Simulation and optimization of NO generation characteristics of ultra-supercritical compact boiler

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Abstract. Computational fluid dynamics numerical simulation method was used to numerically simulate the combustion process in 700 ℃ ultra-supercritical compact swirl opposed coal-fired boiler. The flow field distribution, composition distribution and NO distribution in the furnace were obtained through simulation. Simulating the NO generation in the boiler when the burner is put into different operation modes under different loads. The results show that the velocity and temperature fields in the ultra-supercritical compact boiler have the same characteristics as the typical swirl opposed coal-fired boiler. The O₂ concentration showed good consistency with the main gas products CO and CO₂ concentration. To a certain extent, NO generation and distribution characteristics are related with the temperature field. When the burner is put into operation in different ways, NO generation and distribution are different correspondingly. The simulation and test can provide theoretical basis for the technical implementation and structural optimization of the ultra-supercritical compact boiler at 700 ℃.

1. introduction

The 700-Degree ultra-supercritical power generation technology refers to the high-parameter ultra-supercritical coal-fired power generation technology with the main steam temperature and the reheated steam temperature reaching 700 ℃ or above. When the steam temperature reaches above 700 ℃, the main steam pressure will also reach about 36MPa. With the improvement of steam parameters of ultra-supercritical units, its thermal efficiency is nearly 10% higher than that of average existing units. 700 ℃ power generation technology is currently the main development direction of international thermal power units. In order to promote the development of 700 ℃ high-parameter coal-fired boiler technology, China Huaneng Group Xi’an Thermal Engineering Institute proposed a new type of compact boiler. Compared with conventional boilers, this type of boiler reduces the height of the outlet header of superheater and reheater (total height of the boiler is 44 meters), shortens the length of the expensive high-temperature steam pipeline connecting the boiler and the steam turbine. Thus saving the construction cost of the unit.

The thermal test is difficult to detect the change of NOₓ in the furnace, and the workload is huge; Numerical simulation can reflect the characteristics of NOₓ generation in the combustion process in the furnace in detail, and has been widely used in the study of NOₓ generation characteristics in the combustion process in the furnace [1-4]. This paper carries out a numerical simulation for this new
compact boiler [5-7], calculates the NO\textsubscript{x} generation during the combustion process of the boiler, and compares the numerical calculation results with the test results. The comparison shows that the numerical calculation can accurately predict NO\textsubscript{x} generation characteristics during combustion in the furnace.

2. Models and calculation methods

2.1. Physical model and meshing
The research object of this paper is a 660 MW ultra-supercritical parameter coal-fired once-through boiler. Due to the special structure of the new boiler, the furnace area adopts left and right wall layout swirl burners for opposed firing. The overall boiler is a three-flue M-type layout, and the total length of the boiler is 56.45 Meters, the height is 44 meters, the width is 14.96 meters. The heating surfaces of superheater and reheater are arranged in the flue at the rear of the boiler in turn. In order to increase the uniformity of the flow field in the area of the high-temperature heating surface of the flue at the rear of the boiler., four deflectors were added to the water-cooled hopper bottom area at the rear of the boiler. M-type boiler contains a total of thirty burners and the boiler adopts a positive pressure direct firing coal pulverizing system, equipped with six coal mills, each coal mill corresponds to five burners on the same layer of the same wall, each on the left and right walls above the burner arrange a layer of over fire air nozzles, the specific arrangement is shown in Figure 1(b).

The ICEM pre-processing software is used to establish the model of the actual boiler and grid division, and the boiler is divided into six areas, including the front water-cooled hopper bottom area, the burner area, the upper horizontal flue of the furnace, the middle flue, the rear water-cooled hopper bottom area and the rear flue. Mesh each area separately, and the grid of the burner area is encrypted to improve the simulation accuracy [8-10]. After verification of grid independence, the optimal number of grids was determined to be 3.17 million.

