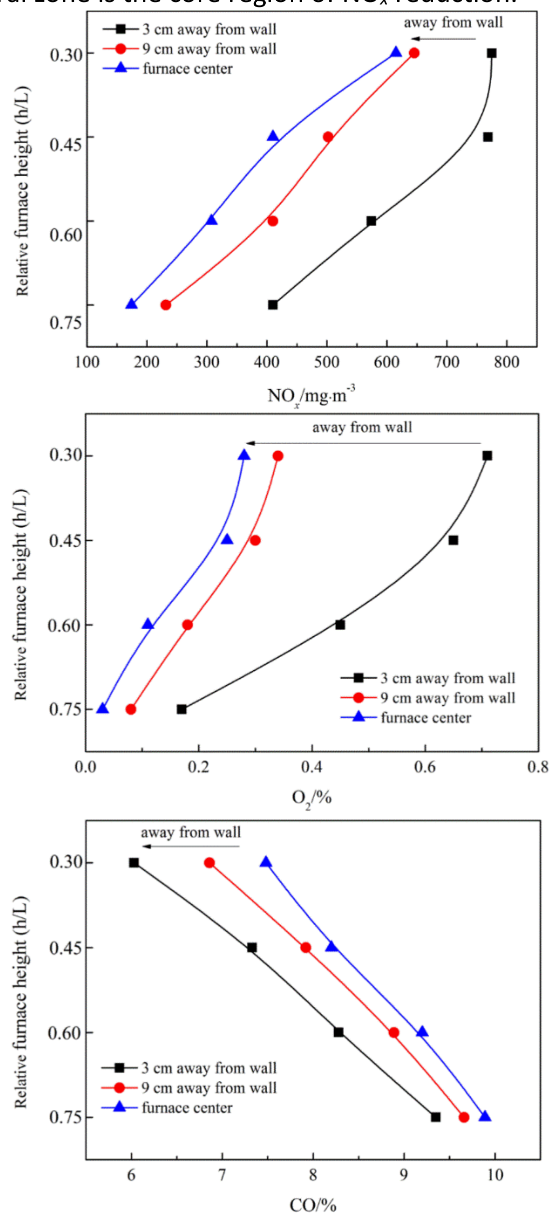

Fig 4 The distribution of flue gas components in the radial direction of the cyclone barrel.

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