Steady combustion test and numerical simulation analysis of a single direct-flow pulverized coal burner at low load

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Abstract. In this paper, the low load steady combustion test of a single burner was carried out on the 30MW thermal test bench of the State Key Laboratory of efficient and clean coal-fired power plant boiler. Combined with numerical simulation, the lower limit of the minimum stable combustion load of the burner was tried to find out, which provided the basic test data for the furnace combustion stability during the deep peak load regulation of the boiler. The experimental and numerical simulation results show that under 40% rated load, the outlet flame is stable and bright, and the negative pressure in the furnace is stable, which can realize the stable combustion of a single burner.

1. Introduction

China is rich in coal, poor in oil and gas, and the total installed capacity of coal-fired power generation ranks first in the world [1]. In order to achieve carbon emission reduction, the grid connected capacity of renewable energy is expanding year by year [2]. High proportion of renewable energy will bring challenges to the stability of power system. However, due to the instability of photovoltaic and wind power, the problem of abandoning light and wind power is serious. Therefore, in order to improve the absorption capacity of renewable energy, thermal power units which undertake more than 70% of the national power generation capacity must undertake the peak load regulation task of power grid. The minimum generating load of the power plant with deep peak load regulation is reduced from 50% of the original rated load to less than 35% of the rated load, so as to improve the absorption capacity of renewable energy [3-5].

China plans to implement the flexibility transformation of 220million kW coal-fired units during the 13th-five-year plan [6]. This makes the deep peak load regulation of coal-fired unit boiler become a research hotspot in the current energy industry. In this paper, a direct-flow burner which is widely used in the market is taken as the research object. The influence of load reduction on the temperature field, CO/NOx generation characteristics and combustion stability in the State Key Laboratory of efficient and clean coal-fired utility boilers in Harbin Boiler Works was studied. The minimum stable combustion load of the once through burner is obtained. This is the first time that a single direct-flow pulverized coal burner was studied on a pilot scale. It is of great significance to national carbon emission reduction, energy diversity and security.
2. Test conditions

2.1. Test equipment
Figure 1 shows State Key Laboratory of Efficient and Clean Coal-Fired Utility Boilers in Harbin Boiler Company Limited which is the burner test-bed with the largest thermal power, and adopts horizontal "Π" type layout. The outer layer of the furnace is a steel plate shell supported by a steel frame. Water cooling pipes are arranged above and below the inner layer. The left and right sides are of thermal insulation structure. The burner is selected as the research object, which is widely used in the market. The burner structure is shown in Figure 2. The burner nozzle is shown in Figure 3.

![Figure 1. 30MW thermal test bench.](image1)
![Figure 2. A model of direct-flow burner.](image2)
![Figure 3. Nozzle of a direct-flow burner.](image3)

2.2. Test coal quality data and test condition
The coal used in this test is blended coal. The coal quality related parameters are shown in Table 1.

| Item    | Unit | Data |
|---------|------|------|
| Mar     | %    | 10.41|
| Mad     | %    | 2.58 |
| Aar     | %    | 20.12|
| Vdaf    | %    | 36.17|
| Sd,ar   | %    | 0.23 |
| Qnet,v,ar | kJ/kg | 5123 |
| Car     | %    | 56.86|
| Har     | %    | 3.40 |
| Oar     | %    | 8.13 |
| Nar     | %    | 0.84 |

Table 2. Test condition.

| Item                  | Unit | Data    |
|-----------------------|------|---------|
| Condition             | /    | 1 2 3 4 |
| Burner load rate      | %    | 56.6 42.7 27.7 36.3 |
| Input heat load       | MW   | 7.950 5.994 3.891 5.087 |
| Actual coal consumption| t/h  | 1.342 1.012 0.657 0.859 |
| Primary air volume    | Nm3/h| 3700 3700 3700 3700 |
| Primary air temperature| ºC  | 81 83 90 88 |
| Primary air speed     | m/s  | 27.1 27.2 27.8 27.6 |
| Secondary air volume  | Nm3/h| 7500 5500 4500 4500 |
| Secondary air temperature| ºC | 264 289 258 288 |
Table 2 shows four working conditions in this test. Condition 1 is the control condition and condition 2 - 4 is the test condition.

3. Test results and analysis

3.1. Influence of load reduction on furnace temperature

As shown in Figure 4, at 56.6% load, the maximum temperature of furnace inner wall is 1250 ℃, which is 7m away from the nozzle. At 27.7% load, the maximum temperature of furnace inner wall is 1050 ℃, which is 4m away from the nozzle. Therefore, the maximum temperature in the furnace decreases with the decrease of load, and the main combustion zone is gradually close to the nozzle.

