NUMERICAL SIMULATION OF THE EFFECT OF OVER-FIRE AIR ON FLOW AND COMBUSTION IN FURNACES

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ABSTRACT The use of over-fire air as a means of reducing the concentration of NOx emitted by boiler, has gradually got popularized in China. A numerical simulation study on the effect of over-fire air on flow, combustion and heat transfer, during full capacity operation of a pulverized coal fired 600MW boiler with cross firing, has been started. Mixture fracture/probability density functions are used to simulate turbulent combustion; a P-1 radiation model is used for simulating radiation heat transfer, the Langrange/Euler's method is used for dealing with momentum, mass and energy exchange between the solid and the gas phase; the single rate model for devolatilization and the kinetics/diffusion limited combustion model for simulating surface combustion of pulverized coal particles. Study results indicate that over-fire air helps the current to spread wider in the furnace, delays the introduction of oxygen during the combustion process; the reducing atmosphere in the furnace gets boosted, and the maximal flame temperature is reduced, which helps to reduce the concentration of emitted NOx. But on the other hand, the use of over-fire air reduces the combustion efficiency of pulverized coal, Figs 5, Tables 2 and Refs 8.

Keywords: engineering thermophysics and mechanical engineering, boiler, numerical simulation, over-fire air

With development towards larger capacity, higher parameters and lower emission of the pulverized coal boiler, the wall firing boiler has stepped into a new development era. In modern wall firing boiler, the furnace air stage combustion technology is widely adopted. That is, the over-fire air (OFA) is introduced which divides the combustion process into two steps to further reduce the concentration of emitted nitrogen oxides (NOx).

In recent years, some scholars such as Xia Jun[1,2], Zhang Ji[3] and Zhang Yun[4] have made corresponding researches on the furnace process of the wall firing boiler using the numerical simulation. On the one hand, those results are coincident with the actual operating facts. On the other hand, lack of enough computing grids and too much simplification on the structures of furnace and burner are the common weakness of those researches, what's more, the condition of introducing the over-fire air is not mentioned.

Applying the Fluent 6.1, the numerical simulation on the furnace flow, combustion and heat transfer process of a 600MW opposed wall firing boiler has been carried out. Besides, the effect of introducing the over-fire air on the furnace flow and combustion situation has been discussed.

1. RESEARCH OBJECT AND MESHING

1.1 Research Object

The research object is the furnace of a 600MW opposed wall firing boiler. Three layers low NOx swirling burners are laid on the front and rear wall respectively. The air in the burner is divided into four parts: the central air, the primary air, the secondary air and the tertiary air. There are five pulverized coal burners on each layer and thirty burners in all. The five OFA burners are distributed on top of the third layer pulverized coal burners and there are ten OFA burners in all. The air in the OFA burner is divided into two parts: the primary air and the secondary air, the primary air is direct while the secondary air is swirling. The platen superheater and the final superheater are located on the upper zone of the furnace.

Shanxi bitumite and the direct-fired pulverizing system are used here. There are six pulverizing mills in total. For each pulverizing mill, five coal burners are located in one layer which is on one side of the wall. Five of the six coal pulverizing mills are used during full capacity operation while the rest one is stand-by. The designed pulverized coal fineness R90 is 20–25%.

1.2 Computing Zone and Meshing

The geometrical scale of computing model and the antetype is 1:1. The computing zone is the furnace and the platen superheater is located on its top. Basically, there's no simplification on the structure of the burner during numerical simulating. There're central air, primary air, secondary air and tertiary air in the model, the feature of dual-channel is emphasized. Few simplifications have been done to the furnace, burner and heating surface structure in the computing model compared to the antetype. Five layers of pulverized coal burners (in which three layers are in the front wall and two are in the rear wall) and two layers of OFA burner (one in the front wall and the other in rear) are located in the computing model. The above distribution is according to the operating feature of using five pulverizing mills when the boiler is running full capacity operation.

