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NUMERICAL SIMULATION OF COMBUSTION PERFORMANCE OF PULVERIZED COAL BURNER

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ABSTRACT

The combustion mechanism of pulverized coal in a DRB-4Z burner are analyzed and the temperature distribution, char burnout and CO production in the burner outlet area are obtained. The gas phase turbulence model is the Realizable k-ε two equation model, and radiation heat transfer model is P-1 radiation model. The discrete phase model is used to simulate the force and motion trajectory of the pulverized coal particles, and the stochastic model is used to simulate the flow of coal particles. The combustion model is non-premixed combustion model, and the devolatilization model is two competing rates model; char combustion model is kinetics/diffusion-limited model. Numerical results revealed the mechanism of pulverized coal devolatilization and char combustion, and the solution may give reference to air arrangement of the same type of burners.

Keywords: pulverized coal burner, combustion mechanism, numerical simulation.

1. INTRODUCTION

Although hydroelectricity and wind power generation in China have been developing, the electric power market in China gives priority to thermal power generation [1, 2], of which about 70% is coal-fired power unit [3]. Most coal-fired power plants use pulverized coal combustion boiler. Working condition of pulverized coal combustion boiler is very complex, involving combustion, flow and heat transfer process; it is influenced by many factors such as airflow velocity, the ratio of the airflow, coal type, coal fineness, power unit load, and so on. These factors are intertwined and often affect one another, increasing the complexity of the combustion process. Therefore, many problems often appear in pulverized coal combustion boiler in actual operation: low combustion efficiency, low combustion stability, flue gas temperature deviation, and pollutant emission, to name a few. These problems directly affect the security and economy of power plant boiler operation.

Chemical reactions of pulverized coal combustion is pretty complex, only by studying the mechanism of combustion can we fundamentally summarize the regularities of pulverized coal complete combustion and less CO generation, so as to improve the combustion efficiency. So it is necessary to dissect the coal combustion mechanism. Dou et al. [4] simulated the combustion process of pulverized coal under different injection velocities to study anthracite combustion mechanism, and suggested that the main combustion mechanism of the anthracite coal in calciner is mixed-diffusion rate control combustion. Xie et al. [5] and He et al. [6] performed numerical simulations on the combustion process of pulverized coal in calciner and rotary kiln, respectively; the results revealed the volatile release and combustion process as well as analyzed the combustion mechanism of char. Ariyama et al. [7] obtained combustion mechanism by using high speed camera to observe the combustion process in the furnace directly. Wang et al. [8] introduced several main processes of fuel particles combustion in internal circulating fluidized bed, and proposed a model of fuel particles combustion efficiency. Wu [9] and Li et al. [10] studied combustion mechanism and dynamic characteristics of pulverized coal in fluidized bed boiler through experiments.

However, there are few literatures about research on the combustion mechanism of pulverized coal in power plant boiler. Thus there are some researches can be done about combustion mechanism in power plant boilers. In view of the fact that there are multiple burners in boiler furnace and they affect one another to make the problem more complicated and difficult to make accurate analysis and judgment. Therefore, it is necessary to study the combustion mechanism in single burner outlet area.

In this paper, a DRB-4Z burner in a power plant boiler is studied. Due to the high operational reliability requirements of power plant boiler, conducting experiments on operating boiler is not practical. With advantages such as low cost, high efficiency and convenience, the computer simulation technology are more and more widely used in engineering practice, and pulverized coal combustion numerical results have been regarded as important references in a lot of boiler designs and burner retrofit schemes. Through numerical simulation, we study the temperature distribution, char burnout and CO production in the burner outlet area, and try to analyze pulverized coal combustion mechanism using the simulation results. The solution may give reference to air arrangement of the same type of burners.

