The Combustion Numerical Simulation of a Liquid Slag Pulverized Coal Burner in the High Temperature Secondary Air

Huaizhi Zhao¹,² and Jingfu Wang¹,²,*

¹MOE Key laboratory of Enhanced Heat Transfer and Energy Conservation, The Faculty of Environment and Life, Beijing University of Technology, Beijing, China
²Beijing Key Laboratory of Heat Transfer and Energy Conversion, The Faculty of Environment and Life, Beijing University of Technology, Beijing, China

*Corresponding author email: jfwang@bjut.edu.cn

Abstract. Taking a liquid slag pulverized coal burner as the research object, the combustion characteristics of the burner in different high temperature secondary air were simulated by Fluent commercial software, and the combustion characteristics of temperature field distribution and the change of component concentration were obtained. The simulation results show that the burner can form a front ignition zone, the air vortex low temperature zone, the central DC flame and the annular flame in the hot state. It can be found that increasing the secondary air temperature can improve the combustion intensity of the burner, promote the formation of CO, and form a high temperature reduction zone, which is conducive to inhibiting pollutant emissions. The research results provide theoretical support for the application of the burner in practice.

Keywords: Liquid slagging burner; Numerical simulation; Secondary air.

1. Introduction

China's energy structure is rich in coal, lack of oil and gas. Therefore it is crucial for the effective utilization of coal resources. At present, the serious gas pollution and poor energy utilization of coal have become important factors restricting the development of coal energy. In the 20th century, Wang et al. [1] proposed a pulverized coal combustion device with liquid slag discharge. It has the characteristics of high slag capture rate, high combustion efficiency, high volumetric thermal strength, low pollution and easy maintenance. However, due to the strong combustion process, it also has the safety problems caused by thermal corrosion and high NOx pollutant emissions, which limits the further development of this combustion device. With the development of science and technology, the shortcomings of the combustion device are gradually overcome, and the adaptability of the coal type of the combustion device is strong, which can effectively use some coal types with low volatile content and high ash content, so that its application is gradually strengthened, and it is back to everyone’s vision. In recent years, the high temperature air combustion technology, which is considered to be energy-saving, improve flame stability and reduce NOx emission, has been concerned and studied [2-5], and the high temperature is needed for liquid slag. In this paper, a liquid slag pulverized coal burner in high temperature secondary air is numerically simulated, which provides theoretical support for its practical application.

2. Physical Model and Meshing

A liquid slag pulverized coal burner discussed in this paper is improved on the basis of the design by...
Wang et al [1]. The structure diagram is shown in Figure 1. Cylinder length 1.2 m, diameter 0.48 m, outlet diameter 0.3 m, primary air inlet area $3.47 \times 10^{-3} m^2$, Secondary air area $9 \times 10^{-3} m^2$. The pulverized coal nozzle adopts axial swirl vane type, and the burner adopts tangential secondary air structure. The swirl direction of secondary air is consistent with the swirl nozzle.

![Figure 1. Structure diagram of burner and pulverized coal nozzle.](image)

The burner is applied structural mesh. Local mesh refinement was adopted near the primary and secondary air inlets. The overall mesh division is shown in Figure 2(a), and the mesh division of the axial swirl blade pulverized coal nozzle is shown in Figure 2(b). After mesh independence verification, it can be found that the outlet velocity is 21.56 $m/s$ when the number of grids is 1.13 million, and 21.58 $m/s$ when the number of grids is 1.43 million. Considering calculation accuracy and calculation speed, the total number of mesh is about 1.43 million.

![Figure 2. Mesh generation of burner.](image)

3. Mathematical Model and Calculation Conditions

3.1. Mathematical Model

Realizable k-ε turbulence model is more suitable for simulating strong swirling flow and is used in this paper [6]. Considering that the volume fraction of pulverized coal is small, the Euler-Lagrange method is selected in this paper. In the calculation of gas phase combustion, this paper adopts the PDF model which is widely used. The two-competing-rates model with more accurate calculation accuracy and less calculation is used to simulate the coal devolatilization process. The kinetic/diffusion limited model is applied to the coal combustion. This paper chooses the P-1 model which occupies less CPU resources to simulate the radiation heat transfer in the burner.

