Experimental Study on Combustion Characteristics and NO_X Emissions of Pulverized Anthracite Preheated by Circulating Fluidized Bed

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A 30 kW bench-scale rig of pulverized anthracite combustion preheated by a circulating fluidized bed (CFB) was developed. The CFB riser has a diameter of 90 mm and a height of 1,500 mm. The down-fired combustion chamber (DFCC) has a diameter of 260 mm and a height of 3,000 mm. Combustion experiments were carried out using pulverized anthracite with 6.74% volatile content. This low volatile coal is difficult to ignite and burn out. Therefore, it requires longer burnout time and higher combustion temperature, which results in larger NO_X emissions. In the current study, important factors that influence the combustion characteristics and NO_X emissions were investigated such as excess air ratio, air ratio in the reducing zone, and fuel residence time in the reducing zone. Pulverized anthracite can be quickly preheated up to 800℃ in CFB when the primary air is 24% of theoretical air for combustion, and the temperature profile is uniform in DFCC. The combustion efficiency is 94.2%, which is competitive with other anthracite combustion technologies. When the excess air ratio ranges from 1.26 to 1.67, the coal-N conversion ratio is less than 32% and the NO_X emission concentration is less than 371 mg/m^3 (@6% O_2). When the air ratio in the reducing zone is 0.12, the NO_X concentration is 221 mg/m^3 (@6% O_2), and the coal-N conversion ratio is 21%, which is much lower than that of other boilers.

Keywords: circulating fluidized bed; preheat; pulverized anthracite; NO_X

Introduction

The anthracite coal reserves in China are huge, up to 360 billion tons, which make up approximately 17% of the reserves of coal used for power generation [1]. By 2006, power generation provided by anthracite accounted for 5.5% of the overall thermal power generation of the country, and this ratio will increase continuously in the future. It is estimated that anthracite power generation capacity will increase to 20 GW in 15 years [2].

Anthracite is characterized by low volatile content and high fixed carbon content. Such features make it difficult to burn out. Methods for boiler design and operation to solve this problem include improving combustion temperature, enhancing flow field disturbance, and prolonging combustion time [3–5]. Nowadays, boilers widely used in China for anthracite combustion are tangentially fired boilers, W flame boilers, and circulating fluidized bed (CFB) boilers. However, the NO_X emissions of tangentially fired boilers and W flame boilers are high, generally 850–1,300 mg/Nm^3(@6% O_2) [6]. Furthermore, the boilers experience serious deposition and slag, and

high combustible substance content in fly ash [7]. Such problem exists in CFB; the mass fraction of combustible substance in fly ash is generally 10%–20%, sometimes even up to 30% [8, 9].

The present study of our research team focuses on combustion and pyrolysis of coal, biomass and sludge by CFB [10–12]. A new technology based on pulverized coal preheated by CFB was proposed by Lü Qing-gang [13]. This technology is expected to achieve flame stability, high combustion efficiency, and low NO_X emissions of pulverized anthracite combustion. Experimental studies show that Datong bituminous coal with 30.6% volatile combust stably and achieve low levels of NO_X emissions [14].

This paper aims to identify the preheating of pulverized anthracite in CFB and the combustion stability of preheated pulverized anthracite, and evaluate NO_X emissions and the conversion ratio of coal-N to NO_X with variations of excess air ratio, air ratio in the reducing zone, and residence time in the reducing zone. Hence, experiments were carried out using pulverized anthracite with volatile content lower than 8%.

Experimental set-up description

Experimental apparatus

As shown in Fig. 1, the 30 kW test rig was composed of a CFB, a down-fired combustion chamber (DFCC), and an auxiliary system.

The test rig system is based on the system described in reference [14]. To obtain better heat balance for pulverized coal combustion between the CFB and the DFCC,

this test rig system was optimized with a smaller CFB and a bigger DFCC, compared with the system in reference [14]. With the advantage of strong gas-solid turbulence for faster heat and mass transfer in the CFB, pulverized coal can be preheated quickly before entering the DFCC for combustion.