2. MODEL ESTABLISHMENT AND NUMERICAL SIMULATION

2.1 Geometric model

The geometric model is established for numerical simulation based on a DRB-4Z burner in a power plant boiler. Figure 1 shows the air duct structure of the burner. There are 4 layers of airflow tunnels: primary air, transition secondary air, inner secondary air and outer secondary air (from inside to outside) [11]. Primary air and transition secondary air is direct flow, inner and outer secondary air is swirling.

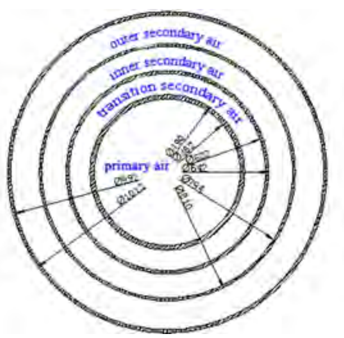


Fig. 1 DRB-4Z burner air duct structure

Figure 2 shows the boundary conditions. In order to study the single burner combustion and species concentration conveniently, it is assumed that air and pulverized coal inject into a large cylindrical space, radius of 1.8m, depth of 12.3m. Cylindrical surface is set as symmetry boundary condition to prevent the influence on air flow. The end of calculation domain is set as pressure outlet boundary condition, and the contraction at the end is to prevent the backflow that influence the simulation results.

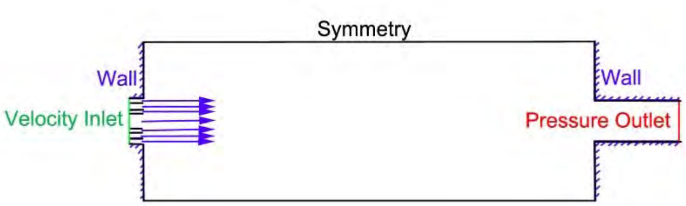


Fig. 2 Boundary conditions

For mesh sensitivity analysis, the authors took three reference points in the computational domain, and calculated reference points' temperature of mesh number of 82,000, 133,000, 156,000, and 189,000, respectively. The results are shown in Figure 3. It can be seen that, with the increase of mesh number, the reference points' temperature no longer change after the mesh number reaching to 133,000. Therefore, mesh number of 133,000 is used in the paper. The mesh is shown in Fig. 4. Quadrilateral mesh is used in the whole space, and the grid is denser around the burner and near the outlet of the computational domain.

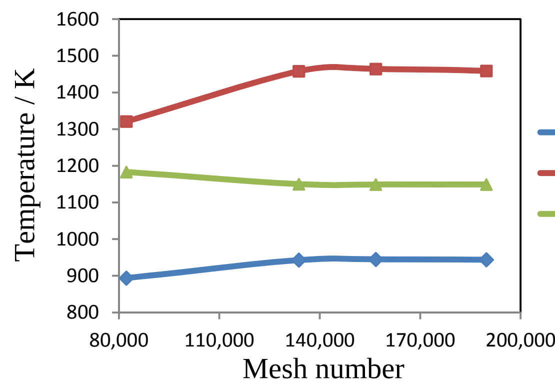


Fig. 3 Reference points temperature variation with the mesh number

Fig. 4 Grid division

2.2 Mathematical model

The commercial package Fluent® has been used to solve the problem. The gas phase turbulence model is the Realizable k-ε two equation model, and radiation heat transfer model is P-1 radiation model. The discrete phase model is used to simulate the force and motion trajectory of the pulverized coal particles, and the stochastic model is used to simulate the flow of coal particles. The combustion model is non-premixed combustion model, and the devolatilization model is two competing rates model; char combustion model is kinetics/diffusion-limited model.