The block structure meshing technology is adopted in the process of grid generation. On one hand, this technology can make grid generation much easier, structural grid will be generated conveniently in each piece. On the other hand, it is easier to acquire denser grids in some local. The research zone is divided into four parts:
the upper furnace, the lower furnace, the furnace hopper and the burner. Structural grid is generated in each part independently. The burner and lower furnace zones have the largest meshing density while the furnace hopper has the smallest one. The total number of grids in computing area is 470,000. Figure 1 shows the computing zones and its meshing.

![Figure 1 Sketch of the computing zone and its meshing](image)

2. MATHEMATICAL MODEL

Taking the gas phase as the continuous phase medium and describing it in Eulerian coordinate system, the gas phase turbulent transportation is simulated by applying the standard k-ε Turbulence model. The mixture-fraction/Probability Density Function (PDF) is used to simulate the gas phase turbulent combustion. The simulation on radiation heat transfer is carried out by using the P-1 radiation model. The pulverized coal particles are described as discrete phase in the Lagrangian coordinate system. The Lagrangian-Euler method is adopted to deal with the pulverized coal’s combustion, devolatilization of volatile constituents, the combustion process of coal coke, the interaction of mass, momentum and energy between the gas and the solid phase. The single rate model is used to simulate the devolatilization of volatile constituents and the kinetics/diffusion reaction rate model is adopted to simulate the surface combustion of pulverized coal particles. The particle radiation and gas radiation are taken into account.

The control equation of the three dimensional gas phase flow, the heat balance and combustion can be written as follows:

\[
\frac{\partial (\rho \phi)}{\partial t} + \frac{\partial (\rho \phi)}{\partial x} + \frac{\partial (\rho \phi)}{\partial y} + \frac{\partial (\rho \phi)}{\partial z} =
\]

\[
\frac{\partial}{\partial x} \left[ \rho \left( \frac{1}{ho} \frac{\partial P}{\partial x} + \frac{\partial \tau_{x} \phi}{\partial x} \right) \right] + \frac{\partial}{\partial y} \left[ \rho \left( \frac{1}{ho} \frac{\partial P}{\partial y} + \frac{\partial \tau_{y} \phi}{\partial y} \right) \right] + \frac{\partial}{\partial z} \left[ \rho \left( \frac{1}{ho} \frac{\partial P}{\partial z} + \frac{\partial \tau_{z} \phi}{\partial z} \right) \right] + S_{\phi} + S_{\phi}(\phi)
\] (1)

In the equation, \( \phi \) can stand for the velocity u, v, w, respectively, \( k \) stands for the turbulent kinetic energy, \( \varepsilon \) stands for the turbulent kinetic energy dissipation rate, \( \bar{f} \) stands for the time averaged mixing fraction, g stands for the fluctuate root-mean-square value of the mixing fraction, \( h \) stands for enthalpy, \( \gamma_{i} \) stands for the mass fraction of constituent i. \( \Gamma_{\phi} \) is the diffusion coefficient. When \( \phi=1.0 \), equation (1) is the continuity equation. \( S_{\phi} \) is the source term caused by gas phase, \( S_{\phi} \) is the source term caused by solid particle.

Given the distributions of gas phase flow field, temperature field and the constituent field, the motion locus of pulverized coal can be obtained in the Lagrange coordinate system according to the differential equation of particle force. Thus, the calculation along the motion locus can be carried out by choosing proper mathematical models of volatile constituents’ devolatilization in pulverized coal, the models of pulverized coal’s combustion and coal coke’s combustion. And the released constituents, heat and momentum in the pulverized coal’s locus could be considered as the source item in the gas phase field. Solving the control equations of discrete items and continuous items alternatively, until both items are convergent, thus the coupling calculation of gas phase and solid phase can be gotten.

The single coal model is used to describe the process of the volatile constituents’ devolatilization. This model consumes that there’s a first power relationship between the devolatilization rate and the amount of volatile constituents contained in coal.

\[
\frac{dm_{p}}{dt} = k \left[ m_{p} - (1 - f_{v,0}) m_{p,0} \right]
\] (2)

\[
k = A_{c} e^{-(E/RT)}
\] (3)

For the designed coal in this research, \( A_{c}=492000, E=7.4 \times 10^{12} \) (kJ·mol⁻¹).

