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RESEARCH ARTICLE

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Comparison of combustion characteristics of petroleum coke and coal in one-dimensional furnace

Abstract The effect of primary air fraction f_1, outer secondary air swirl strength and excess oxygen coefficient on the combustion characteristics of petroleum coke, Hejin lean coal and Shenmu soft coal are researched on a one-dimensional furnace using a dual channel swirl burner. The results show that with the increase in primary air fraction f_1, the NO_x emission concentrations of both Hejin lean coal and petroleum coke increase, and the combustion worsens in the earlier stage, but the burn-out rate of Shenmu soft coal is improved. The NO_x emission concentration obtains a minimum value with an increase in f_1. The ignition and burn-out rate of petroleum coke and Shenmu soft coal are optimal when Ω_{dl} is minimum and Ω_{dl}= 0.87, respectively. However, both the NO_x emission concentration of petroleum coke and Shenmu soft coal are minimum when Ω_{dl}= 1.08. The increase in excess oxygen coefficient delays the ignition of petroleum coke, worsens the combustion condition and increases the NO_x emission concentration, but it greatly decreases the NO_x emission concentration of Shenmu soft coal.

Keywords petroleum coke, Shenmu soft coal, Hejin lean coal, combustion characteristics, experimental research

1 Introduction

Coal plays a dominant role in China. With the development of the economy, the consumption of energy is increasing at high speed. Coal and petroleum, as the main sources of energy, have finite reserves. Petroleum coke, as a by-product of oil refining, has high heat value, less volatility, easy fragmentation, and less moisture and ash content. Because of these characteristics, petroleum coke has attracted a great deal of attention as a substitute fuel for coal [1].

A lot of mechanism research has been done on petroleum coke as fuel. Kocaefe et al. have done further research into the pyrolytic characteristics of four different kinds of petroleum coke [2]. Wu et al. have conducted experimental research into the burning pollutants of petroleum coke and the emission characteristics of NO_x and SO_2 in the 1t/h fluid bed boiler [3]. Luo et al. have studied the effects of some factors on the emission characteristics of SO_2 and NO_x using mixed burning petroleum coke as fuel in a pulverized coal boiler. The factors include the fineness of the power, the blending ratio of coal and coke, and the respective nitrogen and sulfur content of the coal and coke [4]. Wang et al. have investigated the effect of primary air fraction, excess air coefficient, Ca/s ratio and feeding coal on the mixed burning temperature field of petroleum coke and coal, and the NO_x and SO_2 emission concentrations [5,6]. Yang and Cai have researched the ignition and burn-out characteristics of coke by putting soft coal and petroleum coke together for mixed burning in a pulverized boiler [6,7].

However, most of the hot tests for petroleum coke are done to research the mixed burning of coal and petroleum coke in a circulating fluidized bed. In contrast, few researches have been done to study the procedure of petroleum coke particularly burning in the pulverized coal boiler. Therefore, a comparative analysis of the combustion characteristics of petroleum coke, Hejin lean coal and Shenmu soft coal in a one-dimensional furnace is conducted in this paper in order to understand the similarities and differences between petroleum coke combustion and coal combustion, and to give guidance for the NO_x emission control and combustion optimization of petroleum coke.

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2 The experimental system and measuring principle

2.1 Fuel's characteristics

The ultimate analysis and proximate analytic data of Shenmu soft coal, Hejin lean coal, and petroleum coke used in the experiments are shown in Table 1.

2.2 Experimental system

The schematic diagram of the experimental system is shown in Fig. 1. A dual channel swirl burner is installed at the top of a one-dimensional furnace. The whole system can be divided into a combustion system and a measuring system. The combustion system consists of a one-dimensional furnace, a swirl burner, an air-supply system, an air-induced system, a powder-feed system and an ignition burner. The one-dimensional furnace and the swirl burner are kernel parts. The air-supply, the air-induced and the power-feed subsystems provide the air and pulverized coal/ petroleum coke which are essential to combustion. The ignition system ensures the preheating of the furnace before ignition and experimentation. The measuring system consists of a temperature measuring system, a flue gas measuring system and a fly ash collecting system. The temperature measuring points are arranged along the stroke from the top of the furnace to the tail duct to get the temperature of the central line of the furnace with the thermocouple. The sampling points of fly ash are set at the bottom of the furnace. The fly ash particles, which are collected with a fly ash sampling gun, can retrieve the carbon content of the combustion experiment. The exhaust gas sampling place is set after the economizer. Using the water-cooled gas sampling and Gasmet FTIR gas analyzer, the concentrations of NO_x, CO and CO_2 in the flue gas are obtained. Finally, the flue gas is made to go through the UK KM9106 Portable Comprehensive Gas Analyzer so that the oxygen concentration in the flue gas can be measured.

