Study on combustion and nitrogen oxide emissions of gas boiler

Yanyan Ji¹², Songsong Zhang²*, Kejian Wang¹*, Guoli Qi²

¹ School of mechanical engineering, Beijing University of Chemical Technology, Beijing, 100029, China
² China Special Equipment Inspection and Research Institute, Beijing, 100029, China
*Corresponding author’s e-mail: zhangsong0536@163.com, wangkj@mail.buct.edu.cn

Abstract. In order to reduce the emission of nitrogen oxides in gas-fired boilers, the effects of excess air ratio and flue gas recirculation on nitrogen oxide emissions during natural gas combustion are studied by numerical calculation. By adding flue gas recirculation, the generation of nitrogen oxides is significantly reduced. When the flue gas recycling rate is 20%, the emission of nitrogen oxides is minimized to about 40 mg/m³.

1. Introduction

The impact of NOₓ on the environment is receiving more and more attention. The emission standards for boiler air pollutants issued by Beijing in 2015 [1]: The NOₓ emission limit of new boilers before March 31, 2017 is 80mg/m³ (standard status), and the new boiler NOₓ emission limit after April 1, 2017 is 30mg/m³. From this point of view, it is necessary to effectively control the nitrogen oxides produced during the combustion process to achieve low nitrogen combustion. Natural gas low-nitrogen combustion technology mainly focuses on how to reduce combustion temperature and reduce thermal NOₓ formation. Its main technologies include staged combustion (air classification, fuel classification), lean-burn premixed combustion, flue gas recirculation, flameless combustion, etc. [2].

As a commonly used method for reducing nitrogen oxides, flue gas recirculation is widely used in industry and is divided into internal flue gas recirculation and external flue gas recirculation. Internal flue gas recirculation refers to the structural design of the burner and the furnace (including the entrainment of high-speed jets, swirling or bluffing of the bluff body), so that the flue gas is recirculated and returned to the combustion zone in the furnace to participate. The flue gas external circulation is to spray a part of the lower temperature of the boiler tail into the furnace to reduce the oxygen content in the furnace and make the natural gas stay in an anoxic combustion state, thereby reducing the combustion temperature and reducing the formation of nitrogen oxides.

The external flue gas recycling technology extracts a part of the flue gas at the tail of the flue, and uses the circulating fan to send the flue gas to the furnace inlet for re-combustion without the need to modify the burner, which is relatively economical [3]. Xie Zhengwu [4] discussed the impact of flue gas recirculation on boiler thermal calculation. Zhang Liqin [5] and others have shown that under oxygen-rich conditions, flue gas recirculation makes NOₓ content in flue gas increase after pulverized coal combustion, and NOₓ conversion rate decreases significantly. Zhao Zengwu [6] and Hu Manyin [7] studied the effect of flue gas recirculation on NOₓ generation by numerical simulation. It was found that flue gas recirculation effectively reduced the oxygen content in the combustion-supporting gas and reduced the overall furnace and flame. The temperature in the local high temperature zone effectively
suppresses the generation of thermal NOx and achieves low nitrogen combustion.

2. Model and numerical simulation method

2.1 Physical model
The combustion mode of the gas boiler studied in this paper is diffusion type combustion, and the burner and furnace are properly simplified. The final model is shown in Figure 1. The furnace is simplified to a cylinder with a diameter of 800 mm and a length of 2000 mm. In the pre-processing software ICEM provided by Fluent, the grid is divided into a structured grid and an unstructured grid. The structured grid is dominated by hexahedrons, and the results of calculations are easy to converge. The non-structured grids are mainly tetrahedral. The advantage is that meshing is easy, and very complex models can be quickly divided. So in engineering practice it can be widely used on the application. Since the actual burner model is studied, the structure is more complicated, and unstructured meshing is used. By setting the maximum grid value, some important faces are locally encrypted, and finally a grid of about 3 million is obtained, and the quality is above 0.35, which can meet the requirements of simulation.

