Numerical Simulation of NO\textsubscript{x} Emission Characteristics of a Cyclone Boiler with Slag-Tap Furnace

Weishu Wang, Yezhu Sun, Zhihao Huang, Yihan Liao,* and Fan Fang

ABSTRACT: In order to optimize the parameters of boilers and realize the burning of pure, high-alkali coal, the velocity field, temperature field, and component distribution characteristics of a new cyclone boiler with slag-tap furnace were numerically studied using ANSYS software. The influence law of the over-fire air rate on the NO\textsubscript{x} emission of the cyclone boiler with slag-tap furnace was established, and the optimal over-fire air rate was determined. The renormalization-group $k$−$\varepsilon$ double equation model was used to simulate the gas phase flow, the discrete phase model was used to compute the gas–solid two-phase flow, and the high-alkali coal combustion model was revised based on experimental data. The results show that the overall aerodynamic field in the entire boiler with slag-tap furnace is favorable, the flue gas is completely formed, and the cyclone burners in a staggered and reversed arrangement can enhance combustion. The temperature near the wall of the cyclone can reach 1700–2100 K, which satisfies the requirements of a liquid slag discharge. The temperature under various over-fire air rate conditions can allow the high-alkali coal to burn normally and ensure fluidization of its ash. The greater the over-fire air rate, the lower the average temperature in the furnace and the lower the NO\textsubscript{x} concentration at the outlet of the furnace. Considering that it is not easy to fluidize the ash of high-alkali coal when the average temperature in the cyclone boiler with slag-tap furnace is very low, an over-fire air rate of 10% is selected for the optimal air-staged combustion scheme.

1. INTRODUCTION

High-alkali coal has a large heating value, and there are rich reserves of this coal in China. However, the detrimental and slugging characteristics of high-alkali coal significantly limit its combustion and utilization.\textsuperscript{5,6} The cyclone boiler with slag-tap furnace is a new type of high-efficiency combustion equipment for high-alkali coal combustion. It has been designed to solve the problem of strong slugging when burning pure Xinjiang high-alkali coal. The cyclone boiler with slag-tap furnace has the characteristics of high combustion efficiency of the cyclone burner and a high slag capture rate of the boiler. It has been designed to achieve clean and efficient utilization of pure, high-alkali coal. The alkali metals and alkaline earth metals stored in high-alkali coal considerably affect the combustion in a furnace.\textsuperscript{4–6} The research and application of cyclone combustion technology in developed countries have matured relatively, and cyclone furnaces in the United States have been widely used in the combustion of powder river basin (PRB) high-alkali coal.\textsuperscript{6} In some other countries, the cyclone furnace is mainly used for the gasification of pulverized coal. In this process, coal or coke was used as a raw material, and oxygen (air, oxygen-enriched or industrial pure oxygen) and water vapor were used as a gasification agent under high temperature and pressure. The combustible part of coal or coal char is converted into combustible gas through a chemical reaction, which improves the efficiency of coal utilization and reduces environmental pollution, which has good social and environmental benefits.\textsuperscript{7–9} Zarzycki et al.\textsuperscript{10} modeled the combustion process in the cyclone furnace and proved the reliability of the numerical simulation results through comparison with experiments. Carson et al.\textsuperscript{11} and Yi et al.\textsuperscript{12} studied the co-firing characteristics of different coals in the cyclone furnace and put forward some considerations to pave the way for the popularization and application of the cyclone furnace. Related studies have shown that the air-staged technology can decrease NO\textsubscript{x} emissions during the combustion of pulverized coal, and it has been widely used in boilers.\textsuperscript{13–15} Huang et al.\textsuperscript{16} numerically studied the effect of various over-fire air
parameters on the combustion and NO\textsubscript{x} emission characteristics of a 670 t/h boiler. The calculation results were essentially consistent with the actual measured values, which verified the reliability of the numerical simulation. Bai et al.\textsuperscript{17} studied the effect of the tertiary air rate on the combustion efficiency and NO\textsubscript{x} emissions of a 300 MW pulverized coal boiler with a swirl burner, and the results showed that, when the ratio of upper tertiary air increases, the concentration of NO\textsubscript{x} decreases, but the carbon content in fly ash increases and affects the efficiency of combustion. Kuang et al.\textsuperscript{18} studied the characteristics of deep air-staged combustion technology on low-volatile coal combustion and NO\textsubscript{x} emissions and improved the technology to extend the residence time of pulverized coal in the furnace. It can be found from those studies that most of the pulverized coal can be used by gasification, but it is not suitable for low-quality coal such as high-alkali coal. Thus, a new type of cyclone combustion method was proposed in the study, which can use high-alkali coal while ensuring that NO\textsubscript{x} emissions are within a certain range. In this work, to optimize the parameters of the boiler and realize the burning of pure high-alkali coal, the effects of various over-fire air rates on the combustion and NO\textsubscript{x} emission characteristics of cyclonic boilers with slag-tap furnace were numerically studied using CFD software. The research results can provide a theoretical basis for the optimal operation and design of cyclonic boilers with slag-tap furnace.

