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Experimental Research on NOx Emission Characteristics During Coal Combustion in the Stoker-fired Boiler

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Abstract. In this paper, the combustion stability and nitrogen oxides (NOx) emissions test were made in two coal-fired chain grate boilers with hot water supplies of 29MW and 46MW. The investigations aim to clarify the key characteristics of NOx emission, e.g.instability of NOx emission, temperature and gaseous components profiles and the unsteady variation of NOx emission with power level changing. Main conclusions include: 1) In the process of stable combustion, NOx emissions still have±5% fluctuations, it is not stable. 2) The furnace temperature distribution show double temperature peaks. One peak (~1500°C) is located on the burning solid-fuel surface on the chain grate, and the other (~1050°C) is ~5.6m above the arch. 3) With increasing the thermal power, NOx emission shows a dramatic increase, higher around 1.25 times, as due to the rapid adjustment of coal feeding in grate furnace. Those above show the NOx control difficulty and the proper injector location of SNCR (selective non-catalytic reaction), which is key data collected for further NOx reduction retrofits.

1. Introduction

Coal accounts for a large proportion of China's energy structure. Nitrogen oxides emitted from coal-fired power station boilers are one of the key control targets for air pollution. In the northern part of China, the central heating in winter uses a large number of coal-fired boilers. The furnace type in the north is characterized by large number, small single-unit capacity, uneven distribution, low coal burn-up rate, and large pollutant discharge. It has great pressure on environmental pollution and urgently needs to be solved. The nitrogen oxides emitted by industrial boilers account for 15%-20% of the total nitrogen oxide emissions in China[1], while the layered combustion chain furnace is the main component of industrial boilers, and the nitrogen oxides emitted by it cannot be ignored. In this regard, the state has also increased its control to reduce the emission of nitrogen oxides from coal-fired boilers. The stratified combustion of coal is divided into four sections: preheating drying stage, volatile precipitation stage, coke combustion stage, and burnout stage. The fuel is first cracked under high temperature conditions, and the volatile matter of coal are precipitated, followed by coke combustion, and finally the ash is discharged out of the furnace [2]. The combustion of coal is mainly composed of two processes: volatile matter precipitation combustion and coke combustion. Therefore, fuel N is divided into volatile matter N and coke N in different precipitation stages [3]. The generation and emission of NOx are related to factors such as temperature, combustion atmosphere, and oxygen concentration. More than 90% of the NOx in the stratified furnace belongs to fuel type NOx[4]. For the NOx in the chain furnace, Zhao Laifu used industrial experiments and unit furnace experiments to verify the effectiveness of the unit furnace method in the study of the NOx precipitation law of the coal seam in the layer-burning boiler, proposed to use anaerobic pyrolysis combustion method to select appropriate coal seam thickness to reduce NOx emissions[5]. Song Shunxin et al. carried out a transformation experiment on a SNCR (selective non-catalytic reduction) process for a 35 t/h layer furnace, the denitration rate of the chain furnace was between 13% and 32%, which preliminarily verified the use of SNCR technology on small and medium industrial chain furnaces is feasible[6].

In regard of the above research and industrial transformation of NOx control in chain furnaces, the research on combustion and NOx emission characteristics in layer furnaces is not specific, and no multi-load and versatility studies have been conducted. Therefore, this paper systematically studies the instability of NOx emissions from boilers, the flame temperature/component distribution in the furnace, and the changes in NOx emissions during load changes in large-grain coal stratified combustion, expects to provide detailed key data support and guidance for the low NOx combustion retrofit in the furnace and the rational position design of SNCR ammonia.

2. Brief Introduction and Test Method of Tesearch Layer Burning Boiler

The test was conducted on two layer hot water boilers, with powers of 29 MW and 46 MW respectively. The design and operation parameters of the two boilers are shown in Table 1, the analysis data of the burning coal quality is shown in Table 2.

