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Influence of Recirculated Flue Gas Distribution on Combustion and NOx Formation Characteristics in S-CO_2 Coal-fired Boiler

Peipei WANG, Mingyan GU*, Yao FANG, Boyu JIANG, Mingming WANG, Ping CHEN

School of Energy and Environment, Anhui University of Technology, Ma'anshan, 243002, China

***Corresponding Author:** *Mingyan Gu, Ma'anshan, 243002, China, gumy@ahut.edu.cn*

Abstract:
Supercritical carbon dioxide (S-CO_2) Brayton power cycle power generation technology, has attracted more and more scholars' attention in recent years because of its advantages of high efficiency and flexibility. Compared with conventional steam boilers, S-CO_2 has different heat transfer characteristics, it is easy to cause the temperature of the cooling wall of the boiler to rise, which leads to higher combustion gas temperature in the furnace, higher NO_X generation concentration. The adoption of flue gas recirculation has a significance impact on the combustion process of pulverized coal in the boiler, and it is the most effective ways to reduce the emission of NO_X and the combustion temperature in the boiler. This paper takes 1000MW S-CO_2 T-type coal-fired boiler as the research target to investigate the combustion and NO_X generation characteristics of S-CO_2 coal-fired boilers under flue gas recirculation condition, the influence of recirculated flue gas distribution along the furnace height on the characteristics of NO_X formation and the combustion of pulverized coal. The results show that the recirculated flue gas distribution has the great impact on the concentration of NO_X at the boiler outlet. When the bottom recirculation flue gas rate is gradually increased, the average temperature of the lower boiler decreases and the average temperature of the upper boiler increases slightly; The concentration of NOx at the furnace outlet increases.
Keywords: *S-CO_2 boiler; Pulverized coal combustion; NO_X emission; Flue gas recirculation; Recirculated flue gas distribution*

1 Introduction

In 2020, China's CO_2 emissions reached about 9.894 billion tons, with the power industry being the largest source of carbon emissions. With the proposal and advancement of the carbon peaking and carbon neutrality goals, it is necessary to raise the efficiency of coal-fired systems power generation to reduce CO_2 emissions from coal-fired systems power generation. In recent years, China has vigorously developed clean renewable energy power generation, such as solar energy and wind power. However, the peak shaving effect of thermal power also makes a significant contribution in ensuring China's power system safety.

The traditional coal-fired boiler uses water vapor as the working medium, the power generation efficiency can reach 47%. Continuing to improve the efficiency of power generation will make a higher demand on the material of the cooling wall, thereby greatly increasing the cost of power generation [1]. Previous studies have found that for the traditional steam boiler 33MPa/620℃ ultra-supercritical unit, if the power generation efficiency is further improved from 47%, the boiler water wall temperature should reach 700℃. The expense of boiler materials will increase greatly. Therefore, countries all over the world are actively trying to increase technological innovation and explore new roads to raise the productivity of coal-fired boilers [2-3]. Many scholars have great interest in Supercritical carbon dioxide (S-CO_2) Brayton power cycle power generation technology. It has attracted people's attention because of its many advantages, such as compact system structure, high cycle efficiency and low cooling pipe corrosion. In recent years, more and more research results on S-CO_2 coal-fired power generation systems have continued to emerge at home and abroad, including the design optimization of Brayton cycle system, the structure of the boiler furnace, the heat transfer surface and the cooling wall arrangement, etc. [4-6]. And in-depth studies on cooling wall layout, combustion heat transfer characteristics and the layout of the internal heat exchange tubes of S-CO_2 boiler combined with coal-fired power generation have also been rapidly carried out [7-9].

Moullec et al have developed various conceptual designs of S-CO_2 coal-fired cycle systems with a power generation efficiency of 47.8% [10-11], while the maximum power generation efficiency of steam coal-fired boilers

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with the same capacity is 45.4%. Zhang et al [12] have designed several S-CO_2 Brayton cycle coal-fired boilers. The research results indicate that compared with boilers with the same parameters, for the system parameters of 31 MPa/ 600 ℃/ 620 ℃, the maximum power generation efficiency can be increased from 45.96% to 50.71%. Zhou et al also have carried out the optimization design of the S-CO_2 Brayton cycle, and realized that the energy efficiency of 1000MW S-CO_2 coal-fired power plant was increased to 45.4% under the maximum operating parameter of 605 ℃/603/274 bar, which was about 3.5% higher than that of traditional ultra-supercritical units [13].

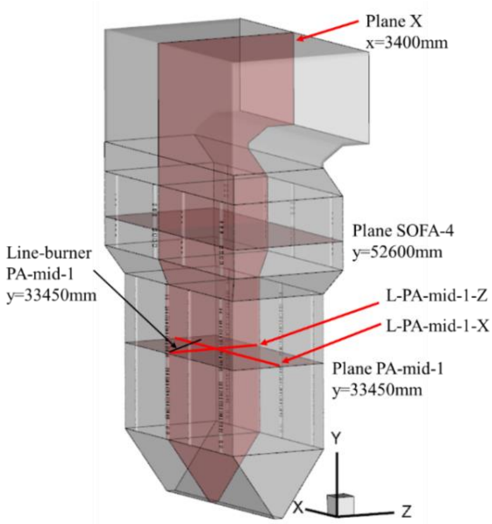
However, previous studies have found that, compared with traditional furnace, S-CO_2 with a higher temperature enters the boiler, so the entire cooling wall in the furnace has a higher temperature accordingly, then the local high temperature zone of combustion will cause the temperature of the water wall to rise more than 700 ℃ [14-17], which will significantly affect the NO_X generation and the combustion of pulverized coal in the furnace. Local over-temperature of water wall in S-CO_2 coal-fired boilers will also affect its operating efficiency.

Flue gas recirculation can effectively reduce the formation of NO_X, and is also an effective way in reducing the local high temperature in furnace. Zhou et al [18] have proposed the method of combining flue gas recirculation and expanding the size of furnace, which can increase the heat transfer area while ensuring the pulverized coal ignition and combustion, to achieve stable combustion and avoid local over-temperature of the cooling wall. Because of the complex combustion process of pulverized coal in the boiler, the aerodynamic and combustion characteristics in the furnace will be changed after flue gas recirculation, which will directly affect the NO_X generation characteristics in the furnace. There are many ways to inject circulating flue gas into the furnace, such as injecting it after mixing it with air or setting up a flue gas injection inlet separately. All these ways would have different effects on the process of pulverized coal combustion.