2. MODEL AND RESEARCH CONDITIONS

2.1. Physical Model. The research object of this study is the cyclone boiler with slag-tap furnace burning pure, high-alkali coal, and it is based on a demonstration project. The boiler is an ultrahigh-pressure, once-through boiler with slag-tap furnace produced by the BABCOCK company in Germany. The rated capacity is 830 t/h. Two burnout chambers, one slag chamber, and one vertical flue are arranged symmetrically on both sides of the boiler to form a double U-shaped furnace and tower structure. Eight cyclone burners are arranged on the top of each burnout chamber in a staggered arrangement. Each cyclone burner is equipped with a primary air inlet and two secondary air inlets, and the coal particles are transported by the primary air inlet.

According to the structural characteristics of the cyclone boiler with slag-tap furnace that burns pure, high-alkali coal, the symmetrical part of the boiler is selected as the calculation domain and the geometric model of the boiler is constructed according to the actual size, scale 1:1 as shown in Figure 1. The width of the model, which is 1/2 of the actual boiler width, is 4196 mm, the depth of the model is 12480 mm, and the width of the burnout chamber is 4910 mm. Figure 2 display a top view of the cyclone burner area. The swirl directions of adjacent burners are always opposite. This arrangement can increase the mixing degree of the pulverized coal and flue gas flow, enhance combustion and heat transfer, and improve the efficiency of the boiler.

To optimize the mesh model, the calculation domain is partitioned to divide the entire model, and the actual calculation domain is divided into the cyclone burner area, burnout chamber area, slag chamber area, and vertical flue area. According to the geometric characteristics of each area, different grid techniques were adopted for mesh modeling. The cyclone burner area has a complicated structure and high turbulence intensity, and hence an unstructured grid was used to adapt to its complicated physical and chemical processes.
calculation amount comprehensively, a meshing scheme of 6.84 million was selected as the calculation grid.

2.2. Mathematical Model of Numerical Simulation. The high-alkali coal in the cyclone boiler with slag-tap furnace burns violently, involving a gas flow and heat and mass transfer. In this study, the RNG $k$–$\varepsilon$ model was used to solve the complex three-dimensional gas-phase turbulent flow with a strong swirl.

The mathematical model of the RNG $k$–$\varepsilon$ model is as follows:

$$\begin{align*}
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_i)}{\partial x_i} &= \frac{\partial}{\partial x_j} \left( \alpha k \frac{\partial k}{\partial x_j} \right) + G_k + G_b - \rho \varepsilon - Y_M + S_k \\
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_i} &= \frac{\partial}{\partial x_j} \left( \alpha \varepsilon \frac{\partial \varepsilon}{\partial x_j} \right) + C_{1\varepsilon} \rho \varepsilon \left( \frac{G_k}{k} + C_{\mu\varepsilon} G_b \right) - C_{2\varepsilon} \rho \varepsilon^2 \\
&\quad - R_\varepsilon + S_\varepsilon
\end{align*}$$

where

$$\begin{align*}
G_k &= \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \right) \\
G_b &= \beta G_k \frac{H_e}{P_r} \frac{\partial T}{\partial x_i} \\
Y_M &= 2 \rho \varepsilon M_i^2
\end{align*}$$

The RNG $k$–$\varepsilon$ model is a turbulence model obtained from the Navier–Stokes equations according to the “renormalization-group” (RNG) mathematical method, and its mathematical expression contains additional functions. Compared with the standard $k$–$\varepsilon$ model, the RNG $k$–$\varepsilon$ model considers the effect of turbulence and improves the accuracy of calculations under strong swirling conditions. The RNG $k$–$\varepsilon$ model provides an analytical derivative differential formula for effective viscosity, which can solve the effect of a low Reynolds number. Thus, the RNG $k$–$\varepsilon$ model is more accurate, reliable, and applicable in a wider range than the standard $k$–$\varepsilon$ model.

