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Numerical Study on Combustion Characteristics of Wall-type Tangential Boiler

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Abstract: The research object of this paper is a 600MW wall-tangentially fired boiler of a power plant. In order to understand the combustion characteristics of the boiler, this paper first analyzes the flow characteristics in the furnace at 600MW to make familiar with the flow in the furnace. Combined with the flow characteristics in the furnace, the combustion conditions of the boiler under three different loads of 600MW, 480MW and 360MW are analyzed. It can be seen from the simulation results that as the boiler load increases, the temperature level in the furnace increases significantly, the flame length increases and the ignition distance of the pulverized coal jet decreases slightly. The burnout distance of the pulverized coal from the burnout zone to the flame angle is increased. The O₂ concentration gradually decreases, CO₂ concentration gradually increases and unburned carbon loss increases. Combined with the boiler thermal design parameters, it can be seen that the simulation results are basically the same as the design combustion parameters, which indicates that the simulation results can more accurately depict the combustion characteristics of the boiler.

1. Introduction

As for the wall-mounted DC cut-off pulverized coal boiler, the combustion characteristics in the furnace are very complicated, and the combustion effect of the boiler mainly depends on the aerodynamic characteristics in the furnace. Compared with the four-corner tangential boiler, the wall-type tangential boiler has advantages of strong jet rigidity, good gas supply conditions on both sides of the jet, free from flame deflection and stable combustion in low-load furnace, etc.[1] At present, relatively few studies are made on the combustion characteristics of wall-type tangential boilers both in China and abroad. Most of them mainly study the combustion state of this type of boiler under design conditions at full load, but its research under variable load conditions is relatively rare. In this paper, a numerical study of a 600MW ultra-supercritical wall tangential boiler in a power plant will be carried out to analyze the combustion characteristics of this type of boiler under different loads, and the design parameters under different loads of the boiler will be compared to verify the accuracy of the simulation results.

2. Introduction to Boiler Body Structure

This paper takes a 600MW wall-tangentially fired boiler of a power plant as the research object, and the overall structure of the boiler is shown in Figure 1(a). The boiler model is HG-1795/26.15-YM4. The boiler is an ultra-supercritical pressure-transformed direct-flow boiler, a full suspension structure Π boiler with the characteristics of a single furnace, one reheat, balanced ventilation, tight-fitting and solid-state slag, all-steel frame.
3. Numerical Calculation of Combustion Characteristics in Furnace

3.1. Mathematical Modeling and Meshing

The combustion characteristics of the boiler furnace simulated in this paper are based on engineering practicability and simulated by the actual size and structure of the boiler. Due to the complicated structure of the boiler, the furnace is divided into 8 parts by gambit, as shown in Fig. 2(a). In order to reduce the pseudo-diffusion, a non-uniform hexahedron mesh is used to make the mesh perpendicular to the fluid flow direction, so as to improve the quality of the mesh[2]. Figure 2(b) is a cross-sectional grid of the main combustion zone. Figure 2(c) shows the cross-sectional grid of the A-A burnout zone. The total number of furnace grids is 683,000.
In order to study the dynamic characteristics of the wall-tangentially fired boiler, the Fluent software is used to simulate the boiler. The flow in the boiler is extremely complicated three-dimensional turbulent flow. Since this paper simulates single-phase turbulent flow, based on the current research on single-phase turbulent simulation calculation, this paper will use the Realizable k-ε two-equation model, assuming that the furnace is steady-state flow, using the finite-volume method discrete differential equation, and solving with SIMPLE algorithm, applying QUICK format of difference, so that the simulation results can reflect the flow state in the furnace.

According to the combustion characteristics of the boiler, and based on the previous research results, the gas phase turbulent combustion in this paper uses a mixed fraction-probability density function PDF model. The volatile matter is precipitated by using a two-step competitive reaction model. The combustion of coke is based on a kinetic/diffusion controlled reaction rate model, and the radiant heat transfer is based on the P-1 model.

