Research Inside a Gas Heating Device with Different Heat Transfer Medium

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Abstract: Natural gas heating device occupies an important position in natural gas industry, and the most widely used one is the cylindrical heating device with heat transfer medium. The key factors affecting the thermal efficiency of the cylinder gas heating device with heat transfer medium are the type of heat transfer medium and the flow field organization. In order to study the influencing factors of thermal efficiency of the heating device, a visualized practical gas heating device experiment system was established, and a two-dimensional heat transfer model fitting the real object was established, too. The unstructured fitting mesh was used to divide the physical model, and the finite volume method was used for discrete solution, while discrete coordinate (DO) radiation model is used to solve radiation equation. In this paper, water and ethylene glycol are used as heat transfer media to simulate and measure the heat flow field in the cylinder. The results show that ethylene glycol can broaden the application range of gas heating device. Under the same experimental conditions, the heat efficiency of the heating device with ethylene glycol as heat transfer medium is at least 3.8% higher than that of the heating device with water as heat transfer medium. The thermal efficiency of gas heating devices is generally less than 87%.

1. Introduction
Gas heating device is an indispensable equipment in the application of natural gas. In the process of using natural gas, heating is often needed. For example, in gas-fired generating units, the process has a high requirement on the temperature of fuel gas, so the natural gas used in power plants must undergo heat treatment. LNG also needs to be heated in the gasification process [1]. Therefore, it is of great significance to design and manufacture gas heating devices with high efficiency and energy saving.

2. Characteristic and experimental system of gas heating device
The structure of gas heating device is shown in figure 1(a). Fire tube and flue tube bundle are filled with flame and smoke from fuel combustion. The convective tube bundle is filled with natural gas to be heated. The intermediate heat transfer medium fills the inner space of the whole cylinder, and transfers the heat generated in the fire tube and flue tube bundle to the natural gas in the convective tube bundle to complete the heating process of natural gas. In this process, the type of heat transfer medium and its flow field organization are the key factors affecting the thermal efficiency of gas heating device [2]. At present, water and ethylene glycol are the main heat transfer medium used in heaters [3].

The experimental system of gas heating device is composed of test body, gas burner, smoke exhaust system, heated gas system and data acquisition system [4]. Nine-joint armored thermocouple and
single-joint thermocouple are installed on A-A section to test the temperature distribution of heat transfer medium in cylinder, as shown in figure 1(b). During experiments, the fuel rates were set at 8 m³/h, 10 m³/h, 12 m³/h, 14 m³/h, 16 m³/h, and the flow rate of the heated gas was set at 1.67 m/s; the pressure and inlet temperature of the heated gas are 5.5 MPa and 280 K, respectively.

Figure 1. The experimental system of gas heating device.

3. Mathematical model

The object of numerical simulation in this paper is the two-dimensional circular section in the middle of the heater cylinder. The structure is shown in figure 2. Among them, D1 is 1300 mm, D2 is 325 mm, b1 is 540 mm and b2 is 510 mm. The diameter of flue tube is 42 mm and the distance between them is 68 mm. The diameter of the convective tube is 38 mm, b3 is 90 mm, b4 is 65 mm, and the angle is 60°.

Figure 2. Numerical model simulating a cross-section of the heating device.

Based on the boussinesq assumption[5], the governing equations of two-dimensional flow and heat transfer in combination of natural convection and participating medium radiation are listed below[6].

Continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$  \hspace{1cm} (1)

Momentum equations:

$$\rho (u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y}) = -\frac{\partial p}{\partial x} + \mu (\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2})$$  \hspace{1cm} (2)

$$\rho (u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y}) = -\frac{\partial p}{\partial y} + \mu (\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}) + \rho g \beta (T - T_\infty)$$  \hspace{1cm} (3)

Energy equation:

$$\rho c_p (u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y}) = \alpha (\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}) - Q_s$$  \hspace{1cm} (4)