A large amount of heat is generated during the combustion process of pulverized coal, and the temperature in the furnace is high. Therefore, the heat in the flue gas is mainly transferred to other heated surfaces such as water walls by radiative heat transfer. It is crucial to choose a reasonable radiation model for the simulation and prediction of combustion and heat transfer in the furnace.

The P-1 radiation model is the simplest P-N model and can be used in the field of combustion, taking into account the effects of diffusion on combustion. The mathematic model of radiant heat flow $q_i$ in the P-1 model is

$$q_i = -\frac{1}{3(a + \sigma_i)} \nabla G$$

In the formula, $a$ is the absorption coefficient, $\sigma_i$ is the scattering coefficient, $G$ is the incident radiation energy, and $C$ is the linear anisotropic phase function coefficient. To simplify the parameters, the parameter $\Gamma$ is introduced and defined as follows:

$$\Gamma = \frac{1}{3(a + \sigma_i)} - C\sigma_i$$

Then, eq 7 can be simplified as follows

$$q_i = -\Gamma \nabla G$$

The equation of $G$ is

$$-\nabla \cdot G = aG + 44n^2\sigma T^4 = S_G$$

In the formula, $n$ is the refractive index of the medium, $\sigma$ is the Stefan–Boltzmann constant, and $S_G$ is the user-defined radiation source.

Combining eqs 8 and 9

$$-\nabla q_i = aG - 44n^2\sigma T^4$$

In the cyclone boiler with slag-tap furnace, many types of NO$_x$ are produced by fuel combustion and their generation mechanisms are also different. To suppress NO$_x$ generation in the furnace and reduce NO$_x$ emissions at the outlet of the boiler, it is particularly important to understand the NO$_x$ generation mechanism. In general, the NO$_x$ produced by pulverized coal combustion mainly includes thermal NO$_x$, prompt NO$_x$, and fuel NO$_x$.

The thermal NO$_x$ is formed by the N$_2$ in the air entering the boiler together with the oxidant and being oxidized by the high-temperature environment. Its generation is significantly affected by the temperature. The chemical reaction of thermal NO$_x$ generation was first proposed by Zeldovich et al. The second mechanism of NO$_x$ formation was first determined and proposed by Fenimore and referred to as “prompt NO$_x$.” Studies have confirmed that, in certain combustion environments, such as low temperatures, fuel-rich conditions, and short residence times, a large amount of prompt NO$_x$ can be formed. The last type of NO$_x$ is fuel NO$_x$. There are two types of intermediate products of fuel NO$_x$ during the production process: HCN and NH$_3$. In this study, the thermal NO$_x$ and fuel NO$_x$ are mainly considered because the generation of prompt NO$_x$ is very small.
The method is to divide the air required for pulverized coal combustion into two or more streams and put it into the furnace. In the initial stage of combustion in the furnace, only part of the air is injected so that the main combustion area is a fuel-rich zone and only part of the fuel is burned, reducing the generation of fuel NOx. The remaining secondary air used for complete combustion is injected downstream of the fuel-rich area to construct a secondary combustion area where the fuel is completely burned. In addition, under the condition of air-staged combustion, the fuel combustion is carried out step by step, and the overall temperature of the flame, including the temperature of the secondary combustion zone, is lower than that in the case of the no air-staged, so the formation of NOx in the furnace is limited. The principle of air-staged combustion is shown in Figure 4.

**2.4. Research Conditions.** To solve the control equation accurately and reduce the calculation error, it is very important to use the known parameters reasonably and define the different types of boundary conditions accurately for the numerical simulation of the combustion process of a cyclone boiler with slag-tap furnace burning pure, high-alkali coal. Boundary conditions refer to the changing law of the dependent variable with time and space in the defined solution area. In this work, the mass flow inlet, pressure outlet, and wall boundary conditions are needed. The specific input data are presented in Table 1. The primary air inlets in the upper part of the cyclone burners adopt the mass flow inlet where the mass flow is 3.08 kg/s and the temperature is 333.15 K. The tangential secondary air inlets on the wall of the cyclone burners adopt the mass flow inlet where the mass flow is 6.16 kg/s and the temperature is 603.15 K. The pulverized coal inlet adopts an inlet velocity of 30 m/s at a temperature of 333.15 K. The entire cyclone boiler with slag-tap furnace is in an environment with a local gravity acceleration of 9.8 m/s². The outlet pressure is −100 Pa. The proximate and ultimate analyses of the high alkali coal are presented in Table 2.