After the volatile constituents’ devolatilization is finished, it steps into the coal coke combustion process until the combustible constituents are all burnt out. The reaction of coal coke and oxygen is considered as the single rate reaction according to the calculation which means the carbon is directly oxidized into carbon dioxide. And the kinetic/diffusion control reaction rate model is adopted in this study. This model assumes that the surface reaction rate is affected by both diffusion process and kinetic process. The combustion rate of coal coke can be expressed as follows:

\[
\frac{dm_{p}}{dt} = -\pi d_{p}^{2} P_{a} \frac{D_{0} R}{D_{0} + R}
\] (4)

\[
D_{0} = C_{1} \left( \frac{T_{p} + T_{2}}{2} \right)^{0.75}
\] (5)

\[
R = C_{4} e^{-(E/RT_{p})}
\] (6)

For the designed coal in this research, \( C_{1}=5 \times 10^{12}, C_{4}=0.002, E=7.9 \times 10^{13} \) (kJ·mol⁻¹).

3. OPERATING MODE AND BOUNDARY CONDITIONS

Two kinds of operating modes were investigated which are named mode 1 and mode 2. Both the two modes are during full capacity operation with the designed fuel. The difference between these two modes is that the over-fire air is introduced in mode 1 while it is not in mode 2. The pulverized coal particle burners adopted are the same for both modes. The distributions of burners are as below: three layers in the front wall (they are named A, B and C from bottom to the top respectively); two layers of burners in the rear wall (named D and F from bottom to top respectively). Layer A and D as well as layer C and F are in the same height, respectively. The total air supply and coal supply are the same for both modes.

The inlet boundary condition is set at the inlet of burner. The inlet velocities are assigned to the central air,
primary air, the secondary air and the tertiary air, respectively. The pulverized coal mass flow rate of each burner is 2.229kg/s and the diameter of pulverized coal particle is 70μm. The furnace outlet condition is set as the outlet boundary condition. The boundary condition is in constant pressure. The solid wall boundary condition is applied for the surfaces of water wall and flatten superheater, using the standard wall function as the modification. According to the related information concerning thermal calculation in boiler, the wall temperature of water wall is 705K while the wall temperature of flatten superheater is 823K and the wall’s emissivity is 0.78.

4. NUMERAICAL SIMULATION RESULTS AND DISCUSSION

4.1 Characteristic of Gas Flow

In the above two modes, the flow momentum entered from the front wall is larger than that entered from the rear wall. This would certainly arouse the attention that whether the main gas flow would sweep or deflect to the rear wall. The computing results show that the main gas flow basically remains in the middle zone along the furnace depth and has a small deflection to the rear wall. There’s no obvious phenomenon that main gas flow sweeps or deflects to the rear wall or front wall. The gas flow momentum difference between the front and rear wall in mode 2 is larger than that in mode 1. Therefore, the deflection of main gas flow to the rear wall is more obvious than that in mode 1.

The extent of current’s spread in furnace is a hot subject while discussing the flow condition in the furnace. Because a good extent of current’s spread is very important to acquire suitable residence time and to prevent slagging. The current’s spread coefficient of cross-section gas flow φ is used to evaluate the extent of current’s spread. When the ascending velocity through the furnace horizontal cross-section is larger than a certain qualitative value, its occupying area divided by the horizontal cross-section area is the definition of φ. And this qualitative value is usually set as 10% of weighted mean velocity of the burner outlet velocity; it is set as 3m/s in this article. The studied horizontal cross-section zone is from Z=29m (about 3m above the OFA burner) to Z=40m (the start of arch nose). The ascending velocities of the two modes are the same in this zone, which can make the further comparison much easier. See figure 2 for more details. The larger value of φ means the better extent of current’s spread. Generally, φ is hoped to be between 0.8 and 0.95. For these studied two modes, φ increases along the furnace height. With respect to the current’s spread, Mode 1 is obviously better than mode 2. The extent of current’s spread has reached the expected value in mode 1. Therefore, it can be concluded that the introduction of over-fire air has apparently improved the current’s spread. The main reason for the improvement of the current’s spread is that the OFA has reduced the total gas flow momentum injected into the furnace and the gas flow momentum injected by each single burner.