3 Experimental results and analysis

For the convenience of data processing, the definition of the relative distance of temperature measuring points is given below:

Table 1 The industrial ultimate analysis and proximate analysis and calorific value of fuels

fuel	proximate analysis /%			ultimate analysis /%					calorific value $Q_{net,ad}$ /(MJ·kg^{-1})
	M_{ad}	A_{ad}	V_{ad}	C_{ad}	H_{ad}	N_{ad}	O_{ad}	$S_{t,ad}$	
Shenmu soft coal	2.6	6.56	32.76	73.63	4.54	0.95	11.38	0.34	28.37
Hejin lean coal	2.34	29.47	19.26	56.55	3.14	0.69	5.46	2.35	22.735
petroleum coke	0.93	0.94	11.67	86.33	3.36	1.14	2.52	4.78	34.3

Notes: M_{ad}–air-dried moisture; A_{ad}–air-dried ash content; V_{ad}–air-dried volatile content; C_{ad}–air-dried carbon content; H_{ad}–air-dried hydrogen content; N_{ad}–air-dried nitrogen content; O_{ad}–air-dried oxygen content; $S_{t,ad}$–air-dried total sulfur content

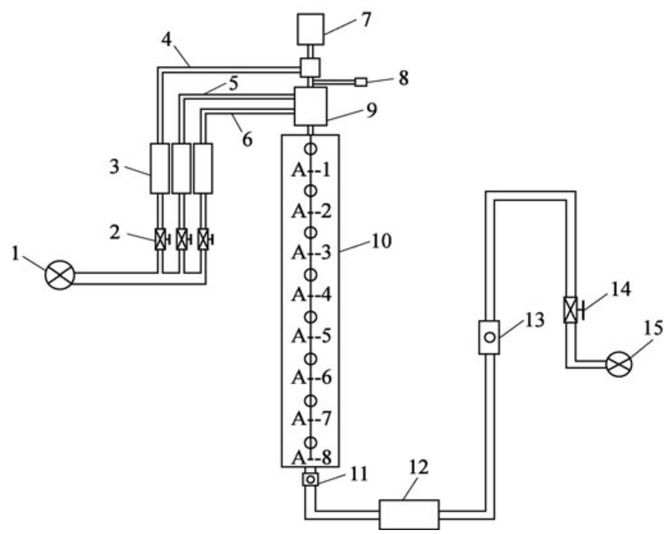

Fig. 1 The schematic diagram of experimental system
1—supply blower; 2—control valve; 3—flowmeter; 4—primary air pipe; 5—inner secondary air pipe; 6—outer secondary air pipe; 7—pulverized coal feeder; 8—outlet for liquefied petroleum gas; 9—swirl burner; 10—one-dimensional furnace (A1–A8 measure points for the temperature of the center of furnace); 11–fly ash sampling hole; 12—economizer; 13—sampling hole for exhaust fume; 14—control valve; 15—induced draft fan

$$X = \frac{L}{D}, \tag{1}$$

where L is the distance between the measure point and the burner spout, and D is the outer secondary air spout diameter of the burner.

The measured concentration of NO_x should be converted to a value under the O_2 concentration = 6% to get the same baseline. The definition is given below [8,9]:

$$C_{NO_x} = 2.05 \times \frac{1.4\alpha'}{\alpha}(C'_{NO} + C'_{NO_2}), \tag{2}$$

where C_{NO_x} is the measured NO_x concentration, which is the conversion to the condition of standard excess air (O_2= 6%), mg/m^3; C'_{NO_x} is the measured NO_x concentration, 10^{-6}; α is the standard excess air coefficient; and α' is the measured excess air coefficient.

