Numerical Simulation of Oxy-Fuel Combustion of Predrying Lignite

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Abstract. In this paper, the combustion characteristics of lignite with different levels of predrying and the influence of different oxy-fuel concentration on the combustion characteristics of pulverized coal are studied with CFD software. The results show that with the increase of lignite moisture content, the temperature level in the burner decreases gradually, which affects the ignition of pulverized coal and the thermal efficiency of the furnace, and the amount of NO and intermediate products in the furnace also decreases. The flame distance of pulverized coal in oxy-fuel combustion is shortened and the combustion rate is accelerated. The ignition temperature and the production of NO and SO₂ are reduced, and the concentration of CO₂ can reach more than 90%. The local high temperature will appear in oxy-fuel combustion, and it will increase as the oxygen concentration increases, and the temperature of surrounding flue gas will become more uniform.

1. Introduction
At present, lignite plays an important role in the process of replacing the increasingly exhausted high-quality coal resources. The stable supply capacity and low cost of coal are very important for global economic development [1]. For a long time, the "three high and two low" characteristics of lignite have restricted its utilization. The development and utilization level of lignite in China is not very high, and the technical data are not comprehensive. It is still necessary to have intensive study on the structure, performance and combustion of lignite.

Oxy-fuel combustion technology is considered as a new clean coal combustion method, which can control the emission of coal-fired pollutants in power plants and industrial boilers. Because of the advantages of oxy-fuel combustion technology in many aspects, it is called "resource creative technology" by some developed countries [2]. Buhre et al. [3] analyzed the technical and economic feasibility of oxy-fuel combustion process, and introduced several oxy-fuel combustion processes studies by different research institutions around the world. In Australia, this technology is used to store
the separated CO₂ in the direct transformation of existing coal power plants [4]. In China, the application of oxy-fuel combustion technology in industrial furnaces is becoming more and more mature. Predrying lignite coal-fired power generation system can solve various problems caused by High Moisture Lignite combustion. At present, this technology is lack of case application and has many problems [5].

In this paper, the combustion characteristics of lignite with different drying degrees in air and different oxy fuel concentrations are studied. Firstly, the combustion of lignite in a single burner is simulated, and the influence of different water content of lignite on combustion is compared; secondly, the influence of water content of lignite and different oxy fuel concentration on lignite combustion in a full-scale boiler is studied. Through the above simulation work, the combustion theory and numerical simulation can be well combined to explore the combustion characteristics of lignite, in order to reduce the emission of pollutants in the combustion process, and also provide theoretical support for the optimal design and reasonable operation of the boiler.

2. Research object

2.1. Geometric model

2.1.1. Geometry model of single burner
The geometric model of a single burner is shown in Figure 1, including the secondary air flow of the outermost concentric opening, the coal of the inner concentric ring and the primary air feed port.

![Figure 1. Burner inlet structure](image1)

2.1.2. Swirl burner and furnace structure
The structures of swirl burner and furnace are shown in Figure 2. The burner is composed of internal primary air channel and external swirl secondary air channel. The primary air carries the pulverized coal and the secondary air to mix and burn at the flare. The main parameters of the burner are: 2.5MWe furnace, the axial wind speed of primary and secondary air is 28m / s and 32m / s respectively (selected by the design manual), and the temperatures of primary and secondary air are 340K and 570K respectively.

![Figure 2. Swirl burner furnace structure diagram](image2)

2.1.3. 30MWe boiler model
The low calorific value of lignite is 13710 kJ / kg, the excess air coefficient is set as 1.2, and the calculated fuel consumption is 7.18 kg / s. The boiler is 6200mm wide, 6800mm deep and 22500mm high. The angle of ceiling is 8 degrees, the angle of folding flame is 45 degrees, and the angle of ash
hopper is 53.24 degrees. The horizontal spacing of burners is 2200mm, and the vertical spacing is 2300mm. The array arrangement is conducted in the horizontal and vertical directions. Boiler furnace structure is shown as Figure 3.

Figure 3. Boiler furnace structure diagram

2.2. Mesh generation

Figure 4 shows a schematic diagram of the burner furnace grid.

Figure 4. The grid schematic of the burner

The grid division of the boiler is more complicated than that of a single burner. Because the size of the boiler is large, and it is very different from that of the burner.

