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Research Article

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Research on heat transfer coefficient of horizontal tube falling film evaporator

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ABSTRACT

The principle of operation, characteristics and heat transfer process of horizontal tube falling film evaporators were introduced. Previous experimental correlations of the heat transfer coefficient on the outside of the evaporative tube and the heat transfer coefficient on the inside of the horizontal tube falling film evaporator was summarized. Analysis was conducted on the flow of the liquid film on the inside and outside of the evaporator tube under steady working conditions and the effects of evaporation temperature, heat transfer temperature difference, and tube diameter on the local heat transfer coefficient and the total heat transfer coefficient. The experimental correlation between the heat transfer film coefficient of the condensation side and the evaporative side of the horizontal smooth tube was compared. An empirical formula relating the condensation heat transfer film coefficient and the evaporation heat transfer film coefficient was derived which was suitable for the initial engineering design of horizontal tube falling film evaporators.

Key words: horizontal tube; falling film evaporation; heat transfer coefficient; experimental correlations; evaporation temperature;

INTRODUCTION

The mechanical vapor recompression (MVR) evaporator is a new type of highly efficient and energy saving evaporator. It uses a compressor to compress the secondary steam, raising its heat and pressure in order to increase the internal energy before sending the steam back into the evaporator for condensing heat transfer and ultimately saving energy[1].This new type evaporator is widely used in chemical, pharmaceutical, food, waste water treatment, desalination and other industries. Evaporators, one of the key parts of MVR evaporation technology, can be classified into different types including climbing film evaporator, falling film evaporator, forced circulation evaporator, horizontal tube evaporator, etc. The MVR evaporation system often uses vertical or horizontal tube falling film evaporator [2]. The horizontal tube falling film evaporator when compared with the vertical version not only has lower power consumption, reduced equipment height requirements, and smaller heat transfer temperature difference due to the high heat transfer coefficient and low vapor phase resistance caused by the thin liquid film.

For the smooth tube, the heat transfer coefficient of horizontal tube is three times that of flash distillation and twice that of a vertical tube evaporative device [3]. The high heat transfer coefficient of horizontal tube falling film evaporator, the required heat load of the same heat transfer area can be greatly reduced. Due to the fact that the horizontal tube falling film evaporator can transfer heat with small temperature differences, the degree of superheating of the tube surface is lower and the scaling on the surface of the tube also can be reduced. Horizontal tube falling film evaporators are widely used because of these advantages over other evaporators. Horizontal tube falling film evaporator has only been developed for a relatively short amount of time and inadequate research has been done. There exists large differences between the research on heat transfer coefficients on the inside and outside of the tube where the applicability of empirical formulas is insufficient[4]. This paper conducts comparative analysis on several classic formulas in order to find the more adaptive empirical formulas to provide guidance in the theoretical design evaporators.

1. THE HEAT TRANSFER PROCESS OF THE HORIZONTAL TUBE FALLING FILM EVAPORATOR

For the horizontal tube falling film evaporator, the steam flows on the inside of the tube while the solution flows outside the tube. Steam condenses on the inside of the tube to release heat which is then absorbed by the solution on the outside. In Fig. 1, the solution is preheated before entering the evaporator; the pressure in the evaporator is then reduced by suction from the compressor which reduces the boiling point of the solution and allows the solution to first become saturated liquid and then subsequently evaporates into saturated steam. The saturated steam undergoes compression and then goes through the heat exchange tube to become superheated steam. Superheated steam goes into the evaporator heat exchange tube to exchange heat with the tube solution before condensing[5]. With the operation of the system, heat is continuously sent to the evaporation device and the temperature inside the device will gradually rise. Pressure inside the evaporator will rise along with the temperature and after reaching the energy equilibrium, the system achieves a stable working condition. From this point, only the state changes within the evaporator under the stable working condition is considered. The heat exchange process inside of the tube can be divided into three stages [6]. During the first stage, the high temperature and high pressure superheated steam cools into saturated steam. During the second phase, the saturated team releases its latent heat to change into saturated water. During the final stage, the saturated water cools into cold water. The heat exchange process on the outside involves saturated water transforming into saturated team.