**3. RESULTS AND DISCUSSION**

**3.1. Analysis of Velocity Distribution.** Figure 5 shows the velocity distribution along the Y = 6.9 m longitudinal section of the furnace. As can be observed, the velocity in the boiler is high in the middle and low on both sides. The velocity of the air flow in the cyclone burner is higher, and the velocity gradually decreases along the direction of the air flow flue. The velocity at the outlet section of the cyclone burner is approximately 40 m/s. As the air flow enters the burnout chamber, the cross-sectional area increases, and the velocity of the air flow decreases. The velocity of the airflow in the burnout chamber is maintained at 30 m/s with the coupling disturbance of the air flow of each cyclone burner. When the air flow passes through the slag chamber, the central velocity of the furnace rises to approximately 40 m/s after entering the

| number | name                              | value | unit |
|--------|-----------------------------------|-------|------|
| 1      | mass flow of the primary air inlet| 3.08  | kg/s |
| 2      | temperature of the primary air inlet| 333.15 | K |
| 3      | mass flow of the secondary air inlet| 6.16  | kg/s |
| 4      | temperature of the secondary air inlet| 603.15 | K |
| 5      | temperature of wall of the burnout chamber area| 1400  | K |
| 6      | temperature of wall of the slag chamber area| 1600  | K |
| 7      | temperature of wall of the vertical flue area| 1200  | K |
| 8      | pressure of the outlet section| −100  | Pa |

**Table 2. Analysis Data of Pulverized Coal (ad)**

| ultimate analysis | value | unit |
|-------------------|-------|------|
| carbon (C)        | 54.58%|      |
| hydrogen (H)      | 3.02% |      |
| oxygen (O)        | 20.32%|      |
| nitrogen (N)      | 0.57% |      |
| sulfur (S)        | 0.23% |      |
| moisture          | 11.6% |      |
| volatile matters  | 31.19%|      |
| fixed carbon      | 47.53%|      |
| ash               | 9.68% |      |
| lower heating value| 26.37 MJ/kg |

**Note:** ad means as-dried basis.
vertical flue because of the reduction in the cross-sectional area. As the flue gas flow passes through the heating surfaces, the velocity gradually decreases, and the velocity at the outlet section of the furnace is approximately 10 m/s. From the enlarged view of the cyclone burner, it can be seen that the velocity inside the furnace is the highest near the secondary air inlet where it can reach 85 m/s because high-velocity secondary air enters here. According to the velocity distribution along the $Y = 6.9$ m longitudinal section in the cyclone burner shown in Figure 6, it can be observed that the velocity is symmetrically distributed in the radial direction of the cyclone burner, and the velocity is lowest in the center.

3.2. Analysis of Temperature Distribution. Figure 8 shows the temperature distribution along the $Y = 6.9$ m longitudinal section of the furnace. It can be observed that the highest temperature appears in the cyclone burner outlet and the upper and middle areas of the burnout chamber because the main combustion area of high-alkali coal is in the cyclone burner. The pulverized coal was heated to release volatile components (such as CH$_4$, CO, etc.), and a large amount of heat was released because of the oxidation reaction between these combustible gases and oxygen, which made the temperature of the area rise rapidly. After the flue gas flow enters the burnout chamber, the unburned pulverized coal particles continue to be burned by the swirling air airflow, and the pulverized coal is burned out in the upper and middle areas of the burnout chamber where the temperature reaches a peak value of approximately 2100 K. As depicted in the enlarged viewer of the cyclone burner, the temperature is low in the middle and high areas of the cyclone burner on both sides and the temperature near the wall of the cyclone burner is lower. Under the coupling influences of the vortex primary air and tangential secondary air, the high-alkali coal particles moving with the airflow are thrown toward the wall of the burner. The airflow rotates around the wall at high velocity, and thus the temperature at the center of the cyclone burner is lower than at the sides. As shown in Figure 9, the temperature distribution along the $Y = 6.9$ m longitudinal section in the cyclone burner is symmetrical in the radial direction, and it is highest at 1/3 of the distance from the central axis to the wall of the cyclone burner because of the large amount of pulverized coal burning.
here. The closer to the wall of the cyclone burner, the lower the temperature of the flue gas is. Because of the rebound effect at the wall of the cyclone burner, the pulverized coal particles cannot stay and the temperature is then lower.