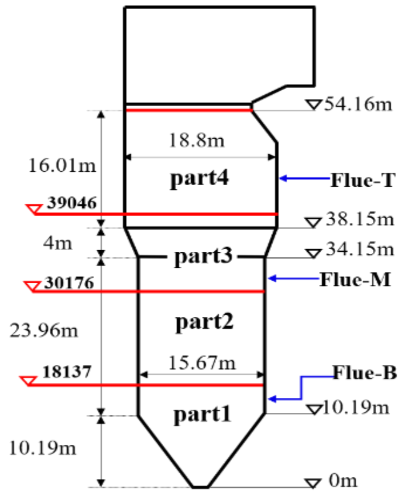
In order to investigate the combustion characteristics of S-CO_2 coal-fired boilers and control the generation and emission of NO_X, this paper takes T-type 1000MW S-CO_2 coal-fired boiler as the research object [19], and analyze in detail the influence of the distribution ratio of recirculating flue gas injected into the furnace at different positions on the characteristics of combustion and the generation of NO_X in the boiler to provide theoretical basis and guidance for the structural design and optimal combustion of S-CO_2 coal fired boilers and realization of low emissions of NO_X.

2 1000 MW T-type S-CO_2 Boiler Parameters

The boiler structure adopted in this paper is shown in Figure 1. It is divided into cold ash hopper, small furnace chamber, large furnace chamber and horizontal flue area. Since this paper focuses on the pulverized coal combustion characteristics and generation of NOx in the boiler, the effects of super-heater and re-heater in the horizontal flue are not considered in the simulation process, and the air preheater and economizer are also ignored. The total height of the boiler is 71.56m, the height of the cold ash hopper is 10.189m, the size of the small furnace chamber is 23.961m × 34.22m×15.67m, the height of the transition section of the large and small furnace chambers is 4m, and the size of the large chamber is 16.01m×41.06m×18.8m.



(a) The S-CO_2 boiler structure



(b) The partition layout of boiler cooling wall

Figure 1 Schematic configuration of 1000MW T-type S-CO_2 boiler

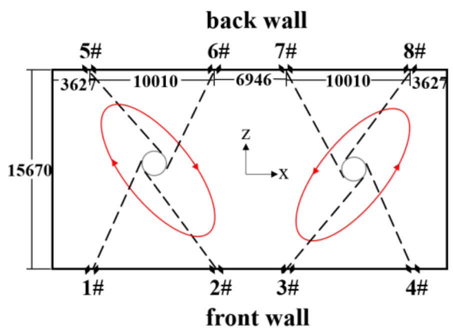


Figure 2 The arrangement of the burner nozzles in 1000MW S-CO_2 boiler

The arrangement of the burner nozzles on the horizontal section is shown in Figure 2. The arrangement of burners is designed as a reverse double tangential circle combustion system with a total of 8 columns of burners arranged on the front and rear walls of the furnace, each column includes flue gas recirculation nozzles, over-fire air nozzles, secondary air nozzles, primary air nozzles. All air and pulverized coal are sprayed vertically along the nozzle to form two reverse double tangent circles.

The specific positions of flue gas recirculation nozzles, over-fire air nozzles, secondary air nozzles and primary air nozzles on the furnace wall are shown in Figure 3. As can be seen from Figure 1, the main combustion zone of the boiler is divided into upper and lower parts. There are 18 layers of primary air nozzles in total, divided into two layers. 8 layers are set in the upper main area of combustion, 10 floors are set in the lower main area of combustion. There are 12 layers of secondary air nozzles, and the upper and lower parts of the main combustion area have 6 layers each. The secondary air nozzles at the top and bottom of the upper and lower main combustion zones is half of the area of other secondary air nozzles. The secondary air nozzles and the primary air nozzles are arranged alternately. Two layers of bottom flue gas recirculation nozzles are arranged below the secondary air nozzles in the main combustion zone, and two layers of middle flue gas recirculation air nozzles are also arranged above the main combustion zone. Above the middle flue gas recirculation air nozzles, 4 layers of over-fire air nozzles and 3 layers of top flue gas recirculation air nozzles are arranged.

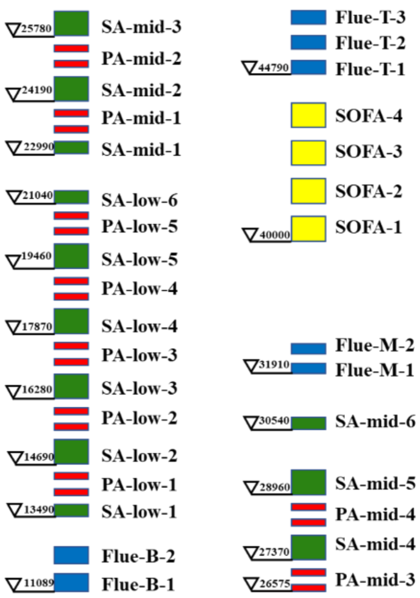


Figure 3 Burner nozzle distributions along the height of the furnace

3 Mathematical Model and Simulation Parameters

3.1 Numerical Models

The general control equation for three-dimensional steady-state turbulent heat and mass transfer commonly used for numerical calculations of flow and heat transfer is in the form of [20-21]:

$$\frac{\partial(\rho u\varphi)}{\partial x}+\frac{\partial(\rho v\varphi)}{\partial y}+\frac{\partial(\rho w\varphi)}{\partial z}=\frac{\partial}{\partial x}(\Gamma\frac{\partial\varphi}{\partial x})+\frac{\partial}{\partial y}(\Gamma\frac{\partial\varphi}{\partial y})+\frac{\partial}{\partial z}(\Gamma\frac{\partial\varphi}{\partial z})+S \quad (1)$$

In the formula: φ is a generic variable, which can represent velocity, temperature, component mass concentration, etc.; ρ is the generalized density; S is the generalized source term; Γ is the generalized diffusion coefficient.

The turbulent flow model is used to numerically simulate the turbulent flow in the S-CO_2 boiler furnace adopting the Realizable k-ε model. Particle moving model is adopted in particles random trajectory model. The radiation model uses the P_1 radiation model, and the absorption coefficient calculated by the WSGGM model. The coal volatilization analysis adopts a two parallel competitive reaction model to describe the volatilization rate. The uniform combustion of volatile matter of pulverized coal was calculated by finite rate/vortex dissipation model. The reaction rate of char depends on the diffusion rate of oxygen on the surface of char and the chemical kinetic rate calculated by the diffusion kinetic model. Thermal NO_X is simulated by extended Zeldovich Mechanism. For fuel-based NO_X calculations, HCN and NH_3 are currently widely accepted nitrogen-containing intermediates. The nitrogen in char generates NO_X in high-temperature combustion. The simultaneous reaction also includes the reduction of NO.

