Heat Transfer Calculation of Organic Heat medium Heater and Analysis of maximum film temperature

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Abstract: Medium hot oil is applied to heat transmission when accurate temperature of process is required and process should be heated homogenously and slowly in petroleum industry. Organic heat medium heater is applied to process whose outlet temperature is below 400℃. Organic heat medium heater is listed as B grade, C grade and D grade as per Boiler Safety Technical Supervision Administration Regulation. Heat transfer calculation is mentioned about Organic heat medium heater and max. Film temperature calculation is also demonstrated in order to explain deterioration of hot oil.

1. Forword
Organic heat medium heaters are widely used in petroleum and chemical industries. In recent years, organic heat medium heater is also used in solar electric generation system, which is vigorously developed in China. The medium is heated to a target temperature in the heater then exchange heat with process in exchanger.

Heat mediums mainly divided into organic heat medium and inorganic heat medium. Inorganic salts can be heated above 400℃, such as molten salt. It is stable and safe that molten salt is heated to500℃.

Heat medium heater for heating inorganic salts is not inspected by the government, which is different from steam boilers and organic heat medium heaters. Organic heat medium, also known as hot oil, is generally used in situations below 400 ℃. There are many kinds of hot oil, such as Dowtherm, YD, Syltherm and so on. Organic heat medium heaters are classified as B-grade, C-grade and D-grade boilers according to different loads in the scope of Boiler Safety Technical Supervision Administration Regulation.

2. Product Type
At present, there are two main type of organic heat medium heater: one is skid helical coil cylindrical type, the other is radiation-convection vertical cylindrical heater or vertical box type. The former is derived from Germany. This type of organic heat medium heater can be designed to 20 MW Generally. And it is assemble in shop before delivery and could be hoisted on site as whole with less site installation work. The heater arch is under positive pressure in operation. The latter comes from the fire heater type in API standard. The radiation tube in the heater is vertical or horizontal arrangement, and is located along the wall or in the middle. Horizontal finned tube of convection is used to enhance
heat transfer. This kind of organic heat medium heater can be used for both large and small heat loads. API type organic heat medium heater has large site work, long installation period and relatively high cost. Large-scale organic heat medium heater must adopt API type. The heater arch is under negative pressure in operation. Figures 1 and 2 are outlines of two types of organic heat medium heater.

3. Heat Transfer Calculation of Heater

The core component of the organic heat medium heater is the coil. The design of the heater coil is related to the thermal performance and safety of the organic heat medium heater. Organic heat medium heaters manufactured and operated in China must be inspected by government. Organic heat medium heaters exported usually require design and manufacture in accordance with ASME standards to obtain stamp. The design of coil and heat exchange surface in heater is determined by thermal calculation and hydraulic calculation. Checking calculation is usually used to calculate the heat transfer area. Firstly, the structure parameters and area are assumed preliminarily, and the heat transfer quantity is calculated. The heat transfer quantity and the required heat transfer quantity are found to be consistent (generally, the error is less than 2%). Checking calculation is the most commonly used calculation method [1]. Regardless of the type of heater, the heat transfer calculation block diagram in the heater is similar, mainly divided into radiation heat transfer and convection heat transfer.
The Robo-Evans module is used to calculate the radiant heat transfer in heater. The heat transfer rate equation of radiant chamber is [2]:

\[ Q_R = 5.72 \alpha A_{cp} F \left( \frac{T_g}{100} \right)^4 - \left( \frac{T_w}{100} \right)^4 \] + \frac{h_{RC} A_R (T_g - T_w)}{1}

\( Q_R \) – Radiant quantity, W  
\( \alpha \) – Angular coefficient  
\( A_{cp} \) – Cold flat area, \( \text{m}^2 \)  
\( A_R \) – Radiant area, \( \text{m}^2 \)  
\( F \) – Exchang factor  
\( h_{RC} \) – Convective heat transfer coefficient in radiant chamber, \( \text{W}/(\text{m}^2 \text{K}) \)  
\( T_g \) – Flue gas temperature in radiant chamber, K  
\( T_w \) – Outer skin temperature of radiant chamber, K  

