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CASE REPORT

Combined operation mode of sub-critical W-flame boiler and coal mill optimized numerical simulation

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ABSTRACT

The flow, combustion, heat transfer and NO_x emission characteristics of a 600 MW subcritical W-flame boiler were numerically simulated under different combined operation modes of coal mills, and compared with the measured results. The results show that the combustion, average residence time, burnout rate, NO_x emission characteristics and temperature distribution near the side wall of pulverized coal particles in the furnace have different effects on the combined operation mode of pulverized coal. In the combustion efficiency of give attention to two or more things, screen superheater section of fly ash carbon content and flue gas temperature of entrance at the same time, compared with six coal mill run at the same time, 5 coal mill run, shut down near the side wall of the coal mill is beneficial to reduce NO_x emission concentration, to achieve the emission reduction, at the same time under the wing wall and side wall area chamber of a stove or furnace slagging significantly reduce.

Keywords: Subcritical W-Flame Boiler; Combustion Optimization; Combined Operation Mode of Coal Mill; NO_x Emission Characteristics; Numerical Simulation

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1. Introduction

Low volatile coal resources in China have large reserves and wide distribution, but the low volatile content of coal powder makes it difficult to ignite and has poor stable combustion characteristics. W-flame boiler has good adaptability to the combustion of low-volatile coal and other inferior coals, so it has been widely used in China in recent decades. However, most W-flame boilers have such disadvantages as ignition delay, poor stability, low burnout rate (the carbon content of fly ash is 8%–15%) and high NO_x emission (the emission mass concentration of NO_x under $\varphi(O_2)$ = 6% is 1100–2000 mg/m^3)[1]. In order to ensure the fire stability of pulverized coal, the combustion belt is generally laid around the lower furnace and the furnace arch area, resulting in a higher temperature in the furnace, which is an important reason for the higher NO_x emissions from the outlet of the furnace. Gb13223-2012 Emission Standard of Heavy Gas Pollutants for Thermal Power Plants puts forward stricter requirements for NO_x emission control of W-flame coal burning boiler, and limits the emission mass concentration of NO_x (NO_2 as measurement standard) of W-flame coal burning boiler to within 200 mg/m^3. In this regard, in recent years, a series of combustion control technologies and methods to reduce NO_x emissions have been developed, and have been widely used in coal-fired power plant boilers, such as reburning technology, exhaust air technology, shade deviation technology and flue gas recycling technology, etc. Among them, the exhaust air technology has been widely used in domestic coal burning power plants because of less investment and more obvious NO_x emission reduction effect.

There are more and more literatures on the combustion, slagging and NO_x emission of pulverized coal boilers by means of numerical simulation. Many scholars have carried out a great deal of research on the low-NO_x combustion technology of tangential combustion boilers[2-4]. Fang *et al*.[5] conducted numerical simulation on the NO_x emission characteristics of an ultra-supercritical offset combustion boiler under different combined operation modes of coal mills. The results show that the combustion characteristics and NO_x emission characteristics of boilers are affected by different combined operation modes of coal mills. Scholars at home and abroad have also carried out some studies on W-flame boiler by using numerical simulation methods[6-9], but there are few numerical simulations on the combined operation modes of different coal mills. Fang *et al.*[10] conducted numerical simulation on slagging characteristics of a DG1025/18.2-II4W boiler when it was fired with different types of coal, and the results showed that the slagging locations were mainly the wing wall of lower furnace, the area of furnace arch burner and local areas of front and rear walls. Stopping the coal mill near the wing wall could effectively reduce the slagging tendency of the wing wall. Kuang *et al.*[11,12] studied the influence of burnout air position and burnout air Angle of furnace arch on combustion characteristics and NOx emission characteristics of a 350 MWe pulverized coal boiler through numerical simulation and experiment. The results showed that burnout air was sent from the furnace arch to the lower furnace at 40°, which could effectively reduce NO_x emission. According to Li[13], such as high efficiency low NO_x combustion was put forward with the combination of number value simulation principle and technology, including dual channel vane shade separation technology, reasonable decorate shade pulverized coal and air flow and secondary air downdip technology, burning wind technology and alleviate the wing wall slagging technology, part or all of these techniques was applied to some boiler, good results are obtained. Gao *et al*.[14] studied the influence of boiler structure on W-flame by means of numerical simulation.

Numerical study on the flow, combustion, heat transfer and NO_x emission characteristics of a 600 MW subcritical W-flame boiler under rated full load condition and different combined operation mode of coal mills is carried out, which provides reference for the optimization of combustion and pollutant emission characteristics of the same type of boiler.