Figure 5 shows that the number of grids divided by burners is large, accounting for 60% of the total grid of the whole boiler. The grid quality at the corner of the flame is more important. The inclination of the grid can be effectively improved by changing the type of points on the surface at the corner of the flame, that is, changing the default S-type point to C-type or R-type point. Through these measures, the grid density, grid precision, grid direction and flow direction orthogonality are effectively improved.
3. Model setting
The governing equations used in numerical simulation include: energy equation, mass equation, momentum equation and component equilibrium equation. The first-order scheme is used for initial value calculation, then the second-order upwind scheme is used for the convection interpolation (momentum equation). The Green-Gauss element based interpolation method is selected for the gradient interpolation of diffusion term. The PRESTO (pressure stacking option scheme) pressure interpolation which can accurately capture the characteristics of high swirling flow is selected because of the study of the circular strong swirling jet in this paper [6]. Gas phase turbulent flow model using Realizable k-ε model. The radiation selects the P-1 radiation model which considers the heat exchange of gas phase and particle phase simultaneously. The gas-phase turbulent combustion selects the general EBU (vortex breaking) model under the limited speed, under which the thermal calculation of the material parameters of the pulverized coal studied and the setting of the gas-phase reaction formula are carried out by using the coal calculator. A one-step gas-phase reaction model is set up in the panel, and the volatiles directly generate CO2. There is NO intermediate product such as CO. The reaction rate can be obtained by means of Arrhenius (Eddy Dissipation Concept Model). The particle phase flow is based on the random orbit model. The char combustion is based on the dynamic / diffusion control combustion model.

4. Simulation results and analysis

4.1. Thermal simulation in a single burner
The combustion of coal particles needs to be heated first to promote the evaporation of water, which has an important influence on the combustion process of lignite powder. In this paper, lignite with different water content and the combustion field in the furnace is studied. The simulation results of 0%, 20% and 40% conditions are given respectively.

Figure 6. The temperature and emissions under different water along the furnace axis
Figure 6 (a) shows the temperature value on the furnace center line under the water content of 0%, 20% and 40%. The combustion process of pulverized coal starts from the non-isothermal heating and drying stage, and then enters to the water balance evaporation stage [7]. Before the peak temperature, it is mainly in the stage of volatilization and ignition of pulverized coal. At 0.5m, the peak temperature appears, and the combustion flame of pulverized coal closes here, and then the combustion is mainly coke combustion. With the increase of water content, the temperature values under the corresponding three kinds of water at the same location are very different. This is mainly because water heating and evaporation need to absorb the heat in the furnace, and the volatile matter needs to be separated after most of the water evaporates. It can be seen that lignite moisture has a significant adverse effect on furnace temperature and furnace efficiency. The specific performance is that the increase of water content will affect the ignition and combustion of coal. The temperature of furnace will decrease and the thermal efficiency will be reduced.

Figure 6 (b), (c) and (d) show the influence of moisture on pollutant components in the furnace. NOx is the main gas pollutant in the process of coal combustion. At the beginning of pulverized coal combustion, devolatilization is the first step, and the nitrogen combined in some form in volatiles is also released. The released products include HCN, NH, NHZ, NH₃ and CN, mainly NH₃ and HCN, respectively corresponding to Figure 6 (b) and Figure 6 (c). It can be seen from the three diagrams that the peak value of NH₃ and HCN corresponds to the low peak value of NO in Figure 6 (d), which is mainly due to the intermediate product of NO generated in this stage. It can also be seen from the three diagrams that the amount of HCN generated is higher than that of NH₃, so the concentration of NO emission will be mainly affected by the concentration of HCN. With the increase of temperature, the formation rate of NO increased rapidly, the intermediate products of NH₃ and HCN consumed rapidly, and reached the peak value of NO at 0.5m. The main factors affecting the formation of NO are the amount of volatile intermediate products, while the main factors affecting the formation of HCN and NH₃ are temperature, pressure, particle size, heating rate, residence time, reactor type and coal type. With the increase of water content, the level of NOx pollutant decreases, which is mainly due to the decrease of furnace temperature, and directly leads to the decrease of furnace thermal efficiency.

4.2. Thermal simulation in boiler

4.2.1. Influence of water content on combustion of pulverized coal boiler

The economic impact of wet pulverized coal combustion with different water content on boiler operation, and what measures can be taken to reduce or eliminate these effects? In this paper, the boiler with 0%, 20% and 40% external moisture is set up for combustion, and the coal type is Indonesian lignite.

