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Study on heat transfer of falling film evaporation characteristics on heat pipes in negative pressure

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ABSTRACT

As a high performance heat transfer method, heat pipes are being widely used in different fields of industry. Based on the boundary layer theory in the article, the rules of the velocity and the thermal boundary layers outside the heat pipe falling film evaporation in the negative pressure are discussed, and the formulas of thickness of both velocity and thermal boundary layers are given. Then based on these formulas, the calculation method of the falling film evaporation heat transfer coefficient outside the heat pipe is discussed. The effects of vacuum, falling liquid load, temperature gradation and etc. on the evaporation performance of heat transfer are analyzed. It provides the guidance in desalination application of the evaporation outside the heat pipe in negative pressure.

Keywords: Heat pipe; Falling film evaporation; Negative pressure

1. Introduction

Falling film evaporation outside of pipes is an effective heat transfer mode as it has a high heat transfer coefficient at low heat temperature and small temperature difference. The liquid flow outside the pipe makes for the steam and liquid phase to be separated as soon as possible, which makes the heat transfer coefficient relatively high. In the multiple effect distillation (MED) desalination system, falling film evaporation is usually used for desalination at temperatures below 70°C. In this heat transfer method, metal pipes cannot be easily corroded by seawater below 70°C and the temperature of the heat resource required is also low which helps to utilize low-grade waste heat.

Gao [1] gave a new desalination approach which is falling film evaporation desalination with heat pipes. A falling film on one side of the heat pipe evaporates in negative pressure and the other side of heat pipe is heated using all kinds of low quality heat, such as solar energy, gas waste heat and cooling water heat; at the same time, it makes the desalination structure easy. Because evaporation in negative pressure accelerates the steam and liquid phase separating, it has a higher heat transfer coefficient. Now, a lot of studies on falling film evaporation has been done. According to Parken [2] and Mitrovic [3], the heat transfer coefficient increases with the falling film flow rate. Yang [4] experimentally studied the falling film on horizontal tubes. Bourouni [5] presented a theoretical investigation on heat transfer in a liquid film flowing around a horizontal tube.

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The main objective of this paper is to propose a more complete model to analyze the heat transfer of the falling film evaporation in the negative pressure by using the boundary layer approach. Based on the boundary layer principle, the rules of the formation of both velocity and thermal boundary layers of a falling film flowing outside the heat pipe under the action of gravity are discussed. At the thermal balance, the heat transfer characteristics were found.

2. Numerical model

For the falling film evaporation process on the horizontal heat pipe, the quantity of heat needed is from the heat pipe and it is transferred to the surface of the liquid film outside the pipes. The state of falling film evaporation outside the pipe is 4 < Re < 350 [6], which is deemed as a continuum film. Seawater is supplied uniformly to the surface of the heat pipe through a feeder, then the falling film is formed on the pipe. Here the liquid film would be heated to evaporate. The adhibiting coordinate was employed and the surface of heat pipe was spread by the circle of the pipe. Fig. 1 gives the calculative model. So, the surface coordinate of the heat pipe can be descriptive in the right-angle coordinate *x*–*y*.

In the theoretical analysis we presume that: 1) the falling film is laminar flow and the flow velocity is small; 2) the surface of the film has no fluctuation; 3) the surface tension of the film is not calculated; 4) the shearing effect of the heat pipe to the film is neglected; 5) the physical identity is constant.

The mass conservation equation is:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

The momentum conservation equation is:

$$u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho_l}\frac{dp}{dx}+g+\upsilon\frac{\partial^2 u}{\partial y^2} \tag{2}$$

From the interface relation of the liquid and the gas

$$\begin{cases}\dfrac{\partial p}{\partial y}=0\\[2mm] \dfrac{dp}{dx}\approx g\rho_v\end{cases} \tag{3}$$

Through Eq. (2),

$$\mu\frac{\partial^2 u}{\partial y^2}=-g\left(\rho_l-\rho_v\right)\sin\left(\frac{x}{R}\right) \tag{4}$$

The density of the liquid and solid varies little, but the density of gas varies much. So, ρ_v is steam pressure of the definite negative pressure in Eq. (4).

