EXPERIMENTAL STUDY ON COMBUSTION CHARACTERISTICS OF PULVERIZED COAL PREHEATED IN A CIRCULATING FLUIDIZED BED

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Abstract –A new technique for preheating pulverized coal by a circulating fluidized bed was adopted. This process takes place in two stages: the pulverized coal is first preheated in a circulating fluidized bed, and then the resulting fuel gas and char particles are burned in a down-fired combustor under air-staging conditions. Experiments conducted with two types of coal, three preheating temperatures, and three air ratios in the circulating fluidized bed, were carried out. The preheating and combustion processes under all the experimental conditions were stable. For both types of coal, the preheating temperature in the circulating fluidized bed could be adjusted in a large range of 800~950 °C, the ratio of primary air could be lowered to 0.15. Moreover, the testing system could run stably with the input power of 0.11~0.27MW, while the designed value was 0.2MW. In conclusion, the combustion efficiency of the whole process was high, which could reach 98%.

INTRODUCTION

Coal is the primary source of energy, sharing 29.2% of global primary energy consumption.[1] Kinds of firing methods, each of which has its own advantages and disadvantage, have been developed and used in power plants, as well as industrial production. Pulverized coal fired boiler is the most widely used, attributed to is high combustion efficiency, low energy consumption, and easy enlargement. However, NO_x emission of pulverized coal fired boiler is considerable due to its high combustion temperature, even if numbers of low-nitrogen combustion technologies have been applied. Moreover, pulverized coal fired boiler has low fuel adaptability and narrow load regulation range of 70%~100%. Circulating fluidized bed (CFB) boiler, which developed rapidly, has lower NO_x emission, larger load regulation range, and wider adaptability for coal type than pulverized coal fired boiler. Admittedly, high energy consumption, serious wear of equipment and complex control system restrict is further development[2-6].

A new technique combined CFB and pulverized coal fired boiler has been adopted. This process takes place in two stages: the pulverized coal is first preheated in a circulating fluidized bed, and then the resulting fuel gas and char particles are burned in a down-fired combustor under air-staging conditions. This process integrates the advantages of both CFB and pulverized coal fired boiler. As ignition and partial combustion is conducted in a CFB in the first stage, the ignition characteristic is not strictly required. Even low volatile fuels including anthracite, semi-coke, and residual carbon powders could ignite smoothly and be preheated steadily. The CFB undertakes low combustion fraction that it is small in size, leading to a low energy consumption. The main combustion takes place in the down-fired combustor and this ensures a high combustion efficiency.

A series of previous studies have been conducted to investigate the combustion characteristics and mechanisms of NO_x formation of pulverized coal preheated in a CFB. The effects of coal type, air ratios, pulverized coal sizes, preheating temperatures were previously investigated[7-10]. However, previous experiments were carried out in bench scale, the results of which are experimental. In order to promote the industrial application, a pilot plant with the input power of 0.2 MW was built and realized stable running. The coal types, preheating temperature, input power changing and other operating data were obtained.

EXPERIMENTAL SECTION

Coal Analysis. The coal used in the experiments was obtained from Datong and Shenmu, China and the proximate and ultimate analyses are shown in Table 1. The diameters of the two coals were 84 μm with a mean particle diameter (d_{50}) of 20 μm.

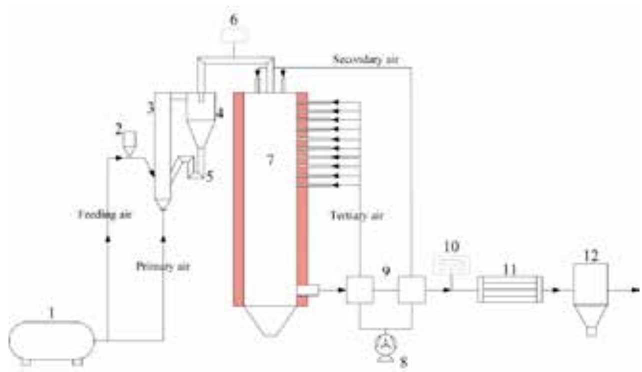
Table 1 Proximate and ultimate analyses of Datong and Shenmu bituminous coal

Coal samples	Proximate analysis				Ultimate analysis					$Q_{net,ar}$ ($MJ\cdot kg^{-1}$)
	M	FC	V	A	C	H	O	N	S	
Datong	2.20	44.38	27.37	26.05	58.08	3.73	8.58	1.04	0.32	22.61
Shenmu	11.80	47.80	30.57	9.82	62.94	3.88	10.18	0.98	0.40	24.43

ar—as received basis; ad—air dried basis; Q_{net}—net calorific value.