2. Overview of boiler

The boiler is a type π drum boiler of 1,778 T/h subcritical natural circulation, primary intermediate reheating, single furnace, open air arrangement, full steel suspension structure, balanced ventilation, solid state slag discharge, and is manufactured by Dongfang Boiler (Group) Co. The furnace is divided into upper and lower parts, total. The height is 50.150 m, the size of the upper furnace is 34.481 m × 9.906 m, and the size of the lower furnace is 34.481 m × 16.012 m. The lower furnace bore is double arched, and a burning belt is laid on the water cooling wall and near the furnace arch. Using W flame combustion mode, the whole boiler is equipped with 6 double inlet and double outlet coal mills (A coal mill ~ F coal mill), each mill with 6 burners, A total of 36 burners, symmetrically arranged on the furnace arch before and after the furnace. The corresponding arrangement of coal grinder and burner nozzle is shown in **Figure 1**.

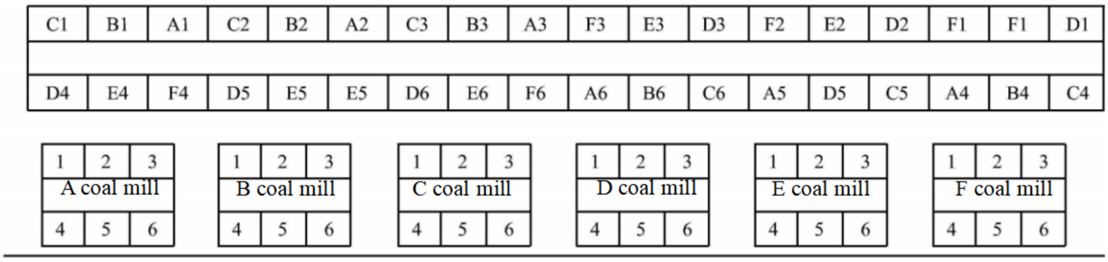

Figure 1. Schematic diagram of coal mill layout.

3. Mathematical model and calculation conditions

3.1 Mathematical model

Pulverized coal combustion includes a series of complex physical and chemical processes such as pulverized coal pyrolysis, combustion, turbulent flow and heat and mass transfer. The standard K-ε bidirectional turbulence model is used to simulate the turbulent gas flow. The probability density function (PDF) model is used for turbulent gas combustion. A parallel reaction model is used for coal pyrolysis. Coke combustion adopts dynamic/diffusion control reaction rate model. The motion of pulverized coal particles is modeled by particle random orbit. PI model is adopted for radiation heat transfer calculation. The detailed description of the model is referred to the reference[15].

For NO_x modeling, the main consideration is NO, and the “post-treatment” method is used to calculate the NO production. The generation of NO in pulverized coal furnace mainly involves two kinds of mechanism: thermal type NO and fuel type NO. Due to the small proportion of fast type NO and its main presence in the flame of hydrocarbon rich fuel, it will not be considered here. Thermal NO is mainly generated by the oxidation of N_2 in the air. Affected by temperature and O_2 concentration, it can be described by the extended Zeldovich machine[16]. For the [O] and [OH] groups, the partial equilibrium method is used. Fuel type NO is mainly generated by the pyrolysis and oxidation reaction of nitrogen in fuel, which is the main source of NO in pulverized coal combustion. The generation and reduction process of fuel type NO is not only related to the characteristics of coal, the form and distribution of nitrogen functional groups in fuel, but also closely related to combustion conditions (such as temperature and O_2 concentration, etc.). Fuel type NO is described by de Soete model[17]. Nitrogen in fuel is mainly distributed in volatile matter and coke, and nitrogen in volatile matter is released in the form of HCN and NH_3, while nitrogen in coke is directly oxidized to NO.

3.2 Calculation conditions

According to the actual physical structure size of the boiler, the geometric model is established, and the furnace is divided into cold ash bucket region, burner region, burnout region, screen superheater region and high temperature reheater region. The grid is divided into hexahedral grids with high quality. Grid encryption of the burner area to reduce the numerical calculation error. After the grid independence test, the total number of the model grid is 3.85 million. The boiler furnace geometric model and mesh division are shown in **Figure 2**.

3.3 Calculation conditions

Based on the rated load condition, the numerical simulation is carried out under ABCDEF (working condition 1), ABCDF (working condition 2), ABCDE (working condition 3) and ABCEF (working condition 4) combined operation mode. Under the rated load condition of the boiler, the excess air coefficient is 1.12, the volume fraction of operating O_2 is 2.25%, the primary air volume and the exhausted air volume (71.99 kg/s) account for 11.11% of the total air volume, and the total secondary air volume is 471.62 kg/s, of which the exhausted air volume is 129.6 kg/s. The regional excess air coefficient of the main burning is 0.8.