As $y = 0$, $u = 0$

$$y=\delta,\ \frac{\partial u}{\partial y}=0 \tag{5}$$

From Eq. (4) and boundary condition Eq. (5),

$$u=\frac{g\left(\rho_l-\rho_v\right)}{\mu}\left[\delta y-\frac{1}{2}y^2\right]\sin\left(\frac{x}{R}\right) \tag{6}$$

Through Eq. (6) and mass conservation Eq. (1),

$$v=-\frac{g\left(\rho_l-\rho_v\right)y^2}{2\mu}\left[\frac{d\delta}{dx}\sin\left(\frac{x}{R}\right)+\frac{1}{R}\left(\delta-\frac{y}{3}\right)\cos\left(\frac{x}{R}\right)\right] \tag{7}$$

At the random position *x*, the liquid mass flow rate is:

$$m=\int_0^{\delta}\rho u(y)dy \tag{8}$$

Eq. (6) is calculated in Eq. (8) and the thickness of velocity boundary layer is:

$$\delta=\left[\frac{3\mu m}{\left(\rho_l-\rho_v\right)^2 g\sin\left(\dfrac{x}{R}\right)}\right]^{\frac{1}{3}} \tag{9}$$

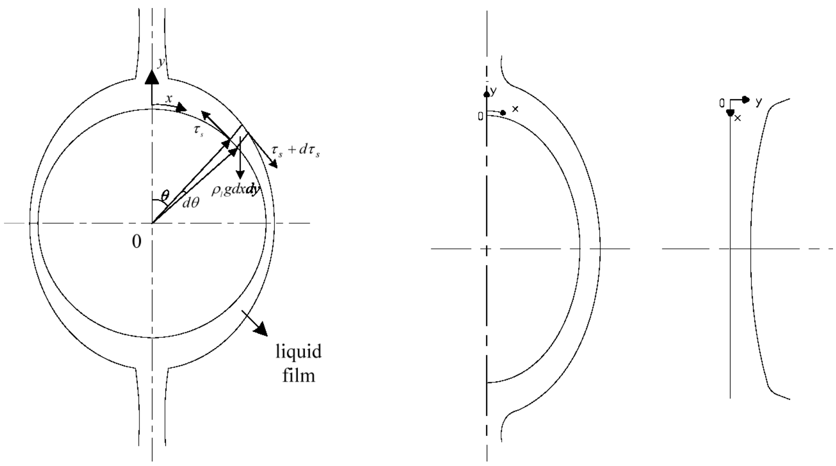

Fig. 1. Liquid boundary layer model outside the pipe.

When the falling film is in negative pressure, the falling water temperature is 30–70°C, so that Pr is 2.2–5.4. Based on the measure stage of boundary layer [7], $\partial^2 t/\partial x^2 << \partial^2 t/\partial y^2$, the conduction heat is deemed along y orientation and dissipated heat is neglected.

The energy integral formula is:

$$\frac{d}{dx}\int_0^{\delta_t} u\left(t_f - t\right)dy = a\frac{\partial t}{\partial y}\Big|_{y=0} \tag{10}$$

In Eq. (10), t_f is the mainstream temperature outside of film.

$$\frac{d}{dx}\int_0^{\delta_t} u\left[\left(t_f - t_w\right)-\left(t - t_w\right)\right]dy = a\frac{\partial t}{\partial y}\Big|_{y=0} \tag{11}$$

In Eq. (11), t_w is the heat pipe wall temperature.

As Pr > 1, the thickness of velocity boundary layer δ is thicker than the temperature boundary layer. So, the velocity distributing in the temperature boundary layer is linear.

$$u = \frac{\partial u}{\partial y}\Big|_{y=0}\cdot y \tag{12}$$

Through Eqs. (6) and (12), the velocity distributing in the temperature boundary layer is

$$u = \frac{g\left(\rho_l - \rho_v\right)}{\mu}\sin\left(\frac{x}{R}\right)\delta\cdot y \tag{13}$$

According to [7], the temperature distributing in the temperature boundary layer is:

$$\frac{t - t_w}{t_f - t_w} = A\frac{y}{\delta_t} + B\left(\frac{y}{\delta_t}\right)^3 \tag{14}$$

Through the differential coefficient, Eq. (14) is transformed as

$$\frac{\partial t}{\partial y}\Big|_{y=0} = A\frac{t_f - t_w}{\delta_t} \tag{15}$$

From Eqs. (11), (13)–(15)

$$\frac{d}{dx}\int_0^{\delta_t}\frac{g\left(\rho_l - \rho_v\right)\delta}{\mu}\sin\left(\frac{x}{R}\right)y\left[\left(t_f - t_w\right) - A\left(t_f - t_w\right)\frac{y}{\delta_t} - B\left(t_f - t_w\right)\left(\frac{y}{\delta_t}\right)^3\right]dy = a\cdot A\cdot\frac{t_f - t_w}{\delta_t} \tag{16}$$

In Eq. (16), $a = \lambda / (\rho c)$ is thermal diffusion rate.