![Figure 4. Furnace inner wall temperature of different loads.](image)

3.2. Influence of load reduction on NOx and CO

Figure 5 shows the NOx emissions under different loads. It can be found that when the load is 56.6%, the NOx concentration level is lower. When the load drops to 42.7%, the NOx content increases. When the load drops below 36.3%, the NOx emissions concentration rose substantially. Figure 6 shows the CO content in the flue gas. When the load is reduced from 56.6% to 27.7%, the CO concentration in the flue gas first increases slightly, and then decreases significantly. But the overall concentration is kept at a low level. From the above two points, it can be concluded that when the burner is at a load of about 40%, its NOx production and CO concentration meet the emission index requirements, which proves that the minimum stable combustion load of the burner can reach 40%.

![Figure 5. NOx concentration in tail gas of different loads.](image)  ![Figure 6. CO concentration in tail gas of different loads.](image)
3.3. Influence of load reduction on combustion stability

The fluctuation of the negative pressure in the furnace is the main basis for reflecting the stability of pulverized coal combustion [7]. The smaller the negative pressure fluctuation in the furnace, the more stable the combustion in the furnace [8]. Figure 7 shows the real-time monitoring results of negative pressure in the furnace under different loads during the experiment. Under the four working conditions, when the boiler load is reduced from 56.6% to 36.3%, the negative pressure fluctuation in the furnace gradually increases, but stable combustion can still be ensured; when the load is reduced to 27.7%, the negative pressure in the furnace appears to be large fluctuations, unable to sustain stable combustion.

![Figure 7. Negative pressure in furnace of different loads.](image)

(a) Flame shape at 56.6% load  
(b) Flame shape at 42.7% load  
(c) Flame shape at 36.3% load  
(d) Flame shape at 27.7% load

Figure 8. Flame shape at different loads.
The flame shape of the burner can also be used as a basis for judging the combustion stability. Figure 8 shows that when pulverized coal is injected into the furnace, the volatiles are first ignited, making the external flame blue [9]. The carbon particles will delay ignition and make the inside of the flame red. At the same primary wind speed, the flame stiffness decreases as the load decreases. When the load is high, the shape of the internal flame is straight and slender, and the edge line is obvious and regular [10]. When the load is low, the flame shape is curved, the internal flame is short and thick, and the flame boundary is greatly curved and divergent. When the loads are 56.6%, 42.7% and 36.3%, the flame edge is regular and clear, with high stability. At 27.7% load, the flame will diverge severely and fluctuate sharply.

4. Numerical simulation

4.1. Governing equation and calculation methods
The basic governing equations of this order value simulation calculation are mass conservation equation, momentum conservation equation, energy and composition conservation equation. The general differential equations for fluid turbulent flow and combustion process in the furnace are established, and some related models are added to make it universal. The system of differential equations is closed and thus solved.

Continuity equation:
\[
\frac{\partial \rho}{\partial t} + \frac{\partial \rho \bar{u}_i}{\partial x_i} = 0
\]  
(1)

Momentum conservation equation:
\[
\frac{\partial \rho \bar{u}_i}{\partial t} + \frac{\partial \rho \bar{u}_i \bar{u}_j}{\partial x_j} = \frac{\partial \rho}{\partial x_j} \left( \mu \frac{\partial \bar{u}_i}{\partial x_j} - \rho \bar{u}_i \bar{u}_j \right) - \frac{\partial p}{\partial x} + S_i
\]  
(2)

Energy conservation equation:
\[
\frac{\partial \rho c_p T}{\partial t} + \frac{\partial \rho c_p \bar{u}_i T}{\partial x_j} = \frac{\partial \rho}{\partial x_j} \left( \lambda \frac{\partial T}{\partial x_j} - \rho c_p \bar{u}_j T \right) + S_f + S_R
\]  
(3)

\(u_i\) is the average velocity in the three coordinate directions; \(\bar{u}_j\) is the pulsating velocity in the three coordinate directions; \(T\) is the average temperature; \(\mu\) is the dynamic viscosity coefficient caused by the molecular thermal motion; \(\lambda\) is the thermal conductivity caused by the molecular thermal motion; \(S_i\), \(S_R\) are source items.