3.3. Analysis of Component Distribution. Figure 10 shows the distribution of the O2 mass fraction along the Y = 6.9 m longitudinal section of the furnace where the unit is 100%. It can be observed that the area with the largest O2 mass fraction is in the upper part of the cyclone burner because the primary air and secondary air enter in this area. With the combustion of pulverized coal, the O2 content in the cyclone burner gradually decreases and shows a symmetrical distribution. The mass fraction of O2 in the center and near the wall area of the cyclone burner is relatively higher. When the flue gas flows through the burnout chamber, the mass fraction of O2 in the flue gas is only 0.02, and the pulverized coal is basically burned completely at this time. According to the distribution of the O2 mass fraction along the Y = 6.9 m longitudinal section in the cyclone burner shown in Figure 11, the mass fraction of O2 is lowest at 1/3 of the distance from the central axis to the wall of the cyclone burner, and it is also lower at the central axis. The closer to the wall of cyclone burner, the larger the mass fraction of O2 is. Compared with the temperature distribution in Figure 6, it can be observed that the lower temperature in this area indicates that there are fewer pulverized coal particles and less O2 is consumed.

Figure 12 shows the distribution of the CO mass fraction along the Y = 6.9 m longitudinal section of the furnace where the unit is 100%. It can be observed that the CO mass fraction in the cyclone burner area is the highest, and it is distributed symmetrically. According to the distribution of the CO mass fraction along the Y = 6.9 m longitudinal section in the cyclone burner shown in Figure 13, the CO mass fraction is the highest at 1/3 of the distance from the central axis to the wall of the cyclone burner, and it is the lowest in the center and sides of the burner. Compared with the temperature distribution in Figure 9, the mass fraction of CO is high in areas with high temperature and it is low in areas with low temperature. Under the same external factors, the higher the temperature is, the more pulverized coal is in this area, and the more CO is generated.

Figure 14 shows the distribution of the CO2 mass fraction along the Y = 6.9 m longitudinal section of the furnace, where the unit is 100%. It can be observed that the mass fraction of CO2 in the cyclone burner area is the highest, and it is distributed symmetrically. According to the distribution of the CO2 mass fraction along the Y = 6.9 m longitudinal section in the cyclone burner shown in Figure 11, the CO2 mass fraction is lowest at 1/3 of the distance from the central axis to the wall of the cyclone burner, and it is also lower at the central axis. The closer to the wall of cyclone burner, the larger the mass fraction of CO2 is. Compared with the temperature distribution in Figure 6, it can be observed that the lower temperature in this area indicates that there are fewer pulverized coal particles and less O2 is consumed.
value in the vertical flue region. As depicted in the enlarged view of the cyclone burner, the mass fraction of CO₂ in the cyclone burner has a middle, low, and high on both sides, and it is the lowest at the area near the burner wall. According to the distribution of the CO₂ mass fraction along the Y = 6.9 m longitudinal section in the cyclone burner shown in Figure 15, the mass fraction of CO₂ is highest at 1/3 of the distance from the central axis to the wall of the cyclone burner, and it is slightly lower at the central axis. Compared with the temperature distribution in Figure 9, the mass fraction of CO₂ is relatively high in areas with high temperature and it is relatively low in areas with low temperature. Under the same external factors, the higher the temperature is, the higher is the burnout rate of pulverized coal and the more CO₂ is generated.

3.4. Analysis of the NOₓ Concentration Distribution. Figure 16 shows the distribution of the NOₓ concentration along the Y = 6.9 m longitudinal section of the furnace, where the unit is mg/m³. As can be observed in the figure, the areas with a high NOₓ concentration appear in the burnout chamber and the cyclone burner. This occurs because the pulverized coal is mainly burned in the cyclone burner and burned out in the burnout chamber. The more complete the pulverized coal combustion is, the higher the flue gas temperature and the higher the generation of thermal NOₓ. After the flue gas flows through the slag chamber, the concentration of NOₓ in the flue gas is basically stable. Combining this result with that in Figure 6, it can be observed that the NOₓ concentration distribution is similar to the temperature distribution along the Y = 6.9 m longitudinal section of the furnace. This indicates that the generation of NOₓ is significantly affected by the temperature distribution and the NOₓ concentration is higher in regions with high temperature. Because of the higher temperature, more intermediate products such as CH, HCN, and NN were generated by the thermal decomposition of pulverized coal in this area and a greater amount of fuel NOₓ is generated by the reaction of these intermediate products with oxygen. This conclusion was also consistent with other results.15 The enlarged view of the cyclone burner in Figure 17 shows that the NOₓ concentration along the Y = 6.9 m longitudinal section in the burner is distributed symmetrically. The NOₓ concentration is highest at the central axis, and it is lower than that in the surrounding environment at approximately 1/3 of the distance from the central axis to the wall. According to the analysis in Section 2.2, the pulverized coal is mainly burned at approximately 1/3 of the distance from the central axis of the cyclone burner, and a large amount of NOₓ is generated there. However, the central area has negative pressure because of the
strong swirling flow, and thus a large amount of NOx moves to the central area. According to Figure 13, the peaks of the distribution of CO mass fraction appear at approximately 1/3 of the distance from the central axis to the wall, and the mass fraction of CO is higher in the central area. The NOx concentration is lower because of the reduction in CO.