The riser of the CFB is 90 mm in diameter and 1,500 mm in height. The air distributor is at the bottom of the riser. A port for feeding coal is 240 mm above the air distributor, which is the only place where pulverized coal was supplied.

Primary air is supplied to the bottom of the riser through the air distributor, with 10%–30% of theoretical air for coal combustion. The primary air fluidizes the bed materials and provides oxygen for partial combustion of pulverized coal. The temperature of the bed materials can be maintained and pulverized coal can be preheated up to 800℃ using heat from partial combustion of pulverized coal in the CFB.

The DFCC is 260 mm in diameter and 3,000 mm in height. Secondary air is injected into the top center of the DFCC through a tube with an inside diameter of 10 mm and velocity ranging from 18 to 60 m/s. High temperature pulverized coal from the CFB was carried to the top center of the DFCC and was injected into the DFCC (shown in Fig. 2). The secondary air is 10%–50% of the theoretical air for coal combustion.

Tertiary air, which promotes combustion, can be supplied to the DFCC at 200, 600, and 1,200 mm below the top of the DFCC. It first enters an annular channel, and then enters the DFCC through three supporting tubes with an inside diameter of 10 mm each (Fig. 3).
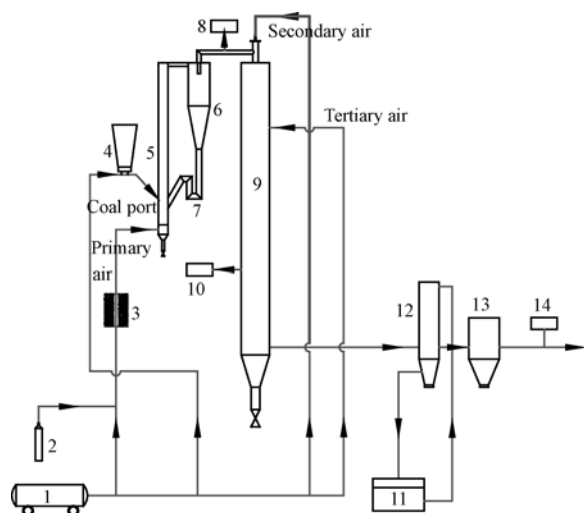

1 Air compressor, 2 Liquefied petroleum gas, 3 Heater, 4 Coal feeder, 5 Riser, 6 Cyclone separator, 7 U-valve, 8 Gas analyzer, 9 DFCC, 10 Gas analyzer, 11 Water tank, 12 Water cooler, 13 Bag filter, 14 Gas analyzer

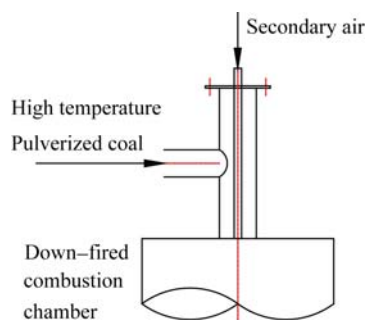**Fig. 1** Schematic of the experimental system
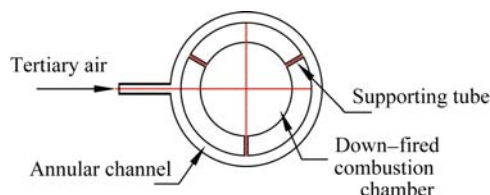

Fig. 2 Inlet of secondary air

Fig. 3 Inlet of tertiary air

The area between the secondary and tertiary air ports of the DFCC is the reducing zone. Different reducing conditions can be set according to the change in the secondary air flow, tertiary air flow, and tertiary air port. Therefore, the influence of reducing conditions on preheated pulverized coal combustion efficiency and NO_x emission can be studied.

Seven sampling ports are set: at the outlet of the cyclone separator of the CFB for sampling preheated pulverized coal, at the outlet of bag filter for sampling exhaust, and five ports at the DFCC, namely, 100, 400, 900, 1,400, and 2,400 mm below the top of the DFCC.

