Simulation analysis of boiler high temperature corrosion atmosphere under lean oxygen operation

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Abstract. High-temperature corrosion is a major threat to the safe operation of thermal power plants. The reducing atmosphere induced by boiler lean oxygen combustion has close relation with the water walls corrosion. In this paper, the reducing atmosphere such as CO, H₂S concentration distribution was simulated targeted on a boiler. Under the full load, the atmosphere and the temperature distribution in low nitrogen combustion mode were further studied on different excess air ratios and the rates and position of the SOFA air conditions. With the SOFA rate increasing, the flame centre moved up, the boiler temperature is more uniform, and the temperature at the furnace outlet increased. the concentration of CO and H₂S in the main combustion zone is obviously increased. In the burnout zone, there is almost no CO and H₂S due to the supplement of SOFA.

1. Introduction
The four-tube leakage of coal-fired boilers in thermal power plants is one of primary reasons for unscheduled closing [1]. Pipeline blasting leaks are generally caused by the long-term operation in harsh environments such as high temperature, high pressure and corrosion [2]. According to the American Electric Reliability Association (NERC), the data indicated that 40% of four tube bursts were due to the boiler water cooled wall in power station boilers [3]. In 1992, 36% and 10% of Chinese electricity generation accidents belonged to four-tube leakages and boiler water cooled wall explosions, respectively [4]. In 1991, the boiler water cooled wall explosion led to 15.53% of the electric lost in China [5]. The American Electric Power Research Institute indicated that the tube burst was caused by stress fracture, water side corrosion, smoke side corrosion, wear, fatigue, or quality defects [6]. However, the water cooled boiler wall failure caused by high temperature corrosion was more than 80% in the boiler water cooled furnace wall bursting accident. Therefore, it is important to study and prevent the high temperature corrosion in boiler, especially in water cooled boiler walls [7].

Temperature of the water cooled wall will be very high, when parameters of large power station boilers are above the subcritical conditions. A lean oxygen state was obtained by the low NOx staged combustion technology leading to the serious high temperature corrosion [8]. According to Air Pollutant Emission Standards for Thermal Power Plants (2014) and Complete Implementation of the Work Plan for Ultra-Low Emissions and Energy-saving Reconstruction of Coal-fired Power Plants (2015), emission amounts of nitrogen dioxide should be controlled at 100 and 50 mg/m³, respectively [9]. The reducing atmosphere near the surface of the water cooled boiler wall will be stronger. Higher concentration of pulverized coal and combustion temperature are required for anthracite and lean coal...
to ignite and burn, which will cause the strong reducing atmosphere. Thus, if the low-volatility anthracite and lean coal are still burned, there will be a more serious high temperature corrosion.

In this work, tangentially fired boiler of 300 MW was employed to simulate the combustion process. Under the full load, the atmosphere and the temperature distribution in low nitrogen combustion mode were further studied on different excess air ratios and the rates and position of the SOFA air.

2. Simulation of boiler

A tangentially fired boiler of 300 MW with “π” shape of furnace (12468×14048×52837 m³) was employed for simulation, as shown in Figure 1(a).

![Figure 1](image)

(a) the structure of boiler (b) the structure of burner

**Figure 1.** The structure of the boiler.

The whole group of burner structure was showed in Figure 1(b). The four corners had air distributions; six pulverized coal burners (A, B, C, D, E, F); nine auxiliary air (AA, AB, BC, CC, CD, DE, EE, EF, FF); three oil guns (AB, CD, EF); four air SOFAs (I, J, K, L).

2.1. Numerical method

2.1.1. **Mesh.** In the simulation, structured hexahedral mesh with a number of one million were used. The grid of the burner area was refined to 500000. The overall grid was showed in figure 2. The grid near the exit of the burner was refined, and near the center of the boiler was sparse. To prevent pseudo-diffusion, the burner cross-section octagonal PAVA grid was used for PAVA grid.
2.1.2. Simulation condition. The simulation was carried out under 300MW to calculate the excess air coefficient, the different SOFA wind rate, the different SOFA position and the different coal (mainly changing the S and N content). The simulation conditions were showed in Table 1 and the coal quality information can be seen in Table 2. They were all equipped with four corners.