3.2 Simulation Conditions

In the simulation, the temperature of primary air powder is 593K, the temperature of secondary and over-fire air is 673K, and the temperature of circulating flue gas is 633k when flue gas recirculation is adopted. According to the conceptual design of the 1000MW S-CO_2 coal-fired boiler, the wall temperature is 50～100K higher than that of S-CO_2 working medium. Since the temperature of the working medium in each part of the water wall tube on the furnace wall does not change that much, the wall temperature of each part is set to be constant, and the average of inlet and outlet temperature of the working medium in each part of the water wall tube is added by 50K, and the emissivity of wall is 0.7. The parameters used are shown in below.

Table 1 1000MW S-CO_2 Coal-fired Boiler Operating Parameters

	Primary air ratio	Secondary air ratio	Over-fire air ratio
mass flow rate ratio (%)	19	56	25
the temperature of inlet (K)	593	695	695
Coal flowrate (t/h)		296.59	
excess air coefficient		1.2	

S-CO_2 temperature (K)	part1		part2		part3		part4	
	inlet	outlet	inlet	outlet	inlet	outlet	inlet	outlet
	796	852	796	852	835	883	837	884

Table 2 shows the composition analysis of bituminous coal. The size of pulverized coal particle is given according to rosin Rammler distribution and the detailed particle size data of bituminous coal are shown in the below.

Table 2 Composition analysis and diameter distribution of bituminous coal

Proximate analyses (%, ar)	Volatile	Fixed carbon	Ash	Moisture	
	26.27	49.38	8.8	15.55	
Ultimate analyses (%, ar)	C	N	H	O	S
	61.7	1.12	3.67		0.6
Calorific value of coal (kJ/kg, ar)	23400				
diameter distribution of pulverized coal (μm)	The minimum size	The maximum size	The mean size		
	5	250	60		

3.3 Solution Methods

The calculation problem between velocity and pressure is solved by SIMPLE algorithm and the first-order upwind scheme is used. It is considered that the simulation process converges when the absolute residual of several important parameters is less than 10^{-5}.

3.4 Grid Independence Test

Firstly, the grid independence test is carried out for four groups of grid domains: 3.53 million, 3.08 million, 2.61 million, 2.45 million. Figure 4 is a distribution of area-weighted average temperature with furnace height. The results shown that, there is no significant difference in temperature distribution between 3.08 million and 3.53 million grid cells. However, there is a great temperature differences between the main combustion regions of the 2.61 million and 3.08 million grids. And the simulation results presented are obtained with the grid domains of 3.08 million.

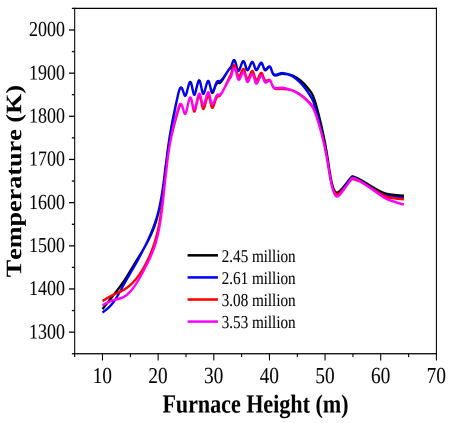


Figure 4 Area-Weighted Average Temperature Distribution with Furnace Height under Different Grid Systems

3.5 Model Validation

In order to further study the characteristics of pollutant emission and combustion of S-CO_2 coal-fired boiler, it is necessary to verify the numerical model. Because there are no S-CO_2 boiler entities and experiments, The development of steam boiler has been very mature. A traditional steam boiler with equal power is selected as experimental verification.

Table 3 Model verification results

	NO_X concentration (mg/m^3)	Burnout rate (%)	Outlet temperature (K)
Simulation results	307	98.9	1444
Measured value	272	98.8	
Simulation results from Literature [22]	270	98.8	1427

Table 3 shows the comparison between the numerical simulation results and the measured data, and the outlet NOx concentration as well as the burn rate are also given. Due to the different working fluids in the simulation and experiment, the concentration of NOx is also different. In the case of very low NOx concentrations, the predicted burn rate is consistent with the experimental date. The results show that the total relative error of the model is less than 10%, which verifies the reliability of the model. The simulation results are in good agreement with the measured data of the actual industrial steam boiler. Therefore, the simulation results of S-CO_2 coal-fired boilers are reasonable, indicating that the current models and methods can predict the flow, heat transfer, combustion and NOx generation characteristics of S-CO_2 boilers with good accuracy.

4 Results and Analysis

Recirculated flue gas is provided with three injection positions in the height direction of the furnace. The influence of recirculated flue gas distribution ratios on the characteristics of NOx generation and combustion of S-CO_2 coal-fired boiler with double furnace was studied when the flue gas recirculation rate was 27%. Table 4 shows the simulated conditions under different flue gas circulation distribution ratios.

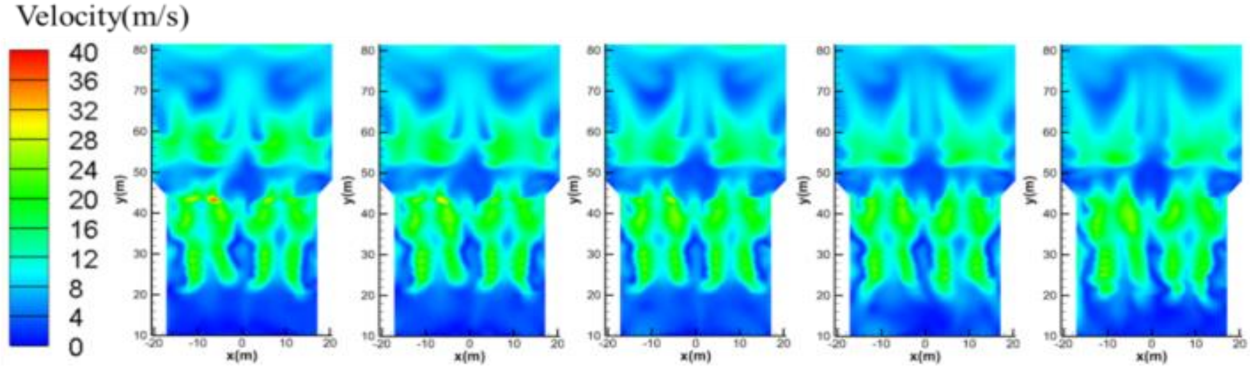
The location of the cross sections intercepted in the data analysis of this chapter is shown in Figure 1.