3.1 Effects of primary air fraction f_1 on combustion characteristics of different kinds of fuel

Figure 2 shows the comparison of NO_x emission concentrations of the three kinds of fuels in the tail duct at different primary air fractions f_1. It can be seen that, in the tested range, with the increase in primary air fraction the NO_x emission concentrations of both Shenmu soft coal and Hejin lean coal in the tail duct decrease first and then increase but in that of petroleum coke keeps increasing all the time. The NO_x emission concentration of Hejin lean coal in the tail duct is more than 1.5 times the other two fuels. However, it can be seen from Table 1 that the nitrogen content of Hejin lean coal is higher than that of the other two fuels. The reason for this is that the ash content of Hejin lean coal is higher than that of both Shenmu soft coal and petroleum coke. The increasing ash, to a certain extent, is caused by the fact that the destruction of coke's reaction activity point inhibits its reduction ability. Because Hejin lean coal has less volatile content, the fuel nitrogen can be precipitated mostly at the time of coke burning, namely the reduction of CO_2 is mainly determined by the coke. So the NO_x emission concentration of Hejin lean coal is much higher than that of the other two kinds of fuels.

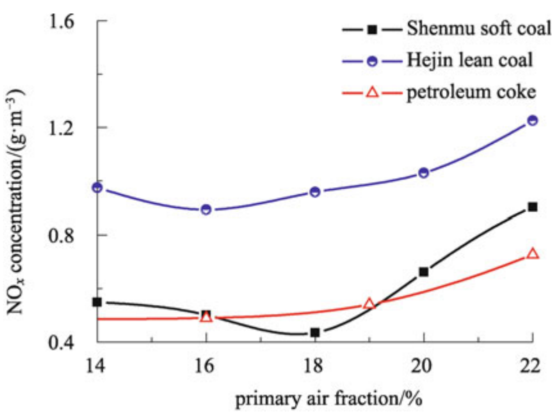

Fig. 2 Comparison of NO_x emission concentration at different primary air fractions f_1

Figure 3 shows the comparison of carbon content of the three kinds of fuels in fly ash at different primary air fractions f_1. With the increase in primary air fraction, the carbon content of Shenmu soft coal decreases, whereas that of petroleum coke increases. The carbon content of Hejin lean coal decreases a little and then increases slightly. The optimal primary air fraction f_1= 20% when the extent of burn-out is largest.

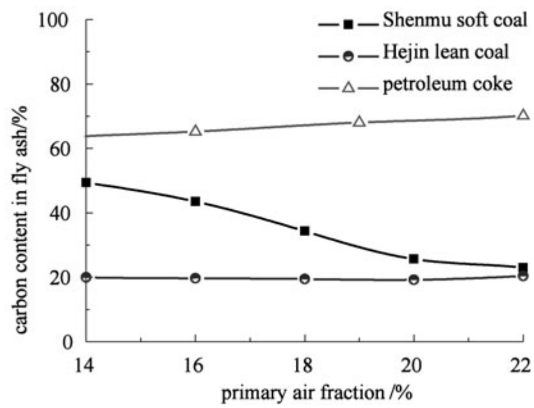

Fig. 3 Comparison of carbon content in fly ash at different primary air fractions f_1

Figure 4 shows the temperature curve of the three kinds of fuels at the center of the furnace. It can be seen that the fuels have delays in ignition and in the downward shift of the combustion region with the increase in primary air fraction. When the primary air fraction f_1= 22%, both Hejin lean coal and petroleum coke show a worsening of combustion in the earlier stage. The ignition of Shenmu soft coal is earliest and easiest, while the ignition of petroleum coke is much later than the other two fuels. With the increase in primary air fraction, the nitrogen of petroleum coke's precipitation is delayed. There is not enough time to deoxidize the NO_x produced in the reaction before it is brought out from the furnace. Thus, the NO_x emission concentration in the tail duct increases.