### 3.2. Boundary Conditions

This paper will simulate the combustion state of the boiler under the conditions of combustion design coal quality, the boiler load is 600MW, 480MW and 360MW respectively. The results of coal quality analysis in the simulation are shown in Table 1.

| Name        | Unit | 600MW | 480MW | 360MW |
|-------------|------|-------|-------|-------|
| Mar/        | %    |       |       |       |
| Mad/        | %    |       |       |       |
| Aar/        | %    |       |       |       |
| Vdaf/       | %    |       |       |       |
| Car/        | %    |       |       |       |
| Har/        | %    |       |       |       |
| Oar/        | %    |       |       |       |
| Nar/        | %    |       |       |       |
| Sar/        | %    |       |       |       |
| Qnet,ar/(MJ·kg⁻¹) |   |   |   |   |

In the simulation calculation, the pulverized coal gas flow rate of the burner nozzle is used as the inlet boundary condition. The speed and temperature of the pulverized coal gas flow at the burner inlet, and the specific parameters of the pulverized coal, such as the particle size and mass flow rate etc, are set in accordance with the boiler’s design parameters. The specific parameters are shown in Table 2.

According to the actual operation law of the site, in the simulation calculation of this paper: at 600MW, grinding A is stopped running, with grinding B, C, D, E, F being put in operation; at 480MW, grinding A and F are stopped running, with grinding B, C, D and E being put in operation; at 360MW, grinding A, C and F are stopped running, with grinding D and E being put in operation.

\[
D_{ab} = \frac{2ab}{a + b} \quad (1)
\]

\[
I = 0.16(Re)^{0.125} \quad (2)
\]

a and b are the length and width of each nozzle, Re is the gas flow Reynolds number. In the simulation calculation, the pulverized coal gas flow rate of the burner nozzle is used as the inlet boundary condition. The speed and temperature of the pulverized coal gas flow at the burner inlet, and the specific parameters of the pulverized coal, such as the particle size and mass flow rate etc, are set in accordance with the boiler’s design parameters. The specific parameters are shown in Table 2.

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4. Simulation Results and Analysis
Before analyzing the combustion characteristics of the boiler, the flow characteristics in the wall-type tangential boiler are first analyzed, because the combustion effect in the furnace mainly depends on the flow characteristics of the boiler. The wall-type tangential boiler has the advantages of strong jet rigidity, large diameter of the tangential circle and good filling degree in the furnace. In order to explain the above advantages of the wall-type tangential boiler, the following is an example of the furnace dynamics at 600 MW.

4.1. Analysis of Flow Characteristics in the Furnace
It can be seen from Fig. 3(a) that a complete tangential circle is formed on the cross section of the main burner layer, and the tangential circle is basically located at the center of the furnace, with a larger diameter, more uniform velocity distribution and a better fulling condition. The airflow is rigid and the jet attenuation is slow. The air supply conditions on both sides of the jet are good, but the right side of each jet has a lateral thrust from the angular airflow, which makes the rotating tangent have an outward diffusion phenomenon\(^4\). It can be seen from Fig. 3(b), that it is in complete agreement with the motion characteristics of the tangential boiler. Fig. 3(c) shows the velocity distribution vector distribution of the cross section of the main burner layer. It can be seen from the figure that the flow state on the cross section is very complicated. This is conducive to the mixing and burning of pulverized coal gas stream.

![Figure 3. The velocity distribution of the intersecting surface](image)

Figure 3. The velocity distribution of the intersecting surface

Figure 4 is a diagram showing the distribution of the Y-direction velocity in the height direction of the furnace, as can be seen from the figure: the center of the furnace forms a rotating airflow, and as the height of the furnace increases, the speed of the rotation increases. There is a rotating downward airflow around the furnace wall near the lower portion of the main burner. This is mainly due to the formation of a large vacuum in the center of the furnace. This area with downward rotation is mainly present in the area below the third burner. The flow in the boiler furnace is symmetric with respect to each other, left and right, and front and rear, and is evenly distributed.
the excess air coefficient in the furnace decreases, and with the increase of the total radiation in the furnace is a high temperature zone not far from the spout, which is caused by the release of a large amount of heat from the intense combustion of the pulverized coal gas stream and the high temperature flue gas reflux. It can also be seen from the figure that the temperature distribution in the furnace is uniform and symmetrical.