Among them, u, v are the velocity components on x, y directions, respectively; p is the pressure; \( \mu \) is the fluid dynamic viscosity; \( \beta \) is the fluid volume expansion coefficient; \( \rho \) is the fluid density; \( T \) is the temperature; \( T_\infty \) is the fluid reference temperature; \( \alpha \), thermal diffusivity; and \( c_p \) is the specific heat; \( Q_s \) is the source term of radiative heat transfer. The radiation transfer equation is solved by discrete coordinate method.
The wall of the cylinder is treated as an adiabatic boundary; the average temperature of the fire tube wall is set as 368K, and the average temperature of the flue tube bundle wall is set as 356K; the boundary condition of the third kind is applied to the boundary of the convective tube bundle, and it is expressed as:

\[-k_e \frac{\partial T_w}{\partial n} = h(T_w - T_g)\]  

where \(k_e\) is the thermal conductivity of heat-transfer medium; \(n\) indicates the wall normal direction; \(T_w\) is the wall temperature; and \(T_g\) is the heated gas temperature. The average temperature of the heated gas in the first and second tube passes is 290 K, and the average temperature of the heated gas in the third and fourth tube passes is 310 K. \(h\) is the heat transfer coefficient calculated by

\[h = \frac{Nu k_g}{d}\]  

in which \(k_g\) is the thermal conductivity of gas inside the convective tube bundle; \(d\) is the diameter of the convective tubes; and the Nusselt number is calculated by a correlation[7]:

\[Nu = 0.023 Re^{0.8} Pr^{0.4}\]  

Where \(Re\) is the Reynolds number for the gas flow inside the convective tubes, and \(Pr\) is the gas flow Prandtl number.

This paper uses the commercial software Fluent 6.3 to simulate, and uses the finite volume method to discretize. The DO radiation model is adopted because this radiation model can not only solve the S2S problem, but also solve the participating radiation problem of the medium [8]. The physical model uses unstructured Cartesian body-fitted grid [9-10]. The grid is refined near the boundary surface and the grid independence test is carried out [11].

4. Results and discussion

The isothermal cloud images and velocity vector distributions of water and ethylene glycol are shown in figure 3 and figure 4, respectively.

The temperature distribution on the cross section of heater is uneven. Generally speaking, the highest temperature is at the top of the fire tube and flue tube bundle, followed by their outer wall. The temperature at the bottom of the cylinder is usually the lowest.

![Isothermal contour (K)](image1) ![Flow vectorgram (m/s)](image2)

(a) Isothermal contour (K) (b) Flow vectorgram (m/s)

Figure 3. Temperature and flow fields with medium water.

As can be seen from the temperature distribution of water in figure 3(a), the high temperature region at the top of the flue tube bundle presents a wide trunk shape due to the heat transfer behavior of the high-temperature medium water when it flows upward. Due to the strong influence of the low temperature fluid around the convection tube, the high temperature area around the fire tube moves to the left and right. As can be seen from the flow vectorgram in figure 3(b), the water near the fire tube is heated to form upwelling. The water near the first and second convection bundles falls because of lower temperatures. In a traditional heating furnace, heating surface and cooling surface are arranged symmetrically. If there is no proper flow channel between the two surfaces, the relative flow of medium...
water will be in conflict, as shown in figure 5(a). The chaotic flow field of circular cross section is consistent with the actual working behavior.

Figure 4 (a) shows the isothermal contour of ethylene glycol. As can be seen from the figure, the top of the flue tube bundle appears to be a wide treelike region of high temperature, which is similar to the situation when the medium is water. But at the top of the fire tube, there is a long and narrow high temperature zone, which is shifted to the right and left by the strong influence of the cold fluid around the first pass of the convective tube bundle. According to the velocity vector distribution in figure 4(b) that the ethylene glycol on the top of the fire tube flows upward and to the left and right. At this time, there is still collision between the heating surface of the fire tube and the cooling surface of the convection tube bundle, as shown in figure 5(b), which forms an opposition zone and hinders the development of natural convection flow field, thus greatly reducing the heat transfer efficiency.

![Figure 4](image)

(a) Isothermal contour (K)  (b) Flow vectorgram (m/s)

Figure 4. Temperature and flow fields with medium ethylene glycol.

Although the viscosity of ethylene glycol is larger, the velocity of ethylene glycol is a little faster than that of water under the effect of coupled natural convection and participating radiation, and the impact phenomenon of ethylene glycol has been improved slightly than that of water, as shown in figure 5.