4. OPTIMIZATION OF AIR-STAGED COMBUSTION

Figure 18 shows the characteristics of particle residence time under different over-fire air rates. As can be observed, the particle residence time varies significantly under different conditions. The larger the over-fire air rate is, the longer the particle residence time in the furnace. The residence time of high-alkali coal particles changed from 11.12 s in the original condition to 36.98 s in the 15% over-fire air rate condition, and thus this rate has the greatest influence on particle residence time. On one hand, the increase in the over-fire air rate results in a reduction in the secondary air rate, the velocity of gas flow in the cyclone burner decreases, and the residence time of pulverized coal particles in the cyclone burner increases. On the other hand, the greater the over-fire air rate is, the greater is the disturbance between the airflows in the burnout chamber, which enhances the mixing between the pulverized coal airflows and extends the particle residence time.

Figure 19 shows the average temperature distribution in the furnace under different over-fire air rates. As can be observed, the characteristic of the temperature distribution is the same under different conditions. Along the direction of the flue gas flow, the average temperature in the furnace first rises then decreases, then rises again, and finally becomes stable. Pulverized coal particles enter the cyclone burner and absorb heat and then burn immediately after reaching the ignition temperature, releasing a large amount of latent heat. The temperature is the highest near the center of the burnout chamber at Z = −10 m. Because of the input of over-fire air, the temperature decreases at Z = −6 m. Then, the pulverized coal continues to burn out, the temperature increases, and the temperature of the flue gas in the slag chamber decreased rapidly. It can also be observed in the figure that the larger the over-fire air rate is, the lower is the average temperature in the furnace and the lower is the temperature at the outlet. When the over-fire air rate increases from 0 to 15%, the temperature of flue gas at the outlet of the furnace decreases from 1372.5 to 976.3 K. The O2 supply in the cyclone burner area is insufficient, and the pulverized coal is incompletely burned, which reduces the maximum temperature of the main combustion zone. At the same time, the air-staged combustion provides the conditions required for the complete combustion of pulverized coal as it can continue to burn. Therefore, the temperature of the flue gas in the furnace increases slightly after the over-fire air is added, but the overall temperature is lower than that in the original condition. The reduction in temperature in the furnace can effectively suppress the generation of NOx and reduce the NOx emission at the outlet of the furnace.

Figure 20 displays the distribution of the NOx concentration in the furnace under different over-fire air rates, where the unit is mg/m3. It can be observed that the trend of the NOx concentration in the furnace along the direction of the flue gas flow under different conditions is the same: it tends to rise first then decrease, then rise again, and finally decrease. The fuel enters the cyclone burner, and the volatiles are separated by heating. The fuel burns, and the temperature rises. At this time, the NOx concentration rises rapidly. In the upper part of the...
burnout chamber, from $Z = -11$ m to $Z = -8$ m, part of the NO$_x$ is reduced by the high CO concentration, and hence the NO$_x$ concentration decreases slightly. At the $Z = -6$ m section, the supplemental over-fire air enters the boiler, and the pulverized coal continues to burn out, generating NO$_x$ and the NO$_x$ concentration reaches the maximum at the bottom of the slag chamber. Finally, the flue gas enters the vertical flue, and the NO$_x$ concentration gradually decreases. The greater the over-fire air rate, the lower the NO$_x$ generation in the furnace. Combining with Figure 19, it can be seen that increasing the over-fire air rate will cause the temperature in the furnace to decrease and suppress the generation of thermal NO$_x$. On the other hand, the air-staged combustion makes the excess air coefficient of the cyclone burner area less than 1, and the reduction reaction between CO produced by incomplete combustion of pulverized coal and NO$_x$ occurs, reducing the NO$_x$ concentration.