It can be seen from Fig. 5 that as the boiler load increases, the temperature level in the furnace increases significantly. This is because that as the load increases, the amount of coal-burning increases, the excess air coefficient in the furnace decreases, and with the increase of the total radiation in the furnace, the combustion becomes more severe. As the load increases, the pulverized coal flame is significantly prolonged, and the flame temperature at the root of the downstream pulverized coal gas stream also rises. However, the temperature in the high temperature zone not far from the burner nozzle is not reduced, but as the load increases, the distance between the high temperature zone and the nozzle is reduced, but the powdery gas flow near the burner nozzle is still stored at around 400K, within the safe temperature range.

Figure 5 is a temperature distribution diagram of the B-layer main burner section under different loads. It can be seen from the figure that the powder-containing gas stream injected by the burner burns violently after leaving a certain distance from the burner, and when the top of the flame reaches the downstream adjacent nozzle jet, the downstream powder-containing gas stream will be ignited. There is a high temperature zone not far from the spout, which is caused by the release of a large amount of heat from the intense combustion of the pulverized coal gas stream and the high temperature flue gas reflux. It can also be seen from the figure that the temperature distribution in the furnace is uniform and symmetrical.

It can be seen from Fig. 5 that as the boiler load increases, the temperature level in the furnace increases significantly. This is because that as the load increases, the amount of coal-burning increases, the excess air coefficient in the furnace decreases, and with the increase of the total radiation in the furnace, the combustion becomes more severe. As the load increases, the pulverized coal flame is significantly prolonged, and the flame temperature at the root of the downstream pulverized coal gas stream also rises. However, the temperature in the high temperature zone not far from the burner nozzle is not reduced, but as the load increases, the distance between the high temperature zone and the nozzle is reduced, but the powdery gas flow near the burner nozzle is still stored at around 400K, within the safe temperature range.

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burning wind and the high wind speed at the four corners of the burning wind. Therefore, the high temperature zone in this area is mainly concentrated in the central part of the furnace.

It can also be seen from Fig. 6 that as the boiler load increases, the overall temperature of the main burner region rises, the high temperature region in the furnace becomes larger, and the furnace outlet temperature becomes higher. This is mainly because that as the boiler load increases, the coal consumption is relatively increased, causing the decrease of the excessive air ratio of the boiler. Both the air volume and the amount of powder increase lead to an increase in the flow rate of the flue gas at high load, shortened the burning time of the pulverized coal in the furnace. With the load increases, the temperature in the area of the flame-extinguishing angle becomes relatively large, causing the increase of the temperature of the outlet flue gas[5].

![Figure 6. The temperature distribution on the section of the center line](image)

Figure 7 is a diagram showing the distribution of the O2 molar concentration of the longitudinal section of the front and rear walls of the furnace. It can be seen from the figure that in the main burner area, the O2 concentration of the secondary air nozzle is higher, while the O2 concentration of other areas is basically 0%, this is because most of the oxygen required for combustion in this area is provided by the secondary air vent. Due to the rigidity of the jet, the concentration of O2 in this area is large, while the O2 in other places is basically burned out[6]. In the burnout wind area, due to the large amount of burnt air, and the burnt air vents are arranged at the four corners, its tangential circle is smaller than the wall tangential circle, so the pulverized coal concentration in the center of the furnace is higher in this area. The unburned pulverized coal in the area will continue to burn, so in this area, the O2 concentration in the center of the furnace is low. When reaching the flame-extinguishing corner, the pulverized coal will be substantially burned. The flue gas mixes with each other and is substantially evenly distributed at the exit of the furnace.

As the boiler load increases, the O2 concentration at the furnace outlet gradually decreases, which is caused by an increase in the excess air ratio and an increase in the air-powder ratio as the load increases. As the boiler load increases, the burnout point of the upper pulverized coal in the burnout area is increased, which is mainly because that as the load increases, the flue gas flow rate increases, leading to the relative decrease in O2 concentration. At 360 MW, compared with the pulverized coal combustion in the central portion of the furnace, the input of the secondary air at the bottom of the main burner zone is excessive, while the O2 concentration in the corresponding region of the burner is still low. As the boiler load increases, the amount of coal-burning increases, the excessive air ratio decreases, the bottom secondary air is insufficient to burn out a small amount of pulverized coal in the center of the furnace. As can be seen, when the furnace center is at 480 MW, the O2 concentration is substantially decreased into 0%.
Figure 7. The distribution of concentration of O₂ on the section of the center line

