Combustion Simulation of 130KW Large Cylinder Natural Gas Heater with Intermediate Heat Carrier Medium

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Abstract: In order to study the combustion temperature distribution of the fire tube and flue tube of the large cylinder natural gas heater with intermediate heat carrier medium, and to select a more appropriate combustion method, this paper separately simulates two kinds of combustion methods: premixed combustion and diffusion combustion. Using a standard turbulence model to describe the turbulent conditions of the flue gas, the turbulent diffusion combustion model and the vortex crushing model were used to simulate the diffusion combustion and the premixed combustion respectively. The results show that this structural model is more suitable for the diffusion combustion method.

1. Introduction:
In recent years, with the adjustment of China's energy structure and the increasing environmental pressure on coal consumption and utilization, the consumption of clean natural gas, as a reliable source of energy, has increased significantly. China’s natural gas consumption exceeded 200 billion cubic meters in 2016[1]. Natural gas is often heated during mining, transportation and application. Because natural gas contains hydrates, heating is required during long distance transportation to prevent the hydrates from condensing and solidifying due to the low temperature of natural gas, thereby blocking the pipeline equipment and causing accidents. In addition, in the natural gas application process, decompress is often required, and when the pressure drop is large, the temperature drop of the natural gas is too large and the heating is also required. Moreover, due to the need of the process, natural gas is required to maintain a certain temperature, heating is required. Therefore, heating equipment is often installed in the natural gas decompression system and the gas supply system[2,3]. However, as the main equipment for the transmission and distribution of natural gas, the natural gas heater has many defects such as huge structure, low thermal efficiency and large metal consumption, and it is urgently needed to improvement and optimization[4]. Therefore, in this paper, a more accurate and physically fitted physical model is used for the fire tube and flue tube part, numerical simulation of the fire tube and flue tube of natural gas heater, analyze the temperature distribution and pollutant emission concentration when using different fuel delivery methods[5,6].

2. Structure of large cylinder gas heater with intermediate heat carrier medium
Large cylinder natural gas heater with intermediate heat carrier medium is mainly used for heating, gasification and decompression of natural gas. Its structure is shown in Figure 1. The fuel and air enter the burner to burn and generate heat and high temperature flue gas. The heat in the fire tube and the flue tube is transmitted to the natural gas in the convection tube bundle through the intermediate heat carrier medium. The heat of exhaust gas is absorbed and the low temperature exhaust gas is discharged
through the chimney[7,8].

![Figure 1. Schematic diagram of the heating furnace of a medium-sized heating medium with a large cylinder 1-burner; 2-fire tube; 3-tube; 4、 5-convection tube bundle; 6-chimney]

The mixture way of fuel and air plays an crucial role in the fuel's combustion efficiency, and different mixing methods will also affect the emission of NOx and other pollutants. At present, gas-fired field heating furnaces mostly use fuel gas and air to be sent separately and premixed into two methods[9]. The combustion of the fuel gas and air to be sent separately is also referred to as diffusion combustion, combustion of gas fuel and air mixed by a mixer in front of the burner and then sent into is called premixed combustion.

3. Model establishment

3.1 Geometric model
This paper will make proper structural simplification for the flue tube and fire tube, use SolidWorks to establish it's physical model. As shown in Figure 2, the flue tube bundle consists of 24 tubes of 42 mm in diameter, the spacing between the tubes is 68 mm. The diameter of the fire tube is 325mm, and the length of the fire tube is 3m. In this paper, 16 measurement points are set on the axis of the flue tube and the fire tube to measure the simulation result data. The distance between two measuring points is 500mm, and set more measuring points in the bend section of the fire tube. The location of measuring points are shown in Figure 2.

![Figure 2. Three dimensional model of flue tube and fire tube and distribution of measuring points]

3.2 Solution Model

3.2.1 Turbulence flow model
Fuel gas and air have high gas flow rates in the furnace, and the chemical reactions produced by the combustion are intense and rapid. The flow of high temperature flue gas generated in the tube is turbulent[11]. The study will use a standard $k-\varepsilon$ two equation model, and the turbulent energy equation can be expressed as Equation 1:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_j k)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + \mu_t \left(\frac{\partial u_j}{\partial x_i}\frac{\partial u_i}{\partial x_j} + \frac{\partial u_i}{\partial x_j}\frac{\partial u_j}{\partial x_i}\right) - \rho\varepsilon$$  \hspace{1cm} (1)

The turbulent energy dissipation rate equation is shown in Equation 2:
\[
\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_g} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \frac{C_1 \varepsilon}{k} \mu_t \frac{\partial u_i}{\partial x_j} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_j} \right) - C_2 \rho \frac{\varepsilon^2}{k}
\] (2)

Among them, \( \mu_t = \rho C_{\mu} \frac{k^2}{\varepsilon} \) is turbulent viscosity, \( \mu \) is average speed, and \( k = \frac{u_i u_j}{2} \frac{u_i^2 + v^2 + w^2}{3} \) is turbulent pulsating kinetic energy. The value of the \( C_1, C_2, C_{\mu}, \sigma_s, \sigma_s \) use recommended experience constant of Launder and Spalding is \( C_1 = 1.44, C_2 = 1.92, C_{\mu} = 0.09, \sigma_s = 1.0 \) \( \sigma_s = 1.3 \).