Table 4 Simulation conditions under different recirculated flue gas distribution

	Flue gas circulation distribution ratios		
	Bottom flue gas nozzle	Middle flue gas nozzle	Top flue gas nozzle
Case 1	0%	45%	55%
Case 2	10%	40%	50%
Case 3	20%	35%	45%
Case 4	30%	30%	40%
Case 5	40%	25%	35%

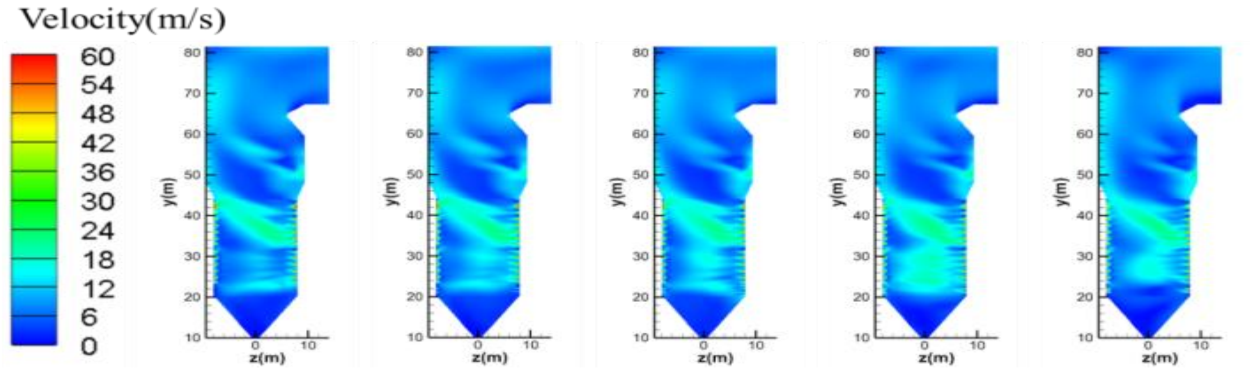
4.1 The Distribution of Velocity

Figure 5 depicts the velocity distribution on the cross section in the furnace under different flue gas circulation distribution ratios. Through observation, it can be seen that the cold ash hopper to the horizontal flue, there is primary air, secondary air, over-fire air and circulating flue gas in turn. As can be seen from Figure 5(a), due to the double tangential combustion arrangement, two large symmetrical velocity zones appear in the over-fire air zone in the large furnace and the main combustion zone in the small furnace respectively. It can be observed from Figure 5(b) that the three high-speed zones respectively appear in the direction of the nozzles downward and those upward in the main combustion zone in the small furnace as well as the direction of the over-fire air nozzles. When the bottom recirculated flue gas increasing, the velocity in the lower main combustion zone in the small furnace increases, and the velocity in the over-fire zone in the large furnace and the upper main combustion zone in the small furnace decreases. It can be observed from Figure 5(c) that there are also two reverse tangential circles in the height direction of the furnace, and the velocity in the direction of airflow injection is higher. The results show that the high-speed zones are mainly distributed near the small furnace burner, while other areas such as cold ash hopper and the over-fire zone in the large furnace are low-speed zones.



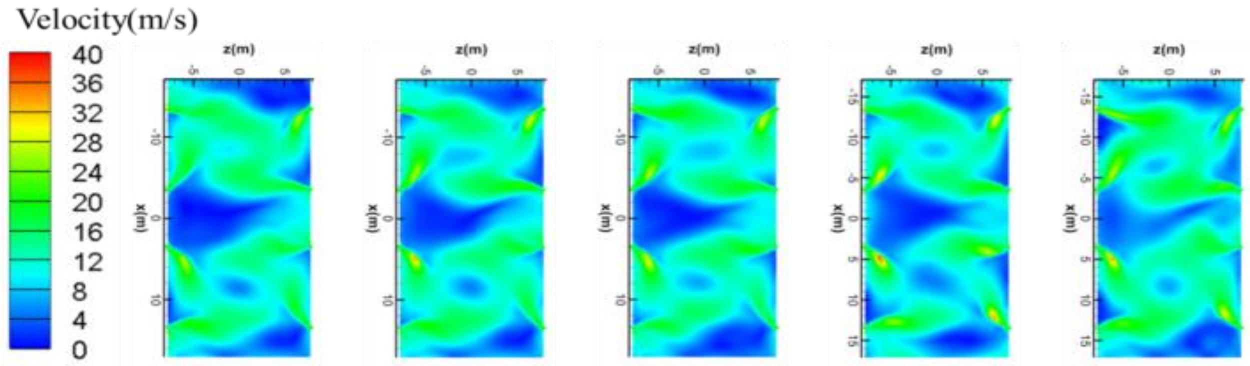
Case 1 Case 2 Case 3 Case 4 Case 5

(a) Gas velocity distributions (Z=0m)



Case 1 Case 2 Case 3 Case 4 Case 5

(b) Gas velocity distributions (X=3.4m)



Case 1 Case 2 Case 3 Case 4 Case 5

(c) Gas velocity distributions (Y=33.45m)

Figure 5 Gas velocity distributions at different recirculated flue gas distribution

Figure 6 shows the variation of the average gas velocity along the furnace height at different recirculated-flue gas distributions. With the bottom recirculated-flue gas increasing, the flue gas flow rate gradually increases at the bottom of the small furnace while the flue gas flow rate decreases in the large furnace. In the cold ash hopper region, the gas flow rate is relatively low. From the lower small furnace to the upper large one, the gas velocity gradually increases with the furnace height. For the lower small furnace, the gas velocity in the lower and upper burners tends to increase with furnace height in a fluctuating trend due to the combustion of pulverized coal. However, in the upper large furnace, because of the expansion of the cross-sectional size of the furnace, the gas velocity decreases again, and for the injection of a large amount of air from the over-fire air nozzles, the gas velocity increases with the furnace height.