2.2. Mathematical models and calculation methods
The description of the gas-phase turbulent flow adopts the k-\(\varepsilon\) double equation model; and the near-wall function method was used to handle the transition calculation of the near-wall area equation; use Mixture-Reaction/PDF to simulate gas-phase turbulent combustion; use P-1 Radiation Model to calculate radiation heat transfer; A single-step reaction model is used to calculate volatile matter release; coke combustion uses a kinetic/diffusion control combustion model, and coal particle tracking uses a stochastic tracking model. The calculation of NO adopts the post-processing method. The simulation mainly considers the production of fuel-type NO and thermal-type NO. In the analysis, the concentration of NO approximates the concentration of NO\textsubscript{x}. The convergence standard of the calculation result is that the residual error is less than 10\textsuperscript{-8}.

![Figure 1. Structure of the boiler and the distribution of burner](image-url)
2.3. Boundary conditions

Based on the reasonable distribution of the cold flow field in the furnace, the numerical simulation studies the full-load operating conditions of the boiler under the design coal. The industrial analysis and element analysis of the design coal are shown in Table 1. In the simulation, the center air and the primary air of the boiler are injected with the irrotational flow, the secondary air and the tertiary air are injected with the rotational flow, the secondary air and the tertiary air are rotate in the opposite directions. The wind speed and wind temperature of the burner in the numerical simulation are shown in Table 2 (Since the secondary air and tertiary air are injected by rotational flow, the secondary air and tertiary air speeds in the table are axial/tangential speeds). The outlet boundary condition adopts the pressure outlet and is set as a slightly negative pressure outlet. The pulverized coal particles enters the furnace for combustion from the jet of the primary air, and the particle diameter is distributed according to the Rosin-Rammler method, the minimum particle diameter is 7μm, the maximum particle diameter is 200μm, the average particle diameter is 134μm, the spread parameter is 4.5, and the fineness of the coal powder is 32%. Each surface of the boiler and the wall of the water-cooled hopper bottom area are set as constant temperature wall surfaces.

Table 1 Approximate and ultimate analysis of the coal

| Industrial analysis/% | Element analysis/% | Qnetar/(MJ/kg) |
|-----------------------|-------------------|----------------|
| Vdaf                  | FCdaf             | Aarf           | Mar                | Cadf               | Hdaf             | Odaf               | Nadf             | Sadf             | Qnetar/(MJ/kg) |
| 27.00                 | 47.00             | 12.00          | 10.00              | 61.45              | 3.61              | 7.80               | 0.71              | 0.43              | 23.42            |

Table 2 Design parameters of burner

| Primary air velocity/(m/s) | Primary air temperature/℃ | Secondary air velocity/(m/s) | Secondary air temperature/℃ | Tertiary air velocity/(m/s) | Tertiary air temperature/℃ | Over fire air velocity/(m/s) | Over fire air temperature/℃ |
|---------------------------|----------------------------|-------------------------------|-------------------------------|----------------------------|-----------------------------|------------------------------|-----------------------------|
| 29                        | 78                         | 19/21                        | 347                          | 13/39                      | 347                         | 45                           | 347                         |

3. Results and Discussion

3.1. Flow field analysis

Figure 2 shows the velocity distribution and temperature distribution at the burner nozzles and the cross-sections of the burn-out air nozzles at different layers of the boiler furnace area, and the gas component distribution at different heights at the front of the boiler. Figure 2(a) shows that the horizontal cross-section velocity field of the burner nozzles at different layers of the new boiler furnace is similar to the airflow distribution of the burner layer of a typical swirling opposed boiler. The airflow from any two burners arranged oppositely on the same cross-section forms a good hedging. The range of the airflow emitted by the burners in each layer of the furnace decreases with the increase of the furnace height, and the airflow at different heights has certain regularity.