Table 1. The major parameters of chain grate boiler

	Boiler-1	Boiler-2
Rated Heating Capacity, MW	29	46
Nominal Water Pressure, MPa	1.6	1.6
Number of Drums	Single	Double
Design Efficiency of Boiler, %	82.30	82.50
Return Water Temperature, °C	70	70
Nominal Hot Water Temperature, °C	100	100
Grate Length/Width, m	11.595/5.82	14.54/12.16

Table 2. The industrial and elemental analysis of coal

M,ar/%	M,ad/%	A,ad/%	V,ad/%	FC, ad/%	Q,gr ad/kJ/kg	Q,net ad/kJ/kg
9.1	3.91	16.3	30.19	49.6	26.199	23.672

During the test, the flame temperature, gas composition, NOx emissions, etc. were tested mainly at the fire hole of the boilers. Oxygen concentration and NOx emissions were tested at the outlet of the boiler air preheater. The measurable position in the furnace is shown in Figure 1. There are 5 fire holes in the vicinity of the layer burning furnace, and the fire hole size is about 40cm. The data was tested at the left and right points of a fire hole, and the data of 9 points was obtained (points 1 to 9 in Fig. 1). In addition, there are 5 measuring points at different heights of the furnace (points 10 to 14 in Figure 1). The heights of the five points from the layer burning are 1.35m, 3.4m, 5.56m and 9.2m respectively (where the measuring point 11 and 12 are at the same horizontal position, the two measuring points are 0.93m apart). Due to the limitations of the conditions, the temperatures of these five locations were measured.

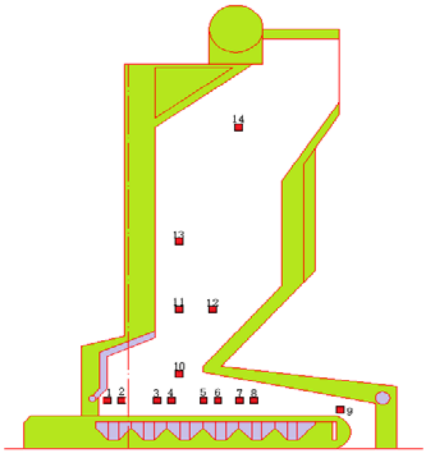

Figure 1. The location of the station in boiler one

During the test, the data was collected by inserting the thermocouple measuring point and the high temperature resistant steel pipe to the center of the boiler and using the "small fan exhaust-cooling-flue gas analyzer test" method. The results below are the average values, and the test data fluctuates within ±5% of the test error. The measured NOx value is converted by the following formula:

$$[\text{NOx}, \text{mg/Nm}^3] = [\text{NOx}, \text{ppm}] \cdot \frac{46.0}{22.4} \cdot \frac{21\% - 9\%}{21\% - [\text{O}_2, \text{vol\%}]}$$

In the formula, the ppm unit of NOx is converted into the concentration corresponding to NO_2, and the oxygen concentration in the flue gas is converted to 9%. Refer to the national standard [GB13271-2014] [7].

Table 3. The test list of condition

	Boiler	Experimental Purpose	Actual Heating Load	Percentage of Full Load	Steady State or Unsteady State
1	Boiler-1	NOx release rule under stable working condition	~25.4MW	87.5%	Steady State
2	Boiler-2	Law of NOx release in process of instantaneous load increase	34-44MW	73.8%~95%	Unsteady State
3	Boiler-1	Measurement of temperature field and gas composition field on grate	~25.4MW	87.5%	Steady State
4	Boiler-1	Test of temperature components in lower part of throat mouth of boiler	~25.4MW	87.5%	Steady State

3. Experimental Results and Discussion

3.1. NOx Emission Test in Smooth Conditions

Six sets of data tests were carried out for the 1# boiler (load 29MW), as shown in Figure 2, where the load in Figure 2(a) is DCS dial data and the temperature measurement point is measure point 14 in Figure 1. The load of the layer-fired boiler in this half hour is basically maintained at about 25.4 MW, which is only slightly fluctuating. The flame in the furnace is close to the right wall, which is mainly