2.2.1 Devolatilization model

For the problem studied in this paper, the most suitable model is two competing rates model. The pyrolysis process of pulverized coal in the furnace can be expressed as follows:

$$\text{Coal} \xrightarrow{k_1} \alpha_1 V_1(\text{volatile}) + (1-\alpha_1)R_1(\text{residue}) \quad (1)$$

$$\text{Coal} \xrightarrow{k_2} \alpha_2 V_2(\text{volatile}) + (1-\alpha_2)R_2(\text{residue}) \quad (2)$$

where k_1 and k_2 are given by the Arrhenius law, α_1 and α_2 are mass stoichiometric coefficients. At high temperature, reaction (2) is assumed to become faster than the first one, and when the temperature is low, reaction (1) is dominant [12]. Two reactions compete with each other.

2.2.2 Char combustion model

In this paper, the kinetics/diffusion-limited model is used to simulate the combustion of char. In this model, the particle size of spherical particles in the reaction is assumed to be constant, only the density reduces. Both diffusion process and reaction dynamic process control the reaction rate together. The reaction rate control equation is as follows:

$$k_1 = C_1 \frac{[(T_P+T_\infty)/2]^{0.75}}{D_P} \tag{3}$$

$$k_2 = C_2 \exp(-E/RT_P) \tag{4}$$

2.3 Air distribution condition

The element analysis and industry analysis data of coal used in the burner is shown in Table 1, pulverized coal injection quantity use the actual value 2.185kg/s, diameter of pulverized coal is in accordance with the Rosin-Rammler distribution [13], ranging from 10μm to 300μm.

Excess air coefficient is 1.1, three conditions of air-coal ratio of 2.0, 2.5, and 3.0 are calculated respectively, and the air distribution in the air duct is shown in Table 2. The air-coal ratio refers to the ratio of air to coal entering the mill, which means the mass ratio of primary air to pulverized coal. Primary air temperature is 350 K, and the secondary air temperature is 595 K.

Table 1. Element analysis and industry analysis data of pulverized coal

Industrial analysis (Mass percent),				Elemental analysis (Mole percent)				$Q_{net,daf}$
V	FC	A	M	C_{daf}	H_{daf}	O_{daf}	$(N+S)_{daf}$	(MJ/kg)
0.2693	0.4539	0.163	0.1138	0.8133	0.05	0.1142	0.0225	23.16

2.4 Numerical simulation

The finite volume method is used to solve the gas phase discrete equations, and the difference equations are obtained by the first order upwind format. The SIMPLEC algorithm is used to solve the problem of pressure and velocity coupling of discrete equations. The influence of the discrete phase to continuous phase is considered, and every 50 times of continuous phase iterative calculations, the discrete phase iterate 1 time.

Table 2 Air distribution in the air duct

Case			Case 1	Case 2	Case 3
Pulverized coal injection quantity(kg/s)			2.185	2.185	2.185
Air-coal ratio			2.0	2.5	3.0
Proportion of primary air (%)			16.57	20.71	26.38
Air Volume	Velocity of primary air(m/s)		25.88	32.35	38.82
	Velocity of transition secondary air(m/s)		26.92	25.45	23.97
	Inner secondary air	Axial velocity(m/s)	64.08	60.57	57.07
		Tangential velocity(m/s)	76.36	73.19	68.01
	Outer secondary air	Axial velocity(m/s)	64.09	60.57	57.07
		Tangential velocity(m/s)	37.00	34.97	32.95

3 RESULT ANALYSIS AND DISCUSSION

3.1 Temperature field distribution

Figures 5-7 are the temperature contours of Cases 1, 2 and 3. It can be seen that, flame full degree of Case 1 is the best, followed by Case 2, and Case 3 is the worst. Average temperature of calculating area is Case 1 > Case 2 > Case3. The reason is that the larger the air-coal ratio, the greater the jet stiffness and the more slender the flame.

