Experimental study on enhanced heat transfer tubes in falling film evaporation

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Abstract—The vertical tube falling film evaporation experimental platform was built, and the falling film evaporation heat transfer experiment was carried out. Comparative study was carried out between two types of enhanced heat transfer tubes, which are converging-diverging tube and the transversally corrugated tube, to explore their heat transfer characteristics of falling film evaporation. The results show that the falling film evaporative heat transfer coefficient of the two tubes increases with the increase of the unit peripheral flow rate, the heat transfer temperature difference, heat flux and the Reynolds number of the flash steam. The falling film evaporation heat transfer coefficient of the converging-diverging tube is about 1.09 times that of the transversally corrugated tube. According to the experimental data, the falling film evaporation heat transfer correlations of these two types of tubes were obtained. These results provide a useful reference for the using of transversally corrugated tube and converging-diverging tube in vertical falling film evaporator.

1. Introduction

The falling film evaporator has many advantages over the ordinary heat exchangers \cite{1-3}. Many researches were carried out on improving the heat transfer performance of vertical falling film evaporation tubes. Jiang\textsuperscript{4} developed a vertical corrugated tube falling film evaporator to optimize the heat transfer performance; Wei\textsuperscript{5} and Peng\textsuperscript{6} studied the heat transfer performance of falling film evaporation in a vertical tube by inserting a helix in the tube, and the results show that the helix structure can improve the heat transfer coefficient; Huang\textsuperscript{7} applied the converging-diverging tube to the falling film evaporator and found that the converging-diverging rib structure can enhance the heat transfer.

The converging-diverging tube is a kind of high-efficiency heat exchanger element widely used in ordinary heat exchangers. The researches on the heat transfer enhancement of the transversally corrugated tube are mainly focused on the common heat exchanger, and there is no report on the usage of this tube in vertical falling film evaporator in open literature. In addition, the comparative study on the heat transfer performance of falling film evaporation in converging-diverging tubes and cross grooved tubes is still lacking.

In this paper, falling film evaporation heat transfer experiments were carried out on converging-diverging tube (C-D tube) and transversally grooved tube (TC tube) to explore the difference of falling film evaporation heat transfer performance between them.
2. Experimental System and Method

2.1 Experimental process

The experimental flow of falling film evaporation heat transfer is shown in Figure 1.

![Flow chart of falling film evaporation experiment](image)

The liquid working fluid pressurized by the circulating pump flows out from the hot water tank, flows through the turbine flowmeter and enters the preheater. When the temperature of the working fluid rises to the boiling point, it enters the experimental section. The liquid distribution device is set in the experimental section, where the liquid is evenly distributed to the liquid storage device, making the falling film spread along the pipe wall evenly and quickly. Vapor provided by the steam generator is used as the heating source at the shell side.

![Structural parameters of the transversally grooved tube](image)

![Table 1 Parameters of heat exchange tubes](image)

The structure of the C-D tube and the TC tube are shown in Figure 2. The parameters of the heat exchange tube used in the experiments are shown in Table 1. The inner diameter, length and rib height of the C-D tube are the same as those of the TC tube.

2.2 Experimental data processing

The experimental data processing mainly includes as follows.

The calculation formula of unit peripheral flow is calculated as:

$$\Gamma = \frac{M}{\pi d_i}$$  \hspace{1cm} (1)

Where: $\Gamma$ is the liquid flow rate per unit wetted perimeter length, kg/(m·s); $M$ is the liquid flow rate per unit time, kg/s; $d_i$ is the inner diameter of the heat exchange tube, m.

The calculation formula of heat flux is as follows:

$$q = \frac{Q}{S} = \frac{m_r \cdot r}{S \cdot t}$$  \hspace{1cm} (2)
Where: $Q$ is the heat load, W; $S$ is the effective heat transfer area of the heat exchange tube, m$^2$; $m_v$ is the condensation amount of steam, kg; $r$ is the condensation latent heat of saturated steam, kJ/kg; $t$ is the experimental time, s.