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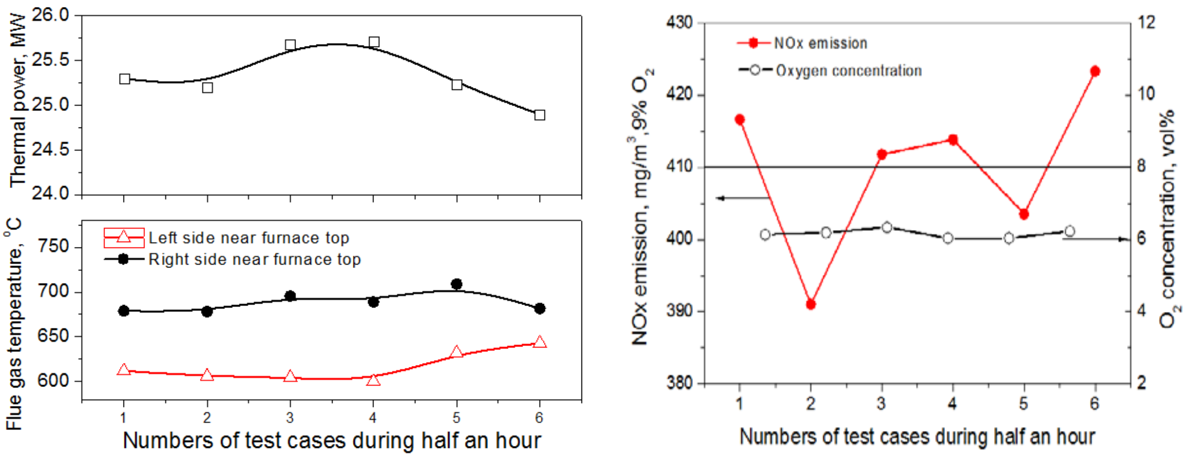
affected by the distribution of the coal in the furnace and the size of the coal. The oxygen concentration in the flue gas is very stable, but the NOx concentration fluctuation range is about ± 5%, the lowest is 390 mg/m^3, the highest is 425 mg/m^3, and the average value is 410 mg/m^3. Under steady conditions, the fluctuation range of NOx concentration is large. It can be seen that the large fluctuation of NOx emission data is a major feature of the layer furnace.



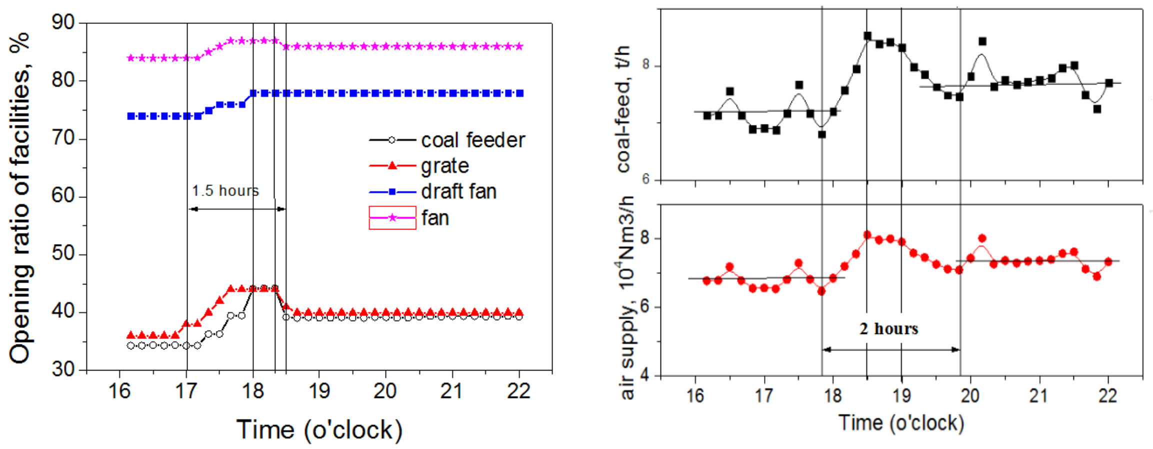
(a) Boiler load and temperature test of two sidewalls