At the same time we can see a long low temperature zone at burner outlet area, and in the low temperature zone there is mainly primary air just injected from the air duct. The temperature of secondary air is relatively higher than primary air located in the center; in this area, pulverized coal severely mix and have heat exchange with high temperature air in preparation for the subsequent combustion reactions. The length of low temperature zone from short to long is Case 1 (3.75m), Case 2 (4.3m) and Case 3(5.1m). Because on one hand, the larger the primary air volume, the greater the ignition

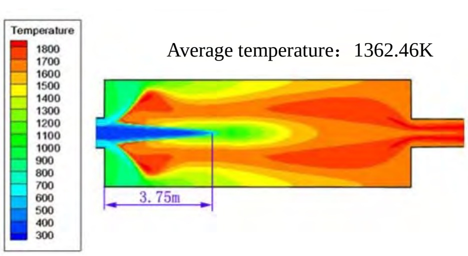


Fig 5. Case 1 temperature distribution

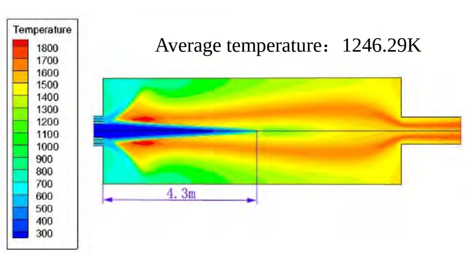


Fig 6. Case 2 temperature distribution

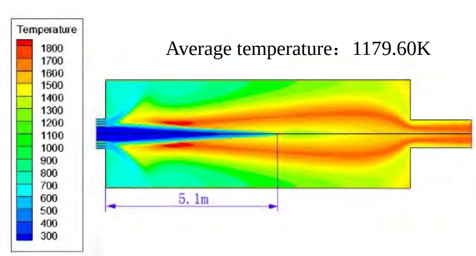


Fig 7. Case 3 temperature distribution

heat, leading to a delay of the ignition; on the other hand, when the primary air velocity is larger than the secondary air, the cold primary air has been ejected far away before having heat exchange with the surrounding hot secondary air.

3.2 Char burnout rate and CO generation

Boiler combustion efficiency refers to the ratio of fuel burning heat to fuel chemical energy [14]; thus combustion heat loss that affect combustion efficiency is Q_3 for gas incomplete combustion heat loss and Q_4 solid incomplete combustion heat loss. Gas incomplete combustion heat loss can be reflected by CO concentration, while solid incomplete combustion heat loss can be show as char burnout rate.

Table 3 is CO concentration, NO_x concentration and char burnout rate of the computational domain outlet. As the table shows, char burnout rate of Case 1 is 97.42%, which basically can be counted as a complete combustion. Char burnout rate of Case 2 is 84.89%, and 15.11% of char is still unburnt. Char burnout rate of Case 3 is the lowest at 71.68%, and 18.32% of char is still unburned. NOx production of Case 1 is the lowest, and Case 3 is the highest. The excess air coefficient of all the three cases studied in the paper is 1.1, on which condition char can be burnt out in theory, so the main reason of low char burnout rate in Case 2 and 3 should be unreasonable air distribution, resulting in bad air-fuel mix, affecting the pulverized coal combustion conditions.

Table 3. CO concentration, NO_x concentration and Char burnout rate of calculation domain outlet

Case	Case1	Case2	Case3
Char burnout rate (%)	97.42	84.89	71.68
CO concentration (%)	0.25	2.68	3.21
NO_x concentration(μL/L)	165.19	228.38	250.18

According to Figs. 8-10 for CO distribution contours and Fig. 11 for CO concentration curves, CO in Case 1 is produced mainly in the front part, then gradually consumed. CO in Case 2 has been generated from anterior to posterior. CO in Case 3 starts to be generated from the middle part, and is still produced at the outlet. Combining with the analysis of temperature field in section 3.1, the greater the air-coal ratio, the more slender the flame shade and the longer the burner outlet low temperature zone. Therefore, air and coal are not well mixed in the radial direction in Cases 2 and 3, resulting in low char burnout rate and high concentration of CO at the outlet.