3.2 Effect of outer secondary air swirl strength Ω_{dl} on combustion characteristics of different fuels

Figure 5 gives the comparison of NO_x emission concentrations of both Shenmu soft coal and petroleum coke in the tail duct at different outer secondary air swirl strengths Ω_{dl}. With the increase in outer secondary air swirl strength Ω_{dl}, the NO_x emission concentrations in the tail duct of both Shenmu soft coal and petroleum coke first decrease and then increase. The lowest NO_x emission concentration appears near Ω_{dl}= 1.08. The reason for this is that with the

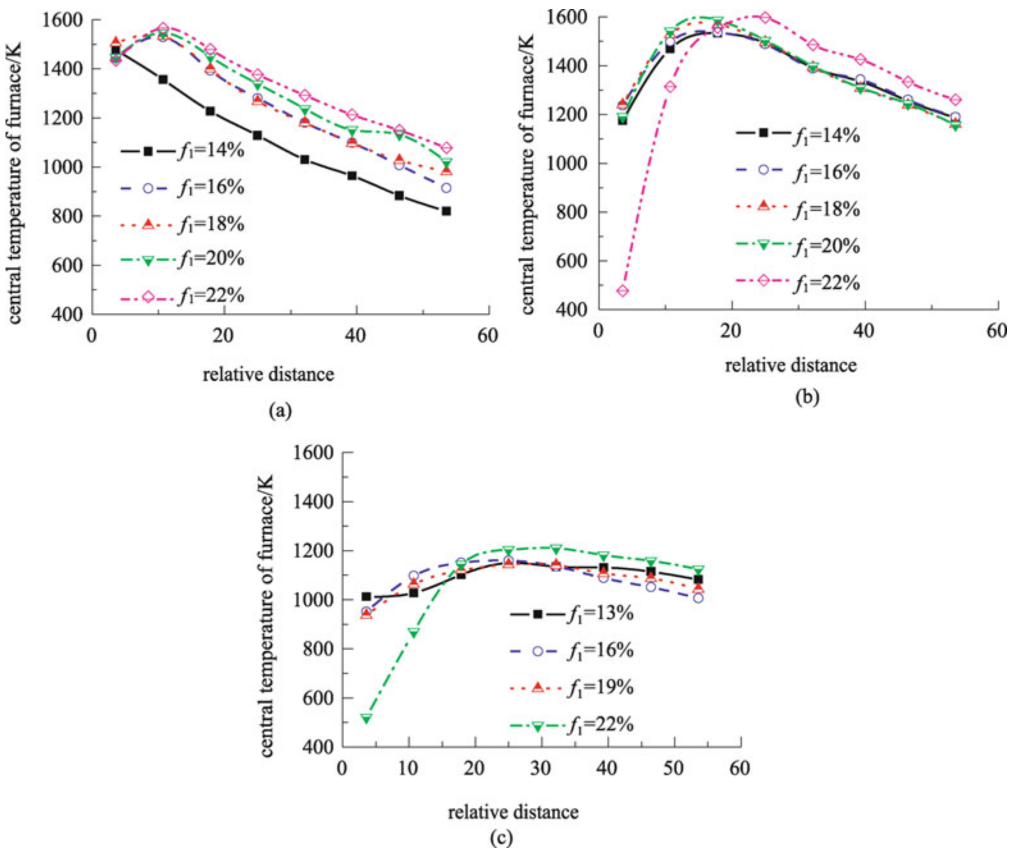

Fig. 4 Comparison of central temperature of furnace at different primary air fraction f_1
(a) Shenmu soft coal; (b) Hejin loan coal; (c) petroleum coke