3.2. Calculation Conditions

In this paper, the amount of coal combustion is 180 kg/h, the excess air coefficient is 0.9, the ratio of primary air to secondary air is 0.2:0.8, and the swirl intensity of primary air is 1.24. The coal properties are shown in table 1.
Table 1. Coal property.

| Proximate analysis /% | Ultimate analysis /% | Net heating value (kJ/kg) |
|-----------------------|-----------------------|--------------------------|
| V_{ar} | A_{ar} | M_{ar} | FC_{ar} | C_{ar} | H_{ar} | O_{ar} | N_{ar} | S_{ar} | Q_{net,ar} |
| 32.04 | 8.27 | 2.30 | 57.39 | 73.92 | 4.37 | 9.92 | 0.91 | 0.31 | 28750 |

The velocity inlet boundary conditions are applied to both primary and secondary air inlets. Given the velocity values under different case, the velocity formula is shown in formula (1), where \( \alpha \) is the excess air coefficient, \( V^0 \) is the theoretical air requirement, \( B_g \) is coal consumption, \( \beta \) is the rate of air, \( T \) is the temperature of inlet and \( A \) is the area of inlet. In this paper, the primary air temperature is set to 323k, the corresponding velocity is 22.74 m/s. Secondary air temperature takes into account 573k, 700k, 800k and 900k in four cases, the corresponding speed values are: 25.68 m/s, 31.38 m/s, 35.86 m/s and 40.34 m/s. Pressure-outlet boundary are applied to outlet. The wall is set to a stationary wall, using standard wall function.

\[
v = \frac{\alpha V^0 B_g \beta T}{3600 A 273}
\] (1)

4. Results and Discussion

In this section, the effect of high temperature secondary air on temperature field and combustion characteristics of liquid slag pulverized coal burner are analyzed. The results show that increasing the secondary air temperature can improve the combustion efficiency and intensity of pulverized coal. The distribution of component concentration is also analyzed. It is pointed out that a high temperature reducing atmosphere can be created when the secondary air temperature is high.

4.1. Temperature Field Distribution of Burner

Figure 3 shows the temperature distribution in the combustor under different secondary air temperatures. It can be found that the temperature distribution in the combustion chamber at different secondary air temperatures is basically similar, and form the ignition zone in the front zone, the low temperature zone of the air vortex, the central DC flame and the annular flame in the rear zone. A little different is that with the increase of the secondary air temperature, the area of the low temperature zone of the air vortex decreases obviously, and the ignition zone becomes asymmetric distribution. This is because as the temperature of the secondary air increases, the temperature in the combustion chamber increases, which causes the air to heat and expand, resulting in a decrease in the low temperature area of the air vortex, and asymmetrical distribution of the ignition area in the front area.

Figure 3. Temperature distribution contour of combustion chamber.
4.2. Effect of Secondary Air Temperature on Combustion Characteristics

In this paper, the PDF model is used to simulate the combustion process of pulverized coal, so the combustion intensity and characteristics inside the burner can be reflected by Mean Mixture Fraction [7]. Figure 4 shows the distribution of axial mean mixing fraction of combustion chamber under different secondary air temperatures. It can be found from Figure 4 that as the secondary air temperature increases, the mean mixture fraction in the combustion chamber shows an overall increase trend, which is because the increase in the temperature of the secondary air promotes the combustion process of pulverized coal. Especially in the rear area of the combustion chamber, the increase in the temperature of the secondary air greatly promotes the combustion of coal and increases the intensity of combustion. This can also be demonstrated by the axial temperature distribution in Figure 5. It can be found that as the temperature of the secondary air increases, the axial temperature in the combustion chamber increases, indicating that the degree of pulverized coal combustion has been strengthened. In addition to the above findings, it can be found that when the secondary air temperature is 573K, the combustion intensity and combustion temperature near 0.2 m in the combustion chamber are higher than other secondary air temperatures. This is because the area of the air vortex low temperature zone formed in the front area is larger than that in other conditions (As shown in Figure 3), and the existence of these recirculation zones entrainment more high temperature flue gas, which makes promote volatilization and combustion, and makes the coal combustion more intense. However, when the secondary air temperature is higher than 800K, the mean mixture fraction is almost unchanged, because the pulverized coal is almost burned out at such a high temperature. So we can know that the highest combustion intensity and efficiency can be achieved in the combustion chamber when the secondary air temperature is about 800K - 900K.