The primary air temperature is 423 K, and the secondary air temperature is 607 K. A, B, C, D, E, F coal mill combined operation mode the mass flow rate of pulverized coal in the next wind is 1.087 kg/s, and the mass flow rate of pulverized coal in the poor air is 0.242 kg/s. ABCDF, ABCDE and ABCEF coal mills combined operation formula for the next air pulverized coal mass flow is 1.304 kg/s, poor air pulverized coal mass flow is 0.290 kg/s; Each burner distributes air evenly, and coal quality analysis is shown in **Table 1**.

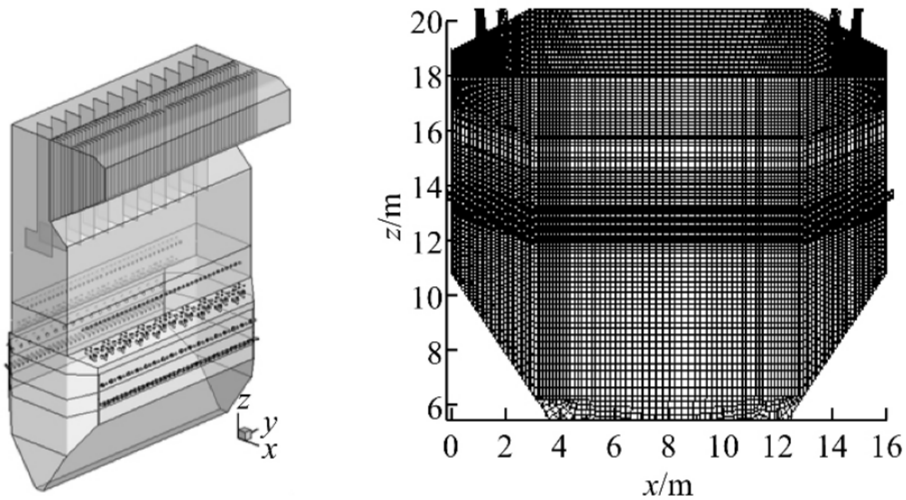

Figure 2. Model and grid division.

Table 1. Quality analysis of coal

Parameter	**Industrial analysis/%**				**Elementary analysis**					**$Q_{net,ar}$**
	w **(V_{ad})**	***w*** **(M_{ad})**	***w*** **(A_{ad})**	***w*** **(FC_{ad})**	***w*** **(C_{ad})**	***w*** **(H_{ad})**	***w*** **(O_{ad})**	***w*** **(N_{ad})**	***w*** **(S_{ad})**	**/(kj·kg^{-1})**
Value	8.27	2.00	39.80	49.94	51.56	2.26	2.46	0.68	1.24	17,370

Burners and exhaust air adopt mass inlet boundary conditions, and inlet flow and temperature are set according to operating parameters. The outlet boundary condition adopts pressure outlet, and the pressure setting value is -60 Pa. The wall surface of the boiler adopts non-slip and temperature boundary strip, different temperatures are set in different sections, and the radiant emissivity of the wall surface is set as 0.6. The diameter of pulverized coal particles is set according to Rosin-Rammler equation, the minimum diameter of pulverized coal particles is 5 μm, the maximum diameter is 250 μm, the average diameter is 54 μm, and the distribution index is 1.5. The prefactor and activation energy of coke combustion kinetic parameters are 0.0016 kg·s·Pa/m^2 and 8.37 × 107 kJ/kmol.

The Simple algorithm is used to solve the pressure and velocity coupling of the discrete equations. In order to ensure the precision of calculation, the discrete scheme of quadratic upwind interpolation is used to solve the governing equation. The convergence conditions of the calculated results are as follows: (1) the residual of the energy equation is less than 10^{-6}, and the residual of other equations is less than 10^{-5}; (2) the furnace outlet velocity and temperature do not change with the iteration.

4. Results and discussion

4.1 Verification of simulation results

According to the method in “power station boiler performance test specification”, the boiler is tested under the load of 600 MW without burnout air, 600 MW with burnout air and 450 MW with burnout air. **Table 2** shows the comparison between simulated and measured results. As can be seen from **Table 2**, under 600 MW load without burnout air, the relative error of flue gas oxygen integral number obtained by simulation and measurement is 2.56%, the relative error of NO_x emission mass concentration is 11.06%, and the relative error of carbon content of fly ash is 0.03%. Under the loading of 600 MW exhaust air, the relative error of simulated and measured flue gas oxygen volume fraction is 3.74%, The phase error of NO_x emission mass concentration is 3.99%, and the relative error of carbon content in fly ash is 0.43%. Under the load of 450 MW exhaust air, the relative error of oxygen volume fraction of flue gas, NO_x emission mass concentration and carbon content of fly ash are 2.65%, 2.63% and 0.19% respectively. The simulated values of flue gas oxygen volume fraction and NO_x emission mass concentration under 600 MW and 450 MW loads are consistent with the measured values, indicating that the model and grid used can reasonably predict the flow, combustion, heat transfer and NO_x emission characteristics in the boiler.