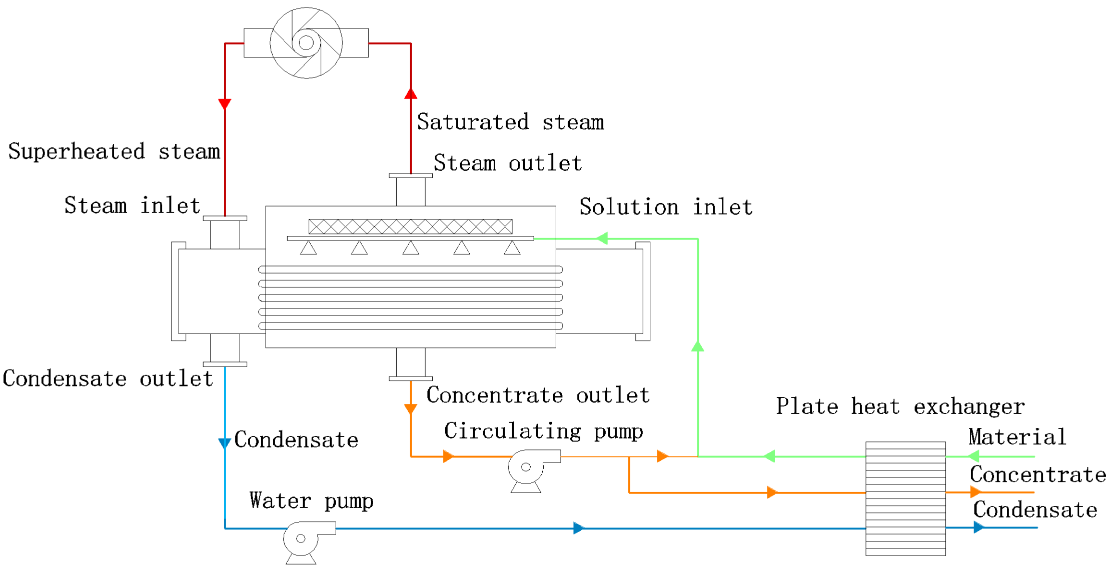

Fig.1 Schematic diagram of horizontal tube falling film evaporator

The heat transfer coefficient of horizontal tube falling film evaporator can be expressed as follows:

$$k=\frac{1}{\frac{1}{h_2}+\frac{D_1}{2\lambda}\ln\frac{D_1}{D_2}+\frac{D_1}{h_1 D_2}} \qquad (1)$$

Where h_1 is tube condensing heat transfer coefficient, kW/(m^2·□); h_2 is tube evaporation heat transfer coefficient, kW/(m^2·□), D_1 is outer diameter of heat exchange tube, D_2 is inner diameter of heat exchange tube, λ is coefficient of thermal conductivity of the heat exchange tube, kW/ (m·□). The heat exchange tube's thermal conductivity can be found in relevant references based on the tube material, and determining the condensing heat transfer coefficient inside the tube and evaporation heat transfer coefficient outside the tube is the key to the study.

2. CONDENSATION HEAT TRANSFER INSIDE A HORIZONTAL TUBE

The condensation heat transfer process inside the horizontal tube is more complex due to the steam condensation and flow changes. Factors, including two phase transformation, inter-atomic forces, and gravity, have a big impact on theoretical analysis. A layer of liquid film can form on the inner wall of the evaporator tube. When the steam flow rate is large and the condensation water flow rate is small, condensation water will be evenly distributed along the tube internal wall and a circular flow is created. As the condensation process occurs, condensed water increases, steam flow rate drops and condensed water gathers at the bottom of the tube due to gravity to form a stratified flow. For the annular flow, the annular liquid film can be considered to be symmetrical axially and the heat transfer can be considered to be uniform along the circumferential direction because the liquid film is spread evenly which simplifies the calculation. In terms of stratified flow, the liquid membrane is thicker at the bottom of the tube, which hinders the heat transfer and changes the heat transfer coefficient, causing the heat transfer coefficient on the steam side and condensation side to be calculated separately. The following models are used to model the annular flow: Nusselt model, shear force model, and boundary layer model.

1) The Nusselt model [7] considers the heat resistance to be concentrated in the liquid film layer and is related to the liquid film thickness. The heat transfer correlations are as follows:

$$h_1 = \frac{\theta}{\pi}\beta\left[\frac{\lambda_l \rho_l \left(\rho_l - \rho_v\right) g r}{\mu_l D_2 \left(t_{\mathrm{s}} - t_{\mathrm{w}}\right)}\right]^{\frac{1}{4}} \tag{2}$$

λ_1 is thermal conductivity of the condensed liquid film, W/(m·□); ρ_l is water density, kg/m^3; ρ_v is steam density, kg/m^3; g is the local acceleration of gravity, m/s^2; r is the latent heat of vaporization, kJ/kg; μ_{l} is water dynamic viscosity, kg/(m·s); D_2 is the inner diameter of the tube, m; t_{s} is steam temperature, □ t_{w} is wall surface temperature, □.