For the temperature boundary layer,

$$\begin{cases} y = 0 : t = t_w \quad \text{and} \quad \dfrac{\partial^2 t}{\partial y^2} = 0 \quad \text{(a)} \\ y = \delta_t : t = t_f \quad \text{and} \quad \dfrac{\partial t}{\partial y} = 0 \quad \text{(b)} \end{cases} \tag{17}$$

Through Eq. (16) and temperature boundary layer condition Eq. (17),

$$\delta_t = \left[\frac{ax\mu^{\frac{2}{3}}}{8\left(\rho_l - \rho_v\right)^{\frac{1}{3}} g^{\frac{2}{3}} (3m)^{\frac{1}{3}} \sin^{\frac{2}{3}}\left(\frac{x}{R}\right)}\right]^{\frac{1}{3}} \tag{18}$$

In Eq. (18), the parameter of matter property is decided by $T = (t_f + t_w) / 2$, (m) is feed water load (kg/(m·s)).

From Eq. (18), the local heat transfer coefficient outside heat pipe is:

$$a_x = \frac{\lambda}{\delta_t} = \lambda / \left[\frac{ax\mu^{\frac{2}{3}}}{8\left(\rho_l - \rho_v\right)^{\frac{1}{3}} g^{\frac{2}{3}} (3m)^{\frac{1}{3}} \sin^{\frac{2}{3}}\left(\frac{x}{R}\right)}\right]^{\frac{1}{3}} \tag{19}$$

The above formula is through integral along heat pipe circle, the average heat transfer coefficient outside heat pipe is;

$$a = \frac{1}{\pi R}\int_0^{\pi R} a_x dx \tag{20}$$

3. Numerical results

3.1. Effect of vacuum on the falling film evaporation heat transfer coefficient

Figs. 2–4 show that the falling film evaporation heat transfer coefficient varies with different heat pipe diameters and in different vacuum conditions. From these figures, with vacuum increasing, the evaporation heat transfer coefficient increases at a definite heat pipe

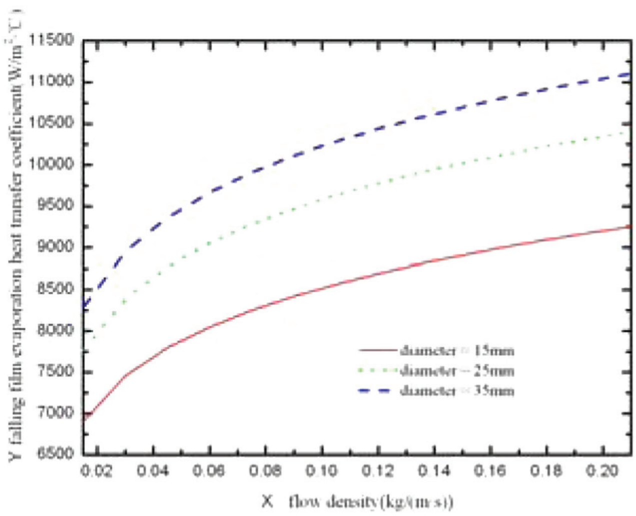

Fig. 2. Effect of vacuum on the falling film evaporation heat transfer coefficient; vacuum 0.03 MPa.

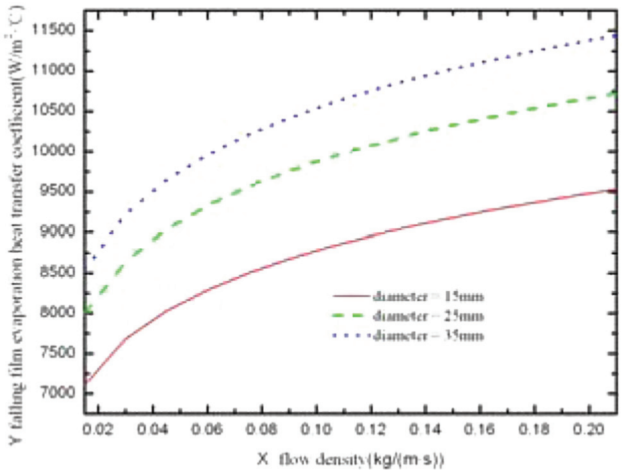

Fig. 3. Effect of vacuum on the falling film evaporation heat transfer coefficient; vacuum 0.05 MPa.