Table 2. Comparison between the simulation and the actual results

Name	Load/MW	The flue gas oxygen body	NO_x emission mass concentration/（$mg \cdot m^{-3}$)	Fly ash contains carbon/%
Simulation results	600	2.28	1,335	1.98
Measured results	No burnout air	2.34	1,501	2.01
Simulation results	600	2.44	759	2.03
Measured results	Burnout air	2.52	751	2.46
Simulation results	450	2.57	631	2.52
Measured results	Burnout air	2.64	648	2.71

4.2 Distribution of each parameter along the furnace height

Figure 3 shows the distribution of temperature along the axis of the primary air nozzle. It can be seen from **Figure 3** that the trend of pulverized coal ignition curve is basically the same under different working conditions. According to literature[18] and literature[19], the point with a temperature of 1000 K is defined as the ignition point of pulverized coal, and the distance from the ignition point to the nozzle exit is the ignition distance. The results show that the ignition distance of pulverized coal airflow changes little when the pulverized coal mill is close to the side wall pulverized coal mill (working condition 4) when the pulverized coal mill is close to the side wall pulverized coal mill combined with the 5 pulverized coal mills, compared with the 6 pulverized coal mills, indicating that the shutdown of pulverized coal mill close to the side wall pulverized coal mill has little influence on the stable combustion characteristics.

Figure 4 shows the distribution of average temperature of flue gas along the height of furnace under different working conditions. It can be seen from **Figure 4** that in the cold ash hopper area, the average temperature of flue gas in the cross-section of the furnace increases rapidly with the increase of the height of the furnace. Area in the main combustion chamber of a stove or furnace section flue gas temperature fluctuation, this is because the z = 12 m and z = 16 m near the secondary air and exhaust air mixed with furnace cross-section flue gas temperature is reduced, the region near the upper exhaust wind area chamber of a stove or furnace section reached the highest average temperature of flue gas furnace under the condition of 1 section is close to 1,500 ℃, the average temperature of flue gas However, the temperature difference between 2 and 4 conditions decreased significantly, and the peak mean temperature difference reached about 50 K in this region. Since the exhaust air volume is large, accounting for 20% of the total secondary air volume, the average temperature of flue gas in the furnace section decreases significantly when the exhaust air is mixed near the section z = 23 m. However, the unburned coke in the later period continues to burn and release heat after the exhaust air is mixed, and the average temperature of flue gas in the furnace section increases. In the upper furnace area, the average temperature of flue gas in the furnace section decreases gradually with the increase of the height of the furnace, because the water wall absorbs a lot of heat. It can also be seen from **Figure 4** that in the main combustion region, working conditions 2 ~ 4 are equivalent to postponing pulverized coal combustion on the basis of working condition 1, and the average temperature of flue gas in the cross-section of the furnace will decrease. In the upper burnout zone, the coal char is further burned in the later stage, and the average temperature distribution of flue gas in the cross-section of the furnace is basically the same, but they are all lower than the working condition 1.

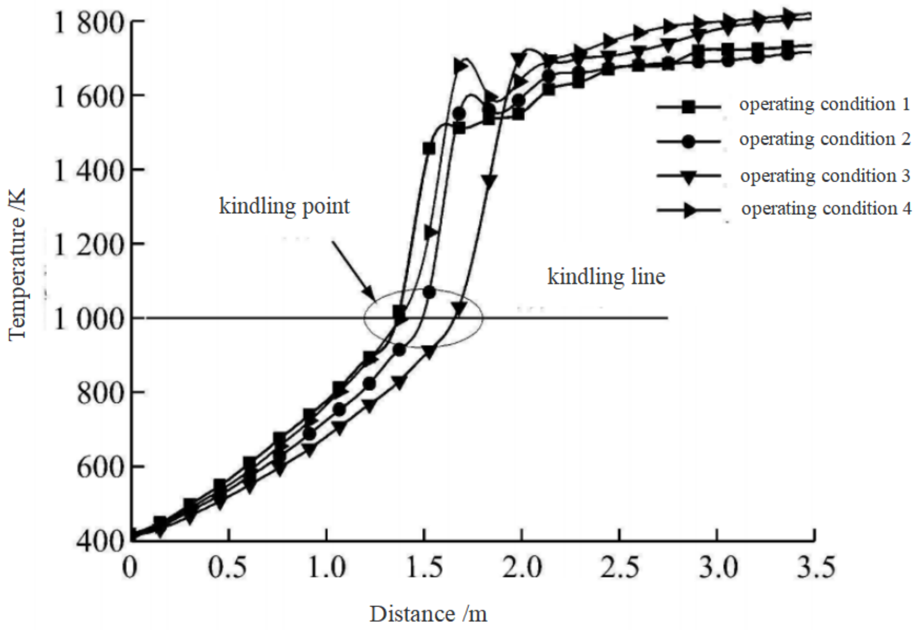

Figure 3. Temperature distribution along the primary air nozzle axis (A3 nozzle).

