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Research Article

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Study on inhomogeneity of heat transfer in tube-side for spiral-wound heat exchanger

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ABSTRACT

Spiral-wound heat exchanger has compact structure, withstand large temperature difference, and high operating pressure. Widely used in various production processes. Due to the different spiral radii lead to different tubes length of layers. The traditional method of calculation does not take into account these differences, so there are some differences in the results with the actual situation. In this paper, the traditional calculation formula were theoretical derivation, obtained correlation correction formula, calculated different correction factor of common heat exchange tubes. The results were validated by CFD software. Quantitative results showed that the modified heat transfer coefficient calculation method will help improve the accuracy of the inner tube heat transfer coefficient.

Key words: Spiral-wound heat exchanger; flow; heat transfer coefficient

INTRODUCTION

Spiral-wound tube heat exchanger has high temperature, high pressure, compact structure, high thermal efficiency, low temperature differential stresses, tube pass can be used multiple streams as well as easy-to-large-scale, etc. [1,2], currently has rapidly developed from refrigeration and other aspects to petroleum, chemical and large-scale equipment.

Although spiral-wound heat exchanger has such numerous advantages, but its design, production process has been controlled by Linde AG long time, very little published research results. At present, using the results of the United States Gilli to calculate the shell surface convective heat transfer coefficient and pressure drop [3]; in recent years, Bengt used alkane experimental methods to study on spiral-wound heat exchanger shell-side heat transfer and pressure containing phase change conditions of natural gas [3,4]; Prabhat also studied the shell-side flow and heat transfer calculating correlations of fin spiral-wound heat exchanger for low temperature [5-7]. In the country is no complete research results currently, only Harbin Institute of Technology Qian Jing [8], Shanghai Jiaotong University Liu Jun Hong [9], Tsinghua University Yin Jie Xi [10] made some applicability partial research for spiral-wound heat exchangers. However, these studies did not involve internal heat transfer coefficient, the current design is still follow spiral heat transfer coefficient calculation. This method of calculation does not consider the entire heat exchanger tubes correction, different wound diameter, the number of wound layers and length of heat exchange tubes to affect heat transfer coefficient within tubes, there are certain differences between actual engineering. In this paper, theoretical analysis corrected the heat transfer coefficient calculation of internal heat exchange tubes, and the numerical method is used to validate, to study this type heat exchanger do a preliminary exploration.

THEORETICAL MODEL

Spiral-wound heat exchanger is composed by core tube, spiral pipes of different spiral diameter and mat strips between the spiral pipes. The spiral direction of each layer heat transfer tubes is contrary. The heat transfer tubes generally used in the thin tube 6-15mm outside diameter, the thickness of mat strips is 1-5mm. Since heat transfer diameter is relatively small, high strength, the high-pressure fluid flow in pipe generally. Its structure is shown in

Figure 1.

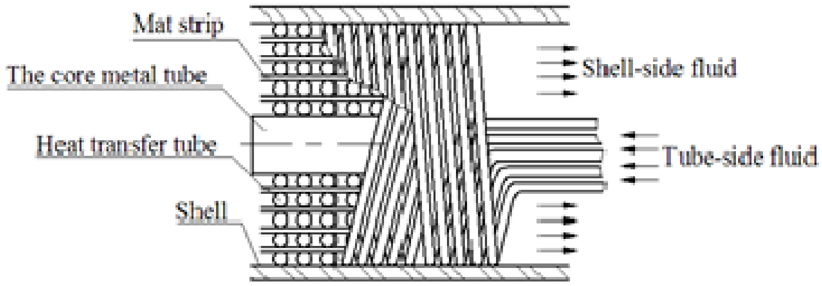

Fig. 1: The structure diagram of spiral-wound heat exchanger

The separated spiral-wound tubes is shown as Figure 2:

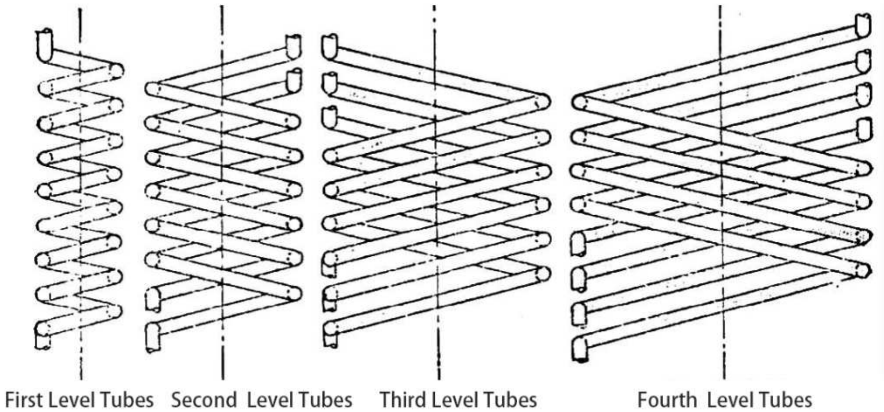

Fig.2: the structure diagram of heat exchange tubes different layers

Can be seen from Figure 2, the heat transfer tubes in different layers, lead to even if the same wound angle, the tubes will have different lengths and different spiral diameters; different diameters of heat transfer tubes will lead to different spiral-wound diameter in the same layers.

The literature [11] recommended, heat transfer coefficient of spiral-wound internal at different Reynolds numbers:
When $100 < \mathrm{Re} < (\mathrm{Re})_c$,

$$\mathrm{Nu} = 3.65 + 0.08\left[1 + 0.8\left(\frac{D_i}{D_e}\right)^{0.9}\right]\mathrm{Re}^i\,\mathrm{Pr}^{1/3} \quad (1)$$

When $(\mathrm{Re})_c < \mathrm{Re} < 22000$,

$$\mathrm{Nu} = 0.023\left[1 + 14.8\left(1 + \frac{D_i}{D_e}\right)\left(\frac{D_i}{D_e}\right)^{1/3}\right]\mathrm{Re}^i\,\mathrm{Pr}^{1/3} \quad (2)$$

When $\mathrm{Re} > 22000$,

$$\mathrm{Nu} = 0.023\left[1 + 3.6\left(1 - \frac{D_i}{D_e}\right)\left(\frac{D_i}{D_e}\right)^{0.8}\right]\mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3} \quad (3)$$

Where: D_i, heat exchange tubes inside diameter, m;
D_e, the spiral median diameter of heat exchange tubes, m;
Nu, Russell authorized number;
Pr, Prang authorized number;
Re, Reynolds number:
$(\mathrm{Re})_c$, the critical Reynolds number, and it is equal to：

$$(\mathrm{Re})_e = 2300\left[1 + 8.6\left(D_i / D_e\right)^{0.45}\right] \quad (4)$$

Thus, the convective heat transfer coefficient is closely related to spiral wound diameter D_e. To calculate the total heat transfer area, you need to know average heat transfer coefficient of the whole spiral-wound bundle.

HEAT TRANSFER COEFFICIENT IN TUBES

Because each layer spiral wound diameter and each layer the tubes number is not the same, resulting heat transfer coefficient different in each layer heat transfer tubes, after must be amendment able to get the entire heat transfer coefficient within heat exchanger tubes. Figure 3 shows the release situation of spiral wound heat exchanger.

