COMPARISON OF HEAT TRANSFER EFFICIENCY BETWEEN HEAT PIPE AND TUBE BUNDLES HEAT EXCHANGER

by

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Original scientific paper
DOI: 10.2298/TSCI1504397W

A comparison of heat transfer efficiency between the heat pipe and tube bundles heat exchanger is made based on heat transfer principle and the analysis of thermal characteristics. This paper argues that although heat pipe has the feature of high axial thermal conductivity, to those cases where this special function of heat transfer is unnecessary, heat pipe exchanger is not a high efficient heat exchanger when it is just used as a conventional heat exchanger in the industrial fields. In turn, there are some deficiencies for heat pipe exchanger, such as complicated manufacturing process, critical requirements for manufacturing materials, etc. which leads to a higher cost in comparison to a tubular heat exchanger. Nonetheless, due to its diverse structural features and extraordinary properties, heat pipe exchanger still has wide applications on special occasions.

Key words: *heat transfer, heat pipe, tubular exchanger*

Introduction

Since the concept of heat pipe was proposed by Gaugler [1] in 1940's and further developed by Trefethen [2] and Grover *et al.* [3] in 1960's, the theory of heat transfer for heat pipe has made great progress [4-7], and the applications of heat pipe, such as space program and electronics cooling and so on in the early stage, have also turned to general industrial energy saving system [8-11]. In this paper, the heat transfer efficiency of the heat pipe and tube bundles heat exchanger is discussed in the two aspects of geometric features and thermal performance. Through the discussion and analysis, the paper emphasizes that although heat pipe exchanger has some special structural features and properties which were emphasized widely, it is not a high efficient heat exchanger when it is just used as a conventional heat exchanger in the industrial fields.

The working principle of heat pipe

A heat pipe (fig. 1) is a heat transfer device that combines the principles of both thermal conductivity and phase transition to efficiently facilitate the transfer of heat between two solid interfaces. At the hot interface of a heat pipe, working liquid in contact with a thermally conductive solid surface turns into a vapor by absorbing heat from that surface. The vapor then travels along the heat pipe to the cold interface and condenses back into liquid releasing the latent heat. The working liquid then returns to the hot interface through either capillary

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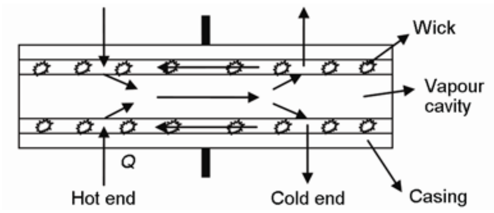

Figure 1. The principle of heat transfer for heat pipe

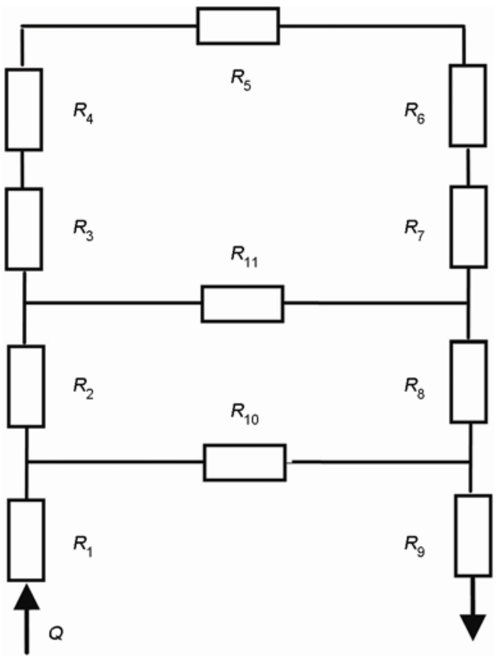

Figure 2. The equivalent thermal resistance network for heat pipe

action or gravity, and the cycle repeats. Due to the very high heat transfer coefficients for boiling and condensation, heat pipes are highly efficient thermal conductors along heat pipe length.

The comparison of heat transfer efficiency

In many textbooks and literatures [12-14] high thermal conductivity along heat pipe length, approaching 100000 W/(mK) for long heat pipes, in comparison with approximately 400 W/(mK) for copper, is often emphasized, but as a general heat exchanger in industrial applications, this feature is unnecessary for the transfer of heat, therefore, it would not be beneficial to enhance the efficiency of heat exchanger. The following comparative analysis will illustrate this.

According to the heat transfer principle, the total thermal resistance of heat transfer is the reciprocal of the overall heat transfer coefficient that relates to the heat transfer efficiency. In the analysis of heat exchangers, it is usually convenient to work with the thermal resistance, so, we only need to compare the magnitude of their total thermal resistances.