Figure 7. Temperature of furnace vertical section contour map under different water, K
Figure 7 is a cloud chart of temperature isoline of section z = -1100mm (vertical section of a certain burner). It can be seen from the figure that the temperature field decreases with the increase of water content. The highest temperature corresponding to the three kinds of water is 1800K, 1600K and 1500K respectively, and the corresponding temperature at the outlet is 1300K, 1200K and 1100K. Because of the existence of the bending angle, the combustion condition in the furnace is improved and the flame fullness of the whole furnace is good, which is also related to the simulation of the aerodynamic field of the furnace in the early stage. With the increase of water content, the high temperature region shrinks. It is also known from the figure that moisture has a great influence on the early and middle stages of combustion, and the latter stage is mainly the combustion of coke. Moisture enters the equilibrium evaporation stage, and the temperature gradient gradually decreases. It can also be clearly observed that the combustion condition of the upper burner is the best, which is mainly because the incomplete carbon particles in the lower combustion mix with the air in the upper layer again with the rise of hot flue gas, so the combustion is more sufficient. It can also be seen in the figure that the flame of each layer of burner moves up from the axis, which is caused by the small density of hot gas and large buoyancy.

![Temperature Chart](image1)

![NH₃ Mass Fraction Chart](image2)

![HCN Mass Fraction Chart](image3)

![NO Mass Fraction Chart](image4)

**Figure 8.** Temperature and pollutant levels on the axis of a burner under different water

The residence time of fuel in the power combustion device is very short. Under various conditions, not only the combustion reaction and heat release should be completed in the combustion chamber, but also the generation of combustion related pollutants should be restrained. Figure 8 shows the temperature and pollutant level on the axis of a burner of the boiler. It can be seen from the figure that with the increase of water content, the average level of temperature field in the whole range decreases. The decrease of temperature affects ignition in the early stage, gas combustion in the middle stage and coke combustion in the later stage. With the increase of water content, the amount of NO pollution in the furnace decreases gradually, and NO production is still dominated by the intermediate HCN, which is sensitive to temperature. The temperature and pollutant distribution trend of the whole boiler furnace in the figure are slightly different from the simulation results of the single burner in the early stage,
which due to the complex condition of the boiler, but basically consistent. Compared with the effect of 0% and 20% moisture on the boiler furnace, the effect of 40% moisture on the furnace has a weakening trend.

4.2.2. Influence of oxygen enrichment on combustion of pulverized coal boiler

In this section, the air combustion and oxy-fuel combustion with the same concentration of oxygen are compared first, and the combustion of pulverized coal under different oxygen concentration is compared at the same time. The temperature distribution and pollutant concentration distribution in the furnace of pulverized coal boiler are obtained.

Figure 9. Temperature of furnace vertical section under air and oxy-fuel combustion, K

Figure 9 shows the temperature isoline cloud diagram of the vertical section of furnace at $z = -1100$mm for air group and oxy-fuel group. It can be seen from the figure that the air and oxy-fuel combustion have similar temperature field distribution in the furnace, and the temperature field distribution is good, and the position of the highest temperature zone still deviates from the axis. The maximum temperature of air combustion is $1800K$, and the outlet flue gas temperature is $1300K$. It is obvious that when the air is changed to oxy-fuel combustion, the flame temperature of the top burner increases to $1900K$, and the position of high temperature flame is close to the middle of the furnace, and the combustion is relatively concentrated. Indicating that the flame of air combustion is relatively longer than that of oxy-fuel combustion, but the flue gas temperature around oxy-fuel combustion is higher. The temperature of flue gas around air combustion is 200 ~ 300K lower than that around oxy-fuel combustion, which is mainly due to the change of heat carrier under the condition of air and oxygen enrichment. Compared with $N_2$ in the air, $CO_2$ belongs to the triatomic gas, its specific heat capacity is larger than $N_2$, and the heat exchange with the surrounding flow medium will be less than $N_2$, which has a certain role in cooling the surrounding flue gas. At the same time, the radiation capacity of $CO_2$ is stronger than that of $N_2$, and the surrounding flue gas temperature is relatively uniform compared with $N_2$.

It can be seen from Figure 10 (a) that the peak band of oxy-fuel combustion is narrow, the central flame temperature is slightly higher than the combustion temperature under air atmosphere, and the combustion is advanced. The overall average temperature is slightly lower than that of air combustion. It can also be seen that the temperature in the range of 0 m ~ 1 m in oxy-fuel atmosphere is lower than that of air in this area, indicating that oxy-fuel combustion can reduce the heat of ignition. Figure 10 (b) shows the generation of NO in the furnace. From the figure, the overall level of NO in the oxy-fuel atmosphere is lower than that in the air. There are three peaks of NO in the figure. The first low peak is the stage of volatilization in the early stage of coal combustion. The intermediate products of NO, NH$_3$ and HCN are mainly separated out. At this time, they are in the inner circulation area of air flow. Therefore, the amount of NO will decrease with the increase of temperature, the volatiles of pulverized
coal are burned, and the intermediate products are quickly consumed and converted into NO under the condition of high temperature with sufficient oxygen, and reach to the second peak value. After the flue gas leaves the combustion area, the NO concentration is diluted, and the trend is basically unchanged. NOx produced by combustion of oxy-fuel boiler mainly comes from fuel type NOx. Figure 10 (c) shows the SO₂ generation in the furnace. It can be seen from the figure that the SO₂ under oxy-fuel condition is lower than the level in air combustion. Under the condition of rich oxygen, the high concentration of CO₂ makes part of the elements transformed into cos product. Figure 10 (d) shows the CO₂ level under the condition of oxy-fuel combustion and air combustion. It can be seen from the figure that the amount of CO₂ generated by air combustion is about 15%, while the amount of CO₂ generated by oxy-fuel combustion can reach about 90%, which is conducive to CO₂ capture and compression. This is also a major feature of oxygen rich combustion.