Apparatus and Method. The schematic diagram of the experimental system is shown in Fig. 1, which consisted of a CFB, a down-fired combustor, air supply devices and some measuring equipments. The riser of the CFB is 160 mm in diameter and 1500 mm in height. The coal feeding port is 285 mm above the air distributor on the riser. 20% of theoretical air, defined as primary air, is supplied from the bottom of the riser. The primary air fluidizes the bed materials and provide a strong reducing atmosphere, which gives rise to partial pyrolysis, gasification, and combustion of the coal throughout the CFB. Besides heating the CFB up to about 900 °C, the reactions produce high temperature coal gas and solid particles, which is defined as preheated coal particles. Through a horizontal tube, the products flow out of the CFB from the center cylinder of cyclone separator and entered a nozzle at the top center of the down-fired combustor with 700 mm in diameter and 7000 mm in height. Secondary air injects into the combustor around the primary nozzle and provides oxygen for combustion of coal gas and preheated coal. Tertiary air is supplied horizontally into the combustor at 1500 mm and 3000 mm below the nozzle to provide extra oxygen for complete combustion.

Four K-type thermocouples are used in the CFB, three in the riser and on in the U-valve. Fifteen S-type thermocouples are set along the vertical direction of the combustor with the spacing of 300 mm, while the highest one is 150 mm below the nozzle. A sampling ports is set at the outlet of the CFB for sampling preheated fuel, and the high temperature coal gas is measured using a MAIHAK S710 analyzer. The flue gas from the combustor is measured using a Gasmet FTIR DX-4000 analyzer. All the gas samples are dried and filtered before they enter individual online analyzers.



1-Air compressor, 2-Coal feeder, 3-Riser, 4-Cyclone, 5-U-valve, 6-Sampling port, 7-Down-fired combustor, 8- Fan, 9-Air preheater, 10- Gas analyzer, 11-Water cooler, 12-Bag filter

Fig. 1. Schematic of the test apparatus.

Experimental Conditions. Experimental conditions are listed in Table 2. The equivalence ratio of primary air, secondary air, and tertiary air are defined as λ_1, λ_2, and λ_3 respectively. The excess air ratio is defined as λ.

Table 2 Experimental conditions

Conditions	E_1	E_2	E_3	E_4	E_5
Coal sample	Shenmu	Datong	Datong	Shenmu	Shenmu
Coal feed rate (kg/h)	28.5	25.38	23.51	29.09	28.94
Theoretical air requirement(Nm^3/h)	189	157	145	27	27
λ_1	0.20	0.14	0.19	0.19	0.19
λ_2	0.63	0.37	0.41	0.15	0.32
λ_3	0.36	0.72	0.59	0.85	0.68
λ	1.19	1.23	1.19	1.19	1.19
Preheating temperature (°C)	900	830	940	892	893

RESULTS AND DISCUSSION

Preheating Process in CFB. The pulverized coal was first fed into the CFB and the temperature variation with time in the CFB under condition E1 is shown in Fig. 2. It can be noted that the pulverized coal could be preheated to about 900 °C steadily and continuously. The composition of the coal gas was measured at the outlet of CFB. The principal constituents were CO, CO_2, CH_4, and H_2 with the concentrations of 7.07%, 10.48%, 2.36%, and 0.96%. This composition indicates that partial pyrolysis, gasification, and combustion took place under anoxic atmosphere in CFB. Besides, the heat value of the coal gas is 1.83 MJ/N·m^3, suggesting that a large amount of heat was still embodied in preheated solid fuels.

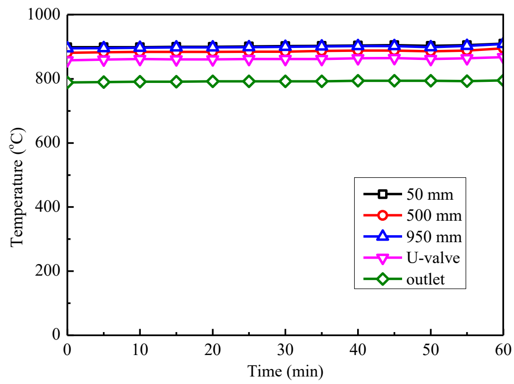


Fig. 2. Temperature variations with time in the CFB.

The effect of λ_1 on the preheating process was analyzed by comparing case E_2 and E_3. As all the reactions in the CFB depend on the primary air, the preheating temperature depends on λ_1, as shown in Fig. 3. The preheating temperature is 830 °C under the λ_1 of 0.14, and it will rise up to 940 °C as λ_1 goes to 0.19. Higher λ_1 means larger amount of oxygen is supplied for the reactions including partial pyrolysis, gasification, and combustion. More calories is released and it heats the solid fuels to a higher temperature.