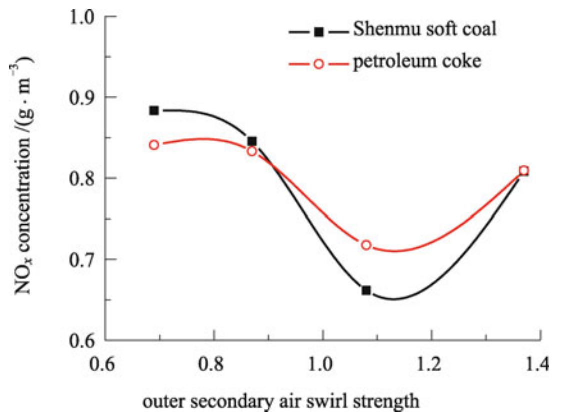

Fig. 5 Comparison of NO_x emission concentrations at different outer secondary air swirl strengths Ω_{dl}

increase in Ω_{dl}, a great amount of hypoxic flue gas is taken entrainment to the recirculation zone, which reduces the local atmosphere and inhibits the formation of NO_x to a certain extent in the anterior furnace. However, with a further increase in Ω_{dl}, there is more flue gas entrainment, which slows down the reduction of NO_x in the furnace downstream and increases the NO_x concentration.

Figure 6 shows the comparison of carbon contents of both Shenmu soft coal and petroleum coke in fly ash at different outer secondary air swirl strengths Ω_{dl}. With the increase in outer secondary air swirl strength Ω_{dl}, the carbon content of Shenmu soft coal in fly ash first decreases and then increases, but that of petroleum coke first increases and then increases again.

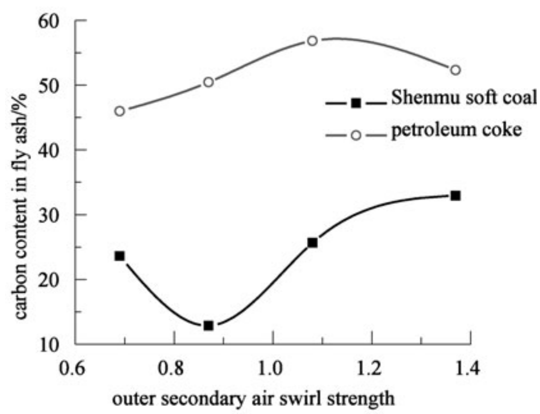

Fig. 6 Comparison of carbon content in fly ash at different outer secondary air swirl strengths Ω_{dl}

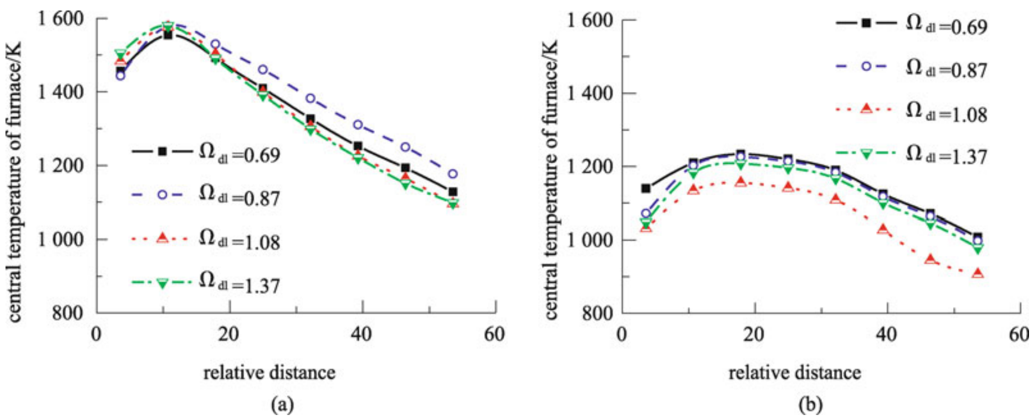

Fig. 7 Comparison of furnace central temperature at different outer secondary air swirl strength Ω_{dl}

Figure 7 shows the furnace central temperature curves of both Shenmu soft coal and petroleum coke at different outer secondary air swirl strengths Ω_{dl}. With the increase in the outer secondary air swirl strength Ω_{dl}, the furnace central whole temperature of Shenmu soft coal first increases and then decreases, while that of petroleum coke decreases all the time. Because the ignition of petroleum coke is hard and relatively late, the high temperature flue gas entrainment cannot been taken to the central recirculation zone. The increase in Ω_{dl} makes secondary air interfuse with primary air too early, which reduces the temperature of primary air and dilutes the fuel, making the ignition more difficult. However, when Shenmu soft coal is burning, the increase in Ω_{dl} can strengthen the ignition of pulverized coal in the outlet. While Ω_{dl} continues increasing, it makes the oxygen supply of coal combustion in the later stage weak and, therefore, has a negative effect on the combustion in the downstream area of the furnace.