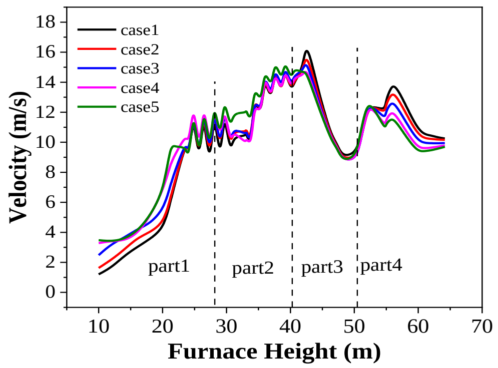
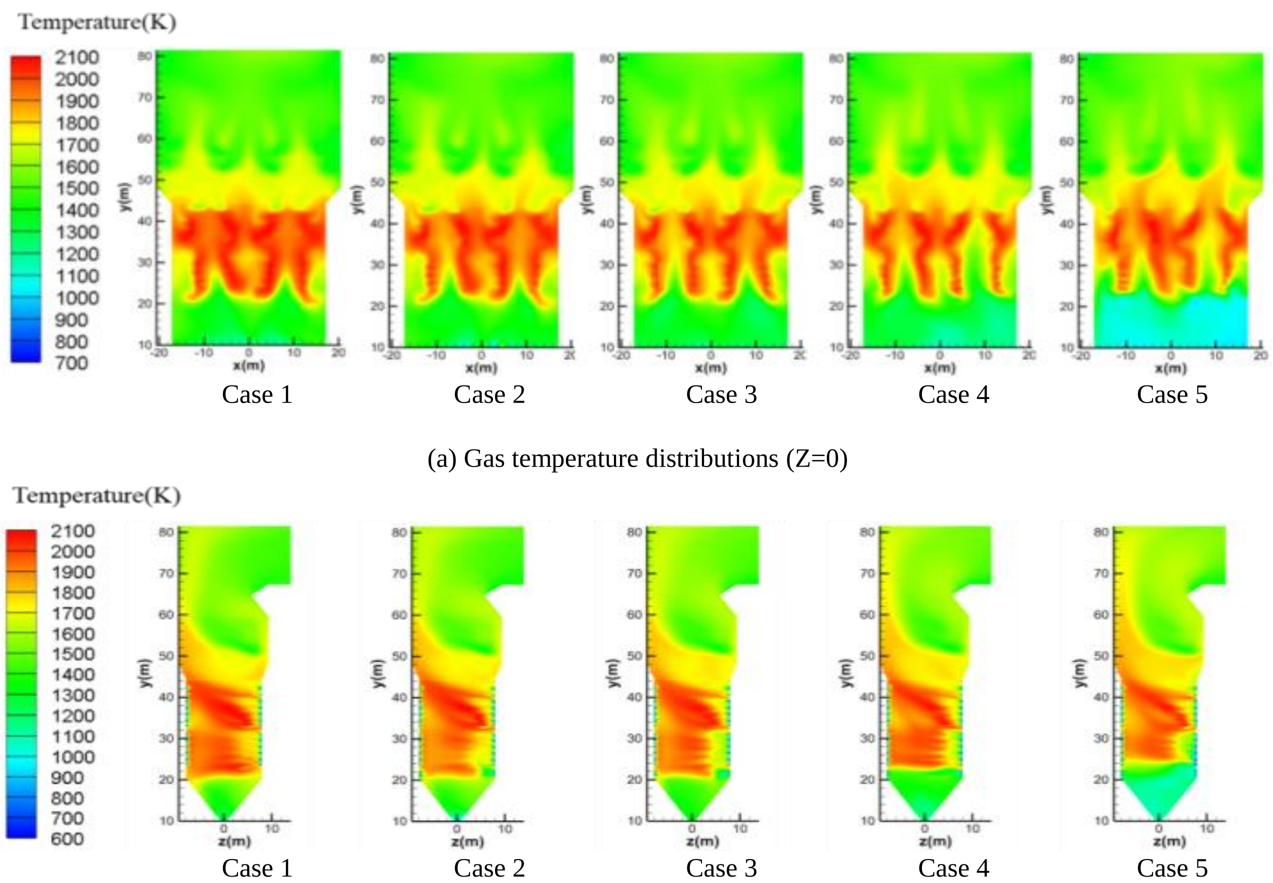


Figure 6 Area-weighted gas velocity along furnace height

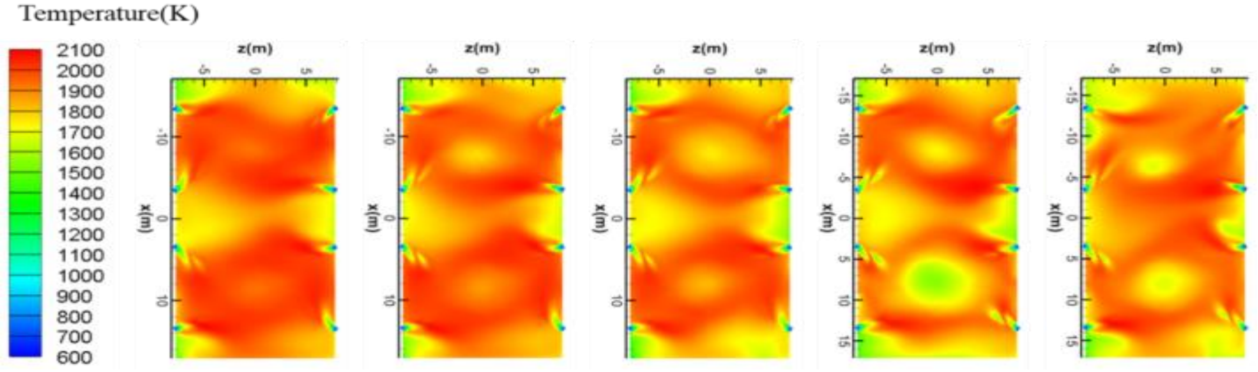
4.2 Gas Temperature Distribution

The temperature distribution on different sections of the furnace under different flue gas circulation distribution ratios are shown in Figure 7. It can be seen that a high temperature zone in the furnace is mainly near the primary air nozzles, and the flame center is in the lower part of the main combustion area in the small furnace. With the increase of recirculated flue gas at the bottom flue gas nozzles, the gas temperature in the furnace gradually decreases. Especially the gas temperature in the cold ash hopper is extremely low. This is because the injection of recirculating flue gas increases the gas flow rate around the flue gas nozzles, which delay the ignition time of pulverized coal and increases the ignition distance. In addition, due to the high CO_2 concentration in the recirculating flue gas, the specific heat increases, which requires more heat. On the other hand, the recirculating flue gas reduces the oxygen concentration in the furnace and delays the ignition time, thus reducing the flame temperature near the burner. In addition, with the increase of recirculating flue gas volume at the bottom nozzles, the airflow velocity in the small furnace increases and the residence time of pulverized coal in the main combustion zone is shortened, thus weakening the combustion efficiency and intensity and reducing the burning temperature in the main combustion zone.



(a) Gas temperature distributions (Z=0)

(b) Gas temperature distributions (X=3.4m)



(c) Gas temperature distributions (Y=33.45m)

Figure 7 Gas temperature distributions at different recirculated flue gas distribution

For the upper furnace area, the flue gas temperature is obviously low because the upper recirculating flue gas is injected above the over-fire air. In addition, the temperature distribution of each section is consistent with the velocity distribution. In the vicinity of the cold ash hopper, Near the cold ash hopper, the injected flue gas prevents pulverized coal from entering the cold ash hopper for combustion since the bottom flue gas nozzles are set below the bottom burner. Moreover, the recirculating flue gas alters the combustion conditions and the ignition and reduces the combustion intensity. Furthermore, the upward movement of the high-temperature gas also concentrates the combustion of pulverized coal in the center of the small furnace, thus further reducing the gas temperature in the cold ash hopper. A pattern of double tangential circles can be clearly seen from Figure 7(c). Since the pulverized coal is mainly burned in these areas, the temperature in the burner area is relatively high. In addition, the gas temperature in the small furnace is higher than that in the large furnace. When reaching the top of the burner area in the small furnace, the flue gas has the highest temperature. In the over-fire air zone, the gas temperature in the furnace is further reduced due to the injection of over-fire air.