In the case of boiler hot combustion, a flame with good symmetry is formed in the furnace. The jet flow of each burner is affected by the erosion of the upstream burner jet and the erosion and impact of the lower burner airflow. The furnace flame is full. Obvious backflow is formed in the secondary and tertiary air areas of the respective jets. The existence of the backflow prevents the pulverized coal particles ejected from the burner from being directly washed to burn near the opposite wall, so there is no obvious burning phenomenon of particles in the burner area. In the furnace, the independence of the hedging burners on the same layer and on the same side is very strong, there is only energy support, and there is no material exchange [9-11]. The higher boiler temperature leads to the complete precipitation of volatile matter from the pulverized coal particles at the burner nozzle, and there is no volatile matter precipitation area inside the boiler. Therefore, the rapid NOx produced by the volatilization analysis is basically negligible. Combined with Figure 2(c), it can be seen that the O2 concentration involved in the combustion reaction is in good agreement with the combustion products.
CO and CO$_2$, that is, where the concentration of the reaction gas is high, the concentration of the reaction gas product is low.

![Velocity field](image1)
![Temperature Field](image2)
![Volume fraction of each gas component](image3)

**Figure 2** Aerodynamic field and the concentration of each component in the burner area

### 3.2. Analysis of the NO generation characteristics

Based on the design conditions, a total of six burners of A, B, C, D, E and F are put into simulation at 100% load, and the obtained NO concentration and HCN concentration are shown in the figure. It can be seen from the HCN concentration distribution of the different burner layout layers that the volatile matter is separated from the coal particles, and the nitrogen in the volatile matter is quickly converted into HCN in a high temperature environment. Therefore, the HCN content is relatively high in about one-half of the trajectory from the exit of each burner to the center of the furnace, and the HCN content in the central area of the boiler is extremely low, and it has basically been converted into NO. Combined with Figure 2, the NO content in the rapid volatile precipitation area is extremely low, which is due to the neglect of the rapid formation of nitrogen oxides in the simulation calculation. Only consider the distribution of thermal nitrogen oxides and fuel nitrogen oxides in the boiler. According to the NO concentration distribution of the different burner layout layers, it can be seen that the NO concentration in the secondary air movement trajectory area and the burn-out air cross-section area of the burners in each layer is higher. This is because the oxygen concentration in these areas is high, and the high concentration of oxygen will oxidize the HCN precipitated in the fuel to produce NO. Due to the graded arrangement of the secondary air and the primary air of the burner, the oxygen supply required for combustion of the pulverized coal is insufficient after being sent into the furnace by the primary air, and the pulverized coal is incompletely combusted to generate CO. Therefore, in the central area of the burner jet, although the HCN concentration is also high, the nitrogen oxide concentration is relatively low. The strong reducing atmosphere formed in the central area of the burner jet effectively inhibits the formation of nitrogen oxides.

As can be seen in Figure 3(b), the peak of NO production is in the middle and upper combustor area. Figure 3(c) shows the average NO distribution curve of different horizontal cross-sections in the front burner area of the boiler along the furnace height. According to the changing law of NO concentration along the furnace height, the furnace can be divided into a rapid concentration increase area along the furnace height, a slight concentration increase area, a slow increase area and a concentration basically unchanged area. 13.47~17.44 m is the area where NO concentration increases rapidly, and it is also the area where the pulverized coal injected by the burners of the A and B layers is put into combustion. In this area, with the continuous input of pulverized coal, the NO concentration in the furnace increases rapidly along the direction of the furnace height. It can be seen from the comparison with Figure 2(b) that the increase in NO concentration in this section is mainly caused by the continuous burning of pulverized coal. Through simulation calculation, it is found that the boiler temperature in this section is relatively low, and there is no obvious thermal NO generation in this area, mainly fuel NO.

In the 17.44~21.84 m section (C, D, E, F layer burner area), it is also the main area where the C and D layer burners inject pulverized coal into combustion. Fuel-type NO concentration continues to
rise, and the temperature in this area is the highest furnace temperature area, and some thermal NO will be generated, but overall the NO concentration in this area increases slowly. It can be seen from Figure 2(c) that this is because more CO is formed by incomplete combustion of pulverized coal in this area, and higher concentrations of CO can reduce NO in flue gas. In addition, the generation of thermal NO cannot balance the reduction of CO, which reduces the concentration of NO in the flue gas, so the overall generation of NO concentration is relatively slow.