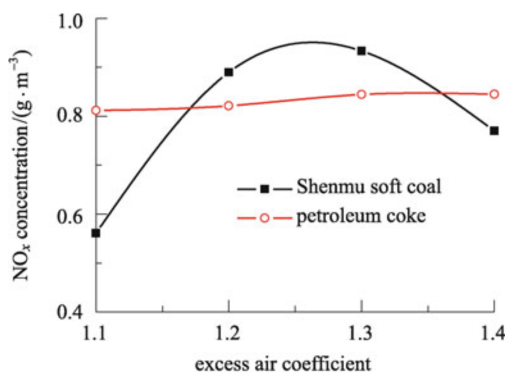

Fig. 8 Comparison of NO_x emission concentration at different excess air coefficient

3.3 Effect of excess air coefficient α on combustion characteristics of different fuels

Figure 8 shows the comparison of NO_x emission concentrations of both Shenmu soft coal and petroleum coke in the tail duct at different excess air coefficients α. Under higher excess air coefficient, the NO_x emission concentration of Shenmu soft coal decreases, but that of petroleum coke slightly increases due to the different NO_x removal effects of the two different fuels. There are two main actions in the process of NO_x removal of high volatile Shenmu soft coal. These are the reduction action of the reducing atmosphere in the volatile burning stage and the reduction action of coke in the coke burning stage. However, the NO_x removal of lower volatile petroleum coke depends mainly on the reduction action of coke. A too large excess air coefficient α always leads to a decrease in retention time inside the furnace of the fuel. However, it has a different effect on these two kinds of fuel. Although the retention time inside the furnace of the fuel decreases, the reduction action of the Shenmu soft coal reducing atmosphere still exists and works. Thus, the final effect is just the decrease in fuel-N precipitation, which is manifested as a decrease in NO_x emission concentration. The decrease in retention time inside the furnace of the fuel has two effects on petroleum coke, which mainly depends on the coke reducing NO_x. These are a decrease in fuel-N precipitation and a decrease in the reduction reaction time of NO_x. Thus, their comprehensive effect is just shown as an increase in NO_x emission concentration with the increase in α, but the increment of the NO_x emission is small.

Figure 9 shows the comparison of carbon contents of both Shenmu soft coal and petroleum coke in fly ash at different excess air coefficients α. With the increase in excess air coefficient α, the oxygen concentration in the furnace continuously increases, which promotes the reaction between C and O. Meanwhile, the temperature in the combustion zone decreases. So with the increase in α, the carbon content in fly ash of these two kinds of fuels first decreases and then increases.

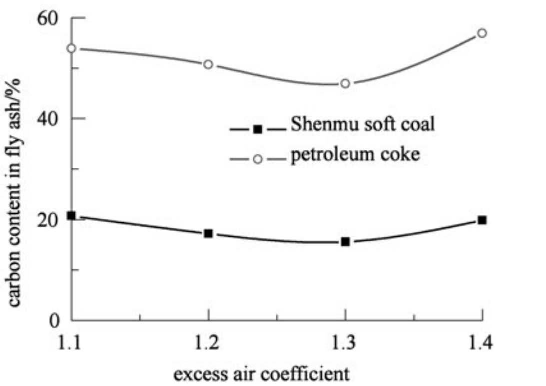

Fig. 9 Comparison of carbon content in fly ash at different excess air coefficient

Figure 10 shows the furnace central temperature curves of Shenmu soft coal and petroleum coke at different excess air coefficients α. The central temperatures of both Shenmu soft coal and petroleum coke have the same change trend with the change in α. Their ignitions both come late with the increase in α. The peak value of the central temperature decreases while the combustion temperature at the later stage increases. The reason for this is that with the increase in air volume, the flow velocity in the furnace increases and the heating time of airflow decreases, which is harmful to the ignition in the prior period. It causes a decrease in temperature in the prior period as well as ignition delay. The delay in ignition then makes it easier to bring the heat produced in combustion to the lower part of the furnace, causing the temperature in the later stage to increase. Although the ignition of petroleum coke is more serious than Shenmu soft coal with the increase in α, different from Shenmu soft coal, petroleum coke is a kind of fuel which is hard to burn. Thus the effect of air volume change on NO_x emission concentration of petroleum coke is not as great as that of Shenmu soft coal.