Test samples

The anthracite used in the experiments was from Yangquan Coalmine, China. Its proximate and ultimate analysis is listed in Table 1. The volatile as dry ash-free basis is 7.58%. The ratio of fixed carbon and volatile is 12.2.

The diameter of the pulverized coal is smaller than 0.355 mm, with 50% cut size about 82 μm. The bed material for CFB in the experiments is silicon sand, with diameters ranging from 0.1 mm to 0.5 mm with a 50% cut size about 210 μm. The size distribution of pulverized anthracite and sand are given in Fig. 4.

Table 1   Coal characteristics

	Items	Value
Proximate analysis w/%	M_{ad}	2.40
	V_{ad}	6.74
	FC_{ad}	82.22
	A_{ad}	8.64
	$Q_{ad,\,L}$ (MJ/kg)	31.04
Ultimate analysis w/%	C_{ad}	82.08
	H_{ad}	3.13
	O_{ad}	1.87
	N_{ad}	1.18
	S_{ad}	0.70
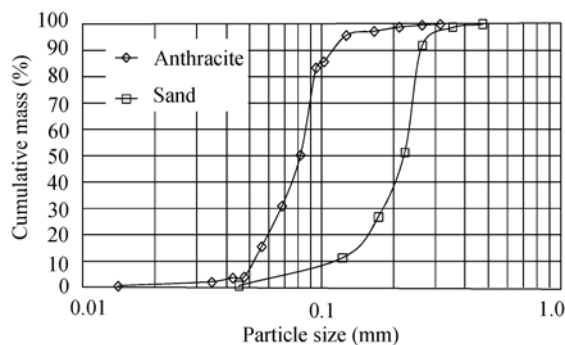
Fig. 4   Size distribution of pulverized anthracite and sand

Experimental conditions

Effect of excess air ratio on NO_X emissions

As excess air ratio increased, the oxygen concentration in the DFCC and the conversion ratio of coal-N to NO_X increased, which led to an increase in NO_X emission concentration [15, 16].

The experiments were carried out by changing the excess air ratio. The excess air ratio, α, is defined as the total air flow supplied to the test rig / theoretical air for pulverized coal combustion.

The experimental conditions of the excess air ratio on NO_X emissions are listed in Table 2.

Table 2   Cases of different excess air ratios

	Case 1	Case 2	Case 3	Case 4
G (kg/h)	3.56	3.91	3.62	3.52
F_{CFB} (Nm³/h)	6.8	7.5	7.0	7.0
α_{CFB}	0.24	0.24	0.24	0.25
α	1.26	1.36	1.48	1.67

where:

G is the weight of pulverized coal supplied to the CFB, kg/h;

F_{CFB} is the primary air supplied to the CFB, Nm³/h;

α_{CFB}, is the total air flow supplied to the CFB / theoretical air for pulverized coal combustion.

Effect of combustion parameters in the reducing zone on NO_X emissions

Air ratio in the reducing zone, α_r, is defined as secondary air flow / theoretical air for pulverized coal combustion.

The research results of Tarelho [17] and Li [18] indicated that, under the air-staged combustion condition, the decrease in α_r normally led to the reduction of NO_X emissions. However, when α_r is too small, HCN, NH_3 and char-N in the reducing zone will increase quickly and will be oxidized in the burn out zone. This leads to increased NO_X emissions.

The NO_X emissions are investigated by changing the air ratio in the reducing zone. The experimental conditions are listed in Table 3.

Table 3   Cases of different air ratios in the reducing zone

	Case 5	Case 6	Case 7	Case 8
G (kg/h)	3.53	3.91	3.76	3.69
F_{CFB} (Nm³/h)	6.7	7.5	6.7	6.9
α_{CFB}	0.24	0.24	0.22	0.23
F_2 (Nm³/h)	5	10	15	20
F_3 (Nm³/h)	29	25	20	15
α_r	0.12	0.24	0.36	0.48
α	1.44	1.36	1.38	1.42

where:

F_2 is the secondary air flow, Nm^3/h;

F_3 is the tertiary air flow, Nm^3/h.