Figure 21 shows the distribution of the NO$_x$ concentration at the outlet of the furnace and the efficiency of NO$_x$ reduction in the furnace under different conditions. As can be observed, the larger the over-fire air rate is, the lower the average NO$_x$ concentration is at the outlet of the furnace. When the over-fire air rate is 15%, the NO$_x$ concentration at the outlet of the furnace is $519.86$ mg/m$^3$, which is 26% lower than the original condition. This occurs because the increase in the over-fire air rate can reduce the temperature in the furnace, and thus the NO$_x$ concentration decreases. It can be known from Figure 19 that the temperature of the slag chamber area is 1604.9 K under the condition of an over-fire air rate of 15%. However, considering the particularity of the boiler with slag-tap furnace, it must be ensured that the wall temperature of the slag chamber is higher than the flow temperature of the pulverized coal in the actual process so that the slag is in a flowing state. It can be seen from the figure that, at the position of 0 m on the abscissa of the lowest part of the slag chamber, the flue gas temperature under the case of OFA = 15% is 1492 K, which is lower than the flow temperature of pulverized coal, 1523 K, and the flue gas under the case of OFA = 10% is 1530 K, which is higher than the flow temperature of pulverized coal. Therefore, the optimal over-fire air rate is determined to be 10%.

5. CONCLUSIONS

(1) The structure of the new cyclone boiler with slag-tap furnace was designed well, the combustion in the furnace was stable, and the fullness of the flue gas was good. The average temperature in the cyclone burner is higher than the fluidization temperature of the high-alkali coal, which ensures the formation of liquid ash. A large range of recirculation zones appeared above the burnout chamber because of the staggered reverse arrangement of the cyclone burners, which strengthened the disturbance of the pulverized coal and strengthened the heat and mass transfer inside the boiler. The calculation results provide theoretical guidance for the design, manufacture, application, and promotion of cyclone boilers with slag-tap furnace burning pure high-alkali coal.

(2) Pulverized coal can be burned stably in the cyclone burner under the conditions of various over-fire air rates. Along the direction of the flue gas flow, the average temperature of the furnace section increases first and then decreases; next, it increases then decreases and finally stabilizes. The average temperature at the outlet section of the furnace is 1358 K. The mass fraction of O$_2$ gradually decreases, and the mass fraction of CO increases first then decreases and then remains stable. The mass fraction of CO$_2$ gradually increases, and the NO$_x$ concentration increases first then decreases and tends to stabilize after the superheater. The NO$_x$ concentration at the furnace outlet is approximately 704.14 mg/m$^3$.

(3) The low NO$_x$ technology that is air-staged can effectively reduce the generation and emission of NO$_x$ in the cyclone boiler with slag-tap furnace. The greater the over-fire air rate is, the lower the average temperature is in the furnace, the higher the remaining O$_2$ mass fraction is in the furnace, the lower are the generated CO and CO$_2$ mass fractions, and the lower the NO$_x$ concentration is at the outlet of the furnace. When the over-fire air rate is increased from 0 to 15%, the NO$_x$ concentration at the outlet of the furnace decreases from 704.14 to $519.86$ mg/m$^3$, and the efficiency of NO$_x$ reduction in the furnace increases from 0 to 26%. Considering that it is not easy to fluidize the ash of high-alkali coal when the average temperature in the cyclone boiler with slag-tap furnace is excessively low, the over-fire air rate of 10% is selected as the optimal scheme of air-staged combustion.

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REFERENCES

(1) Yang, S.; Song, G.; Na, Y.; Yang, Z. Alkali metal transformation and ash deposition performance of high alkali content Zhundong coal and its gasification fly ash under circulating fluidized bed combustion. Appl. Therm. Eng. 2018, 141, 29–41.

(2) Matsuo, K.; Yamashita, T.; Kuramoto, K.; Suzuki, Y.; Takaya, A.; Tomita, A. Transformation of alkali and alkaline earth metals in low rank coal during gasification. Fuel 2008, 87, 885–893.

(3) Fernandez-Turiel, J.-L.; Georgakopoulos, A.; Gimeno, D.; Papastergios, G.; Kolovos, N. Ash Deposition in a Pulverized Coal-Fired Power Plant after High-Calcium Lignite Combustion. Energy Fuels 2004, 18, 1512–1518.

(4) Li, G.; Li, S.; Huang, Q.; Yao, Q. Fine particulate formation and ash deposition during pulsed air coal combustion of high-sodium lignite in a down-fired furnace. Fuel 2015, 143, 430–437.

(5) Liu, C.; Liu, Z.; Zhang, T.; Huang, X.; Guo, J.; Zheng, C. Numerical Investigation on Development of Initial Ash Deposition Layer for a High-Alkali Coal. Energy Fuels 2017, 31, 2596–2606.

(6) Chudnovsky, B.; Talanker, A.; Berman, Y.; Saveliev, R.; Perelman, M.; Korytny, E.; Davidson, B.; Bar-Ziv, E. Prediction of Performance From PRB Coal Fired in Utility Boilers With Various Furnace and Firing System Arrangements. J. Eng. Gas Turbines Power 2010, 132, 27–34.