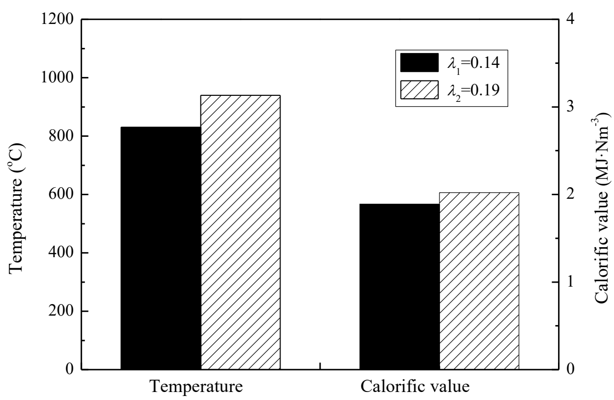


Fig. 3. Preheating temperature and heat value of the coal gas.

The heat value of the coal gas under different preheating temperature are also shown in Fig. 3. It is interesting to notice that the heat value increases with the increasing preheating temperature. This can be explained by the changes of coal gas constituents shown in Fig.4. The conversion of the gas is measured by yield of every gas composition from 1 kg feeding coal.

$$V_g = \frac{V_0 \lambda_1 C_g}{B} \tag{1}$$

V_g is the gas yield generated by 1 kg coal in preheating process, V_0 is the total flue gas, C_g is the gas concentration measured at the CFB outlet, B is the mass of feeding coal.

It can be seen that all the gaseous products increase with the increasing λ_1 and preheating temperature. This indicates that more C and H in the coal was released and transformed to CO, CH_4, and H_2 due to the increase of oxygen, further resulting in the increase in heat value of the coal gas.

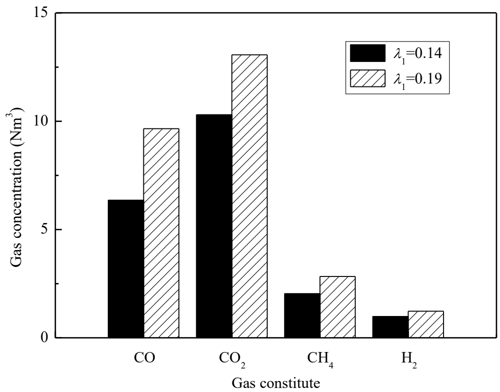


Fig. 4. Yield of the coal gas by preheating process.

Combustion characteristics in the down-fired combustor. The preheated fuel from the center cylinder of cyclone separator then entered a nozzle at the top center of the down-fired combustor and flowed downward. Secondary air injects into the combustor around the primary nozzle and provides oxygen for combustion of coal gas and preheated coal. Tertiary air is supplied horizontally into the combustor at 1500 mm and 3000 mm below the nozzle to provide extra oxygen for complete combustion.

Fig. 5 shows the temperatures at 9 points along the vertical direction in the down-fired combustor varying with time under condition E1. Obviously, the secondary and tertiary air supplied sufficient oxygen for preheated fuel, and the combustion keeps steady in the combustor.

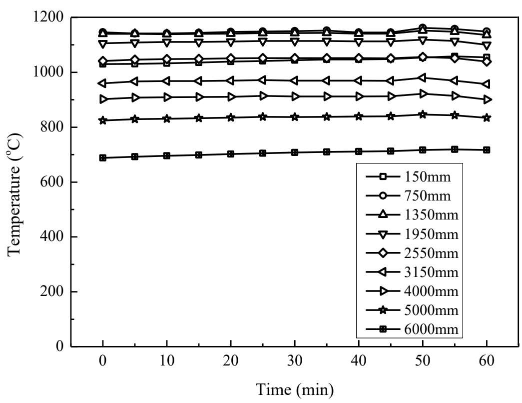


Fig. 5. Temperature variations with time in the down-fired combustor.

The temperature profile along vertical direction of the down-fired combustor, shown in Fig. 6, is uniform. As the preheated fuel flowed into the combustor has a temperature higher than its ignition temperature, there is no ignition problem in the down-fired combustor. As soon as the fuel entered the combustor, the temperature increased from 1020 °C up to 1150 °C, resulting from combustion of the heated fuel supported by the secondary air. The highest temperature took place at the 750 mm below the nozzle. As the preheated fuel flowed into the combustor has a temperature higher than its ignition temperature, there is no ignition problem in the down-fired combustor. Until now, only 0.83 of theoretical air requirement had been fed due to the air staging, the combustion would not finish until the tertiary air was fed. Therefore, the temperature did not rise anymore until the tertiary air was supplied.