The thermal resistance network involved in this heat transfer process of a single heat pipe (as pictured in fig. 1) disregarding radiation resistance is described in the fig. 2, where, R_1 and R_9 are convection resistances, R_2 and R_8 are conduction resistances through the tube wall, R_3 and R_7 are the similar ones through wick inside the tube, R_4 and R_6 are the thermal resistances caused by working fluid evaporating and condensing at hot and cold section, respectively, R_5 is the thermal resistance caused by vapor flowing from hot end to cold end, and R_{10} and R_{11} are the conduction resistances through tube wall and wick from hot end to cold end axially. Based on the principle of electronics, the total thermal resistance of this network is:

$$R_{\text{total}} = R_1 + R_9 + \frac{R_{10}\left(R_8 + R_{11}\sum_3^7 \dfrac{R_k}{R_{11} + \sum\limits_3^7 R_k}\right)}{R_2 + R_8 + R_{10} + R_{11}\sum_3^7 \dfrac{R_k}{R_{11} + \sum\limits_3^7 R_k}} \tag{1}$$

Based on the relative magnitude of the thermal resistances [15-16], R_2, R_4, R_5, R_6, and R_8 are negligible, so the total thermal resistance is written approximately:

$$R_{\text{total}} \approx R_1 + R_9 + \frac{R_{10}\left(R_{11}\dfrac{R_3+R_7}{R_3+R_7+R_{11}}\right)}{R_{10}+R_{11}\dfrac{R_3+R_7}{R_3+R_7+R_{11}}} \tag{2}$$

Let

$$R_P = \frac{R_{10}\left(R_{11}\dfrac{R_3+R_7}{R_3+R_7+R_{11}}\right)}{R_{10}+R_{11}\dfrac{R_3+R_7}{R_3+R_7+R_{11}}}$$

thus

$$R_{\text{total}} \approx R_1 + R_9 + R_{\text{P}} \tag{3}$$

In regard to tubular exchanger, the heat transfer process of a single tube consists of only three thermal resistances (as showed in figs. 3-4). Its equivalent thermal resistance network is pictured in fig. 4. The total thermal resistance of the network after neglecting R_2' is:

$$R_{\text{total}}' \approx R_1' + R_9' \tag{4}$$

where R_1' and R_9' are similar to R_1 and R_9, and R_2' is similar to R_2.

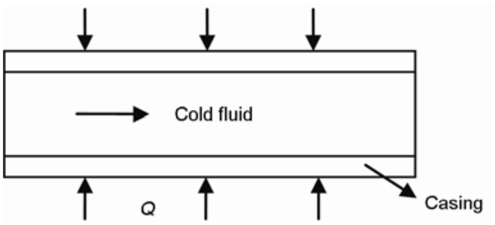

Figure 3.The sketch of heat transfer of a single tube

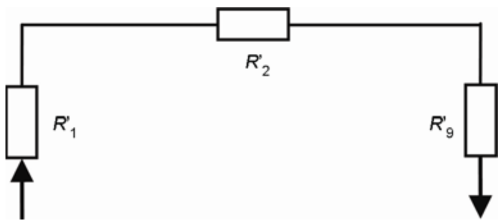

Figure 4. The equivalent thermal resistance network for a single tube

Comparing fig. 2 with fig. 4 shows the thermal resistance of the tubular exchanger with fewer heat transfer links is less than that of the heat pipe. A more detailed discussion on the total thermal resistances is made in the paper.

Firstly, heat pipe exchanger has no advantages in the geometric features with regard to heat transfer surface area. As shown in fig. 1, only half of the heat transfer surface area is used for the transfer of heat along the path of the heat flow, that is, each half of the area is involved in heat transfer at the hot and cold section, respectively. In contrast, the entire heat transfer surface area of tubular exchanger is involved in heat transfer directly between hot and cold fluid through a wall. As a matter of fact, the inner structure of the heat pipe is just like to "thicken" a wall to cause an increase of conduction resistance (see fig. 5). In addition, both heat pipe and tubular exchanger can be finned on the entire outer surface of the tube.

Secondly, the expressions are applied to evaluate the relative magnitude of their thermal resistances. We assume both of the heat exchangers are in the same flow field and the

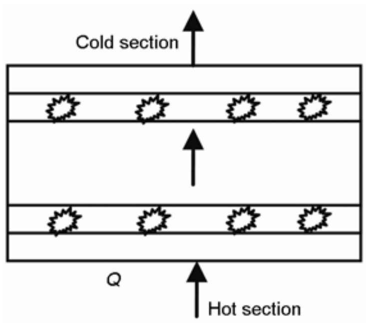

Figure 5. The equivalent path of heat flow for heat pipe

thermal environment. Combined tubular exchanger and heat pipe exchanger in which the wick is neglected is pictured in fig. 6.