Thermal equilibrium equation:

\[ Q_R = B V_y (H_{\text{max}} - H_g) \] (2)

\( Q_R \) – Radiant quantity, W  
\( B \) – Fuel gas consumption, Nm3/\( \text{s} \)  
\( V_y \) – Actual flue gas flow rate, Nm3/Nm3  
\( H_{\text{max}} \) – Enthalpy of Flue Gas at Theoretical Flame Temperature, J/Nm3  
\( H_g \) – Enthalpy of Flue Gas at Arch Temperature, J/Nm3  

Skin temperature calculation formula:

\[ t_w = \frac{1}{2} \left( t_j + t_c \right) + \left( \frac{1}{h_i + R_l + \frac{\delta}{\lambda_s}} \right) q_R \frac{d_0}{d_i} \] (3)

\( t_j \), \( t_c \) – Inlet and outlet temperature of process, \(^\circ\text{C} \)  
\( h_i \) – Convective heat transfer coefficient in tube, \( \text{W}/(\text{m}^2 \text{K}) \)  
\( R_l \) – Fouling resistance in tube, \( \text{m}^2 \text{K}/\text{W} \)  
\( \delta \) – Thickness of tube, m  
\( \lambda_s \) – Conductivity, \( \text{W}/\text{m K} \)  
\( q_R \) – Flux of coil, \( \text{W}/\text{m}^2 \)  
\( d_0 \) – Outer diameter, m  
\( d_i \) – Inner diameter, m

The calculation of hot oil film temperature in organic heat medium heater is also very important. Because the film temperature is higher than the allowable film temperature of hot oil during operation, it will cause the deterioration of hot oil and seriously affect the operation of the whole system. The calculated film temperature must be lower than the allowable liquid film temperature. The calculation of liquid film temperature is introduced separately.

The program diagram of radiation heat transfer in heater is as Figure 3.

About 50% to 80% of the total heat is radiant transfer heat, and the residual heat is transferred to hot oil through convective heat transfer. Because of the liquid phase in tube, the flow is in a turbulent state, and the flue gas velocity outside the tube is 10-20 m/s, which can also reach the turbulent state. However, the convective heat transfer coefficient in the tube is higher than that outside the tube. Even if the finned coil is used in API heater, the thermal resistance is subject to outside the tube. The heat transfer equation [3] is:

\[ Q_c = KA \Delta t_m \] (4)

\( Q_c \) – Convection quantity, W  
\( K \) – heat transfer coefficient, \( \text{W}/\text{m}^2 \text{K} \)  
\( A \) – Convection area, \( \text{m}^2 \)  
\( \Delta t_m \) – Logarithmic temperature difference, \(^\circ\text{C} \)

Thermal equilibrium equation:

\[ Q_c = B V_y (H_{\text{in}} - H_{\text{out}}) \] (5)

\( Q_c \) – Convection quantity, W  
\( B \) – Fuel gas consumption, Nm3/\( \text{s} \)  
\( V_y \) – Actual flue gas flow rate, Nm3/Nm3  
\( H_{\text{in}} \) – Enthalpy of Flue Gas at Theoretical Flame Temperature, J/Nm3  
\( H_{\text{out}} \) – Enthalpy of Flue Gas at Arch Temperature, J/Nm3
$H_{\text{in}}$ – Inlet Enthalpy value of flue gas in convection section, J/Nm$^3$

$H_{\text{out}}$ – Outlet Enthalpy value of flue gas in convection section, J/Nm$^3$

The program diagram of convection heat transfer in heater is as Figure 4.

The thermodynamic calculation process is a trial calculation process. The thermodynamic parameters printed by the calculation of radiation heat transfer and convection heat transfer need to be judged and analyzed by professional knowledge and codes, and unreasonable thermodynamic parameters can be judged. The thermodynamic parameters can be optimized through area changes to meet the requirements of performance and safety.