2.2 Mathematical model
Gas and air are a complicated process in the process of combustion, with flow and heat transfer and accompanying chemical reactions. This process includes turbulence, radiant heat transfer, and component transport. In the simulation of natural gas combustion, the standard $k$-$\varepsilon$ model, P1 radiation model and finite rate model are used. Finally, when calculating the boiler temperature field, the nitrogen oxides use a pollutant model. The air and gas inlets adopt a speed inlet, the walls of the furnace and the burner are set at a constant temperature, and the outlet of the furnace is a pressure outlet.

2.3 Simulation conditions
The conditions simulated in this paper include smokeless gas recirculation and flue gas recirculation. In the case of smokeless gas recirculation, the effects of different excess air ratios (1.0-1.3) on furnace temperature and nitrogen oxide formation are simulated; when the flue gas recirculation is simulated, the excess air ratio is set to 1.1. The effects of different flue gas recirculation rates (0%-20%) on furnace temperature and nitrogen oxide formation are simulated.

The composition of natural gas is shown in Table 1 below. The theoretical air volume of natural gas of this component is 9.71 m$^3$/m$^3$, and the low calorific value is 34417 KJ/m$^3$.

| Species | $CH_4$ | $C_2H_6$ | $C_3H_8$ | $C_4H_{10}$ | $C_5H_{12}$ | $N_2$ | $H_2O$ |
|---------|--------|---------|---------|-----------|-----------|-------|-------|
| Percentage | 93.8   | 3.36    | 0.57    | 0.21       | 0.06      | 0.52  | 1.48  |

3. Simulation results analysis

3.1 Influence of different excess air ratio on NOx emissions
The excess air ratio has a certain influence on the temperature and oxygen concentration in the furnace. From the below cloud Figure 3, the maximum temperature of the $z=0$ section under each working condition can be seen, and the average temperature of the $z=0$ section can also be integrated, and the temperature distribution size and shape can also be seen. Because of the diffusion combustion, natural
gas and air are mixed while burning, and will burn at the exit of the furnace. The temperature of the flame is sequentially lowered from the inside to the outside, and the flame is mainly concentrated in the middle of the furnace. It can be seen from the cloud diagram that as the excess air coefficient increases, the temperature will decrease to a certain extent, and the high temperature region will also shrink. When the excess air coefficient is 1.3, the performance is more obvious, the length of the flame becomes shorter, and the red high temperature portion also significantly reduced.

Figure 3. The temperature cloud diagram of the z=0 section in the order of $\alpha=1.0, 1.05, 1.1, 1.15, 1.2, 1.25, 1.3$.

The data of the highest temperature and the average temperature of the section can be extracted from the cloud Figure 3 for analysis, as shown in Figure 4. It can be seen from Figure 4 that the abscissa is the excess air coefficient, the ordinate is the highest temperature and the average temperature of the section, and the maximum temperature first increases and then decreases with the increase of the excess air coefficient. When the excess air coefficient is 1.05, $z=0$ The temperature of the section is the highest, which is 2178K. At this time, the ratio of natural gas to oxygen in the furnace is close to 1, and complete combustion can be performed, and the heat release is the most complete. When the average temperature of the $z=0$ section exceeds 1.15, the average temperature of the section decreases significantly. At this time, it can be seen from the cloud Figure 3 that the flame becomes shorter and the high temperature region is correspondingly reduced. When the excess air ratio is 1.3, the average temperature of the $z=0$ section is the lowest, which is nearly 90K lower than the highest temperature.

Figure 4. Relationship between excess air ratio and maximum cross-section temperature and average temperature.

In the process of combustion, the amount of oxygen will have an adverse effect on the combustion. If the oxygen is too small, the chemical heat of the fuel will not be fully exerted. However, if the oxygen is too big, the volume of the flue gas of the furnace will increase, and the temperature of the furnace will
decrease. As a result, the thermal efficiency of the heating device is reduced [8]. It is found in the cloud Figure 5 below that there is a significant residual oxygen in the furnace when the excess air ratio exceeds 1.15. In Figure 4, the average temperature of the section shows a significant decrease. It can be seen that as the excess air ratio increases, the residual amount of oxygen in the section of the furnace is continuously increased. The increased oxygen cannot be consumed and the heat of the furnace is absorbed. Further discharge into flue gas will increase the smoke loss [9], and excessive excess air coefficient will reduce the temperature of the furnace, and will also increase the energy consumption of the fan, resulting in a certain waste.