Chato[8] thought that β depends on θ and in the range of 0.72-0.91. Taking into account of the fact that the liquid condensed on the wall is super cooled liquid, the latent heat has been modified in the above equations giving:

$$h_1 = 0.555\left[\frac{\lambda_l^{\,3} \rho_l \left(\rho_l - \rho_v\right) g r'}{\mu_l D_2 \left(t_{\mathrm{s}} - t_{\mathrm{w}}\right)}\right]^{\frac{1}{4}} \tag{3}$$

$$r' = r + \frac{3}{8} C_{\mathrm{P}} \left(t_{\mathrm{s}} - t_{\mathrm{w}}\right) \tag{4}$$

where C_{P} is condensate liquid heat capacity at constant pressure, kJ/(kg·□). Nusselt also proposed a formula for the average heat transfer coefficient of the film condensation, the equation is shown as follows:

$$h_1 = 0.934\left(\frac{g \lambda_l^{\,3} \rho_l^{\,2} r}{\mu_l L \left(t_{\mathrm{s}} - t_{\mathrm{w}}\right)}\right)^{\frac{1}{4}} \tag{5}$$

Where L is the characteristic length, m.

2）The sheer force model, put forward by Carpenter and Colburn[9], assumes that the heat resistance is concentrated in the liquid membrane layer. The inner side of the tube and the annular liquid membrane creates shear forces and the shear stress affects the thickness of the liquid film. The formula for the shear model is as follows:

$$h_1 = 0.043 \frac{\lambda_l \rho_l^{\,0.5} Pr^{0.5}}{\mu_l} \tau_0 \tag{6}$$

Where Pr is the Prandtl number of water, τ_0 is the sheer force between the steam and condensate fluid, Pa.

3) Boundary layer model is also called stratified flow model. The flow distribution of this model is complex and currently there is no clear formula to calculate it. Cavallini [10] believes that when the condensation flow rate is small, the heat transfer coefficient of the flow in the upper strata should be calculated by Nusselt model while the heat transfer coefficient of the lower strata of condensed water should be calculated based on convection heat transfer. Condensing film heat transfer coefficient formula recommended by Kern[11] is as follows:

$$h_1 = 0.023\frac{Re^{0.8}Pr^{1/3}\lambda_l}{D_1}\left(\frac{\mu_l}{\mu_w}\right)^{0.14} \tag{7}$$

where *Re* is Reynolds number of the fluid inside the tube; D_1 is heat transfer outer tube diameter, m; μ_w is the dynamic viscosity of water at the wall temperature, kg/(m·s). Condensation heat transfer coefficients were calculated at different evaporation temperatures using the above formulas under the following conditions: the heat transfer tube has an inner diameter of 0.015m and an outer diameter of 0.019m; the tube has an inner steam flow rate of 0.2m^3/h.

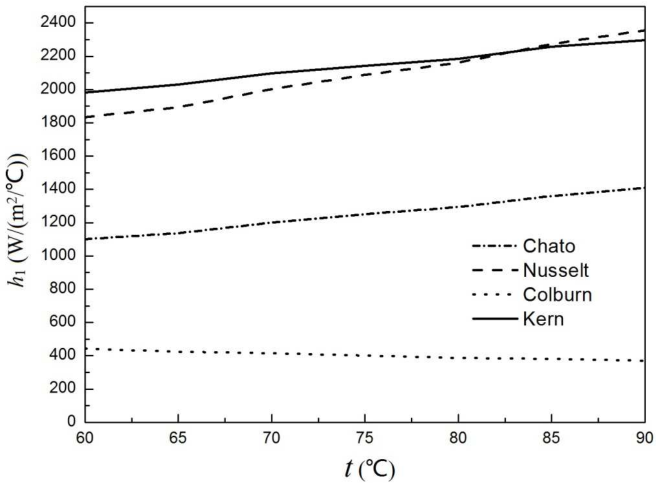

Fig.2 The condensation heat transfer coefficient calculated at different evaporation temperatures

From the calculation, the Nusselt model and the Kern model had similar results. The Colburn model provides the largest differences in the heat transfer coefficients from the other models. The results shows that the Colburn model should not be used to estimate experimental data and that the Nusselt or Kern model should be used for theoretical calculations during evaporator design. The falling film evaporation outside the horizontal tube is driven by gravity. Unevaporated residual water from the upper horizontal tubes drip down to lower horizontal tubes, forming a liquid film in order to achieve the process of evaporation.