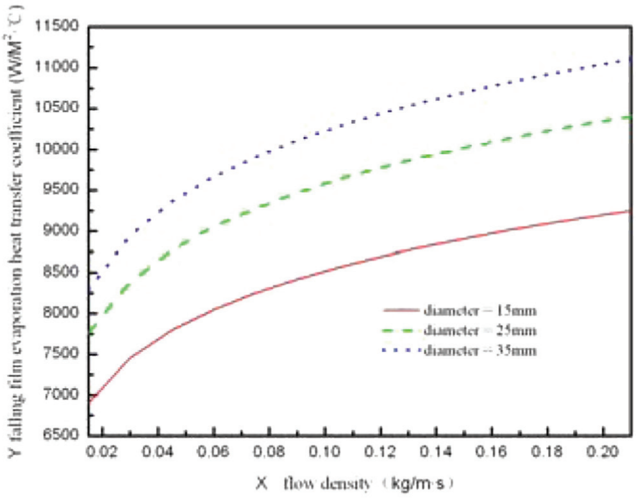

Fig. 5. Effect of flow density on the falling film evaporation heat transfer coefficient.

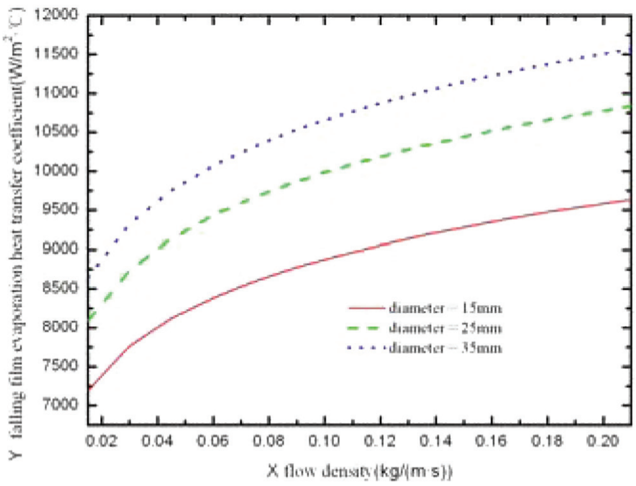

Fig. 4. Effect of vacuum on the falling film evaporation heat transfer coefficient; vacuum 0.07 MPa.

diameter and flow density. The reason is that when the vacuum degree is higher and pressure around the film reduces, the evaporation runs easily.

3.2. Effect of flow density on the falling film evaporation heat transfer coefficient

Fig. 5 shows the influence of flow density on heat transfer coefficient with different heat pipe diameters when the vacuum degree is 0.07 MPa. From Fig. 5, the heat transfer coefficient increases with the flow density increasing at a definite pipe diameter. Higher flow density makes the velocity to increase outside the heat pipe and in the same condition; the temperature boundary layer would attain the mainstream temperature quickly and the thickness of the temperature boundary layer would be less.

3.3. Effect of temperature difference on the falling film evaporation heat transfer coefficient

Fig. 6 shows the influences of temperature difference on heat transfer coefficient at a vacuum degree 0.07 MPa and falling film temperature 69°C. From Fig. 6, the heat transfer coefficient increases slowly with the temperature difference increasing at a definite pipe diameter.

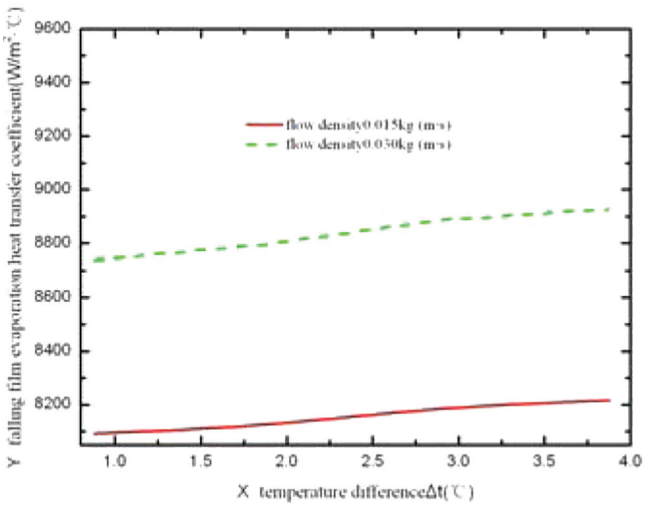

Fig. 6. Effect of temperature difference on the falling film evaporation heat transfer coefficient.

3.4. Effect of pipe diameter on the falling film evaporation heat transfer coefficient

Figs. 7–9 show the effect of pipe diameter on the falling film evaporation heat transfer coefficient in four flow densities and different vacuum degrees.