4.3. Effect of Secondary Air Temperature on Component Concentration

Figure 6 shows the changes in the mole fraction of CO and CO2 in the combustion chamber at different secondary air temperatures. It can be found that as the temperature of the secondary air increases, the mole fraction of CO increases along the axial direction, which is consistent with the conclusion obtained by Wang et al[8]. The reduction reaction is mainly formed in the high temperature region, and the residual carbon and CO2 in the combustion chamber are reduced, generate more CO. This shows that as the secondary air temperature increases, the CO mole fraction increases and the CO2 mole fraction decreases. The large amount of CO generated in the combustion chamber has a strong reducibility, and CO is easier to reduce NOx at high temperatures [9,10], which can reduce the NOx generated during the combustion of pulverized coal. Therefore, it can be inferred that increasing the secondary air temperature can reduce NOx emission.
5. Conclusions
In this paper, the steady state numerical simulation of a liquid slag burner under high temperature secondary air is carried out. The combustion characteristics and component concentration distribution in the burner are obtained. The main conclusions are as follows:

(1) The temperature field of burner can be divided into four zones: ignition zone in front zone, low temperature zone of air vortex, central DC flame and annular flame in rear zone. As the temperature of the secondary air increases, the low temperature area of the air vortex becomes smaller, and due to the thermal expansion of the air in the combustion chamber, it presents an asymmetric distribution.

(2) As the temperature of the secondary air increases, the combustion intensity of the burner increases. In addition, it can also be found that as the temperature of the secondary air increases, the CO content during the combustion process can increase, which is beneficial to control the generation of NOx pollutants. When the secondary air temperature is higher than 800K, the pulverized coal is almost completely burned, and the combustion intensity cannot be improved by increasing the temperature. Therefore, it is recommended that the secondary air temperature of the burner in actual use should be between 800 and 900K.

References
[1] Wang Jf., et al., Study on liquid slag pulverized coal combustion device [J]. Metallurgical energy, 1992(03):19-23.
[2] Zhang Z., et al., Effect of H2O/CO2 mixture on heat transfer characteristics of pulverized coal MILD-oxy combustion. Fuel Processing Technology, 2019. 184: p. 27-35.
[3] Kuang Yc., et al., Effects of oxygen concentration and inlet velocity on pulverized coal MILD combustion[J]. Energy,2020,198.
[4] Yang J., et al., Overview of key technologies of high temperature air combustion (HTAC) [J], City gas, 2019(05):9-12.
[5] Zhang, H., et al., Development of high temperature air combustion technology in pulverized fossil fuel fired boilers. Proceedings of the Combustion Institute, 2007. 31(2): p. 2779-2785.
[6] Sun Xx.et al., Pulverized coal boiler combustion test technology and method [M], Beijing: China Electric Power Publishing House, 2002.
[7] Liu Yl. Reserach on the Near-Wall Burning and Flowing Characteristics of Solid Particulate fuel Swirl Conditions [D]. Nanjing University of Aeronautics and Astronautics, 2016.
[8] Wang Ch. et al., Research on High-Temperature Air Combustion of Pulverized Coal Boiler [J]. Industrial Furnace,2014,36(01):17-20+24.
[9] Zhou Cy. et al., Mechanism analysis on the pulverized coal combustion flame stability and NOx emission in a swirl burner with deep air staging[J]. Journal of the Energy Institute,2018,92(2).
[10] Wang S, et al., Experimental and kinetic study on the transformation of coal nitrogen in the preheating stage of preheating-combustion coupling process [J]. Fuel, 2020, 275.