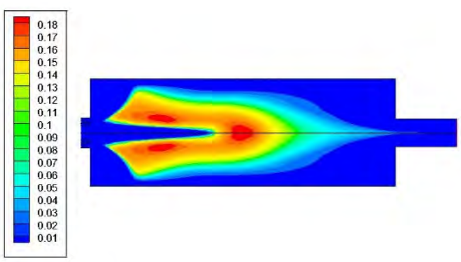


Fig. 8 Case1 CO distribution

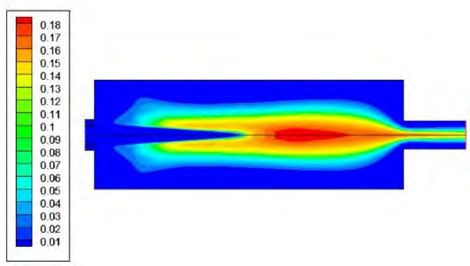


Fig. 9 Case2 CO distribution

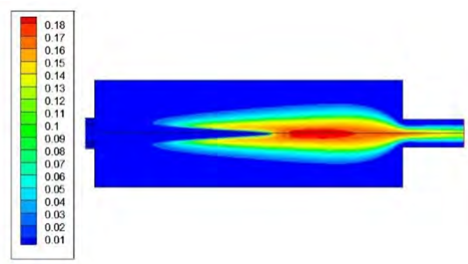


Fig. 10 Case3 CO distribution

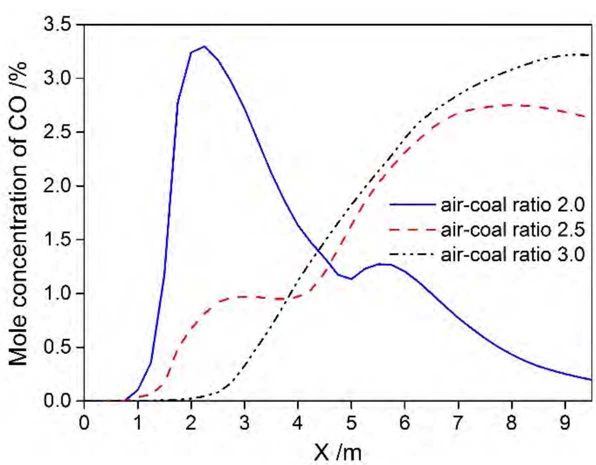
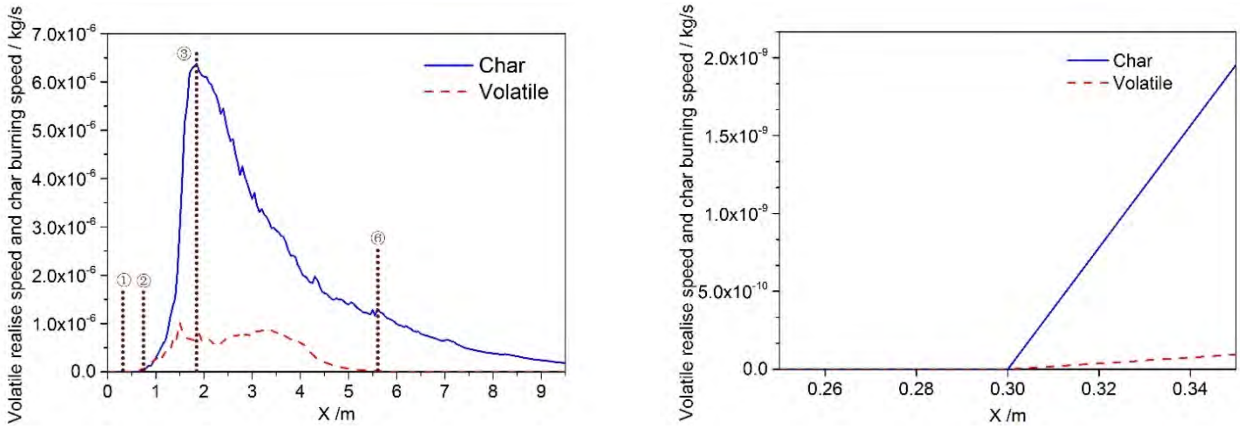