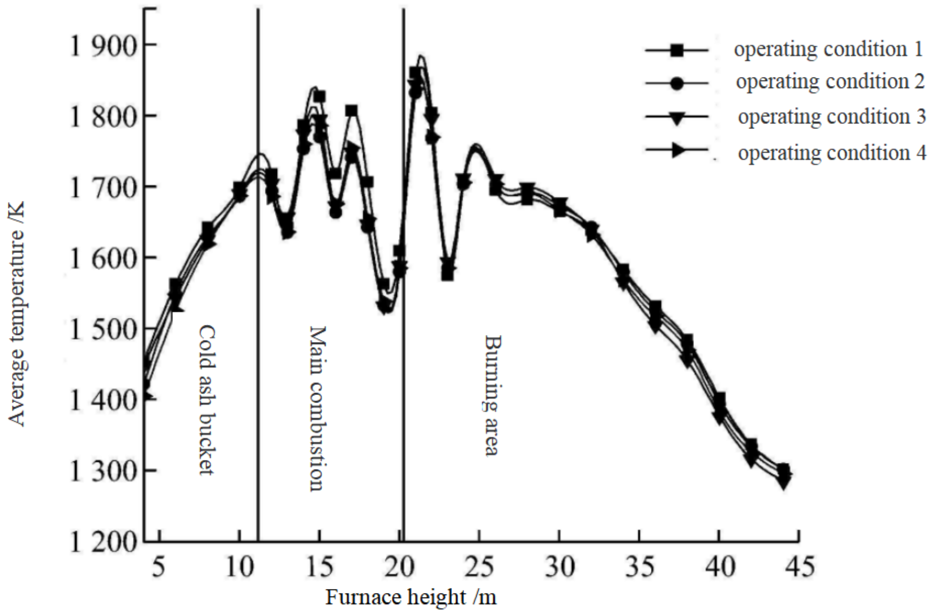

Figure 4. Average flue gas temperature distribution along the height of furnace.

Figure 5 shows the distribution of CO volume fraction φCO along the furnace height. As can be seen from **Figure 5**, the distribution trend of φCO along the furnace height is consistent under different working conditions. In the burner area, the excess air coefficient is 0.8, in the low oxygen rich fuel atmosphere, coal powder into the furnace after the high temperature flue gas reflux coil effect of rapid ignition combustion, due to the excess of fuel to generate a large number of CO, resulting in the area φCO rapidly rising. High φCO is beneficial to reduce NO generation. This is because the amount of volatiles precipitated from low volatile coal during pyrolysis is very small, and the amount of nitrogen gas is even less. Moreover, the expansibility of coke generated from pyrolysis is very small, which may be due to the low amount of gas produced by low volatile coal pyrolysis, low internal pressure and very small pores. Therefore, coke has very few reactive points, and the reducibility of available coke to NO is very small[20], so the reduction performance of CO can be fully utilized to effectively inhibit the generation of NO. It can also be seen from **Figure 5** that in the main combustion area, φCO under working conditions 2 ~ 4 is higher than that under working conditions 1, which is conducive to enhancing the reducing atmosphere in the main combustion area, inhibiting NO generation, and achieving the purpose of reducing NO_x emissions.

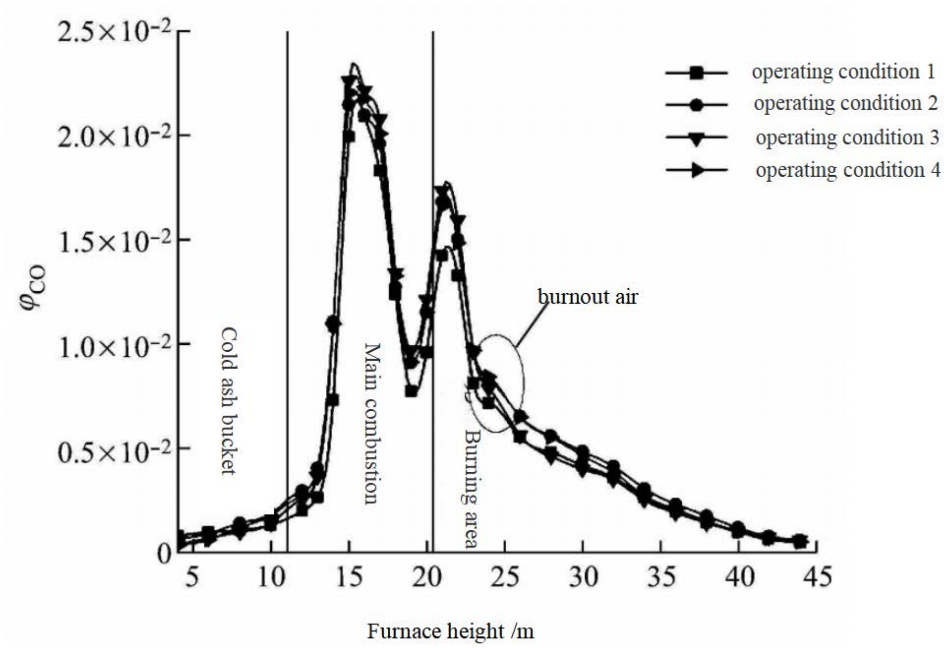

Figure 5. CO volume fraction distribution along the height of furnace.