![Figure 5](image)

(a) Water  (b) Ethylene glycol

Figure 5. Local flow hedging phenomenon.

Figure 6 shows the simulated and experimental temperature distributions of water and ethylene glycol on section A-A under the fuel rate of 10 m$^3$/h. The temperature distribution trend of numerical results and experimental results is consistent. Because the cylinder wall is considered as adiabatic wall, the heat dissipation of the cylinder wall is ignored. Furthermore, the simulation of two-dimensional circular cross section also ignores the axial flow. Therefore, the simulated temperature is usually 1~2.5k higher than the corresponding temperature measured in the experiment.

It can be seen from figure 6 that whether water or ethylene glycol is used as the heat transfer medium, the temperature distribution pattern on the circular section is basically consistent. From the temperature values of each measurement point, it can be seen that at different heights of the circular section, the temperature stratification phenomenon is obvious. However, the temperature difference between the
upper part and the lower part of the flow field is not large, which indicates that the driving force of natural convection is very small. This defect result in a slow start-up of the heater, and it takes 4 to 6 hours for each test condition to reach a stable state. This leads to a great reduction in the efficiency of gas heating device and high energy consumption.

Figure 6. Temperature distributions on section A-A under fuel rate of 10 m$^3$/h.

Figure 6 also shows that, under the same experimental conditions, the temperature at each measurement point of ethylene glycol is 15–30k higher than that of water. There are two reasons. First, the heat capacity of ethylene glycol is much smaller than that of water. Second, the high boiling point and low vapor pressure of ethylene glycol make its operating range much larger than that of water.

Figure 7 shows the heat transfer efficiency of heating device with water and ethylene glycol as heat transfer media respectively under different fuel rates. Gas heating device have the highest thermal efficiency with fuel rates of 12 m$^3$/h of ethylene glycol and 10 m$^3$/h of water. When the experimental conditions were the same, the heat transfer efficiency of the heating device using ethylene glycol as the heat transfer medium was at least 3.8% higher than that of water. As mentioned above, under all corresponding experimental conditions, the operating temperatures of ethylene glycol are higher than that of water. The highest operating temperature of ethylene glycol can reach 440 K, so the temperature difference will be larger and the thermal efficiency is relatively high. It is one of the reasons to choose ethylene glycol as the intermediate heat carrier medium.

However, due to the structural defects of the traditional heating device itself and the high viscosity of ethylene glycol, it is difficult to form an effective heat flow field inside the cylinder, and the thermal efficiency is usually less than 87%.

Figure 7. The thermal efficiency under different fuel rates.

5. Merits and demerits with ethylene glycol as the heat transfer medium

It is important to choose suitable heat transfer medium for gas heating device. The choice of heat transfer medium mainly depends on the heat transfer performance, pressure and temperature.

When water is used as a heat transfer medium, its operating temperature range is very narrow (323–373 K). Steam or ethylene glycol must be used as heat transfer medium when operating temperature exceeds 373K. When steam is used as a heat carrier, it must be observed frequently, but ethylene glycol is not required. Therefore, ethylene glycol is safe and reliable as a heat transfer medium.
The high boiling point and low vapor pressure of ethylene glycol help its heat absorption and exothermic process at operating temperature without phase transition. In addition, ethylene glycol operates in a wide range of temperatures and pressures as long as the temperature is below 450 K.

6. Conclusions

- Under the effect of coupled natural convection and participating radiation, the heat flow field of ethylene glycol has been improved slightly than that of water, although the viscosity of ethylene glycol is larger.
- The operating temperatures of ethylene glycol are higher than that of water under all corresponding operating conditions. Gas heating device have the highest thermal efficiency with fuel rates of 12 m$^3$/h of ethylene glycol and 10 m$^3$/h of water.
- Numerical calculation and experimental results show that the symmetrical arrangement of heating and cooling components in the conventional gas heating device can easily cause the flow field to collide, resulting in the low efficiency of the heating device (less than 87%).
- When the experimental conditions were the same, the heat transfer efficiency of the heating device using ethylene glycol as the heat transfer medium was at least 3.8% higher than that of water. For gas heating device, the advantages of using ethylene glycol as the heat transfer medium is dependent on its operating temperature and the design of heat transfer components.

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