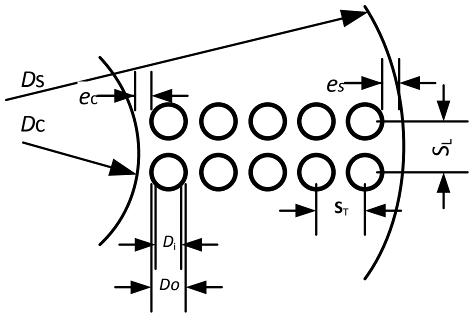

Fig. 3: The arrangement diagram of heat transfer tubes

Where: e, heat transfer tubes interlayer spacing, m;
e_e, the spacing of heat transfer tubes and core tube, m;
e_s, the diameter spacing of heat transfer tubes and shell, m;
D_o, heat transfer tubes outside diameter, m;
D_s, heat exchanger shell inside diameter, m;
D_c, core tube diameter of spiral wound heat exchanger, m;
S_T, the center distance of two adjacent heat transfer tubes, m;
S_L, the center distance of same layer heat transfer tubes, m;

From the above diagram, can be obtained the spiral median diameter $(D_e)_n$ of heat transfer tubes in the n-layer is:

$$\left(D_e\right)_n = D_c + 2e_c + D_o + 2\left(n-1\right)S_T \quad (5)$$

Heat transfer tubes numbers of each layer distribution is Nn, the size calculates according to actual arrangement, generally related with tubes outer diameter, spiral angle and spiral inner diameter.

In $\mathrm{Re} > 22000$ for example calculations.

The definition formula Nu is brought into the Formula 3, obtained the convective heat transfer coefficient as follows:

$$h = \frac{0.023\lambda}{D_i}\left[1 + 3.6\left(1\text{-}\frac{D_i}{D_e}\right)\left(\frac{D_i}{D_e}\right)^{0.8}\right]\mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3} \quad (6)$$

Where: h, the convective heat transfer coefficient, W / (m2.K);
λ, thermal conductivity, W / (m.K).
According to the geometric relationship between the spirals, each circle tubes length is:

$$L_n = \frac{\pi\left(D_e\right)_n}{\cos\beta} \quad (7)$$

Where: β, spiral angle, rad.

The total heat transfer area of each layer tubes single turn is:

$$S_N = N_n \pi D_i L_n \tag{8}$$

The total heat transfer of each layer as follows:

$$Q_N = h_N S_N \left(t_\infty - t_\mathrm{i}\right) \tag{9}$$

Where: t_∞, the main body temperature of fluid in tube, ℃,

t_i, tube wall temperature, ℃

Thus, the quantity of heat transfer corresponding to tubes in whole heat exchanger is:

$$Q = \sum_{N=1}^{N} Q_N \tag{10}$$

The formula 8, 9 is brought into the formula10:

$$Q = \sum_{N=1}^{N} h_n N_n \pi^2 D_i \left(D_e\right)_n \left(t_\infty - t_\mathrm{i}\right) \tag{11}$$

Due to each layer length of spiral-wound heat exchanger, heat transfer coefficients are not same, employ spiral tube average diameter and average heat transfer coefficient to calculate in the project. The average heat transfer coefficient within heat exchange tubes is calculated according to the formula 3, the spiral median diameter (D_e) mid of heat exchange tubes is the average spiral diameter of entire spiral-wound bundle, and it is different from median diameter of the n- layer spiral tube in the formula 5, which is calculated as:

$$\left(D_e\right)_{mid} = D_c + 2e_c + D_o + \left(N-1\right) S_T \tag{12}$$

Since assuming strong turbulent heat exchanger area in the whole derivation process, thus assuming temperature difference equal to between the layers in tubes. This assumption has some error, the following derivation of this article temporarily ignore this error until later study to continue. The total pipe heat transfer of entire heat exchanger is:

$$Q_\mathrm{mid} = N h_\mathrm{mid} N_{mid} \pi^2 D_i \left(D_e\right)_\mathrm{mid} \left(t_\infty - t_\mathrm{i}\right) \tag{13}$$

Where: N, heat exchange tubes layers;
N_mid, middle layer root number of spiral-wound heat exchangers;
(D_e) mid, middle layer spiral diameter, m;
h_mid, the average convective heat transfer coefficient, calculated by the formula 3 to obtain.