(b) Oxygen concentration and NOx concentration in flue gas

Figure 2. Test of NOx and oxygen concentration in flue gas under steady burning condition

3.2. Changes in NOx Emissions during a Sudden Increase in Boiler Load

As shown in Figure 3, this figure describes in detail a typical load change process for 2# boiler (load 46 MW). Figure 3 (a-b) shows the operation change process of coal volume and blower air volume, each quantity will be increased and then reduced, and the whole process will be completed in one and a half hours. During the lifting process, the thickness of the coal seam is certain, and the advance speed of the layer burning is increased to increase the amount of coal burned to the boiler. At the same time, increase the air volume of the blower, give the boiler more air volume, and increase the air volume of the draft fan to ensure the safe operation of the micro-negative pressure in the boiler furnace.



(a) Commissioning data on various equipment of the boiler

(b) Changes of boiler coal and air quantity

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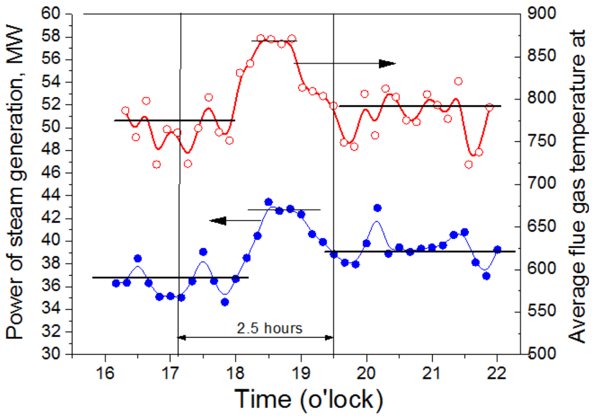
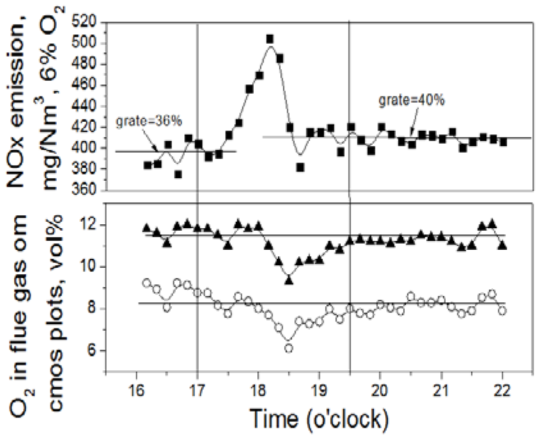


(c) Changes of boiler load and top flue gas temperature



(d) Changes of oxygen and NOx concentrations in flue gas

Figure 3. Boiler one changes in each parameter during load change

Figure 3(c) shows the change in boiler load and flue gas temperature with the boiler operation (temperature measurement point is at the top of the boiler). Figure (d) depicts the process of concentration changes of nitrogen oxides (NOx) and oxygen in the flue gas throughout the load change. When the load is 37MW, the amount of O_2 and the amount of NOx released in the flue gas are both stable and remain basically unchanged. In the process of lifting the load, it takes 2.5 hours for the boiler load to stabilize. That is to say, the stabilization process of the stratified furnace has a significant time delay characteristic compared to the operation. This situation is the lag problem in the control of the layer burner, which is caused by the burning of large particles of coal. At this time, the oxygen concentration in the front and rear stable sections of the flue gas remains the same. During the load change, NOx peaked and its peak value (510 mg/m^3) was increased (24%) from the original stable value (395 mg/m^3). The boiler load suddenly rises and the NOx value jumps. The increase in NOx emissions data is due to the fact that the boiler accumulates instantaneously more coal ash on the grate, the release of N in the coal on the grate increases, and the fuel nitrogen increases, causing a sudden increase in pollutant emissions. When the load in the furnace reaches 39 MW, the NOx content in the flue gas is at a steady state, but the NOx is also increased by about 2.5% compared with the previous stable load. It indicates that the amount of oxygen, coal, air volume remains unchanged, and when the load increases, the NOx content in the flue gas will also increase. It can be seen that the increase of load in the layer furnace will bring more NOx emissions and increase the difficulty of boiler pollutant control.