This numerical calculation uses the finite volume method to solve the control equation. The turbulence model used in the calculation process is a realizable \(k-\epsilon\) two-equation turbulence model. The \(k-\epsilon\) model is based on the assumption of isotropy of turbulent flow [11]. By solving the equations of turbulent energy \(k\) and turbulent dissipation rate \(\epsilon\), the solutions of \(k\) and \(\epsilon\) are obtained, and then the values of \(k\) and \(\epsilon\) are used to calculate the turbulent viscosity, and finally obtained the solution of Reynolds stress by Boussinesq assumption [12]. The realizable \(k-\epsilon\) turbulence model has the following differences compared with the standard \(k-\epsilon\) turbulence model: 1) the calculation term of turbulence viscosity is added; 2) the dissipation rate transmission equation is added [13]. The realizable \(k-\epsilon\) turbulence model has a better representation of rotating flow, flow separation and secondary flow, it can improve the calculation accuracy of the complex flow field in the combustor. The realizable \(k-\epsilon\) model's turbulent kinetic energy \(k\) and turbulent dissipation rate calculation formula are as follows:
\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k \bar{u}_i) = \frac{\partial}{\partial x_i} \left( \mu + \frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial x_j} \right) + G_k + G_b - \rho \epsilon - Y_M + S_k
\]  
(4)

\[
\frac{\partial}{\partial t} (\rho \epsilon) + \frac{\partial}{\partial x_j} (\rho \epsilon \bar{u}_j) = \frac{\partial}{\partial x_i} \left( \mu + \frac{\mu_t}{\sigma_\epsilon} \frac{\partial \epsilon}{\partial x_j} \right) + \rho C_{1\epsilon} S_K - \rho C_2 \frac{\epsilon^2}{k + \sqrt{\epsilon}} + C_{1\epsilon} \frac{\epsilon}{k} C_{3\epsilon} G_b + S_\epsilon
\]  
(5)

Among them, \(G_k\) represents the turbulent kinetic energy term produced by the laminar flow velocity gradient, \(G_b\) represents the turbulent kinetic energy term produced by buoyancy, \(Y_M\)
represents the contribution to the dissipation rate in the process of turbulent pulsation expansion in the compressible flow to the global, $C_1$, $C_2$, $C_3$ is constants, its values are 1.44, 1.92, 0.09, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$[14], which are the turbulence Prandtl numbers of the $k$ equation and the $\varepsilon$ equation, respectively. $S_k$ and $S_\varepsilon$ are user-defined turbulent kinetic energy terms and turbulent dissipation source terms.

The flow in the furnace of a coal-fired boiler is a typical two-phase flow of gas and solid. To solve such problems, the first step is to select a multiphase flow model that best matches the actual flow in the boiler. In this paper, the two-phase flow model adopts the particle trajectory model, namely the discrete phase model. The random trajectory model first calculates the continuous phase transport equation. Based on the continuous phase flow field, the force of each particle is obtained by combining the flow field variables to obtain the particle velocity, and finally the trajectory of each particle.

In terms of heat transfer, the discrete coordinate radiation model is used in the calculation of this order value. Assuming that the temperature of the particle itself is consistent everywhere and the internal thermal resistance is zero, the heat balance equation of the particle temperature $T_p$ and the convection and radiation heat transfer on the particle surface is:

$$m_p c_p \frac{dT_p}{dt} = h A_p (T_\infty - T_p) + \varepsilon \rho A_p \sigma (\theta_R^4 - T_p^4)$$  \hspace{1cm} (6)

In the calculation process, the mass, energy and momentum exchanges between the continuous term and the discrete term are calculated using the following equation:

1) Mass exchange:

$$M = \frac{\Delta m_p}{m_{p,0}}$$  \hspace{1cm} (7)

Among them, $\Delta m_p$ is the mass change of the particles in the control body; $m_{p,0}$ is the initial mass of the particles; $\dot{m}_{p,0}$ is the initial mass flow rate of the tracking particles.

2) Momentum exchange:

$$F = \sum \left[ \frac{18\beta \mu C_D Re}{24 \rho d_p^2} (u_p - u) + F_{other} \right] \dot{m}_p \Delta t$$  \hspace{1cm} (8)

Among them, $\mu$ is the fluid viscosity; $C_D$ is the drag force coefficient; $Re$ is relative Reynolds number; $\rho_p$ is the particle density, $d_p$ is the particle diameter; $u_p$ is the particle velocity, $u$ is the fluid velocity; $F_{other}$ is the interaction force among other terms; $\dot{m}_p$ is Particle mass flow rate, $\Delta t$ is the time step.

3) Heat exchange:

$$Q = \left[ \frac{m_p}{m_{p,0}} c_p \Delta T_p + \frac{\Delta m_p}{m_{p,0}} (-h_{fg} + h_{pyrol} + \int_{T_{ref}}^{T_p} c_p \alpha dt) \right] \dot{m}_{p,0}$$  \hspace{1cm} (9)

Among them, $\Delta m_p$ is the mass change of particles in control body; $c_p$ is specific heat capacity of particles; $\Delta T_p$ is the temperature change of particles in the control body; $h_{pyrol}$ is volatilizes the heat required for pyrolysis; $h_{fg}$ is the latent heat of volatilizes; $T_{ref}$ is enthalpy corresponding to the reference temperature; $T_p$ is the temperature of particles flow out the control body; $c_p,\alpha$ is the specific heat of volatile matter.