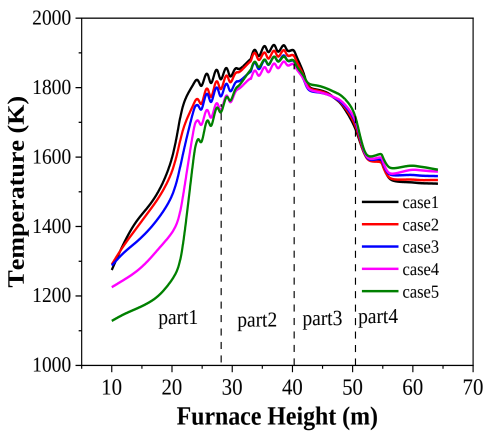


Figure 8 Area-weighted gas temperature distribution

Figure 8 shows the change of the average temperature of flue gas along the furnace height at different recirculated flue gas distribution ratios. The maximum temperature occurs in the main combustion area of the small furnace. In the case of S-CO_2 boiler, the physical properties of CO_2 are different from water. The temperature of the working medium in the S-CO_2 coal-fired boiler is higher, the heat transfer coefficient is lower than that of the steam boiler. When the pulverized coal is injected from the burner, under the action of the high-temperature airflow, the pulverized coal particles are rapidly heated. Due to flue gas circulation, the gas flow velocity in the furnace increases, and the upward movement of particles is more concentrated. In addition, the wall temperature of S-CO_2 boiler is about 200K higher than that of the steam boiler, and the higher wall temperature of Part3 of the S-CO_2 boiler is also one of the reasons for the higher temperature appeared near the Part3.

For different recirculated flue gas distributions, the overall trend of flue gas temperature distribution in the boiler is consistent, but for different areas, the temperature changes greatly. When the increase of the bottom flue gas circulation distribution ratio, the average temperature decreases in the small furnace and increases in the large furnace. This is because with the increase of the bottom flue gas circulation distribution ratio, the gas in the bottom circulating flue gas nozzles is injected with more CO_2. It has a higher specific heat, absorbs more heat and reduces the furnace temperature. When the circulating flue gas enters the furnace, due to the high specific heat of the cold flue gas, the combustion intensity of the pulverized coal is weakened, so the average temperature in the furnace is reduced as a whole, which strongly inhibits the generation of thermal NOx, and the high flue gas circulation distribution ratio at the bottom increases the circulating flue gas volume at the bottom, shortens the residence time of the pulverized coal, and slows down its ignition.

In the process of pulverized coal combustion, along the furnace height, the temperature distribution shows an increasing trend. With the continuous consumption of oxygen, the combustion intensity of pulverized coal decreases, and the temperature in the furnace decreases after reaching the peak value. In addition, the volume of the large furnace is bigger than that of the small one, which reduces the average thermal load, gradually lowering the average temperature in it during the combustion process. Through comparison, it can be seen that the average temperature of the section is the highest at 38.69 meters. In case1 it's 1926K, in case2, 1912K, in case3, 1897K, in case4, 1894K, and in case5, 1879K, with a maximum difference of 47K.

4.3 Concentration Distribution

Figure 9 shows the variation of cross-sectional average O_2 concentration along furnace height at different recirculated flue gas distributions. With the increase of the bottom recirculated flue gas, the O_2 concentration in the large furnace and the lower part of the small one gradually increases. In the lower part of the small furnace, the O_2 concentration increases due to the increase in the flow of recirculating flue gas at the bottom; in the small furnace, the concentration of O_2 in the main combustion area fluctuates, this is due to the continuous introduction of pulverized coal and combustion air in the main combustion zone, and the strong combustion of pulverized coal causes the oxygen to be quickly consumed, which is consistent with the temperature distribution in the boiler; when in the large furnace, the O_2 concentration increases due to the injection of over-fire air, and the unburned pulverized coal from the small furnace reacts with the air, consuming some oxygen and causing the O_2 concentration to decrease.

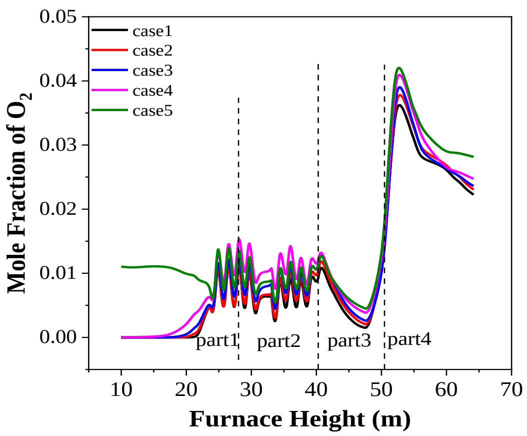


Figure 9 Area-weighted concentrations of O_2

Figure 10 shows the variation of CO average concentration with furnace height at different recirculated flue gas distribution ratios. We can see that the CO concentration increases first with the increase of furnace height, and reaches the highest concentration in the main combustion area. Then it decreases along the height, and increases again, and finally decreases along the height, reaching the lowest at the outlet. With the increase of the bottom recirculated flue gas, the CO concentration decreases significantly in the lower part of the furnace, and then decreases slightly in the upper part. The reason is that when the increase of the recirculation distribution ratio of bottom flue gas, a large amount of flue gas with high specific heat will be generated, which needs to absorb a large amount of heat. Therefore, it will slow down the combustion rate of pulverized coal, reduce its combustion intensity, increase the incomplete combustion degree of pulverized coal particles, and reduce the CO concentration. When the bottom recirculated flue gas ratio is 0, that is working condition case1, the highest CO concentration appears in the main combustion area at Y=29.19 m. However, when the ratio of the bottom recirculated flue gas gradually increases, the highest CO concentration also appears at Y=29.19 m, and the concentration gradually decreases. Obviously, due to the staged combustion of air, the small furnace is in an oxygen-poor environment, and the pulverized coal is not fully burned in the small furnace, which causes the local high CO concentration. With the increase of the recirculated flue gas ratio at the bottom, the amount of recirculated flue gas supplied in the small furnace increases, and the amount of oxygen entering the small furnace also increases, making the peak value of CO concentration gradually decrease.