3.2.2 Turbulent combustion model

This article will study two hybrid methods, and therefore will also use different turbulent combustion mode. A turbulent diffusion combustion model \((k - e - g)\) will be used for the diffusion combustion mode and a turbulent premixed flame combustion rate model \((\text{vortex shedding EBU})\) for the premixed combustion mode.

3.3 Boundary conditions

Natural gas is used as the fuel gas for large cylinder natural gas heater with intermediate heat carrier medium, and its composition is shown in Table 1. The load of the natural gas heater studied here is 130 Kw, and the low calorific value of methane is 42045.6 KJ/Kg. Therefore, the fuel mass flow rate at the burner inlet is 0.0031 Kg/s. The ratio of the theoretical air quantity to the fuel quantity is 14.56, the mass flow rate of the burner inlet air is 0.045 Kg/s, the excess air coefficient is set to 1.2, and the actual air mass flow rate at the burner inlet is 0.054 Kg/s.

| Components | CO₂ | CH₄ | C₂H₆ | C₃H₈ | C₄H₁₀ |
|------------|-----|-----|------|------|-------|
| The mass fraction/% | 0.71 | 89.2 | 3.46 | 2.48 | 3.89 |

4. Calculation results and analysis

This paper uses ICEM software to establish unstructured grids for physical models of fuel-air supply methods. By grid-independent verification, the number of grids is 2,256,325.

4.1 Temperature field analysis

As shown in Figure 3 and Figure 4, the temperature cloud diagrams of diffusion combustion and premixed combustion on \( Y = -0.255 \) cross section, respectively. It can be seen that the premixed combustion can achieve a higher temperature, the highest temperature and the lowest temperature are higher than the diffusion combustion temperature by 300K. Because the fire diameter is smaller than the flame diameter, the first half of the fire tube is in the flame area and the temperature is low. For diffusion combustion, the flame diffusion area is large.

Figure 3. Cloud diagram of premixed combustion temperature at \( Y=-0.255 \) m

Figure 4. Cloud diagram of diffusion combustion temperature at \( Y=-0.255 \)
4.2 Material concentration distribution

4.2.1 Analysis of CO concentration distribution
As shown in Figure 5 and Figure 6, the CO mass fraction cloud diagrams of diffusion combustion and premixed combustion on Y = -0.255 cross section, respectively. CO as combustion product of can reflect the degree of complete combustion of methane. It can be seen from Figure 6 that for diffusion combustion CO is mainly generated near the flame. It can be seen from Figure 5 that for the premixed combustion, the CO concentration is higher at the outlet of the flue tube and the upper in the junction of the fire tube and the flue tube, it is mainly due to the fact that the premixed combustion is performed more rapidly and the oxygen concentration in some areas is insufficient to cause incomplete combustion.

4.2.2 Analysis of NO concentration distribution
As shown in Figure 7 and Figure 8, the NO mass fraction cloud diagrams of diffusion combustion and premixed combustion on Y = -0.255 cross section, respectively. It can be seen that the concentration of NO generated by diffusion combustion is relatively high. The diffusion combustion flame spread area large and produces a lot of NO around the flame. The premixed combustion produces relatively small concentration of NO.

4.3 Measuring point data analysis
As shown in Figure 9, the NO and CO mass fractions of diffusion combustion and premixed combustion are respectively on the cross section Y = -0.255. It can be seen that the NO concentration is low at the inlet, and the NO concentration gradually increases with the combustion. After reaching a peak, it begins to decrease because NO reacts with O₂. However, due to the more intense of the reactions, the temperature is higher, the NO concentration gradually increases. At the same time, it can be seen that the NO concentration produced by premixed combustion is lower than the NO concentration produced by diffusion combustion. At the same time, it can be seen from Figure 10 that the CO concentrations differ little when using diffusive combustion and premixed combustion, respectively.

As shown in Figure 10, the temperature values of the measuring points when using the two combustion methods respectively, it can be seen that the diffusion combustion temperature in the fire tube is higher than the premixed combustion temperature, and the premixed combustion temperature in the flue tube is higher than the diffusion combustion temperature. The average temperature of the
diffusion combustion temperature is higher than the average temperature of the diffusion combustion temperature.

![Figure 9. The mass fraction of NO and CO at the measurement point on the Y=-0.255 cross section](image)

![Figure 10. The temperature at the measurement point on the Y=-0.255 cross section](image)

5. Conclusion
The premixed combustion can reach a higher temperature, but their has reflux at the outlet, burning rapidly, and the flame diameter is large, not suitable for smaller diameter space. At the same time, because of the extremely rapid combustion, resulting in a lack of oxygen concentration in some areas, combustion is not sufficient, so the CO concentration is high. In comparison, the diffusion combustion is relatively stable, but the combustion diffusion area is larger, and the resulting temperature is relatively low. The concentration of CO is relatively lower than the premixed combustion. Fuel combustion is sufficient, but NO concentration is higher, resulting in more serious environmental pollution. Because diffusion combustion is more efficient for fuel combustion, and the premixed combustion flame diameter is too large, leading to a lower temperature in front of the fire tube. Therefore, after comprehensive analysis, it is more appropriate to adopt a diffusion combustion method for this type of large cylinder natural gas heater with intermediate heat carrier medium.

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