Figure 6 shows the distribution of NO volume fraction φNO along the furnace height. As can be seen from **Figure 6**, the distribution trend of φNO along the furnace height is basically the same under different working conditions. In the main combustion area, pulverized coal rapidly ignites and burns after entering the furnace, and nitrogen is constantly precipitated in the coal, which can be roughly divided into two stages: volatile analysis stage and coke combustion precipitation stage[21]. Therefore, the formation of NO from nitrogen in fuel can be divided into two stages: uniform phase formation of volatile matter and heterogeneous phase formation of coke. HCN and NH_3 released in the volatilization process react with O_2 to produce a large amount of NO. In the process of coke combustion, nitrogen in coke is oxidized to NO; at the same time, N_2 in the air also reacts with O_2 to produce a large amount of NO. φNO presents two wave peaks along the high square direction. The formation of the first steep wave peak is mainly due to the rapid volatilization and combustion, and the formation of NO is relatively concentrated. Coke combustion is a relatively slow process, and the formation of the second wave peak is mainly due to the mixture of exhaust air, nitrogen in coke is oxidized to NO. The excess air coefficient in the main combustion region is 0.8, and low oxygen and rich fuel lead to incomplete combustion of pulverized coal to generate a large amount of CO, which is in the reducing atmosphere condition. At the same time, NO reacts with HCN, NH_3 and coal coke, and NO is reduced, so φNO decreases after the two wave peaks.

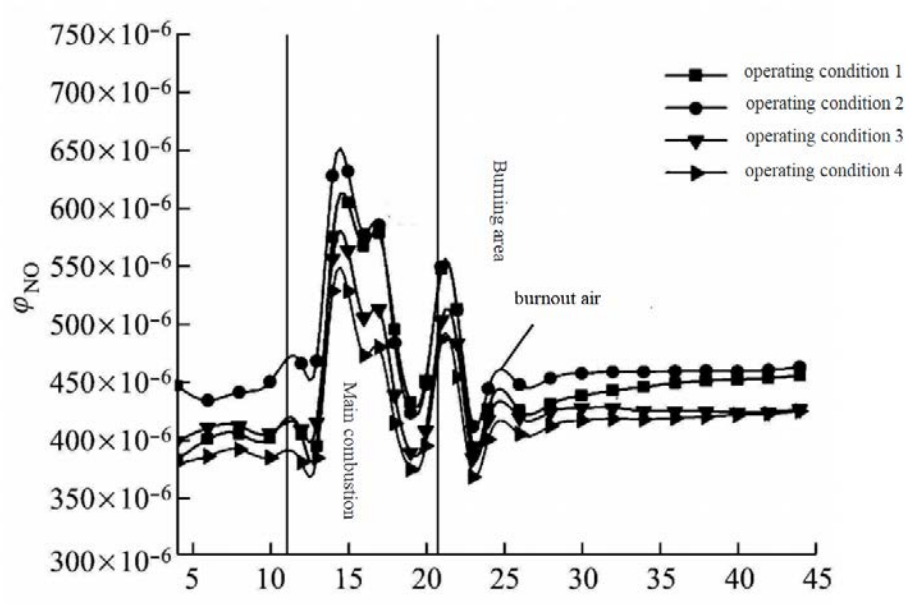

Figure 6. NO volume fraction distribution along the height of furnace.

The combined running mode of different coal mills has certain influence on NO generation. When the shutdown is close to the side wall coal mill (working condition 4), the average temperature of the main combustion area is obviously lower than that of working condition 1 (i.e. basic working condition), which can effectively inhibit the generation of thermal NO, and at the same time φCO is higher, reducing gas. Strong atmosphere, can effectively reduce the generated NO.

4.3 Furnace exit parameters

The simulation results from working conditions 1 to 4 show that the average temperature of smoke gas level at the cross-section of the break flame Angle inlet is 1,484 K, 1,479 K, 1,456 K and 1,470 K, which indicates that the average temperature of smoke gas at the entrance section of the large-screen superheater changes little when the E mill is in operation or out of operation. When F mill is shut down, the average temperature of flue gas at the entrance section of large screen superheater decreases most significantly. When the mill D is shut down, the average temperature of the inlet section of the large-screen superheater decreases less than that of the working condition 1, which is helpful to avoid the overtemperature of the large-screen superheater and avoid a large temperature decrease.