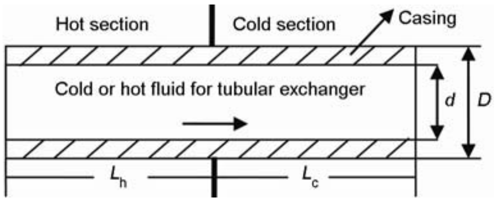

Figure 6. Combined tubular and heat pipe exchanger (neglecting wick)

For the heat pipe exchanger, assume the tube is evenly divided into two parts, the hot section and cold section. L_h and L_c represent the lengths of the tube of the hot and cold section, so we have $L_h = L_c$. Meanwhile, α_h and α_c are corresponding convection heat transfer coefficients at the hot and cold section outside the tube, respectively.

As for tubular exchanger, α_{in} and α_h are the convection heat transfer coefficients inside and outside the tube, respectively, thus, their total thermal resistances are written as:

For the heat pipe exchanger:

$$R_{hp} = \frac{1}{\pi D L_h \alpha_h} + R_P + \frac{1}{\pi D L_c \alpha_c} = R_P + \frac{1}{\pi D L_h}\left(\frac{1}{\alpha_h} + \frac{1}{\alpha_c}\right) \tag{5}$$

Generally, $\alpha_h \geq \alpha_c$ [15, 16, 22], then we have:

$$R_{hp} = R_P + \frac{1}{\pi D L_h}\left(\frac{1}{\alpha_h} + \frac{1}{\alpha_c}\right) \geq R_P + \frac{2}{\pi D L_h \alpha_h} \tag{6}$$

For the tubular exchanger, we have:

$$R_{te} = \frac{1}{2\pi D L_h \alpha_h} + \frac{1}{2\pi d L_h \alpha_{in}} \cong \frac{1}{2\pi D L_h}\left(\frac{1}{\alpha_h} + \frac{1}{\alpha_{in}}\right) \tag{7}$$

where, D and d are the outer and inner diameter of the tube, respectively, and both are taken as equal approximately. Assuming R_P in eq. (6) is negligible and comparing eq. (6) with eq. (7), we can identify that if the following inequality is met:

$$\alpha_{in} > \frac{1}{3}\alpha_h, \qquad \text{or} \qquad \frac{\alpha_{in}}{\alpha_h} > 0.333 \tag{8}$$

Then the total thermal resistance of the tubular exchanger is less than that of the heat pipe exchanger.

For the most heat exchangers used in industrial applications, eq. (8) is met easily. A design example of air pre-heater (flue gas temperature 805 °C and pre-heated air temperature 320 °C) in [17] presented that the ratio of α_{in}/α_h is 0.599, averaged α_{in} = 30.8 W/m^2°C, and α_h = 51.4 W/m^2°C. Another example of a secondary air pre-heater (the flue gas temperature 419 °C and pre-heated air temperature 310 °C) in [18] showed that the ratio of α_{in}/α_h is 0.86,

α_{in} = 48 W/m^2°C, and α_h = 56 W/m^2°C. Moreover, there are more methods to enhance α_{in} than α_h, such as by increasing fluid velocity and using various inserts in the tube which can increase the coefficient of convective heat transfer by 1-5 times or even more [19, 20].

The overall heat transfer coefficient for gas-to-gas recuperative heat exchanger applied in industrial fields is 10-40 W/m^{2}K [21], but a design example of an air pre-heater of finned heat pipe exchanger in [22] showed that the overall heat transfer coefficient is only 19.3 W/m^{2}K.

Conclusions

Heat pipe exchanger has been applied widely in various domains as a device of transfer of heat. However, the comparison of heat transfer performance between the heat pipe and tubular heat exchanger shows that the heat pipe exchanger is not better than a general heat exchanger. On the contrary, there are some deficiencies for the heat pipe exchanger, such as complicated manufacturing process, critical requirements for manufacturing materials, etc., which leads to a higher cost in comparison to a tubular heat exchanger. So, the selection and use of heat exchanger need to be fully measured and considered from the aspects of energy saving and initial investment.

Acknowledgment

This work is sponsored by the NSFC (No. 51576133).

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Paper submitted: January 10, 2015
Paper revised: April 21, 2015
Paper accepted: May 12, 2015