![Figure 5. The oxygen component cloud diagram of the z=0 section in the order of α=1.0, 1.05, 1.1, 1.15, 1.2, 1.25, 1.3.](image)

The excess air ratio has a large effect on the average temperature of the z=0 section, while the temperature type NO$_x$ is sensitive to temperature changes. At temperatures above 1500°C, the rate of formation of temperature-type nitrogen oxides becomes very fast. The effect of excess air ratio on nitrogen oxides is shown in Figure 6. The area in which nitrogen oxides are formed is mainly concentrated in the middle and rear portions of the furnace, and the position at the exit of the burner is small. When the natural gas is injected into the furnace, it first reacts with oxygen, so the concentration of nitrogen oxides at the inlet of the furnace is very low, and in the middle of the furnace, the temperature is very high, reaching 1900°C, at this time, nitrogen oxidation and of hearth is generated very quickly.

![Figure 6. Show the NOx cloud map of the z=0 cross section with the excess coefficients of 1.05, 1.1, 1.15, 1.2, 1.25, and 1.3.](image)

Figure 7 shows the relationship between the average temperature of the z=0 section and the concentration of nitrogen oxides at the outlet of the furnace and the excess air ratio. It can be seen that the law of the variation curve of the concentration curve of nitrogen oxides at the outlet of the furnace and the average temperature of the section is basically. As the excess air coefficient increases, the first slowly changes rapidly. This is mainly because the major factor affecting nitrogen oxides is temperature. When the average temperature of the section decreases, the high temperature zone is shrinking, and the
formation of nitrogen oxides naturally decreases. Finally, when the excess air ratio is 1.3, the outlet is at the exit. The lowest concentration of nitrogen oxides should be the best, and the concentration of nitrogen oxides at the outlet is 50 ppm.

![Figure 7](image)

Figure 7. Relationship between excess air ratio and average cross-sectional temperature and nitrogen oxide concentration at the exit of the furnace.

3.2 Influence of different flue gas recirculation rates on NOx emission

Figure 8 shows the cloud map distribution of z=0 cross section when different flue gas ratios are added. After the flue gas recirculation is added, the furnace temperature is about 200K lower than that without flue gas recirculation, and the temperature drops significantly. This is because the reflux flue gas is an inert gas. When mixed with air, it will reduce the oxygen content in the furnace, thereby reducing the temperature of the furnace and reducing the formation of thermal nitrogen oxides.

As you can see, nitrogen oxides also fall the fastest in this range, from 140mg/m³ to 80mg/m³. It can be seen that the formation of nitrogen oxides is closely related to temperature. Eventually, when the flue gas recirculation rate...
reached 20%, the nitrogen oxide emissions reached a minimum of 40 mg/m³.

![Figure 9. Relationship between flue gas recirculation rate and NOx and average temperature of section.](image)

Under the operating conditions of the actual gas boiler, when the flue gas recirculation rate exceeds 20%, the flame temperature in the furnace is detected to change drastically, and the CO volume fraction increases sharply. At this time, the combustion becomes unstable at this time. The oxygen concentration inside is too low, causing the natural gas to not fully burn [10]. In order to ensure the smooth operation of the boiler and reduce nitrogen oxides, the flue gas recycling rate should be kept within 20%.

4. Conclusions
The simulation of the diffusion gas boiler with smokeless gas recirculation is carried out, and it is found that the flue gas recirculation can effectively reduce the furnace temperature and nitrogen oxide emissions, and has the following rules:

1) With the increase of excess air coefficient, the maximum temperature of the furnace first rises and then decreases. When the air volume is too large, there will be excess oxygen remaining in the furnace, which will take away part of the heat, causing the average temperature of the furnace to decrease. Therefore, the formation of nitrogen oxides will also decrease.

2) Adding flue gas recirculation can effectively reduce the maximum temperature of the furnace, so that the formation of nitrogen oxides will be less. When the excess air ratio is 1.1 and the flue gas circulation rate is 20%, the formation of nitrogen oxides is the lowest. It is about 40mg/m³, which is about 70% lower.

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