Fig. 11 The curves of the CO concentration

Comparing the better operation condition in Case 1 with the worse conditions in Cases 2 and 3, it can be seen that velocity of primary air and secondary transition air is fairly close in Case 1, and the inner and outer secondary air velocity is relatively large, which kind of air distribution is more conducive to air-coal mix and heat transfer in radial direction. While the primary air velocity is much larger than transition secondary air in Cases 2 and 3, and the inner and outer secondary air velocity is pretty small, so the primary air that carrying coal has been ejected so far before having heat and mass transfer with the surrounding secondary air; small velocity of swirling inner and outer secondary air is not conducive to air and coal mixing, so in Cases 2 and 3 combustion conditions are poor.

3.3 Combustion mechanism analysis

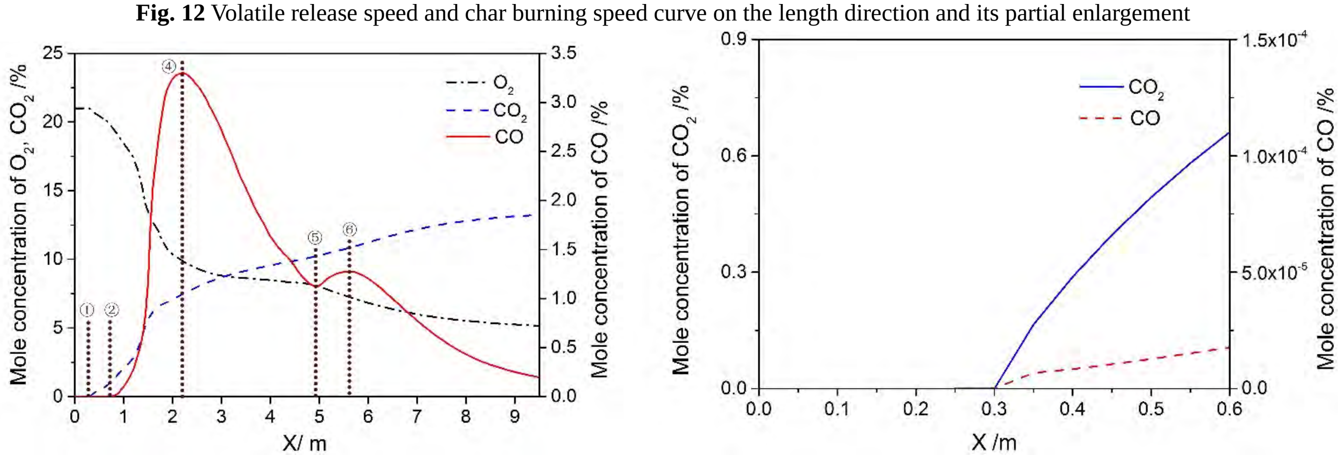
The previous studies showed that the pulverized coal combustion process is mainly divided into four stages: initial endothermic process, devolatilization process, combustion on the surface of char process, and burnout process [15]. In this paper, we will use the best combustion condition Case 1 as an example to analyze combustion mechanism. We will study volatile release, combustion, and char combustion process, and combining with the component distribution curve to try to find out some feature points in the process of pulverized coal combustion. Figure 12 is volatile release speed and char burning speed curve on the length direction, and Figure 13 is mole concentration curve of O_2, CO_2 and CO on the length direction. There are some feature points on these curves that



(a) Volatile release speed and char burning speed curve

(b) Detail with enlarged scale

Fig. 12 Volatile release speed and char burning speed curve on the length direction and its partial enlargement



(a) Mole concentration curve of O_2, CO_2 and CO

(b) Detail with enlarged scale

Fig. 13 Mole concentration curve of O_2, CO_2 and CO on the length direction and its partial enlargement

can reflect the characteristics of pulverized coal combustion mechanism, marked with ①~⑥. Figures 12 and 13 show that the combustion process of pulverized coal is relatively complex; CO production is less, and coal is basically completely burnt at the outlet. This is because the excess air coefficient is large, and the air-coal cooperate well.