The calculation formula of heat transfer temperature difference is as follows:

$$\Delta T = T_{\text{sat}} - T_{\text{wi}}$$

(3)

Where: $T_{\text{sat}}$ is the saturated steam temperature under the operating pressure, K; $T_{\text{wi}}$ is the average temperature of the inner wall of the heat exchange tube, K.

The thermocouple is embedded on the outer surface of the heat exchange tube, so the measured wall temperature is the surface temperature of the outer wall of the tube

$$T_{\text{wo}} = T_{\text{wi}} - \frac{Q}{2\pi L \cdot \lambda_{\text{tube}} \ln \frac{d_o}{d_i}}$$

(4)

Where: $T_{\text{wo}}$ is the average temperature of the outer wall, K; $d_o$ is the outer diameter of the tube, m; $\lambda_{\text{tube}}$ is the heat conductivity of the tube, W/(m·K); $L$ is the length of the tube, m.

The calculation formula of the total heat transfer coefficient is as follows:

$$K = \frac{Q}{A_i \cdot \Delta T_w}$$

(5)

Where: $A_i$ is the inner surface area of the tube, m$^2$; $\Delta T_w$ is the average heat transfer temperature difference between steam and liquid, K.

The total heat transfer resistance is expressed as:

$$\frac{1}{K} = \frac{1}{h_i} + \frac{A_i}{h_f A_i} + R_{\text{wall}}$$

(6)

Where: $A_o$ is the outer surface area of the tube, m$^2$; $h_i$ is the condensation heat transfer coefficient of the steam side, W/(m$^2$·K); $h_f$ is the heat transfer coefficient of the falling film side, W/(m$^2$·K); $R_{\text{wall}}$ is the heat resistance of the tube wall, m$^2$·K·W$^{-1}$.

The condensation heat transfer coefficient ($h_i$) of heated steam outside the heat transfer tube is calculated by the modified Nusselt film condensation correlation$^{[8][9]}$:

$$h_i = 1.76 \lambda_{\text{d.o}} \left(\frac{\rho_{l,o} g}{H_{d.o}}\right)^{1/3} Re_{d.o}^{1/3}$$

(7)

Where: $\rho_{l,o}$ is the density of condensate outside the tube, kg/m$^3$; $g$ is the acceleration of gravity, m/s$^2$; $\lambda_{d.o}$ is the thermal conductivity of condensate, W/(m·K); $\mu_{l,o}$ is the dynamic viscosity of condensate, Pa·s; $Re_{d.o}$ is the Reynolds number of steam.

The heat transfer coefficient of falling film evaporation in the heat transfer pipe is calculated by thermal resistance method:

$$h_f = \frac{1}{K} - \frac{1}{h_i} \frac{d_o}{d_i} \frac{d_i \ln(d_o/d_i)}{2 \lambda_{\text{tube}}}$$

(8)

The dimensionless heat transfer coefficient $h^+$ is used to characterize the heat transfer characteristics of falling film evaporation:

$$h^+ = h_f \left(\frac{v^2}{\lambda_{d.o}^3 g}\right)^{1/3}$$

(9)

3. Experimental Results and Discussion

3.1 Influence of unit peripheral flow rate on heat transfer performance

Fig. 3 shows the variation of heat transfer coefficient of falling film evaporation with different unit peripheral flow rates in the C-D tubes and the TC tube. From the overall trend, the evaporation heat transfer coefficients of the two types of tubes increase with the increase of the $\Gamma$. In addition, by
comparing the heat transfer data between the C-D tubes and the TC tube, it is found that the average heat transfer coefficient of falling film evaporation in the C-D tube is about 1.09 times that of the TC tube at the same flow rate. It can be seen that the converging-diverging structure has a better enhancement effect on the heat transfer of falling film evaporation comparing with the ring rib structure. It may because that the effective heat transfer area of the C-D tube is larger than that of the TC tube when the inner diameter the tube length is same, and the turbulent degree of the falling film on C-D tube is greater due to the continuous change of the cross-section structure.

