Numerical simulation of combustion and emission of blast furnace gas boiler

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Abstract. Taking an 110t/h full-fired blast furnace gas boiler as the research object, the numerical simulation method is used to calculate the combustion process in the furnace. The influence of flow field on combustion is analyzed, and the influence of air preheating temperature and oxygen concentration on combustion and NOx emission is discussed, which provides a theoretical basis for optimal design and reasonable operation of blast furnace gas boiler. The results indicate that with the increase of air preheating temperature and oxygen concentration, the CO consumption rate is increased, the in-furnace maximum temperature and average temperature are increased to different extents, the temperature distribution is basically unchanged, and the NOx concentration at the furnace outlet is also increased. The NOx concentration multiplies as the oxygen concentration increases.

1. Introduction

Blast furnace gas is a by-product gas of the steel industry, and is usually emitted into atmosphere by most middle and small steel enterprises. It can cause serious environmental pollution and waste of resources. How to make efficient utilize of blast furnace gas is the key to achieving energy saving and emission reduction [1-3].

Blast furnace gas as a low calorific value gas, the main components are CO, N₂ and CO₂, and the calorific value is generally 3000~3800KJ/m³. Since blast furnace gas contains a large amount of inert gas and has low calorific value, it is difficult to ignite and unstable combustion in practical application. In response to these problems, the current stable combustion technologies are mainly: mixing high calorific value fuel, preheated air and gas, oxygen-enriched combustion and swirling combustion, etc. These stabilizing measures can achieve the purpose of optimizing the ignition conditions, increasing the flame temperature and optimizing the temperature field distribution, but also affecting NOx emissions [4]. It is of great significance to study the effect of stable combustion measures on NOx emission, and to consider the stable combustion and low nitrogen emission of blast furnace gas, so as to optimize the operation of blast furnace gas boiler and the efficient utilization of blast furnace gas.

In this paper, the 110t/h pure-burning blast furnace gas boiler is taken as the research object, meanwhile using CFD software Fluent for simulating the combustion process in furnace under different air preheating temperature and oxygen enriched concentration. The flow field, temperature field and concentration field distribution in the furnace are analyzed, which provides a theoretical basis for the optimal design of blast furnace gas boiler and the rational utilization of blast furnace gas.
2. Physical and mathematical models

2.1 Physical model

The structure of the boiler and burner is shown in Figure 1. The length and width of the furnace are 6140mm and the height is 21300mm. Boiler combustion system adopt tangential firing combustion method, as well as burner adopts the swirl burners which obtain 2 layers each with four ones. The fuel is blast furnace gas with calorific value of 3338.09KJ/Nm³.

Burner adopts unstructured tetrahedron grid, structured hexahedral grid is adopts in other regions. Also zoning meshing method is adopted to obtain high quality calculation mesh. In order to simulate the field of the burner export area accurately, the grid around the burner area should be encrypted. The total number of grid is 4.5 million, as shown in Figure 2.

2.2 Mathematical model

For combustion, it is necessary to follow the three conservation equations of momentum, mass, and energy, and also follow the chemical composition equilibrium equation. Considering that the reliability of the model and the feasibility of engineering application, “k-epsilon model” is adopted as the model of Gas-phase Turbulent Flow, meanwhile the P-1 is adopted as the model of radiative heat transfer [5-6]. Combustion model uses the “Finite-Rate/Eddy-Dissipation” model. Model solves the coupling of pressure-speed by using standard wall function and SIMPLE algorithm [7-9].

The simulation calculation of NOx is completed by post-processing after calculating the combustion field. Since there are few nitrogen compounds in the gas, the Fuel NOx is negligible, so only Thermal NOx and Prompt NOx are considered [10]. The gas and air import boundary conditions are set to the speed inlet, and the furnace outlet is set to the pressure outlet boundary. Wall boundary conditions are thermal insulation.

3. Simulation results analysis

3.1 Velocity field

Figure 3 shows the velocity distribution diagram of the cross section of the lower burner (z=2.3m), which reflects flow field characteristics of the tangential firing combustion method. After ejecting from the burner, the four streams of gas converge into a tangential circle at the center of the furnace. The flow velocity inside the tangential circle is low, thus forming a vacuum area. Figure 4 shows the velocity distribution of section at the different height. As the height increases, the flow velocity in the furnace gradually decreases. Due to the influence of the updraft, the swirling intensity of the flow is weakened. The vacuum zone in the center of the furnace gradually disappears, and the flow diffuses toward the center.

The jets interact with each other and produce a strong swirl. The heat, mass and momentum exchange of turbulent is strong, which can accelerate the fuel burning velocity after fire. The swirling flame sweeps through most of the furnace volume, and the entire furnace forms a large cyclone combustion chamber, which makes the combustion more complete and the furnace thermal load more...
3.2 Effect of air preheating temperature on combustion process

By preheating the air, the initial temperature field of combustion can be optimized. The different preheating temperature is different, and the heat introduced into the furnace is different, which will affect the combustion efficiency and burning velocity, as well as the NOx production.

Figure 5 is the temperature nephogram of the burner region under different preheating air temperatures. As can be seen from the figure, the temperature at the outlet of the burner rises rapidly, beginning violent burning and releasing a large amount of heat. As the preheating temperature increases, the temperature variation gradient of the burner exit becomes larger, the combustion is more rapid, the high temperature zone in the furnace increases, and the temperature distribution tends to be uniform.

It can be seen from Figure 6 and Figure 7 that as the air preheating temperature increases, the maximum temperature in the furnace and the average temperature at different heights are significantly improved. The temperature rise in the furnace is most obvious when the air preheating temperature is raised from 373K to 423K. When the air preheating temperature reaches 473K, the maximum temperature in the furnace is increased by 63K. The temperature rises and then decreases along the height of the furnace.