The formula 12 is calculated the real heat exchange when considered the actual situation of spiral heat exchange tubes in spiral-wound heat exchanger. The formula 13 is heat exchange calculations accordance with the classical heat transfer theory. Comparing two formulas, we obtain:

$$Q = \eta Q_\mathrm{mid} \tag{14}$$

Where: η, heat transfer correction factor.
The formula 12, 13 is brought into the formula 14:

$$\eta = \frac{\sum_{N=1}^{N} h_n N_n \left(D_e\right)_n}{N h_\mathrm{mid} N_{mid} \left(D_e\right)_\mathrm{mid}} \tag{15}$$

RESULTS AND ANALYSIS

Can be seen from the formula 15, the heat transfer correction coefficient related with many parameters, but some parameters are difficult to determine before convective heat transfer coefficient calculation. Through numerical simulation and analysis of manufacturing process, the correction coefficient relationship between the inner diameter of heat transfer tubes and the number of layers in spiral tube the maximum, the relationship between other parameters smaller.

The formula 15 is difficult to directly applied to engineering calculations, heat exchanger typical parameters of liquefied natural gas - (CH_4, 90%; C_2H_6, 10%; shell temperature is -124 Centigrade / -50 Centigrade, tube temperature is -38 Centigrade / -67 Centigrade) for the physical parameters, the project used heat transfer tubes DN10, DN15, DN20 and DN25 relevant sizes, structure parameters, settings the flow rate, to calculate different (D_e) n and $(D_e)_{mid}$ and are brought into the formula 6 respectively to obtain different spread heat transfer coefficient, and finally are brought into the formula 15. The heat transfer correction coefficient in the chart method for industrial calculated using, as shown in Figure 4:

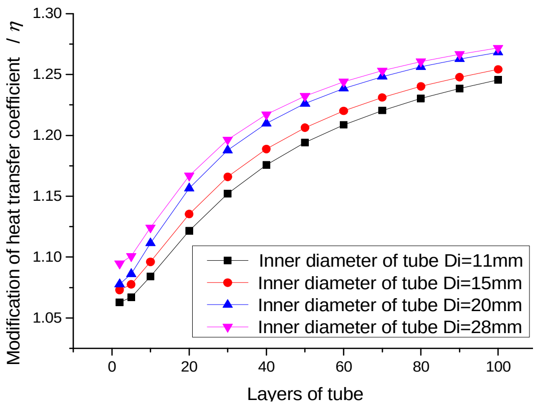

Fig.4: the effects of heat exchange tubes layers to heat transfer correction coefficient

Can be seen from Figure 4, in common 10-50 layer of heat transfer tubes, the correction coefficient increases more. When the 30 layer of heat transfer tubes, heat transfer coefficient calculation according to the radius of middle spiral tube, 15% -20% smaller than the overall manner calculated, this difference has reached the limit of engineering design errors. And the greater tube, the greater correction coefficient; correction coefficient of heat transfer is greater than 1. Thus, according to the method of median diameter calculating, heat transfer coefficient inner tube is too small, heat transfer area calculation is too large. Research not only carried out calculation for spiral-wound heat exchanger in the natural gas liquefaction process, but also for steam condensing heating heat exchangers, high temperature sterilization of food and other conditions to do checking, the results are similar.

Although only the above results derived from the turbulent heat transfer, layer corresponding to 1,2,3 and excessive current flow, with similar results, just because of its (D_i / D_e) index is small, the impact on dimensions of heat transfer tubes to heat transfer coefficient is smaller than the turbulence.

CONCLUSION

1、 the calculated results show that the traditional use median diameter of spiral-wound heat exchanger to calculate heat transfer coefficient is a large deviation. The calculation results of heat transfer coefficient is too small, a lot of time has been greater than the limits of design error; design heat transfer area is too large, need modify. Heat transfer correction coefficient has been given.

2、Due to geometry differences of each layer spiral tube in spiral-wound heat exchanger led to differences between each layer heat transfer coefficient, Even exist temperature difference between each layer heat transfer tubes, the temperature difference will also affect heat transfer coefficient of heat exchanger shell, these effects need further study.

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