By changing the tertiary air port location, the area of the reducing zone can be changed, thus the residence time of pulverized coal can be changed as well. The experimental conditions for the effect of residence time in the reducing zone on NO_X emissions are listed in Table 4.

Table 4 Cases of different residence times in the reducing zone

	Case 9	Case 10	Case 11
G (kg/h)	3.73	3.91	2.60
F_{CFB} (Nm^3/h)	7.3	7.5	7.5
α_{CFB}	0.24	0.24	0.36
F_2 (Nm^3/h)	10	10	10
F_3 (Nm^3/h)	24	25	24
L_3 (mm)	200	600	1,200
v_g (m/s)	1.23	1.14	1.11
t_r (s)	0.16	0.53	1.08
α_r	0.24	0. 24	0.24
α	1.40	1.36	1.99

where:

L_3 is the distance from tertiary air port to the top of the DFCC, mm;

v_g is the mean velocity of flue gas in the DFCC, m/s;

t_r is L_3/v_g, the residence time in reducing zone, s.

Results and discussion

Temperature profiles

In Case 6, α_{CFB} is 0.24, the excess air ratio α, is 1.36. The temperature profiles in the CFB and the DFCC of Case 6 are shown in Fig. 5 and Fig. 6. The temperature profiles in other cases is similar that in Case 6.

Fig. 5 shows that when air flow is only 24% of the theoretical air, the temperature distribution along the riser is uniform, with a maximum temperature difference of only 40 ℃. The preheating of pulverized coal was achieved using CFB in this test rig.
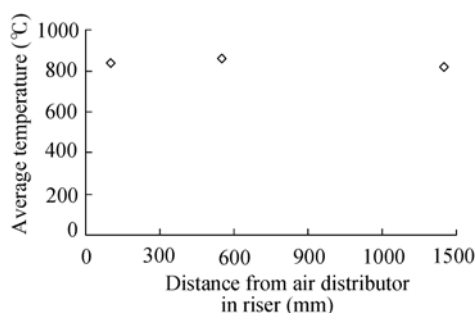
Fig. 5 Axial temperature profile in riser
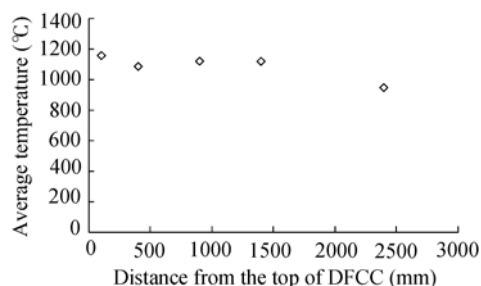
Fig. 6 Axial temperature profile in DFCC

Fig. 6 shows that the preheated pulverized coal combusts quickly in the DFCC. The highest flame temperature is 1,158℃, reached at 100 mm below the top of the DFCC, which is lower than that in the other combustion of pulverized anthracite without preheating [19]. The maximum temperature difference in the DFCC is 213℃.

Combustion efficiency

Ignition and combustion stability were firmly secured with the preheating of the pulverized anthracite. By adjusting the amount of secondary and tertiary air, NO_X emissions were largely reduced, while the combustion efficiency was kept at a relatively higher level.

In Case 9, the mass fraction of combustible substance in the fly ash before the inlet of bag filter is 39%, resulting in a combustion efficiency of 94.2%. In Case 10, for the location lag of the tertiary air, the combustion efficiency decreased to 91%.

Cloke [20] studied anthracite (V_{daf}=16.1%–16.9%) combustion in the drop tube furnace and found that the mechanical incomplete combustion heat loss was approximately 11%, resulting in a combustion efficiency of less than 89%. Thus, preheating the pulverized anthracite could promote its burnout and increase its combustion efficiency.

The property of nitrogen oxidation formation

Some studies on the mechanism of NO_X formation indicated that the thermal and prompt NO_X formation could be neglected when the combustion temperature is lower than 1,500 °C [21]. In this paper, the main part of NO_X formation of coal combustion is fuel NO_X.