The tertiary air was supplied at 1500 mm and 3000 mm below the nozzle so that the main combustion zone was 0~3000 mm from the nozzle. The maximum temperature difference is about 200 °C, far below than that of ordinary combustion of pulverized coal[11,12].

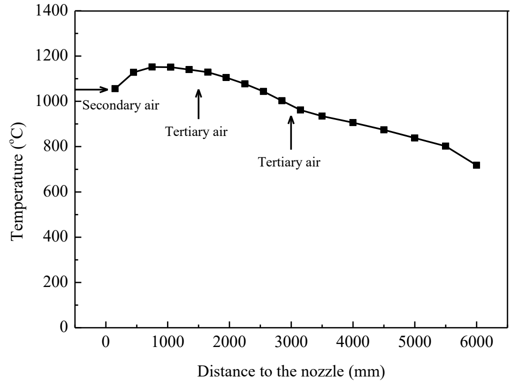


Fig. 6. Temperature profile along the vertical direction of the down-fired combustor.

The combustion efficiency can be defined as follows:

$$\eta = \frac{Q_{\mathrm{net}} - Q_{\mathrm{uburn}}}{Q_{\mathrm{net}}} \tag{2}$$

η is the combustion efficiency, Q_{net} is the heat value of fuel, Q_{uburn} is the heat value of unburned combustible substance, which is calculated according the analyses of the fly ash and exhaust gas sampled at the tail flue. The combustion efficiency of case E_1 is 97.23%.

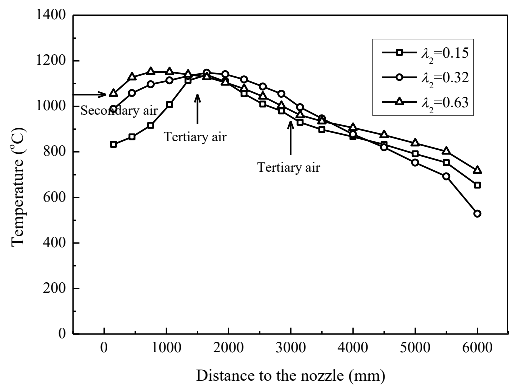


Fig. 7. Temperature in the down-fired combustor under different λ_2.

The effect of λ_2 on the temperature distribution in the down-fired combustor is discussed according the differences among case E_1,E_4 and E_5. The decrease of λ_2 means less oxygen, leading to lower temperature in 0~3000 mm zone. The temperature would not rise up to as high as E_1 until the tertiary air was fed. Therefore, the high temperature zone was shorten and delayed as λ_2 decreases. The reducing and low temperature atmosphere may reduce the emission of NO_x, but it has adverse affect on the combustion efficiency.

Table 3 Combustion efficiency under different λ_2

Experimental conditions	E_4	E_4	E_1
λ_2	0.15	0.32	0.63
Combustion efficiency (%)	87.91	94.15	97.32

The combustion efficiency increases with the increasing λ_2, as listed in Table 3. This indicated that the amount of secondary air should be balanced considering both combustion efficiency and NO_x emission.

Moreover, the testing system could run stably with the input power of 0.11~0.27MW, while the designed value was 0.2MW, showing its large load regulation range.

CONCLUSIONS

In this paper, a testing system combined CFB and pulverized coal fired boiler with the designed input power of 0.2MW was set up. Pulverized coal was first preheated in a CFB and then burned out in the combustor. The preheating and combustion characteristics were investigated and the following conclusions can be obtained:

(1) The testing system could run stably with the input power of 0.11~0.27MW, while the designed value was 0.2MW. The combustion efficiency of the whole process could reach 98%.

(2) Preheated pulverized coal with a temperature of 800~950 °C can be obtained steadily and continuously by partial pyrolysis, gasification, and combustion in the CFB, releasing CO, CO_2, CH_4, and H_2.

(3) The preheating temperature, as well as the yields and heat value of the coal gas increase with the increasing ratio of primary air.

(4) Preheated coal combustion could exhibit a uniform temperature profile along the axis of the combustor by air staging. The ratio of secondary air could influence the temperature distribution in the combustor, further influences the combustion efficiency and NO_x emission.

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NOTATION

λ	excess air ratio	λ_1	equivalence ratio of primary air
λ_2	equivalence ratio of secondary air	λ_3	equivalence ratio of tertiary air
V_g	gas yield L, $Nm^3 \cdot kg^{-1}$	V_0	total flue gas, $Nm^3 \cdot kg^{-1}$
C_g	gas concentration measured	B	mass of feeding coal, kg
η	combustion efficiency	Q	heat value, $MJ \cdot kg^{-1}$

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