Figure 5. The temperature nephogram of the burner region under different preheating air temperatures.

Figure 3. The velocity distribution diagram of the lower burner.

Figure 4. The velocity distribution of section at the different height.
In order to investigate the effect of air preheating temperature on combustion rate and burnout rate, mass fraction of CO at different distance from burner outlet was calculated. As shown in Figure 8, the CO concentration is basically consistent at different air preheating temperature. At the outlet of burner, the reaction starts violently and the CO concentration decreases rapidly. The CO is almost completely consumed at 2m away from the burner outlet, and the reaction is relatively complete. When the air preheating temperature is raised from 300K to 373K, the reaction rate at the outlet of the burner will increase significantly. As the temperature continues to rise, the magnitude of this change tends to flat.

The NOx generated by combustion of blast furnace gas boiler is mainly thermal NOx, and the generation rate can be expressed by the following equation. It can be seen that the main control factors of thermal NOx are temperature and oxygen concentration.

$$\frac{d[NO]}{dt} = 6 \times 10^{16} [O_2]^{0.5} [N_2]^{0.5} T^{-0.5} e^{-69090/T}$$  (1)

Figure 9 shows the change of NOx concentration at the outlet of the furnace with different air preheating temperatures. As the air temperature increases, the temperature in the furnace rises, resulting in increasing in NOx concentration. When the air preheating temperature increased from 423K to 473K, the NOx concentration increased the most. The concentration of NOx at 473K preheating temperature was about 85% higher than that at 300K.

3.3 Effect of oxygen concentration on combustion process
Oxygen-enriched combustion uses combustion-supporting air with higher oxygen content than normal air. This mode of combustion can speed up the reaction rate, reduce the amount of flue gas and thus reduce the heat loss from exhaust and improve the thermal efficiency. It has positive effect on the stable combustion of blast furnace gas.
Numerical simulations were carried out using three different conditions: oxygen concentration of 21%, 25%, and 29%, respectively. The effect of oxygen enriched concentration on the combustion process of blast furnace gas was analyzed. Figure 10 is the temperature nephogram of the section of the burner under three working conditions. The blast furnace gas is quickly burned from the corners to form a high temperature combustion region, and a relatively low temperature region appears in the center of the furnace. As the oxygen concentration increases, the high temperature region increases significantly, the temperature distribution becomes more uniform, and the combustion is more rapid. Figure 11 and Figure 12 show that the temperature in the furnace is improved after the oxygen-enriched combustion is carried out. The maximum temperature at 21% and 29% oxygen concentrations were 1688K and 1729K, respectively. When the oxygen concentration is increased from 21% to 25%, the average temperature in the furnace will increase significantly. When the oxygen concentration increases to 29%, the average temperature does not change significantly.

Figure 10. The temperature nephogram of the section of the burner at different oxygen concentration.

Figure 11. Variation of maximum temperature at different oxygen concentration.

Figure 12. Variation of average temperature at different height with oxygen concentration.

Figure 13. Variation of NOx emission at different oxygen concentration

Figure 13 shows the relation between the oxygen concentration in air and NOx concentration at the outlet of the furnace. It can be seen from the figure that the variation rule of NOx is basically the same as the maximum temperature. As the oxygen concentration increase, the amount of NOx is increasing, and the increment is large. When the oxygen content in the air is 21%, the NOx concentration at furnace outlet is the lowest; when the oxygen content is 25%, the NOx emission is 1.53 times higher than that of normal air combustion; when the oxygen content is 29%, the NOx emission reaches the normal air combustion 2.85 times. This indicates that as the oxygen content in the air increases, the NOx emissions multiply.

According to the analysis, on the one hand, oxygen-enriched combustion can reduce fuel consumption and the amount of flue gas, so that NOx emissions can be reduced to a certain extent. On the other hand, according to equation (1), the thermal NOx formation rate is exponentially related to temperature, which is proportional to the 0.5th power of the oxygen concentration. Due to the increase of oxygen concentration and temperature in oxygen-enriched combustion furnace, the amount of thermal NOx generated is greatly increased. Overall, after oxygen-enriched combustion, the NOx emission is multiplied.
4. Conclusions
The numerical simulation method was used to study the blast furnace gas combustion status under different air preheating temperature and oxygen concentration, and obtained the velocity field and temperature field, concentration field, and draw the following conclusions:

1) The boiler adopts swirling burners and tangential firing combustion method. The gas flow converges into a tangential circle, form a moving vortex from bottom to top, and enhance the disturbance in the furnace. Four flames ignite each other during combustion, which is beneficial to stable and efficient combustion of blast furnace gas.

2) As the air preheating temperature increases, the combustion process of blast furnace gas can be improved. When the preheating temperature reaches 473K, the maximum temperature in the furnace increases 63K, and the high temperature region is obviously increase and the temperature distribution is more uniform. When the preheating temperature is raised from 300K to 473K, the NOx emissions from furnace outlet increased from 18.8ppm to 34.7ppm. The increase of the preheating temperature has little effect on NOx emission, and the combustion air should be fully preheated when the blast furnace gas is burned.

3) The increase of oxygen content in the air will also have a positive effect on the combustion of blast furnace gas, so that the highest temperature and the average temperature at different heights in the furnace are improved. Meanwhile, the increase of oxygen concentration has a great impact on NOx formation, the oxygen concentration is increased from 21% to 29%, and the NOx concentration at the furnace outlet is increased by 2.85 times. Therefore, the oxygen concentration of blast furnace gas during the oxygen-enriched combustion should not be too high. Considering comprehensively, oxygen concentration in combustion air should not exceed 25%.

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