3.3. Temperature Field and Component Field Test on the Grate

Data shown in Figure 4, Figure 5 is measured from the fire hole measurement point shown in Figure 1, the height of the fire hole is 0.54m away from the grate, and each view hole is tested with two sets of data, the test position is close to both sides of the fire hole, the distance is 40cm. The surface temperature of the fuel is not much different from the temperature on both sides of each fire hole, and only one set of data is measured. In the area of 2m to 3.3m, the surface temperature of the coal seam exceeds 1350°C, and there are many thermal NOx. A temperature peak (1500°C) appeared at 2.3 m.

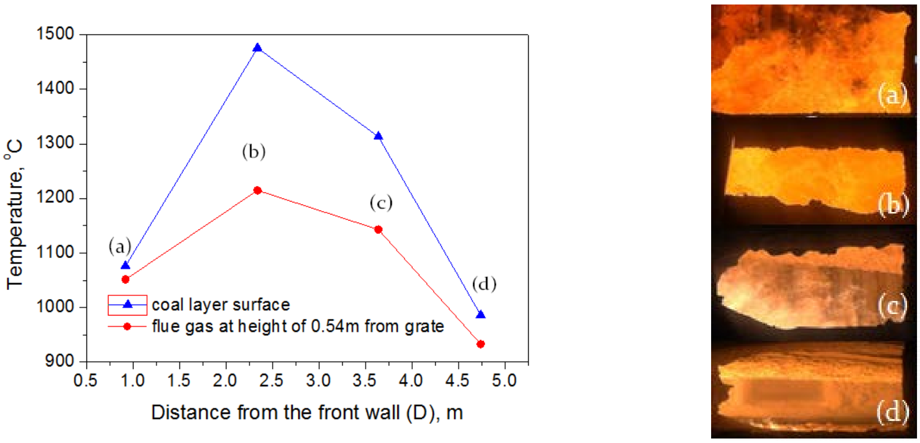


Figure 4. Temperature test (including coal surface and space smoke) in the direction of the furnace.

In combination with Fig. 4 and Fig. 5, it can be seen that in the initial stage of combustion, due to the poor heat transfer performance of large granular coal, the heat generated by the combustion of the upper coal has not yet passed to the bottom, and the coal seam is mainly in a preheated and dry state. The smoke content in this interval is mainly CO_2 and O_2, with a CO_2 concentration of 4% and an oxygen concentration of 17%. After 2.2m along the grate direction, CO_2, CO formation and O_2 consumption in this stage indicate that the upper coal seam in this section is heated and volatilized to precipitate and partially burn. The N element in the fuel is released in the form of HCN, NH3, etc. with the precipitation of volatiles, after volatilization precipitation, it burns inside the coal seam and on the surface of the coal seam. HCN is oxidized to NCO in an oxidizing atmosphere and further oxidized to form NO. NH_3 can react with O_2 to form NO or react with NO to form N_2, depending on the reaction conditions. Since the oxygen concentration is high at the beginning, a large amount of volatile matter N is converted into NOx. The heat released by the combustion of volatile matter causes the coke to burn. The O_2 concentration is rapidly reduced to 0% and maintained at around 0% in the 2.2m-3.9m range, while CO_2 peaks. The lack of oxygen in the coal seam leads to incomplete combustion of the coal seam to produce a large amount of CO, and the CO concentration reaches the highest around 3m from the front wall. The formation of a large amount of reducing gas forms a reducing atmosphere in the coal seam, and the oxygen-reducing strong reducing atmosphere suppresses the formation of NOx. As a reducing gas, CO can reduce the generated NOx. The NOx concentration gradually decreases from 2.7m. After 4m, the O_2 concentration began to rise, and part of it was oxidized to NOx. Due to the coke burning in this area, the coke particles in the coal seam are in a hot and highly active state. The coke layer has a catalytic strengthening effect on CO reduction of NOx [8,9].