Fig. 2 Current’s spread coefficient at different cross-sections along the height of the furnace

4.2 Features of Gas Temperature Distribution

Figure 3 shows the average gas temperature variation of horizontal cross-section along the height of furnace in mode 1 and mode 2. In the area of pulverized coal burner, the excess air coefficient α is 1.0 in mode 1 while α is 1.18 in mode 2. Because of the oxygen supply is more abundant in the burner zone in mode 2 than in mode 1, the coal particles’ combustion and exothermic process is more intense, with more particles will be burnt-out. As a result, the gas temperature in mode 2 is higher than that in mode 1 in this area. In mode 2, the gas temperature (the cross-section average gas temperature and the highest temperature) linearly declines with the height increases in the furnace between the gas leaving the pulverized coal burner area and entering the platen superheater area. The flame’s heat extraction to the heating surface is more intense than the exothermic process of the particles’ combustion. In mode 1, on one hand, the temperature variation pattern is obviously different from the one in mode 2. This is because that the over-fire air is relatively cold air compared with the high temperature of the flame and therefore the cross-section average gas temperature falls drastically as much as 100K after the OFA is introduced. On the other hand, in terms of combustion of pulverized coal particles, the OFA has the effect on oxygen supply in the after burning period which promotes the particles to be burned-out. This phenomenon is embodied in the temperature distribution, which shows that in a long zone (Z=28m–35m) along the furnace height the gas temperature remains to be a constant approximately (about 1620K). This phenomenon indicates that after introducing OFA, the coal particles are “after burning”. In a long distance area (Z=28m–35m) along the furnace height, the flame’s heat extraction to the heating surface is equivalent with the exothermic amount of particles’ combustion, which enables the temperature remain constant approximately. In the horizontal cross-section zone of height Z=35–42m, the “after combustion” process is basically over. The exothermic amount of particles’ combustion is obviously reduced and the gas temperature drops linearly with the increase along furnace height. At the platen superheater inlet, the temperature difference is relatively small between the two modes; mode 1 is just 20K higher than that of mode 2, which is due to the introduction of OFA in mode 1 that lengthened the length of flame.
It can also be concluded from figure 3 that the introduction of OFA can reduce the horizontal cross-section gas temperature in most of the furnace height zone (Z=20~37m). Assume the thermal-nitrogen oxides' main generating area is the area whose horizontal cross-section gas temperature is above 1637K (1400°C), then the height in mode 1 is from 16.45m to 24m and in mode 2 is from 16.45m to 31m. As can be seen that OFA reduces the zone where the thermal NO\textsubscript{x} is generated, so it is benefit to reduce the formation of NO\textsubscript{x}.

### 4.3 Characteristic of Constituents Distribution

The variation of average oxygen and carbon monoxide mole fraction (bulk concentration) on each horizontal cross-section along the furnace height are shown in figure 4 and figure 5. In the pulverized coal particle burner zone, the concentration of oxygen is 1.2% higher in mode 2 than that in mode 1. The reason is that the air supply around coal burner in mode 2 is apparently higher than that in mode 1. Furthermore, this phenomenon is more visible in the burner zone. As can be seen from the distribution of average concentration of O\textsubscript{2} and CO, OFA can boost the reducing atmosphere which is benefit to control the formation of the fuel NO\textsubscript{x} and to speed up the NO\textsubscript{x} reducing reaction. Finally, the NO\textsubscript{x} emission is lowered.

### 4.4 Burn-out Rate of Pulverized Coal Particles

Table 1 shows the pulverized coal particles' burn-out rate at the furnace outlet and the heat loss of unburned matter in fly ash after calculation. It can be concluded that, the heat loss of unburned matter in fly ash is much greater at the condition of introducing OFA, about 2.17% larger than the condition without OFA.