(7) Syred, C.; Fick, W.; Griffiths, A. J.; Syred, N. Cyclone gasifier and cyclone combustor for the use of biomass derived gas in the operation of a small gas turbine in cogeneration plants. Fuel 2004, 83, 2381–2392.

(8) Zarzycki, R.; Jedras, J.; Kobylecki, R. Gasification of Coal Dust in a Cyclone Furnace in an O2/H2O Atmosphere. Energies 2020, 13, 2253.

(9) Alam, M. S.; Wijayanta, A. T.; Nakaso, K.; Fukai, J. Study on coal gasification with soot formation in two-stage entrained-flow gasifier. Int. J. Energy Environ. Eng. 2015, 255.

(10) Zarzycki, R.; Bis, Z. Modelling of the Process of Coal Dust Combustion in a Cyclone Furnace. J. Therm. Sci. 2017, 26, 192–198.

(11) Carson, W. R. T. Cofiring coal-water slurry in cyclone boilers: Some combustion issues and considerations. Fuel Energy Abstr. 1997, 38, 331–332.

(12) Yi, Q.; Qi, F.; Xiao, B.; Hu, Z.; Liu, S. Co-Firing Ramie Residue with Supplementary Coal in a Cyclone Furnace. BioResources 2012, 8, 844.

(13) Yoon, M.-J.; Lee, B.-H.; Song, J.-H.; Kim, G.-B.; Chang, Y.-J.; Jeon, C.-H. Numerical Study of the Optimization of Combustion and Emission Characteristics of Air-Staged Combustion in a Pulverized Coal-Fired Boiler. Trans. Korean Soc. Mech. Eng. B 2010, 34, 587–597.

(14) Gu, M.; Wang, M.; Chen, X.; Wang, J.; Lin, Y.; Chu, H. Numerical study on the effect of separated over-fire air ratio on combustion characteristics and NOx emission in a 1000 MW supercritical CO2 boiler. Energy 2019, 175, 593–603.

(15) Wang, W.; Liao, Y.; Liu, J.; Huang, Z.; Tian, M. Numerical Simulation and Optimization of Staged Combustion and NOx Release Characteristics in Pre-calcliner. J. Therm. Sci. 2019, 28, 1024–1034.

(16) Huang, L.; Li, Z.; Sun, R.; Zhou, J. Numerical study on the effect of the Over-Fire-Air to the air flow and coal combustion in a 670 t/h wall-fired boiler. Fuel Process. Technol. 2006, 87, 363–371.

(17) Bai, T.; Sun, B.; Guo, Y.; Kang, Z. Effects of Tertiary Air Staged Combustion on NOx Emission Characteristic in a Pulverized-Coal Boiler with Swirl Burner. Adv. Electr. Electron. 2012, 155, 255–263.

(18) Kuang, M.; Li, Z.; Wang, Z.; Jing, X.; Liu, C.; Zhu, Q.; Ling, Z. Combustion and NOx emission characteristics with respect to staged-air damper opening in a 600 MW down-fired pulverized-coal furnace under deep-air-staging conditions. Environ. Sci. Technol. 2014, 48, 837–844.

(19) Orszag, S. A.; Yakhot, V.; Flannery, W. S.; Boysan, F.; Choudhury, D.; Maruwzewski, J.; Patel, B. Renormalization Group Modeling and Turbulence Simulations. In International Conference on Near-Wall Turbulent Flows; Tempe, Arizona, 1993.

(20) Cheng, P. Two-dimensional radiating gas flow by a moment method. AIAA J. 1964, 2, 1662–1664.

(21) Siegel, R.; Howell, J. R. Thermal Radiation Heat Transfer; Hemisphere Publishing Corporation: Washington DC, 1992.

(22) Miller, R.; Davis, G.; Lavoie, G.; Newman, C. A Super-Extended Zel’dovich Mechanism for NOx Modeling and Engine Calibration. SAE Trans. 1998, 1090–1100.

(23) Fenimore, C. P. Formation of Nitric Oxide in Premixed Hydrocarbon Flames. Symp. (Int.) Combust. 1971, 13, 373–380.

(24) Smoot, L. D.; Smith, P. J. NOx Pollutant Formation in Turbulent Coal Systems. Coal Combustion and Gasification; Springer: 1983, 548, DOI: 10.1007/978-1-4757-9721-3_15.

(25) Lockwood, F. C.; Romo-Millanes, C. A. Mathematical modelling of fuel-NO emissions from PF burners. J. Inst. Energy 1992, 65, 144–152.