Figure 7 shows the average residence time of pulverized coal particles in the furnace and the carbon content of fly ash at the outlet of the furnace under different working conditions. As can be seen from **Figure 7**, the average residence time of pulverized coal particles in the furnace under working conditions 1 to 4 is 8.922 s, 8.424 s, 8.611s and 8.622 s respectively, and the carbon content of simulated fly ash is 1.81%, 2.51%, 2.59% and 2.24%. Compared with operating condition 1, the carbon content of fly ash from operating condition 2 to operating condition 4 increases by 0.70%, 0.78% and 0.43%, respectively, and the burnout rate decreases, but the carbon content of fly ash from operating condition 4 increases by the least.

Figure 8 shows the NO_x emission mass concentration at the outlet of the furnace under different working conditions. As can be seen from **Figure 8**, the NO_x emission mass concentrations under working conditions 1 to 4 are 759 mg/m^3, 770 mg/m^3, 715 mg/m^3 and 702 mg/m^3, respectively. This shows that the combined operation mode of different mills has a certain impact on the NO_x emission mass concentration of W-flame boiler, which is mainly caused by the difference in the temperature and reducing atmosphere of the main combustion area when the combined operation of different mills. Compared with working condition 1, the NO_x emission mass concentration of working condition 2 is increased, and the NO_x emission mass concentration of working condition 3 and 4 is

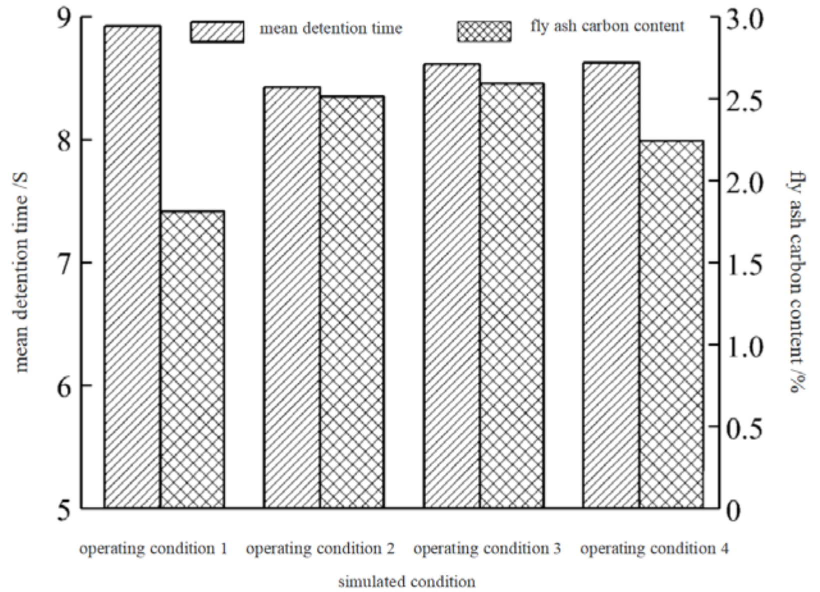

Figure 7. Average residence time of coal particles in the furnace and the carbon content in fly ash at the furnace outlet.

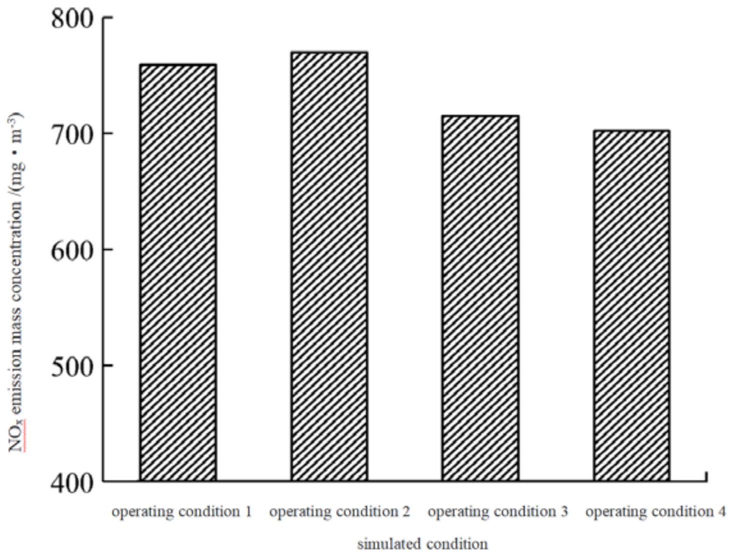

Figure 8. NO_x emission at the furnace outlet.

significantly reduced, and the NO_x emission mass concentration of working condition 4 is the most obvious when the shutdown is close to the side wall coal mill. The above analysis shows that the combined operation of 5 coal mills and the shutdown close to the side wall coal mill are conducive to reducing the NO_x emission mass concentration at the furnace outlet while taking into account the combustion efficiency. The actual operation test shows that the mass concentration of NO_x emission from the furnace outlet is 835 mg/m^3 when the coal mill close to the side wall is shut down, and 891 mg/m^3 when the coal mill is kept running.