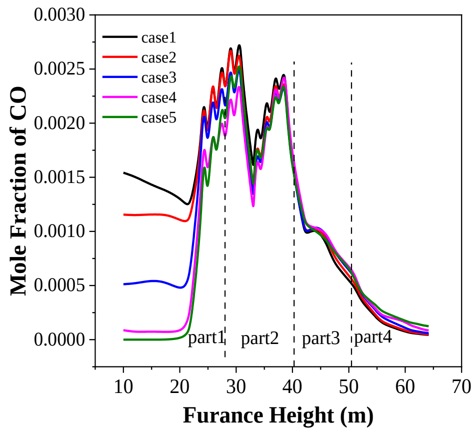
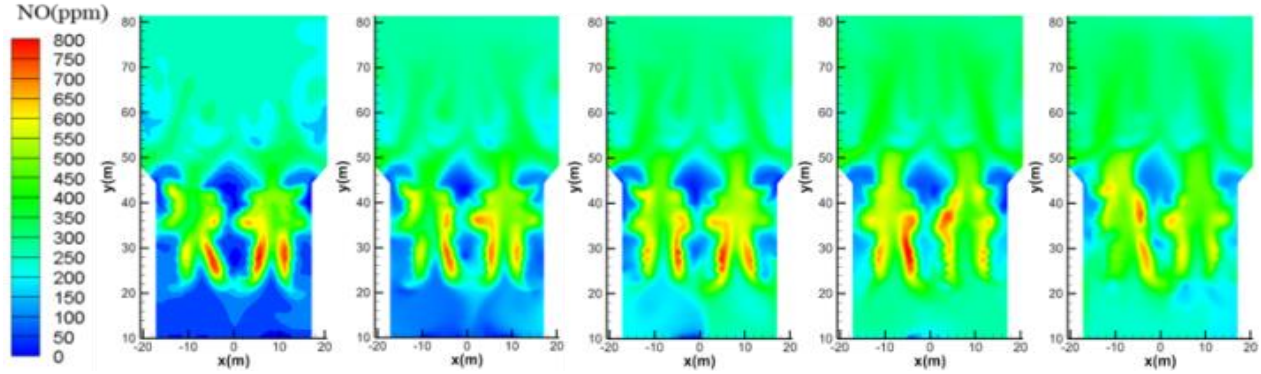


Figure 10 Area-weighted concentrations of CO

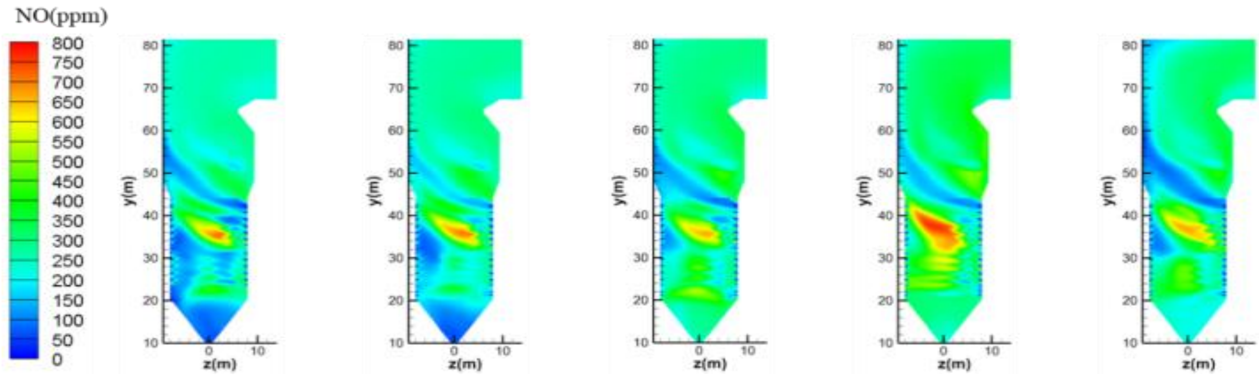
Figure 11 shows the NO concentration distribution on different sections in the furnace at different recirculated flue gas distribution ratios. It can be seen from the figure that the maximum NO concentration occurred in the small furnace. A large amount of pulverized coal particles are burned near the central area of the boiler, which releases volatile N, so NO concentration is relatively higher here. In the center of the boiler, combustion of pulverized coal particles also produced NO, resulting in an increase in NO concentration.

Through comparative observation, it can be seen more clearly that the NO emission concentration of S-CO_2 boilers with low recirculated flue gas distribution ratio at the bottom is uniformly reduced as a whole, and NO emissions are greatly improved. The overall decrease of O_2 concentration and the overall increase of CO_2 concentration in the furnace as well as the decrease of furnace temperature also play an important role in the reduction of fuel NO in the furnace, which is also the reason why NO emissions are greatly improved.



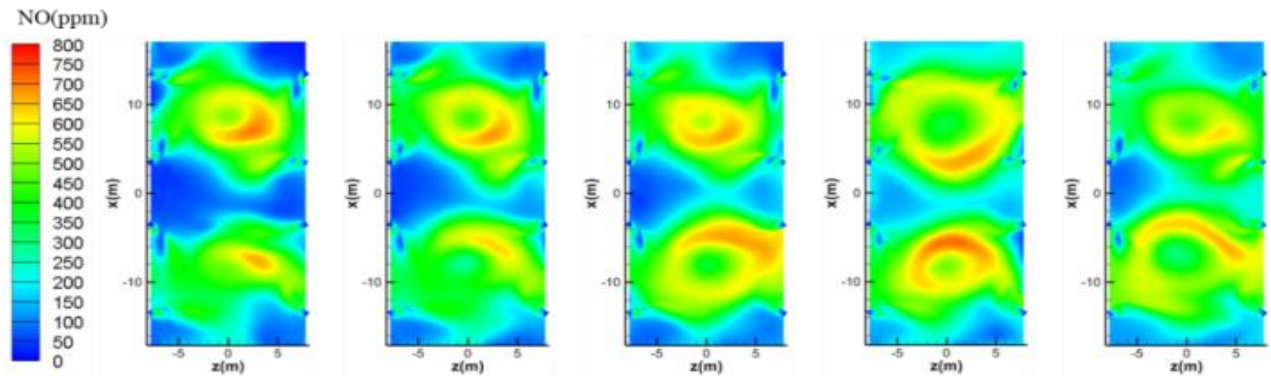
Case 1 Case 2 Case 3 Case 4 Case 5

(a) NO mole fraction distributions (Z=0m)



Case 1 Case 2 Case 3 Case 4 Case 5

(b) NO mole fraction distributions (X=3.4m)



Case 1 Case 2 Case 3 Case 4 Case 5

(c) NO mole fraction distributions (Y=33.45m)

Figure 11 NO mole fraction distributions at different recirculated flue gas distribution ratios

With the increase of the bottom recirculated flue gas, the NO concentration shows a trend of increasing first and then decreasing. The NO concentration in the ash hopper is relatively low. Combined with O_2 concentration distribution, it can be found that with the increase of the circulation distribution ratio of the bottom flue gas, the nozzles are in an oxygen-poor state, which places the combustion reaction in an oxidizing atmosphere, thus reducing the NO emissions reduction effect. In the whole furnace, the concentration of NO at the outlet of the furnace is high due to the large excess air coefficient.