Pressure drop calculation of medium is important in process calculation of organic heat medium heater. Pressure drop is divided into two categories: along-way loss $h_f$ and local loss $h_m$. Pressure drop formula [4]:

$$P = h_f + h_m = \frac{1}{2} \frac{\lambda \rho v^2}{d} + \frac{\xi \rho v^2}{2} \ (6)$$

$P$ – Pressure drop, KPa

$\lambda$ – Along – way loss coefficient

$l$ – Length of coil, m

$d$ – Inner diameter, m

$\rho$ – Process density, Kg/m$^3$

$V$ – Velocity of inner tube, m/s

$\xi$ – Local loss coefficient

Pressure drop in heater is an important basis for selecting circulating pump. The pressure drop of the medium in the furnace is large, the pump head needed is high, so the one-time investment is high, and the operation is not economical. The low pressure drop indicates that the flow rate of medium in the furnace tube is low, the heat transfer is not optimized, and the film temperature and skin temperature is high. Therefore, the pressure drop should consider both the economy of operation and optimization of thermodynamic parameters.
4. Coking mechanism of organic medium

Water and inorganic salts are stable during heating process and are not easy to deteriorate, so there will be no deterioration of heat transfer caused by medium coking in the heater tube during operation. Organic medium belong to hydrocarbon organic compounds. When reaching certain temperature, free radicals R are generated at the weakness of molecular structure. RO2 leads to chain initiation, and then chain transmission, growth and termination. Free radicals are easy to decompose, leading to chain breakage and degradation, resulting in a certain amount of coking matrix with free radicals, while the combination of free radicals increases the molecular weight, gum formation and coking process. The coking rate is mainly related to the coking reaction temperature, i.e. the film temperature. The coking rate equation [5] is as follows:

$$R_c = C_1^n A e^{-E/RT} \quad (7)$$

- $R_c$ - Coking rate, mg cm$^{-2}$h$^{-1}$
- $C_1$ - Coking Matrix Velocity, mg cm$^{-3}$
- $n$ - Reaction order
A – Pre exponential factor $mg^{1-n} \text{cm}^{3n-2} \text{h}^{-1}$
E – Reaction activation energy, KJ/mol
R – General Gas Constants, KJ mol$^{-1}$K$^{-1}$
T – temperature, K

For industrial heaters, Nu, Re and Pr affect film temperature. According to literature [6], the coking rate equation of industrial heaters as below:

$$ R_c = C_2 d / Re^{0.8} \quad (8) $$

$C_2$ – equation coefficient
$d$ – Inner diameter, mm
$Re$ – Reynolds number

The higher the temperature is, the higher the coking rate is; the smaller the Reynolds number is, that is, the smaller the flow rate is, the higher the coking rate is; the larger the diameter of the selected pipe is, the higher the coking rate is.

5. Film Temperature Calculation
The maximum allowable temperature of hot oil is determined by thermal stability test. The test data prove that the deterioration rate caused by thermal cracking will double when the working temperature rises by 10 °C. However, the film temperature can not be determined by experimental method. It is determined by the chemical properties and thermal stability conditions of hot oil [7]. The calculation of film temperature only provides a condition for the safety of organic heat medium heater, and the calculation results are inconsistent with the actual film temperature. In the calculation, the spot film temperature where has the maximum heat flux or the minimum Reynolds number should not be greater than the maximum allowable liquid film temperature of heater.

Film temperature calculation as per Boiler Safety Technical Supervision Administration Regulation explanation Attachment 2:

$$ t_{film} = t_{bulk} + \Delta t_{htf} \quad (9) $$

$$ t_{film} - \text{Max film temperature, } ^\circ\text{C} $$
$$ t_{bulk} - \text{Bulk temperature } ^\circ\text{C} $$

$$ \Delta t_{htf} - \text{Film temperature difference, } ^\circ\text{C} $$

$$ q_{max} - \text{Max flux, } \text{w/m}^2 $$
$$ \alpha_{htf} - \text{Convective heat transfer coefficient in tube, } \text{w/(m}^2\text{ } ^\circ\text{C}) $$
$$ d_{od} - \text{Outer diameter, m} $$
$$ d_{id} - \text{Inner diameter, m} $$