The Rosin-Rammler distribution law was used to analyze the particle size distribution of pulverized coal. The minimum and maximum diameters were respectively 10 and 200 μm. The average particle size reached about 54 μm and the distribution index was 1.2.

2.1.3. Model description. The combustion process of pulverized coal in boiler was very complicated. In this paper, three-dimensional steady state calculation was used. The finite volume method was used to discretize differential equations, and the SIMPLE algorithm was applied to couple the velocity and pressure. The standard k-ε model was used to describe the turbulent flow of gas phase. P-1 model was used for radiative heat transfer. A mixed fraction-probability density function (PDF) model was used to calculate gas phase turbulent combustion. The two competing rate model was used to predict the release rate of pulverized coal. Char combustion used kinetics/diffusion-limited char combustion model to calculate.

Figure 2. The mesh of boiler.
Table 1. Low nitrogen combustion simulation conditions.

| Excess air ratio | Coal feeder /kg-s⁻¹ | Primary air rate /% | Auxiliary air rate /% | OFA air rate /% | SOFA air rate /% |
|------------------|----------------------|---------------------|-----------------------|-----------------|-----------------|
| 1                | 1.273                | 22                  | 50                    | 8               | 20              |
| 2                | 1.2                  | 22                  | 50                    | 8               | 20              |
| 3                | 1.355                | 22                  | 50                    | 8               | 20              |
| 4                | 1.273                | 22                  | 70                    | 8               | 0               |
| 5                | 1.273                | 22                  | 60                    | 8               | 10              |
| 6                | 1.273                | 22                  | 40                    | 8               | 30              |
| 7                | 1.273                | 22                  | 50                    | 8               | 20(up)          |
| 8                | 1.273                | 22                  | 50                    | 8               | 20(down)        |
| 9                | 1.273                | 22                  | 50                    | 8               | 20              |
| 10               | 1.273                | 22                  | 50                    | 8               | 20              |

The Lagrangian random particle orbit model was used for the solid phase flow. The Rosin-Rammler distribution law was used to analyze the particle size distribution of pulverized coal. The Stochastic Tracking model was used to track the trajectory of coal particle. The post-processing method was used to calculate NOx and SOx.

First, the cold state calculation was carried out until the convergence. Then, the hot state calculation was carried out. SIMPLE algorithm was employed to couple the velocity and pressure and calculate relevant parameters. The convergence criterion was that residuals of energy, radiation heat transfer were less than 10⁻⁶, and others were less than 10⁻³.

2.2. Results

2.2.1. Simulations and verification of rated conditions. 1) Velocity field. When the excess air ratio was 1.273 and the SOFA was off, the velocity distribution of the vertical center section of the boiler (the middle of the left and right wall) was shown in Figure 3. The velocity distribution of a layer and f layer burner is shown in Figure 4. Figure 3 indicated that the distribution of the high-speed zone in the main burner area was symmetrical because the SOFA was off. Next, the process of injection of the pulverized coal into the boiler was simulated and shown in figure 4. The pulverized coal was pushed and deflected due to the squeeze flow from the upstream. A tangential circle was formed at four corners. The backfire side of the front and rear walls on the a-layer burner section scoured the wall due to insufficient air supply.

2) Temperature field. When the excess air ratio was 1.273 and the SOFA was off, the temperature distributions of A and F layers and the center section of the burner were shown in Figure 5. The cold pulverized coal was heated due to the radiant heat from the upstream flue gas. Then, it released a large amount of volatiles and began to burn after a certain distance.
With the release of a lot of heat, the temperature rose rapidly and the highest temperature reached 1900K. When the volatiles were completely released, the pulverized coal was stably burned and the temperature was stable at 1700–1800 K. The four-corner burner formed a distinct tangential circle and the overall boiler temperature rose from A layer to F layer. In the center section of the boiler, it can be clearly seen that the high temperature zone is at the height of the main combustion zone, and the temperature is lowered regardless of the top or bottom. The overall temperature distribution of the boiler fitted the experimental measurements well.