Effect of excess air ratio on NO_X emission
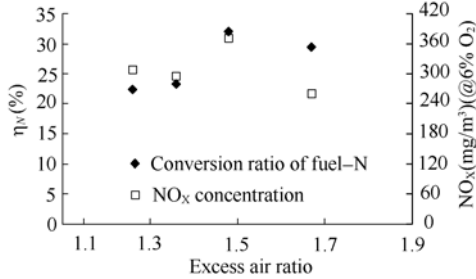
The variations of the fuel-N conversion rate and the concentration of NO_X emissions due to excess air ratio (α) are shown in Fig. 7.

The fuel-N conversion ratio (η_N) is defined as:

$$\eta_N = \frac{\text{the concentration of } NO_x}{\text{the NOx formed from overall Fuel} - N}$$

In Fig. 7, the concentration of NO_X emissions ranged from 250 to 400 mg/m^3, with an excess air ratio between

1.26 and 1.67. Zhao [22] indicated that when anthracite combusts in the W flame boilers, NO_X emission concentration was 351 mg/m^3 with a selective catalytic reduction technology.

Fig. 7   Coal-N to NO_X conversion ratio and NO_X concentration at different excess air ratios

The variation of fuel-N conversion ratio due to excess air ratio (α) was similar to that of the NO_X emissions concentration. When α=1.48, the concentration of NO_X emissions reached the maximum of 371 mg/m^3, with a maximum fuel-N conversion ratio of 32%. As α increased, the fuel-N conversion ratio decreased slightly due to the decrease in flue gas temperature. The concentration of NO_X emissions decreased sharply with increased injecting air and diluted flue gas.

The NO_X concentration profile along the axis of the DFCC when α=1.48 is shown in Fig. 8. As shown in Fig. 8, the NO_X concentration decreased quickly in the reducing zone, and its decrease became slowly in burn out zone.
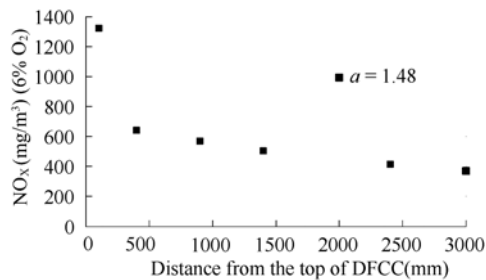
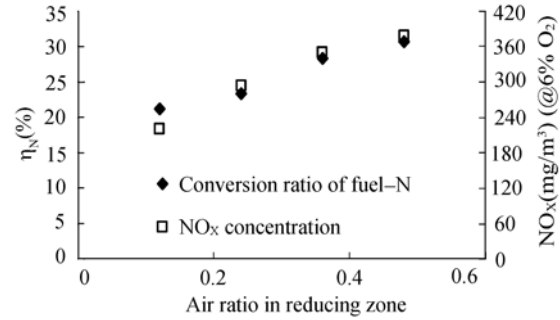**Fig. 8** NO_X concentration at different positions in the DFCC when α=1.48

Effect of the air ratio in the reducing zone on the NO_X emissions

The variations of the fuel-N conversion rate and the concentration of NO_X emissions due to air ratio (α_r) in the reducing zone are presented in Fig. 9.

The fuel-N conversion ratio and the concentration of NO_X emissions increased as α_r increased (Fig. 9). That is, the increase in α_r weakened the air staging level, and the probability of HCN and NH_3 being converted to NO_X

increased due to the enhanced contact of fuel-N with oxygen. Specifically, when α_r=0.12, η_N =21%, and when α_r=0.48, η_N =31%.

The distribution of the NO_X concentration along the axis of the DFCC when α_r=0.12 is shown in Fig. 10.