For the 21.84~25.84 m section, the main areas where the pulverized coal of E and F layers are put into combustion, the NO concentration shows a slower trend. In this area, with the continuous input of pulverized coal, the fuel-type NO concentration increases rapidly along the furnace height. The temperature in this area is lower than that of the C, D, E and F layers, and the thermal-type NO production is less. Moreover, the CO content produced by the incomplete combustion of pulverized coal in this area is higher, and the reduction of NO is stronger, so the overall NO concentration generation is slower.

Above 25.84 m, the NO content is basically unchanged, with only a small increase. The reason is that in this section, no new pulverized coal particles are put into combustion, and no more air is sent in, and the dilution effect of air on the flue gas disappears. Because the flue gas temperature is relatively high, the combustible components in the coal are basically burned sufficiently, and the reduction effect of hydrocarbons on NO disappears. However, if a certain amount of oxygen remains in the flue gas, NO (such as thermal NO) will be generated, and the NO concentration will increase slightly.

It can be seen from the figure 2 that the NO distribution at the furnace outlet of the new compact boiler is relatively even, ranging from 80e-06 to 120e-06, and the overall NO emission concentration is not high. The simulation calculation results show that because the burner uses the primary air and the secondary air to be input in stages, the central area of the burner jet presents a good reducing atmosphere, and the production of NO is still at a low level under the condition of higher temperature. And because of the staged input of the boiler's over-fire air, the excess air coefficient between the boiler burner arrangement area and the over-fire air nozzle arrangement area is less than 1, which also
greatly suppresses the generation of NO in the main combustion zone in the middle of the furnace. The end result is a lower NO emission concentration at the boiler outlet.

3.3. The influence of the operation mode of the burner on NOx

There are 6 layers of burners on the left and right sides of the boiler itself. In this paper, the burners are not separated in the calculation. At 80% load, the boiler can meet the operating requirements by putting in 4-layer burners. Two ways of putting in A, B, C, D burners and C, D, E, F burners are calculated to keep the excess air coefficient consistent. The NO distribution curve in the furnace shown in Fig. 4(a) shows that the NO production in the furnace when the burner is put into the upper burner is significantly higher than that of the lower burner. The reason is that when the upper burner is put in, the lower burner is not completely closed corresponding to the central air and secondary air. The air sent from the lower tuyere causes the pulverized coal fed from the upper burner to get more oxygen to react with it, resulting in the rapid formation of fuel-type NO and the high NO concentration [12-15].

At 60% load, the boiler can meet the operating requirements by putting in three-layer burners. This paper calculates two ways of putting A, B, C burners and D, E, F burners. It can be seen from the figure that the distribution characteristics of NOx in the furnace under the 60% load and 80% load are the same. Comparing Figure 4 (a), (b) and Figure 3, it can be seen that with the change of load, NO production does not increase proportionally. In contrast, the way the burner is put into operation has a significant impact on NO production.

4. Conclusion

(1) The simulation calculation results are qualitatively in good agreement with the test results, indicating that it is feasible to use CFD for the numerical calculation of NO in the boiler combustion process and can more accurately predict the generation characteristics of various combustion conditions.

(2) The staged air supply system of the boiler makes the central area of the burner jet present a good reducing atmosphere; The graded arrangement of the over-fire air makes the excess air coefficient of the main combustion zone of the boiler less than 1, which can well inhibit the generation of NO. The graded air input can reduce the NO emission of the boiler as a whole.

(3) According to the change law of NO concentration along the furnace height, the furnace can be divided into a rapid concentration increase area along the furnace height, a slightly slow concentration increase area, a slow concentration increase area and a stable concentration without change area.

(4) The operating mode of the combustor under variable load conditions is an important factor affecting NO production. Under each load, the NO emission of the lower burner is relatively small when it is put into operation, and it is especially obvious at low load. With the change of load, NO production does not increase proportionally.
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