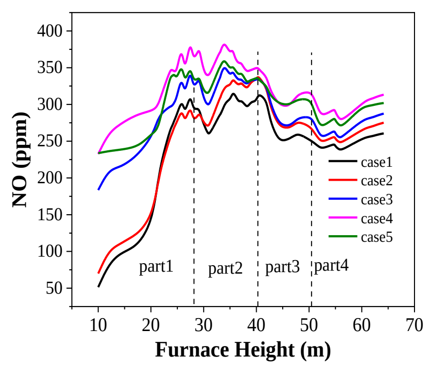


Figure 12 Area-weighted concentrations of NO

Figure 12 shows the variation of the average concentration of NO with the furnace height at different recirculated flue gas distribution ratios. We can see from the figure, the maximum concentration of NO is located in the furnace. It can be seen from the CO distribution (Figure10) that the NO distribution trend is opposite to that of CO. In places with higher CO concentration, the corresponding NO concentration is lower due to the strong reducing atmosphere. When the raise of the bottom flue gas recirculation distribution ratio, NO concentration first increases and then decreases. When the bottom flue gas recirculation distribution ratio was relatively high, NO concentration showed an upward trend, and NO production was the highest at case4. This is because under this condition, the recirculated flue gas brings in a part of oxygen, which increases the oxygen concentration in the main combustion area of the lower part of the staged combustion, resulting in the increase of NO production. However, when the recirculated flue gas distribution ratio continues to increase, the combustion in the furnace is unstable, the pulverized coal combustion conditions are not improved due to the decrease of the temperature in the furnace, resulting in the decrease of pulverized coal combustion rate and the decrease of the NO concentration.

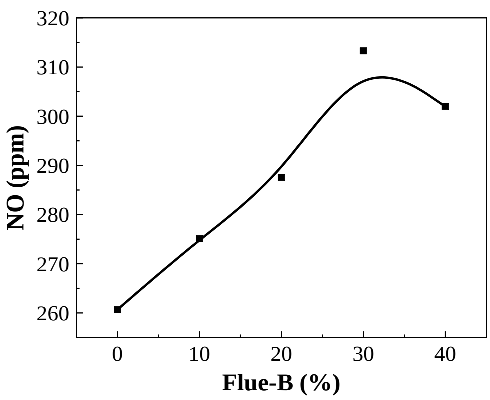


Figure 13 Area-weighted concentrations of NO at furnace outlet

Figure 13 shows the average concentration of outlet NO at different recirculated flue gas distribution ratios. We can see from the figure, the distribution ratio of recirculated flue gas has a great influence on the generation of combustion NO. When the upper, middle and lower distribution ratio is 55:45:0, the outlet NO concentration is 261ppm; When the distribution ratio is 50:40:10, the outlet NO concentration is 275ppm; When the ratio is 45:35:20, the concentration is 313ppm; When the ratio is 35:25:40, the concentration is 302ppm. Among them, when the distribution ratio of recirculated flue gas is 40:30:30, the outlet NO concentration is the highest, 313ppm. When the bottom flue gas circulation distribution ratio is 0-30%, the O_2 concentration at the bottom of the furnace increases, as the distribution ratio increases, promoting volatilization analysis and char combustion in the combustion process, which is beneficial to NO generation; When the bottom recirculated flue gas ratio is further increased, the combustion in the furnace is unstable and the furnace temperature decreases, which is not conducive to the combustion process and reduces NO generation to a certain extent.

4.4 Comparison of Ignition Temperature of Pulverized Coal

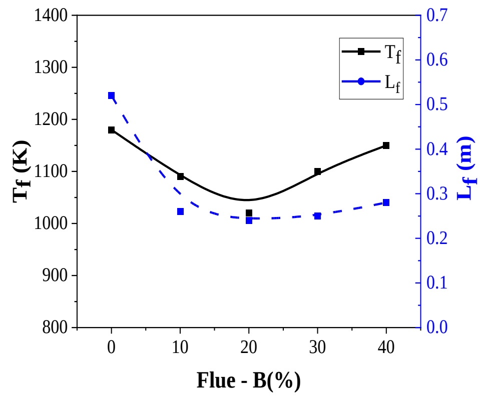


Figure 14 Comparison of ignition distance and ignition temperature at different bottom recirculated flue gas ratios

The pulverized coal carried by the primary air is sprayed into the furnace from the burner, the temperature of the coal particles increases quickly because of the heating of high gas temperature and radiation. When a certain temperature is reached, the pulverized coal starts to burn. The ignition distance L_f and ignition temperature T_f of pulverized coal are obtained along the injection direction Line-burner of the primary air nozzle PA-mid-1 in figure 1. Here, the ignition temperature T_f of the pulverized coal is obtained according to the method of literature [23]. For the temperature distribution along burner central line, calculate the first derivative of the temperature function, and the temperature corresponding to the maximum value of the derivative is the ignition temperature. Figure 14 gives the comparison of the ignition distance and ignition temperature of different recirculated flue gas distribution ratios. We can see from the Figure 14, with the increase of the bottom recirculated flue gas ratio, the ignition temperature and distance first decrease and then increase. The highest ignition temperature of case1 is 1180K, and the ignition distance is 0.52m. The lowest ignition temperature of case3 is 1020K, and the ignition distance is 0.24m. Compared with case1, the ignition temperature is reduced by 160K and the ignition distance is shortened by 0.28m.

5 Conclusion

In the paper, the numerical simulation software ANSYS FLUENT is used to carry out detailed numerical simulation on the generation characteristics of NO and combustion of a T-type 1000MW S-CO_2 coal boiler under the different condition of flue gas recirculation distribution ratios. The effects of recirculated flue gas distribution on the generation characteristics of NO and combustion characteristics are investigated. The results show that:

(1) With the increase of the bottom recirculated flue gas ratio, the outlet NO concentration increases. When the bottom recirculated flue gas ratio is 30%, the outlet NO reaches the maximum, and then decreases if the bottom recirculated flue gas ratio continues to increase;

(2) With the increase of the bottom recirculated flue gas ratio, the average temperature in the lower furnace decreases, which is conducive to reducing the maximum temperature of the cooling wall;

(3) With the bottom recirculated flue gas ratio increases, the ignition distance and ignition temperature of pulverized coal decreases; when the bottom recirculated flue gas ratio is over 20%, the ignition temperature increases and the ignition distance increases slightly.

Author Contributions: Peipei Wang: Software, Data curation, Writing - original draft. Mingyan Gu: Writing - review & editing, Methodology. Yao Fang: Data curation. Boyu Jiang: Investigation. Mingming Wang: Investigation. Ping Chen: Writing - review & editing.

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