Fig. 9   Coal-N to NO_X conversion ratio and NO_X concentration at different air ratios in the reducing zone
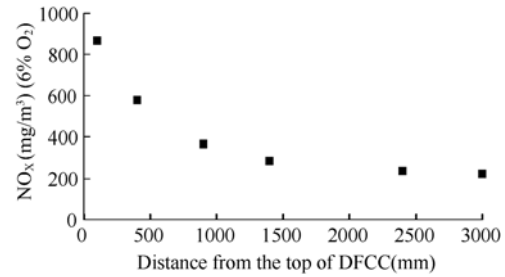
Fig. 10 NO_X concentration at different positions in the DFCC when α_r=0.12

The NO_X concentration is decreased along the axis of the DFCC, with a minimum concentration of 221 mg/m^3 at the end of the combustion chamber, which is much lower than that of the national standard of 1,100 mg/m^3[23] (Fig 10). The decomposition of NO_X was fast in the reducing zone, whereas it was slow in the burn out zone, and the NO_X concentration was stable at the end of the burn out zone.
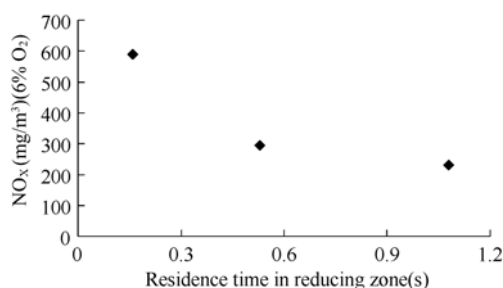
Effect of the residence time in the reducing zone on NO_X emissions

The concentration of NO_X emissions in exhaust at different residence times in the reducing zone is shown in Fig. 11.
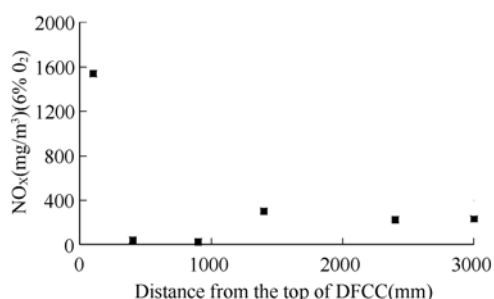
When the residence time in the reducing zone was 0.16 s, the NO_X concentration of the exhaust is 590 mg/m^3. When the residence time increased to 0.53 s, the NO_X concentration in exhaust decreased to 294 mg/m^3. When the time was set to 1.08 s, the NO_X concentration was 230 mg/m^3. Thus, increasing the residence time will decrease the NO_X emission. However, longer residence time would result in higher combustible substance con-

tent in fly ash, which would decrease combustion efficiency.

The different NO_X concentrations along the axis of the DFCC with fuel residence time of 1.08 s are shown in Fig. 12.

Fig. 11 NO_X concentration of flue gas at different residence times in the reducing zone of fuel

Fig. 12 NO_X concentration at different positions in the DFCC when t_r=1.08

As illustrated in Fig.12, when the residence time was longer, the NO_X concentration decreased largely at the reducing zone; at the burn out zone, the NO_X concentration was stabilized at a lower level.

Conclusion

The effect of important parameters on combustion characteristics and NO_X emissions of pulverized anthracite that combust after preheated by a CFB was studied. The following conclusions are obtained.

Pulverized anthracite was preheated quickly up to 800 °C with partial combustion with a primary air of 24% theoretical air in the riser.

The ignition and combustion stability of the pulverized anthracite were firmly secured by preheating pulverized anthracite. The NO_X emissions were reduced by adjusting the amount of secondary and tertiary air, while the combustion efficiency was kept at a relatively higher level. In the experiment, the combustion efficiency could reach as high as 94.2%.

With an excess air ratio of 1.26–1.67, the concentration of NO_X emissions is between 250 and 400 mg/m^3,

which is less than that of the general boilers using anthracite and national emission regulation.

The emissions of NO_X are reduced as the air ratio in the reducing zone is decreased. When the air ratio in the reducing zone is 0.12, the NO_X concentration is 221 mg/m^3 (@6% O_2), and conversion rate of coal-N to NO_X is 21%.

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