In the process, the liquid forms a gas-liquid two-phase flow state on the heat exchange tube. The liquid of the liquid film flow on the horizontal tubes has three main states: droplet flow, columnar flow, and laminar flow. The state of the liquid is dependent on liquid velocity, tube spacing, and the properties of the liquid. When the liquid flow velocity is small, the form of the liquid film is droplet flow; when the liquid velocity increases, the form of the liquid film is columnar flow; and when the liquid velocity increases even more, the form of the liquid film is laminar flow. Many factors influence horizontal tube falling film evaporation and there is still no consensus on its heat transfer law. Nusselt studied falling film evaporation earlier than most other studies but the resulting experimental correlations had poor applicability. Most studies are based on the semi-empirical formula of experimental regression which has some limitations. This paper compares some widely used experimental correlations. The Cooper [12] formula is applied widely at the present and is as follows:

$$h_2 = 90q^{0.67}M_l^{-0.5}P_l^{m}\left(-\lg P_l\right)^{-0.55} \tag{8}$$

$$m = 0.12 - 0.21gR_{\mathrm{P}} \tag{9}$$

$$q = 0.149r\rho_v^{0.5}\left[\sigma g\left(\rho_l - \rho_v\right)\right]^{0.25} \tag{10}$$

where q is heat flux, W/m^2; M_l is the relative molecular mass of the liquid; P_l is the ratio of the pressure of liquid and the critical pressure of liquid; R_{P} is the average surface roughness (0.3 is used in this paper) μm; σ is the surface tension of the liquid-steam interface, N/m.

Chun[13] concluded the following formula after research on the horizontal tube falling film evaporation on the outside of the tube.

$$h_2 = 0.822\left(\frac{\lambda_l^3 g}{\nu_l^2}\right)^{\frac{1}{3}} Re^{-0.22} \quad (11)$$

Where L is the characteristics constant which is assumed to the outer diameter D_1, m. B. Song[14] obtained the following tube outer membrane evaporation heat transfer coefficient calculation formula through experimental analysis:

$$h_2 = 0.177\frac{Pr^{0.5}\lambda_l}{\left(\nu_l^2/g\right)^{1/3}} \quad (12)$$

where ν_l is the kinematic viscosity of the liquid, m^2/s.

Nusselt[15] obtained the following tube outer membrane evaporation heat transfer coefficient calculation formula by experimental analysis:

$$h_2 = 0.728\left[\frac{gr\rho_l\left(\rho_l-\rho_v\right)\lambda_l^3}{\mu_l D_1\left(t_\mathrm{w}-t_\mathrm{b}\right)}\right]^{\frac{1}{4}} \quad (13)$$

Where μ_l is dynamic viscosity of the liquid, Pa·s.

Evaporation film heat transfer coefficients were calculated at different evaporation temperatures according to the above formulas, with the assumptions that, the heat transfer tube has an inner diameter of 0.015m and an outer diameter of 0.019m, and the tube has an inner steam flow rate of $0.2m^3/h$ conditions. The results are shown in Fig.3：

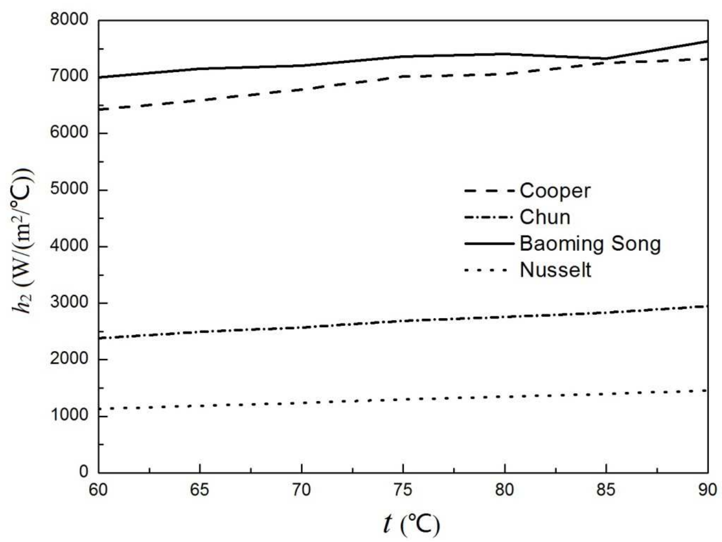

Fig.3 Calculated evaporation heat transfer coefficient at different evaporation temperatures

From the above graph, the results provided by Cooper's and B. Song's formulas (12) were similar. From this comparison Cooper's or B. Song's formulas are recommended.

3. THE FACTORS AFFECTING TOTAL HEAT TRANSFER COEFFICIENT

This article selects Nusselt's formula and B. Song's formula to analyze the factors that influences the total heat transfer coefficient.