3.2 Influence of temperature difference on heat transfer performance

The variation of heat transfer coefficient of falling film evaporation with heat transfer temperature difference is shown in Fig. 4. It can be seen from the figure that the evaporation heat transfer coefficients of the two types of tubes increase with the increase of heat transfer temperature difference. The evaporation intensity of gas-liquid interface in the tube increases with the increase of heat transfer temperature difference, which makes the enhancement effect better. In addition, under the same temperature difference, the evaporation heat transfer coefficient in the C-D tube is always greater than that of the TC tube.

3.3 Effect of heat flux on heat transfer performance

The relationship between heat flux and heating temperature difference is shown in Figure 5. The curves in the figure show that the heat flux in the C-D tube and the TC tube will increase with the increase of heating temperature difference. In addition, under the same condition of Reynolds number, the temperature difference C-D tube needed is about 87% that of the TC tube to reach the same heat flux. This means that the temperature rise of falling film in the C-D tube is larger and the heat transfer effect is better under the same heat flux.

Figure 6 shows the effect of heat flux on the heat transfer performance of falling film evaporation. It can be seen from the figure that the variation curves of the evaporation heat transfer coefficient in the two types of tube show an upward trend with the increase of heat flux. Under the same heat flux, the falling film evaporation heat transfer coefficient in the C-D tube is significantly higher than that in the TC tube.
3.4 Influence of secondary steam on heat transfer performance

Figure 7 shows the influence of secondary steam Reynolds number on the heat transfer coefficient of falling film evaporation.

The calculation formula of secondary steam Reynolds number is shown in equation (10)

\[ \text{Re}_{iv} = \frac{d_0 u_v \rho_v}{\mu_v} = \frac{dm_v}{\mu_v A} \]  

(10)

Where: \( \mu_v \) is the dynamic viscosity of steam, Pa·s; \( \rho_v \) is the steam density, kg/m\(^3\); \( u_v \) is the velocity of steam, m/s.

With the increase of Reynolds number of the secondary steam in the tube, the drag force and disturbance on the liquid film get stronger, and the turbulent degree of the liquid film gets higher. Therefore, the heat transfer effects of the falling film in the heat transfer tubes are enhanced. The turbulent degree of the falling film in the C-D tube is more intense than that in the TC tube, and the drag force of the secondary steam on the film is also greater, making the heat transfer enhancement effect better.

3.5 Correlation of heat transfer characteristics of falling film evaporation

Former study \[10\] shows that the heat transfer coefficient can be expressed as equation (11)

\[ h^* = a \cdot \text{Re}^{n} \cdot \text{Pr}^{r} \]  

(11)

Considering the influence of secondary steam on the heat transfer performance of falling film evaporation, \( \text{Re}_{iv} \) is introduced as a correction term, as shown in equation (12)

\[ h^* = a \cdot \text{Re}_{iv}^{n} \cdot \text{Pr}^{r} \cdot \text{Re}_{iv}^{b} \]  

(12)

The heat transfer data of falling film evaporation in TC tube were fitted and regressed, and the best fitting model was selected. The final correlation is as follows:

\[ h^* = 2.057 \times 10^{-3} \cdot \text{Re}_{iv}^{0.421} \cdot \text{Pr}^{0.0714} \cdot \text{Re}_{iv}^{1} \]  

(13)

The data of falling film evaporation heat transfer of the C-D tube were fitted and regressed, and the best fitting model was selected through constant adjustment as follows:

\[ h^* = 0.0032 \cdot \text{Re}_{iv}^{0.473} \cdot \text{Re}_{iv}^{0.1031} \cdot \text{Pr}^{1} \]  

(14)

4. Conclusion

In this study, the heat transfer characteristics of falling film evaporation in C-D tube and TC tube were carried out. The results show that the evaporation heat transfer coefficient increases with the increase of unit peripheral flow rate, heat transfer temperature difference, heat flux and secondary steam Reynolds number. The heat transfer coefficient of falling film evaporation is improved by using C-D tube and TC tube, and the heat transfer coefficient of C-D tube is about 1.09 times that of the TC tube under the same operating conditions. Based on this research, the correlations of falling film evaporation heat transfer in the C-D tube and the TC tube are obtained. These results can be used as references for engineering application of transversally corrugated tube and converging-diverging tube in vertical falling film evaporator.

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