$$ \Phi_{whl} - \text{Correction Coefficient Considering Tangential Radiation Heat Loss of Tube Wall} $$

$$ \Phi_{whl} \approx 0.9 $$

$$ \alpha_{htf} = \Phi_{bd} \times \lambda_{htf} \times 0.12 \times X \times 0.87 \times X \times Pr^{0.4} \quad (11) $$

$$ \Phi_{bd} - \text{Coefficient Considering the Effect of Tube Bending and Heat Flow Direction} $$

$$ \Phi_{bd} \approx 0.8 $$

$$ \lambda_{htf} - \text{Conductivity of bulk temperature, } \text{w/(m K)} $$

$$ Re - \text{Reynolds number} $$

$$ Pr - \text{Prandtl number} $$

$$ q_{max} = \Phi_{saf} \times X \times q_{fur} $$

$$ \Phi_{saf} - \text{Safety factor, } \Phi_{saf} \approx 1.15 $$

$$ \Phi_{a} - \text{Correction Coefficient Considering Combustion Air Temperature and Excess Air, as per Figure 5} $$

$$ q_{fur} - \text{Flux, } \text{w/m}^2 $$
\[ q_{fur} = \frac{d_{fire}}{D_{fur}X_{a_{fur}}X_0X(T_{f1}^4 - T_{wal}^4)} \] (12)

- \( q_{fur} \) — Flame diameter, m
- \( D_{fur} \) — Average diameter of combustion chamber, m
- \( a_{fur} \) — Heater emissivity, as per Figure 6
- \( T_{f1} \) — Flame Temperature, K
- \( T_{wal} \) — Outer Skin Temperature, K
- \( \sigma_0 \) — Radiation Constant = 5.67X10^{-8} W/(m²K⁴)

**Figure 5.** Correction Coefficient Considering Combustion Air Temperature and Excess Air

**Figure 6.** Heater Emissivity

### 6. Calculation Case

According to the actual project parameters, the relevant thermodynamic calculation parameters are given as below table 1:
Table 1. Comparison Thermal parameters of Two type Heaters

|                          | API skid helical coil cylindrical type |
|--------------------------|----------------------------------------|
| Hot Oil                  | Therminol VP-1                         |
| Allowable bulk temperature ºC | 400                                    |
| Allowable film temperature ºC | 425                                    |
| Inlet temperature ºC     | 301                                    |
| Outlet temperature ºC    | 393                                    |
| Heat load MW             | 18.5                                   |
| Flue gas temperature of arch ºC | 762                                    |
| Radiant flux KW/m2       | 26.6                                   |
| Ratio radiant heat exchange | 80%                                    |
| Discharge flue gas temperature ºC | 386                                    |
| Direction of hot oil     | Convection section–Radiant section     |
| Velocity of Hot Oil m/s  | Inner: 2.8                             |
| Inner diameter of tube mm | 113.9                                   |
| Calculated max. film temperature ºC | 411                                    |
|                           | Outer: 3.46                             |
|                           | 2.5                                    |
|                           | 79                                     |
|                           | 420                                    |

Because the ratio of radiation heat transfer is higher and the radiation heat transfer is stronger than convection heat transfer, the highest film temperature usually occurs in the radiation section. Convection heat transfer is relatively mild, generally there is no case of hot oil deterioration and coking. The average flux of the radiation section of the skid helical coil cylindrical type heater is high. Even if the low temperature inlet process is set in the radiation section, coking will inevitably occur. Therefore, this part of the Heater coil adopts high flow rate and small diameter to obtain lower film temperature.

7. Conclusion
The thermodynamic calculation process in heater needs repeated trial. The final thermodynamic parameters require the thermodynamic calculator to make rational judgment by using professional knowledge and experience.

The risk of deterioration of hot oil is much higher than that of inorganic heat medium and water. Therefore, the calculation of film temperature is particularly important. According to the properties of hot oil, the coil diameter, flow rate, pressure drop, heat transfer area and flux should be taken into account in the calculation of film temperature, so as to ensure that the calculated film temperature is below the allowable maximum film temperature and ensure the safe operation of the equipment.

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