NOx uses the software’s own NOx transport equation, the specific expression form of the equation is:

$$\frac{\partial}{\partial x} (\rho Y_{NO}) + \nabla \cdot (\rho \vec{v} Y_{NO}) = \nabla \cdot (\rho D \nabla Y_{NO}) + S_{NO}$$  \hspace{1cm} (10)

4.2. Setting of boundary conditions

(1) Inlet boundary condition: The mass flow rate inlet is used in the simulation calculation of this order value.

(2) Outlet boundary conditions: The outlet is a pressure outlet.

(3) Wall boundary conditions: use non-slip wall conditions.
The numerical calculation process assumes that the flow is a steady-state flow, the velocity and pressure coupling method selects the SIMPLE algorithm, the gradient term difference method uses the Least Squares Cell Based method, and the pressure term difference uses the second-order method, kinetic energy term, turbulent kinetic energy term, turbulent dissipation term, the energy term and other components are calculated in the first-order format, and after there is a trend of convergence, they are changed to the second-order upwind formula to ensure calculation accuracy.

All calculation parameters of this frequency value calculation are the same as those used in the test process, so they will not be repeated.

4.3. The results of numerical simulation

Figure 9 shows the temperature distribution in the furnace under different loads. It can be found from the figure that as the load decreases, the ignition distance of the pulverized coal (the distance from the ignition point to the nozzle) decreases, and the overall temperature level of the furnace decreases. Due to the decrease of the boiler load, the primary air stiffness decreases, and the ignition of pulverized coal is advanced, so the ignition distance is reduced.

Figure 10 shows the distribution of NOx in the furnace under three loads. It can be seen from the figure that the NOx concentration level is the lowest under the 60% load condition, and the NOx concentration level is the highest under the 50% load condition. The reason for this phenomenon may be that when the load is 60%, although the overall temperature level in the furnace is relatively high, the temperature distribution is relatively uniform, and there is no large area local high temperature phenomenon, so a large amount of thermal NOx will not be generated; when the load drops to 50%, the primary wind stiffness decreases, and a fuel-rich zone with uneven mixing of air and powder appears [15], resulting in excessively high local flame temperature, resulting in a large amount of thermal NOx; when the load is reduced to 40%, uneven coal mixing may also occur, But the furnace temperature is very low under this working condition, which reduces the generation of thermal NOx.

Figure 11 shows the distribution of carbon monoxide in the furnace under three loads. It can be found that the burner is under low load conditions. It still has a good fuel burnout rate.
5. Conclusions

Due to the manual control of the boiler load in the thermal test, it is difficult to ensure that the load accurately reaches the specified load. However, in terms of the overall trend, the calculation results of the above numerical simulations are consistent with the trend of the thermal test results. Therefore, the following conclusions can be obtained by comprehensively comparing the calculation results of the test and the numerical simulation.

The thermal test results show that:

- In the process of boiler load reduction, the ignition distance of pulverized coal is advanced. The reason for this situation is that in the process of the gradual decrease of the load, the primary wind stiffness gradually decreases and the kinetic energy of the air-powder mixture decreases, so the ignition is advanced.
- Before 40% load, the NOx and CO levels of the boiler are within the allowable index range.
- In the process of boiler load reduction, the negative pressure fluctuation in the furnace gradually increases, and the flame shape gradually becomes unstable. Both results show that the minimum stable combustion load of the burner can reach 40%.

Through the numerical simulation results:

- During the process of the burner falling from 60 load to 40 load, the pulverized coal ignition gradually advances and the distance to the nozzle is getting closer. This result is consistent with the trend presented by the test results.
- In the process of load reduction, NOx emissions have increased, and the highest concentration occurs under 50% load conditions. This is because as the load decreases, local fuel-rich areas with uneven mixing of air and powder may appear, resulting in high local temperatures in the furnace and large amounts of thermal NOx generated. Although uneven mixing of air and powder may occur at 40% load, the overall temperature level of the furnace is relatively low, and thermal NOx generation is relatively small. But the NOx levels of the three conditions are within the allowable index range.
- Under the three load conditions, the furnace CO concentration level is maintained in a lower range, and the burner has a better burnout rate under low load.

Through the above conclusions, it can be found that the results of numerical simulation related indicators are highly consistent with the experimental results. Therefore, it is proved that the burner of this structure has low-load stable combustion performance, and all indicators have reached the level of environmental protection requirements, and the minimum stable combustion load is 40%.

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