At position ① (X=0.3), volatile starts to be released, and the release and combustion of volatile are at the same time. Meanwhile char starts to burn, and both processes take place slowly at this time. The concentrations of CO and CO_2 also begin to increase, and O_2 concentration begins to decrease. Due to adequate O_2 at the early stage of combustion, char combustion mainly generates CO_2, and CO mainly derives from the release of volatile.

At position ② (X=0.75), the volatile release speed and char burning speed start to increase significantly, resulting in a substantial increase of the concentration of CO and CO_2, while the concentration of O_2 decreases sharply. Char and volatile compete for O_2 together, and char is in the inferiority. Due to the consumption of O_2 around the pulverized coal, CO not only comes from the release of volatile, but also is produced by char combustion and the latter has a larger magnitude.

At position ③ (X=1.85), char burning speed reaches a maximum value, then at position ④ (X=2.2), CO concentration also reaches a peak. Before position ③, the speed of CO generating due to char combustion and CO consumption speed are increasing along with the rise of temperature, but the former speed is larger than the latter. Therefore, CO around the char particles continues to accumulate, and weakens the temperature influence on char burning speed. In consequence, after position ③, char burning speed starts falling instead of rising, and to the position ④, CO consumption speed exceeds char combustion CO production speed, and CO concentration begins to decrease.

At position ⑤ (X=4.95), CO concentration drops to a valley value. This is because CO concentration gradually decreases due to CO consumption speed exceeds the speed of CO generating due to char combustion after position ④, resulting in the equilibrium shifting. So CO consumption speed begins to decline, and reaches balance to CO generating speed at position ⑤, then is overtook by CO generating speed after position ⑤, and CO concentration starts to rise again.

At position ⑥ (X=5.6), volatile is completely released and burnt. Without volatile's competition for O_2, char is burnt and consumed rapidly; combustion mainly produce CO_2, and CO is produced less. While CO is constantly consumed through combustion, so CO concentration reaches the second peak at the position ⑥. After position ⑥, char is still burning, and at the outlet char is almost burnt out, as well as CO concentration reduces to zero. While concentration of CO_2 and O_2 basically tend to be stable, indicating that reactions have been largely over.

CONCLUSION

Based on the numerical simulation research, the following conclusions are drawn：

(1) The 2.0 air-coal ratio case is the optimal operating conditions for the flame, char burnout rate, CO production or NO_x production. Comparing three operating conditions, the larger the air-coal ratio, the longer the burner outlet low temperature zone, the more unfavorable to the radial direction heat and mass exchange of air and coal, and the more slender the flame shape .

(2) The combustion of pulverized coal includes the release and combustion of volatile, and the combustion of char. Using the better combustion condition, Case 1 (2.0 air-coal ratio case) as an example to analyze combustion mechanism, volatile starts to be released at X=0.3, and is totally released and burnt at X=5.6. Volatile is released and combusted simultaneously, devolatilization speed increase first and then decrease. Char and volatile start burning almost at the same time, both compete for O_2, and char is in the inferiority; combustion produces a small amount of CO. Char burning speed reaches a maximum at X=1.85, and then begins to decrease. After volatile burnout, without volatile's competition for O_2, char is burnt and consumed rapidly, mainly produce CO_2, and char is almost burnt out at the outlet. Concentration of CO is comprehensively influenced by char combustion generating, devolatilization generating and reaction consumption, there are two peaks in the length direction, and CO is on the whole exhausted at the outlet.

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