4 Conclusion

The effect of primary air fraction f_1, outer secondary air swirl strength, excess oxygen coefficient on the NO_x emission concentration, carbon content in fly ash, and furnace central temperature of Shenmu soft coal, Hejin loan coal, and petroleum coke are investigated to study the similarities and differences in their combustion procedures. The following conclusions are drawn.

1) For Hejin loan coal and petroleum coke, the burn-out rate of fuel changes little in the range of the primary air fraction f_1 researched. However, the NO_x emission concentration in the tail duct is lower under a lower primary air fraction f_1; a higher primary air fraction f_1 will worsen combustion in the prior period. Thus, a lower primary air fraction should be selected in the combustion of both Hejin loan coal and petroleum coke. On the other hand, the burn-out rate of Shenmu soft coal is improved with the increase in primary air fraction f_1 in the tested range, but when $f_1 > 18\%$, with the increase in primary air fraction, NO_x emission concentration in the tail duct increases obviously.

2) It is beneficial to the ignition and burning-out of petroleum coke that a low outer secondary air swirl strength Ω_{dl} be chosen. When $\Omega_{dl}= 0.87$ the ignition and burning-out of Shenmu soft coal are optimal. The minimum value of NO_x emission concentrations of both Shenmu soft coal and petroleum coke in the tail duct appears when $\Omega_{dl}= 1.08$.

3) The change in excess air coefficient α has little effect on the NO_x emission concentration of petroleum coke. However, the increase in excess air coefficient α makes the ignition delay of petroleum coke more serious and decreases the reduction reaction time of NO_x. It also worsens the condition of combustion and increases NO_x emission concentration in the tail duct. When the excess air coefficient α is too large, it greatly shortens the retention

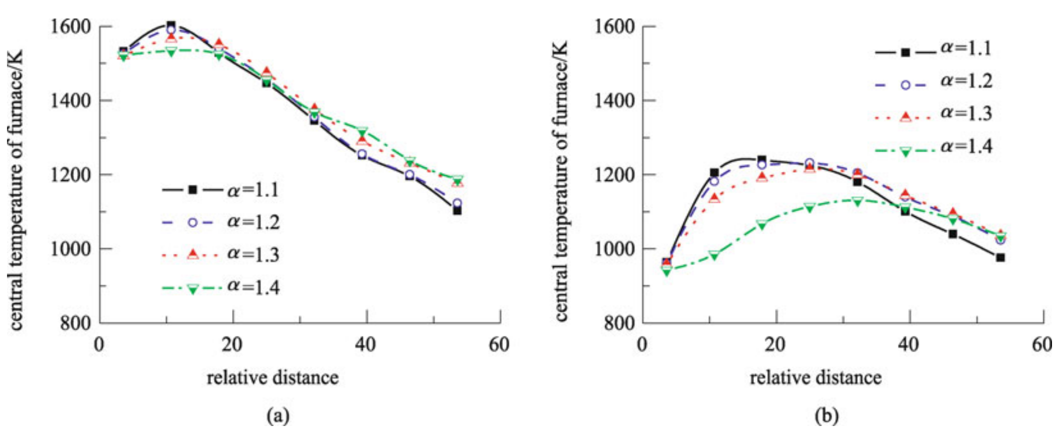

Fig. 10 Comparison of furnace central temperature at different excess air coefficient
(a) Shenmu soft coal; (b) petroleum coke

time of coal inside the furnace and worsens the condition of combustion and NO_x production. As a result, the NO_x emission concentration of Shenmu soft coal in the tail duct decreases.

4) The combustion performance of petroleum coke, including burning, ignition, and so on, is poorer than that of Shenmu soft coal and Hejin loan coal.

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