3) The distribution of flue gas composition. Figure 6 shows the concentration distribution of O$_2$ and CO at the two-layer of the burner. It can be seen that the concentration of O$_2$ is highest and the concentration of CO is zero at the outlet of the burner. At a distance from the burner, the concentration of O$_2$ decreases rapidly to zero and the concentration of CO rises to the highest point due to the release and the combustion of volatiles. This process consumes O$_2$ and generates CO. With the pulverized coal burning, the concentration of CO decreases at downstream.
Figure 5. The temperature distribution of the two-layer burner and the center section (K).

Figure 6. The mole concentration distribution of O$_2$ and CO at a layer and F layer of the burner.

Figure 7 shows the concentration distribution of O$_2$, CO and H$_2$S at the layer of the burner, the region of front wall and left wall. It was observed that there was almost no O$_2$ near wall, because the entire concentration of O$_2$ was not high. The concentration of CO in the upper part of the main burner area was the highest at the height direction. After OFA, the concentration of CO was significantly reduced due to the supplement of oxygen. After SOFA, the concentration of CO decreased and completely disappeared. In regions of the upper part of the main burner and the lower part of SOFA, the concentration of CO significantly reduced at the upstream outlet of the burner. Although the
downstream was still high, it was in good agreement with the experimental tests. The distribution of H₂S was similar to that of CO, which was high at main burner area. After OFA, it was significantly reduced due to the supplement of oxygen. After SOFA, it completely disappeared. It was also low at the upstream and high at the downstream. These phenomenon were consistent with the test results.

The distribution characteristics along the height direction mainly depended on the distribution of excess air coefficient. Due to the secondary air staged, the oxygen of the main burner area was insufficient resulting in a serious reducing atmosphere. After the SOFA, the oxygen was sufficient and, thus, the reducing atmosphere changed obviously. The distribution characteristics along circumferential direction were mainly caused by the tangential combustion, and the whole flow field in the boiler rotated. Therefore, the overall oxygen was insufficient in the main burner area. The upstream volatiles release and react to lead to a serious reducing atmosphere, but the reducing atmosphere reduced at the downstream due to the continuous combustion and the dilution of the atmosphere. In the SOFA region, the upstream CO was firstly oxidized to CO₂ resulting in a significant decrease in the content of CO, but the downstream reducing atmosphere was rather strong due to the hysteresis of oxidation.

From the distribution of CO and H₂S, the high temperature corrosion of the water cooled wall in the height direction was the most serious in the main burner area. After SOFA, the tendency of corrosion is significantly reduced. In the circumferential direction of the furnace, the upstream corrosion of the burner outlet was more serious than the downstream in the middle and lower part of the main burner area. The upstream was hardly corroded and the severely corroded area moved to downstream in the upper part of the main burner area and the SOFA area.

![Figure 7. The mole concentration distribution of O₂, CO and H₂S at the cross section of the a-layer burner and the area near the front wall and left wall.](image)

3. Conclusions

(1) With the amount of oxygen increasing, the flame of boiler center moved downward and the temperature at the outlet of the boiler decreased. When the excess air ratio was too large, the overall temperature, CO and H₂S concentration decreased and the concentration of O₂ and NO increased. Low excess air coefficients were conducive to NOx emission reduction, but not to corrosion protection.

(2) With the SOFA rate increasing, the flame center moved up, the boiler temperature was more uniform, and the temperature at the furnace outlet increased. With the SOFA air rate increasing, the O₂ of the main combustion area decreased, the O₂ of SOFA zone increased, and the outlet oxygen remained constant. With the SOFA rate increasing, the concentration of CO and H₂S in the main area.
combustion zone was obviously increased. In the burnout zone, there was almost no CO and H2S due to the supplement of SOFA. With the SOFA rate increasing, the main combustion zone NO significantly reduced, a small amount of new NO was produced in the burnout zone, and the overall trend was downward.

(3) With SOFA decreasing, the burnout zone moved down slightly. CO and H2S could be completely oxidized when O2 was supplied sufficiently. However, it might increase the form of NO in the burnout zone, but had barely effect on the overall temperature and atmosphere distribution.

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