![Figure 10](image)

Figure 10. The temperature, volatile and the levels of pollutants of one burner axis under air and oxy-fuel combustion

4.2.3. Effect of different oxy-fuel concentration on combustion of pulverized coal boiler

In order to further study the characteristics of oxy-fuel combustion, after comparing the air and oxy-fuel combustion, this paper also carried out a comparison under different oxygen concentration, respectively set 21%, 25% and 30% oxy-fuel concentration. See Fig. 3.7 for temperature contour map of vertical section in three cases.

It can be seen from Figure 11 that the temperature field distribution under the three working conditions is similar. The high temperature area is concentrated in the middle of the furnace, and the flame fullness is good. With the increase of O₂ concentration, the flame temperature and furnace temperature gradient gradually increase, indicating that the combustion in the middle of the furnace has been strengthened, and the maximum temperatures under the three conditions are 2300K, 2100K and 1900K respectively. If 1900K is taken as the base point, the flame temperature field along the burner axis shrinks to the burner mouth. It can be seen that the temperature fields of 1200K and 1300K expand...
to different degrees under the condition of 30% oxygen enrichment, indicating that the temperature distribution of oxygen increase tends to be more uniform.

Figure 11. Temperature of furnace vertical section under different oxy-fuel combustion, K

Figure 12 shows the temperature and pollutant levels on the axis of a burner in the boiler.

Figure 12 (a) shows again that with the increase of oxygen concentration, the combustion area moves forward, the temperature in the combustion center area is higher, and the combustion is accelerated. It can be seen from the figure that the increase of oxygen content has the greatest influence on the early
and middle stage of combustion. Figure 12 (b) shows that the trend of NO products is basically the same under different oxygen concentrations, and decreases with the increase of oxygen concentration. However, SO$_2$ in Figure 12 (c) rises with the increase of O$_2$ concentration. As the mechanism of SO$_2$ generation is still controversial, it will not be studied here. The CO$_2$ concentration in Figure 12 (d) reaches the peak value in the high temperature zone, then diffuses to all parts of the furnace and is diluted. With the increase of oxygen content, the CO$_2$ concentration decreases, but it can still reach more than 80%, which is more conducive to the compression and storage of CO$_2$.

5. Conclusion

5.1. Conclusion of thermal simulation in single burner furnace

The moisture content of lignite affects the whole coal combustion stage. In the early stage of combustion, water evaporates and absorbs heat, the devolatilization occurs subsequently, the ignition of pulverized coal is delayed, and in the middle and late stage of combustion, water enters into the equilibrium evaporation period, which affects the radiation heat transfer in the furnace and reduces the thermal efficiency; the water content of lignite reduces the temperature level in the furnace and the generation of NO pollutants.

5.2. Conclusion of combustion simulation in boiler

The influence of water content of lignite in boiler on combustion is consistent with the analysis of single burner. Compared with the influence of 20% and 0% water content on boiler furnace, the influence trend of 40% water content on each field of furnace is weakened. Compared with air and oxy-fuel combustion, oxy-fuel combustion shortens the flame distance, makes the flame more concentrated, accelerates fuel combustion, strengthens heat exchange efficiency, and improves the cycle. The combustion characteristics of pulverized coal in the boiler are changed by the CO$_2$ in the oxy-fuel atmosphere, and the ignition of pulverized coal is delayed. Under the oxy-fuel atmosphere, the local flame temperature of pulverized coal increases, and the local flame temperature increases as the oxygen content increases. The influence of oxy-fuel concentration on the combustion of pulverized coal in the early and middle stages is great, but in the later stage, the influence of oxy-fuel concentration is weakened, and the combustion tends to be stable. With the increase of oxygen concentration, the production of NO decreases, while the concentration of CO$_2$ decreases, but it can still reach more than 80%, which is far greater than the concentration of 15% in the air condition.

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