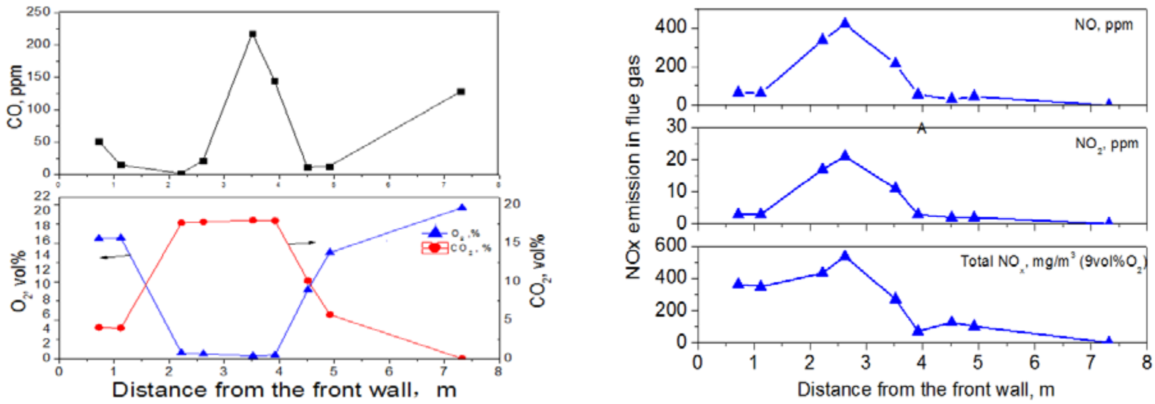


Figure 5. Changes in the composition of the gas in the direction of the furnace

During the diffusion of volatile matter and N in the coke between the coal particles and the coal layer, under the catalytic and reduction of nitrogen oxides by the coke layer and the reducing gas, a large amount is converted into N2. Therefore, although the combustion in this region is very intense, the amount of NOx generated is decreasing. There is more thermal NOx on the grate fuel, and more fuel type NOx is released in the volatile matter burnout position. It can be seen that in the upper part of the grate, the amount of NOx released during the process of volatiles matter precipitation is relatively large, this is the emission reduction position needs to be focused on. When using the low-nitrogen technology in the furnace such as flue gas recirculation or stratified combustion in the stratified furnace, this position should be more focused on for NOx control.

3.4. Temperature and Smoke Composition Test near the Throat

The left graph of Figure 6 shows the temperature profile at vertical height (measurement points 10-14, excluding measurement points 12), and the right graph shows the compositional concentration comparison of points 11 and 12. It can be seen from Fig. 6 that the flame in the vertical direction of the furnace also has a temperature peak (~1050°C), the position is about 5.6m from layer burning height, and when the height is 3.4m, there is a large amount of CO, to 5.6m CO burns out and the temperature reaches its maximum. Therefore, there is another temperature peak in the CO burnout zone. Figure 6 is a diagram showing the composition and temperature of the flue gas at the upper points 11, 12 of the throat, above the rear arch, there is a row of exhausted air vents, the purpose of which is to supply oxygen to burn off carbon and CO in the flue gas, reduce incomplete combustion heat loss, It can be clearly seen from the figure that the measuring point 12 has high oxygen amount than point 11 due to it is opposite to the burnout wind vent, while the CO, CO_2 and temperature are lower than those of measuring point 11, and the NOx is slightly lower, which indicates that the burn-in wind can be added in this position to improve the burnout rate, and the local high temperature can be reduced, thereby reducing the generation of a part of the thermal NOx.