Figure 9 shows the temperature distribution near the side wall surface (about 0.2 m away from the left wall) in the main burning area of W-flame boiler under different working conditions. It can be seen from **Figure 9** that the high temperature area of the lower wall surface is the largest in working condition 3, which may increase the tendency of high temperature slagging on the side wall surface. Under the condition of 4 side near the wall surface temperature decrease, think in terms of temperature, which is beneficial to reduce the possibility of side wall surface temperature and slagging, this is because the shutdown D grinding, low near the side wall surface temperature of the wind mixed with in time, reduces the side near the wall surface temperature, at the same time can be formed near the side wall surface oxidizing atmosphere, and effectively reduce settlement slag. It can be seen that changing the combined operation mode of coal mills has a significant impact on the temperature distribution near the side wall surface in the main combustion area of the boiler. When 5 coal mills are in operation and out of operation close to the side wall coal mill, the possibility of high temperature slagging on the side wall surface in the main combustion area is smaller than that of other combined operation modes of coal mills. In the actual operation, the burner near the side wall was shut down. After a period of operation, it was found that the slagging degree of the wing wall and side wall area was significantly reduced in the middle minor repair.

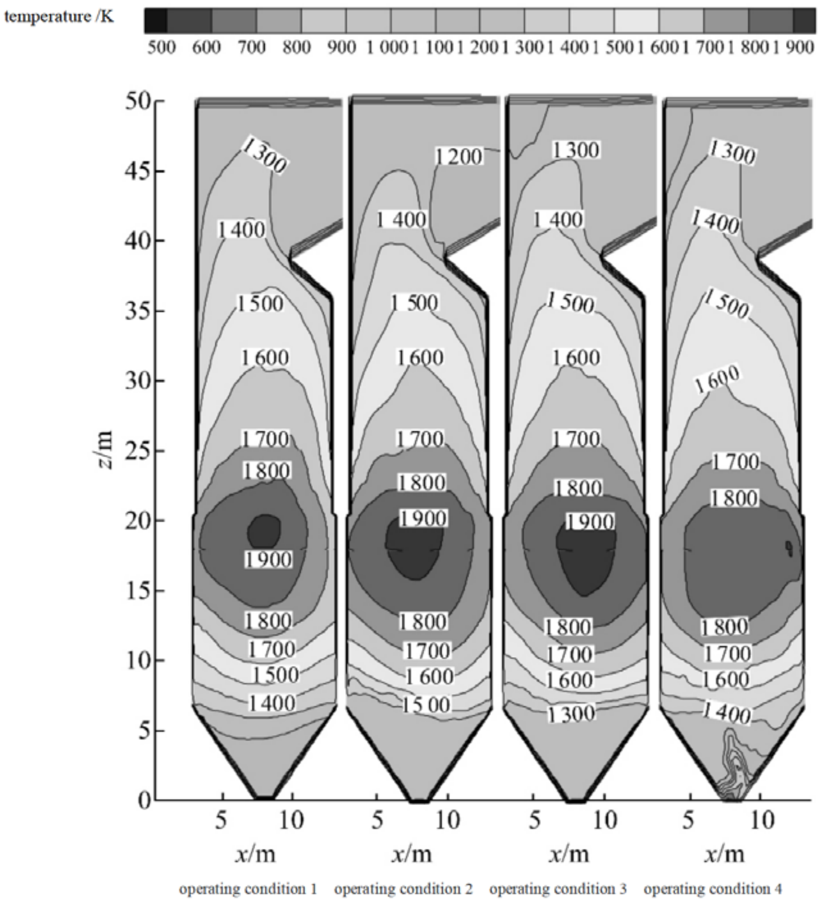

Figure 9. Temperature distribution near the side walls under different conditions.

5. Conclusion

The combustion, average residence time, burnout rate, NO_x emission characteristics and temperature distribution near the side wall surface of pulverized coal particles in the furnace have different effects on the combined operation mode of pulverized coal. While taking into account combustion efficiency, flue gas temperature at the entrance section of large screen superheater and carbon content of fly ash, compared with 6 mills running at the same time, the formula of 5 mills running in combination and stopping operation close to the side wall coal mill has the advantage of reducing NO_x emission concentration, reaching the reduction of emission. At the same time, the slagging degree of the wing wall and side wall area of the lower furnace is obviously reduced.

Conflict of interest

The authors declared no conflict of interest.

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