The OFA delays the oxygen supply in the process of coal particles' combustion, reinforces the reducing atmosphere in furnace as well as decreases the furnace flame temperature and thus inevitably decreases the pulverized coal particles' combustion efficiency.

| Table 1: Burn-out rate of the pulverized coal at the furnace's outlet |
|-------------------------|-----------------|-----------------|
| Volatile constituent burn-out rate/\% | Coke coal burn-out rate/\% | Heat loss of fly ash inflammable matter/\% |
| Mode 1                  | 100             | 93.07           | 4.57                        |
| Mode 2                  | 100             | 96.32           | 2.40                        |

### 4.5 Furnace Outlet Gas Temperature

Table 2 shows the average furnace outlet gas temperature. As it is known that to acquire the furnace data from field experiment is very difficult, thus, to evaluate the accuracy of numerical simulation, the thermal calculation result is mainly compared with the simulation results. Among these data, the most important one is the average furnace outlet gas temperature. It can be seen from table 2 that the results from numerical simulation is almost the same with the ones gotten from the thermal calculation with only a deviation range of 19K to 34K. As a result, it proves the numerical simulation has credibility and accuracy to a large extent. Aside from this, it can also be concluded from table 2 that the introduction of OFA has some effect on furnace outlet average gas temperature. However, this effect is very small; the gas temperature only deviates within the upper limit of 20K.
Tab. 2 Average furnace outlet gas temperature

<table>
<thead>
<tr>
<th></th>
<th>Mode 1</th>
<th>Mode 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average outlet gas temperature of platen super heater /K</td>
<td>1513</td>
<td>1493</td>
</tr>
<tr>
<td>Average furnace outlet gas temperature/K</td>
<td>1280</td>
<td>1294</td>
</tr>
<tr>
<td>Average furnace outlet gas temperature in heat calculation/K</td>
<td>1314</td>
<td></td>
</tr>
<tr>
<td>Temperature difference between numerical simulation and heat calculation /K</td>
<td>-34</td>
<td>-19</td>
</tr>
</tbody>
</table>

5. CONCLUSIONS

The effects of introducing OFA on the furnace flow and combustion process have been studied here via numerical simulation. The results are as follows:

1. The introduction of OFA has improved the current’s spread, delayed the oxygen supply needed in the process of coal particles’ combustion, reinforced the furnace reducing atmosphere, reduced the furnace flame temperature. The introduction of OFA is also beneficial to reduce the final concentration of emitted NOx and narrows the possible area of slagging on water wall.

2. The introduction of OFA leads to the decrease of coal particles’ combustion efficiency.

3. The introduction of OFA has some effect on average gas temperature at furnace outlet. However, this effect is very small; the gas temperature only deviates within the upper limit of 20K.

NOMENCLATURE

- \( I_0 \) diffusion coefficient, dimensionless
- \( \epsilon \) turbulent kinetic energy dissipation rate, dimensionless
- \( A_1 \) factor before the exponent, dimensionless
- \( C_1 \) limited rate diffusion constant, dimensionless
- \( C_2 \) kinetic rate factor before the exponent, dimensionless
- \( D_0 \) constant of diffusion rate, dimensionless
- \( E \) activation energy, J/(kg·mol)
- \( f_{i0} \) mass fraction of particle’s initial volatile constituent, dimensionless
- \( \bar{j} \) time averaged mixing fraction, dimensionless
- \( g \) fluctuate root-mean-square value of the mixing fraction, dimensionless
- \( h \) enthalpy, J
- \( k \) reaction rate constant, dimensionless
- \( k \) turbulent kinetic energy, J
- \( m_{i0} \) particle’s initial mass, kg
- \( m_p \) particle mass, kg
- \( P_{ox} \) partial pressure of the gas phase oxidant around coal particles, Pa
- \( R \) kinetic reaction rate constant, dimensionless
- \( S_o \) source item caused by gas phase
- \( S_{sp} \) source item caused by solid particle
- \( u, v, w \) velocity, m/s
- \( Y_i \) mass fraction of constituent \( i \), dimensionless

REFERENCES