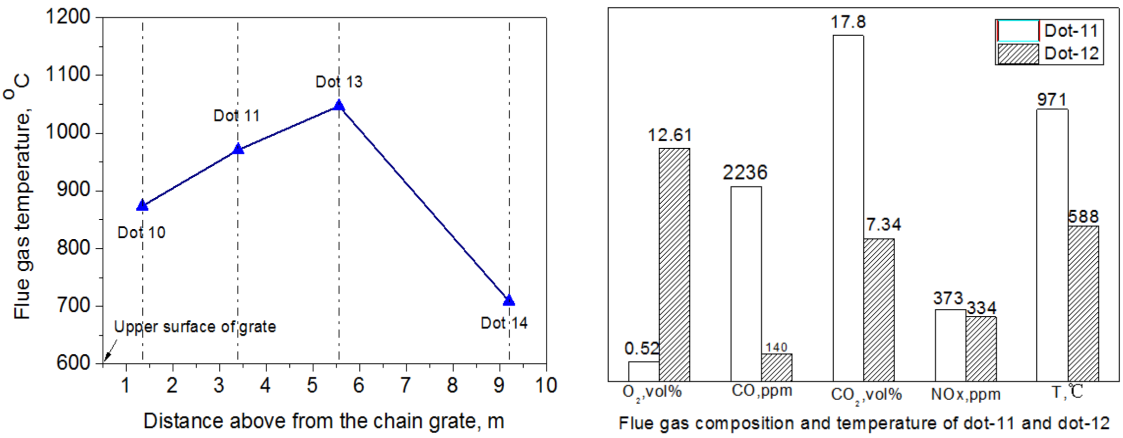


Figure 6. Temperature and composition change in the vertical direction of arch

The selective non-catalytic reduction (SNCR) system is a key method for controlling the layer furnace, it means that the reducing agent ammonia or urea is injected into the furnace without adding a catalyst to reduce NOx to N2[10]. However, SNCR has severe requirements for flue gas temperature, when the reaction temperature is too high, ammonia may directly react with O_2 to form NO, which leads to a decrease in the efficiency of NOx reduction, and also increases NOx emissions. When the temperature is too low, the denitration reaction rate is low, which causes a large amount of NH3 to escape. Therefore, it is necessary to spray an amino solution to a position of about 1000°C, and the temperature window of the SNCR is between 850 and 1100 °C. This experiment provides a preliminary study for the SNCR transformation. Through the research on the combustion and NOx emission characteristics of the layer-burning boiler, we have a deep understanding of the NOx emissions of the layer furnace. At the same time, it also provides a theoretical basis for the installation position of the SNCR, it can be seen from the figure that the optimal installation position of the SNCR of the layer-fired grate boiler in this experiment is between 4.6-5.5 m from the height of the grate.

4. Conclusions

This experiment was carried out on two layer-fired boilers (29 MW and 46 MW), focusing on the temperature field, composition field, and NOx release law in the furnace. The purpose is to reduce NOx emissions from the layer furnace, such as flue gas recycling methods, staged combustion methods, SNCR methods, etc., providing critical boiler data to make it play a denitration effect reasonably. The main conclusions are as follows:
1) In the stable combustion process of the layer furnace, because the furnace is a confined space, the NOx emission still has ±5% fluctuation, which is very unstable;
2) When the boiler needs to change the load, the rapid boiler combustion adjustment will bring about an instantaneous increase in NOx, which is about 24% higher;
3) The temperature distribution in the furnace shows a double peak phenomenon, that is, there is a temperature peak (~1500°C) near the fuel on the grate, and another temperature peak (~1050°C) in the CO burnout area ~5.6m above the inner throat; There is a certain thermal NOx release on the grate, and the release of fuel-type NOx is mainly distributed during the release of volatiles matter. The temperature peak of the space is caused by the combustion of CO, and its position is 3.4m from the grate. The use of a controlled flame method to control NOx should focus on flue gas recirculation and staged combustion techniques at the volatile matter precipitation location, which is beneficial for overall NOx reduction.
4) A reasonable SNCR injection zone, that is, the best installation location is between 4.6-5.5 m from the grate height, at which point the flue gas temperature is within the optimum temperature window temperature (900-1100°C) of the SNCR.

5. Acknowledgment

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