Figure 8 is a diagram showing the distribution of CO₂ molar concentration in the longitudinal section of the front and rear walls of the furnace. It can be seen from the figure that in the main burner area, the CO₂ concentration at the position of the primary air vent is higher, which is because that a lot of CO₂ was produced by the intense combustion of pulverized coal in this area. In the burnout wind area, excessive pulverized coal is burned after a large amount of burnt-out wind, and a large amount of CO₂ is generated. In this part, the concentration distribution of CO₂ is relatively evenly distributed and at the upper side of the burnout wind area, the pulverized coal is mainly concentrated in the center of the furnace, therefore, the CO₂ concentration in this area is higher. The concentration of CO₂ in the area near the water wall is low. The pulverized coal is basically burned out when reaching the flame angle, and then the flue gas gradually mixes and is evenly distributed when it reaches the exit of the furnace.

As the boiler load increases, the CO₂ concentration at the furnace outlet gradually increases. When the boiler load is 360 MW, the pulverized coal at the center of the furnace in the main combustion zone is substantially burned out, and O₂ is excessive, so the CO₂ concentration in this region is lowered. When the boiler load is increased, the CO₂ concentration at the bottom of the furnace is higher due to the action of the smoking gas.

4.3. Comparison of Simulation Results and Design Parameters
The simulation parameters of this paper are mainly based on the thermal design data of the boiler. Table 3 compares the simulation results with the design parameters. It can be seen from table 3 that
the excess air coefficient of the simulation results agrees well with the design values. The simulation results of the outlet temperature of the lower furnace are slightly higher than the design value, within the error range. The simulation results of unburned charcoal loss are smaller than the design value, mainly because the char combustion in this model does not consider the effect of ash on burnup. It can be seen from the comparison results that the simulation results can truly reflect the true combustion state of the boiler.

Table 3. The comparison result of numerical simulation and the design value

| Name                        | Unit | Simulation result | Design value |
|-----------------------------|------|-------------------|--------------|
|                             |      | 360MW  | 480MW  | 600MW  | 360MW  | 480MW  | 600MW  |
| excess air coefficient %    |      | 1.38   | 1.28   | 1.13   | 1.4    | 1.25   | 1.15   |
| Lower furnace exit gas K    |      | 1140   | 1238   | 1307   | 1126   | 1223   | 1289   |
| temperature                |      |        |        |        |        |        |        |
| unburned carbon loss %      |      | 1.33   | 1.02   | 0.89   | 1.5    | 1.2    | 1.0    |

5. Conclusion
A complete tangential circle is formed on the cross section of the main burner, the diameter of the tangential circle is larger, and the velocity distribution is more uniform, with a good fulling condition. The burner jet has a strong rigidity and a slow decay, and it is not affected by the water wall, not brushing the wall. The air supply conditions on both sides of the jet are good, but the right side of each jet has a lateral thrust from the angular airflow, so that the rotary tangential circle has outward diffusion. The center of the furnace forms a rotating upward airflow, and the rotational ascending speed increases as the height of the furnace increases. There is a rotating downward airflow around the lower portion of the main burner near the water wall of the furnace. The flow in the boiler furnace is symmetric with respect to each other, left and right, front and rear, and is evenly distributed.

The pulverized coal gas flows violently after leaving a certain distance from the burner to form a high temperature zone. The top of the flame reaches the bottom of the downstream adjacent nozzle jet, igniting the downstream pulverized coal stream. The temperature inside the furnace is evenly distributed and symmetrical to each other. As the boiler load increases, the temperature level in the furnace increases significantly, the flame length increases, and the distance between the pulverized coal combustion and the burner orifice decreases slightly. The high-temperature combustion zone is mainly concentrated in the main combustion zone, the burn-out zone and the burnout zone to the flame-extinguishing section. As the load increases, the pulverized coal burn-up distance from the burn-out area to the flame-angled area increases.

As the boiler load increases, the O₂ concentration gradually decreases, the CO₂ concentration gradually increases, and the unburned carbon loss increases. The flow state in the furnace affects the distribution of pulverized coal and the O₂ distribution, leading to different combustion state of various parts in the furnace. Thus, through the numerical simulation, the combustion state of different parts of the boiler can be obtained, which provides the basis for the design and transformation of this type of boiler.

The simulation results are compared with the boiler design value, indicating that the simulation results can truly reflect the combustion state of the boiler.

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