Nusselt's formula for condensation heat transfer coefficient inside the tube:

$$h_1 = 0.934\left(\frac{g\lambda_l^3\rho_l^2 r}{\mu_l L\left(t_s - t_w\right)}\right)^{\frac{1}{4}} \tag{14}$$

B. Song's formula for the evaporation heat transfer coefficient outside the tube:

$$h_2 = 0.177\frac{Pr^{0.5}\lambda_l}{\left(v_l^2/g\right)^{1/3}} \tag{15}$$

Total heat transfer coefficient formula:

$$k = \frac{1}{\frac{1}{h_2} + \frac{D_1}{2\lambda}\ln\frac{D_1}{D_2} + \frac{D_1}{h_1 D_2}} \tag{16}$$

Heat transfer coefficient was calculated at different evaporation temperatures according to the above formulas, with the assumptions that the heat transfer tube has an inner diameter of 0.015m and an outer diameter of 0.019m, and the tube has an inner steam flow rate of $0.2m^3/h$ conditions, in order to understand the effect of evaporation temperature on the heat transfer coefficient.

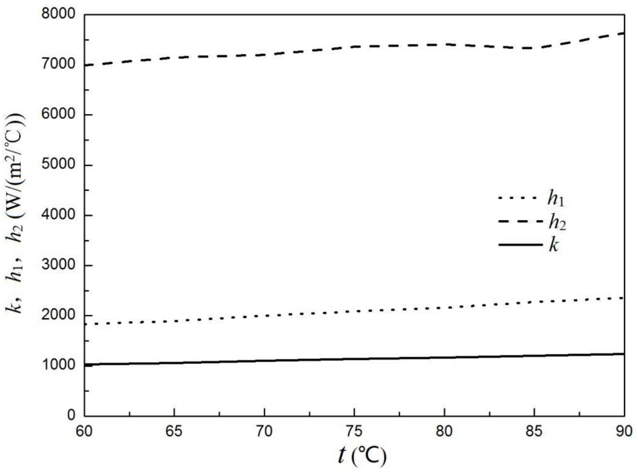

Fig.4 Effect of evaporation temperature on heat transfer coefficients

The graph above shows that h_1 (The heat transfer coefficient on the inner surface of the tube), h_2 (The heat transfer coefficient on the outer surface of the tube) and k (the total heat transfer coefficient) increases as the evaporation temperature increases. Total heat transfer coefficient was calculated at different inner tube diameters according to formula (16), with the assumptions that the water evaporates in the evaporator, the evaporator's evaporation temperature is 70□, and the tube has an inner steam flow rate of $0.2m^3/h$ conditions, in order to understand the effect of tube diameter on the heat transfer coefficient.

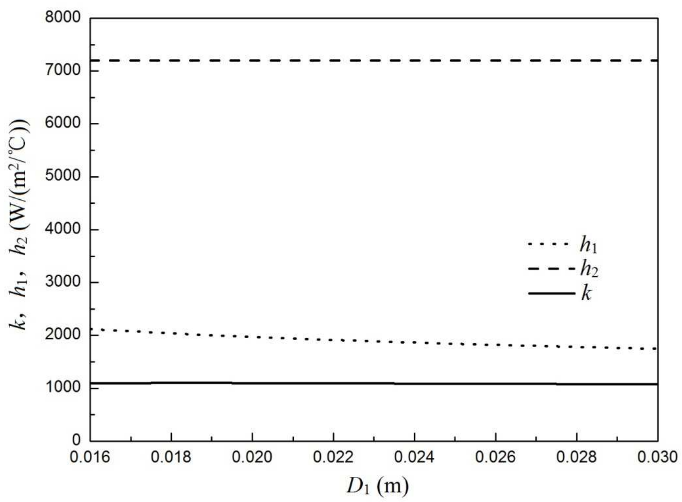

Fig.5 Effect of outer diameter of heat exchange tube on heat transfer coefficients

It can be seen that h_1 (The heat transfer coefficient on the inner surface of the tube) decreases, h_2 (The heat transfer coefficient on the outer surface of the tube) remains relatively constant, and k (the total heat transfer coefficient) decreases slightly as the tube diameter increases.

CONCLUSION

Through the comparison of heat transfer correlation analysis draws the following conclusions: (1) Comparative analysis found that the applicability of the Nusselt formula is better for calculating the condensation side heat transfer coefficient and its use is recommended for estimation purposes at the beginning of the design; (2) For the evaporation side heat transfer coefficient formula, the applicability of the formula which B. Song obtained through experimentation is better and its use is recommended for estimation purposes at the beginning of the design; (3) The analysis found that the total heat transfer coefficient k increases with increases in evaporation temperature and decreases slightly with increases in inner tube diameter.

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