From Figs. 7–9, the heat transfer coefficient increases with the diameter increasing. But after reaching some degree, the increase tends to become relaxative.

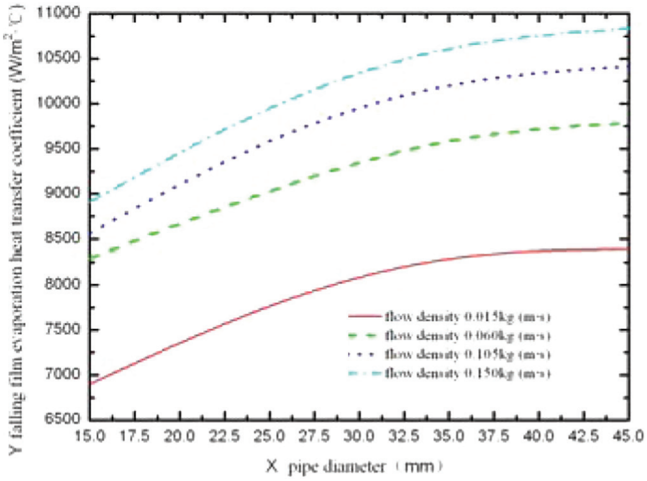

Fig. 7. Effect of pipe diameter on the falling film evaporation heat transfer coefficient; vacuum 0.03 MPa.

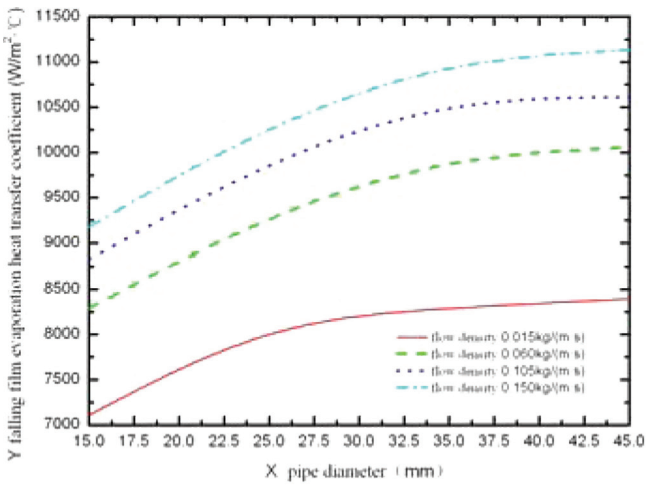

Fig. 8. Effect of pipe diameter on the falling film evaporation heat transfer coefficient; vacuum 0.05 MPa.

4. Conclusion

In this paper, heat transfer characteristics of falling film evaporation outside the heat pipe in the negative pressure was analyzed using the boundary layer theory. The thickness function of velocity and temperature

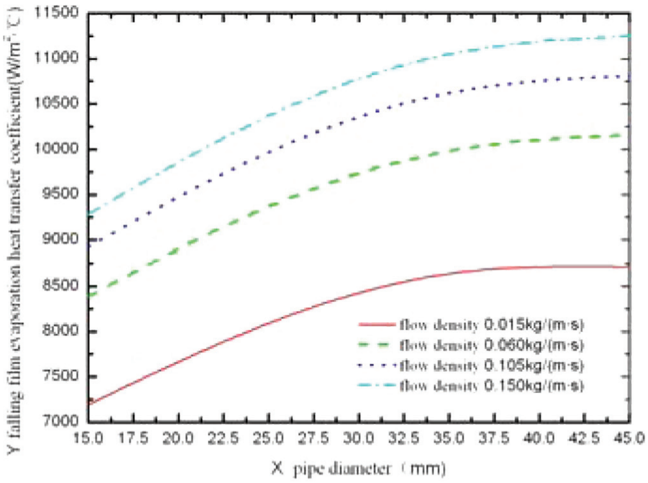

Fig. 9. Effect of pipe diameter on the falling film evaporation heat transfer coefficient; vacuum 0.07 MPa.

boundary layer were educed, and based on these, we got the average heat transfer coefficient rule outside the heat pipe. By calculating and analyzing, the conclusions were drawn as follows:

(1) At a definite heat pipe diameter and flow density, the falling film evaporation heat transfer coefficient increased with vacuum increasing.
(2) When the vacuum degree and pipe diameter are definite, the heat transfer coefficient increased with the flow density increasing.
(3) The falling film evaporation heat transfer coefficient increased slowly with the temperature difference increasing at a definite pipe diameter.
(4) The falling film evaporation heat transfer coefficient increased with the diameter increasing at first. When reaching some point, the increase tended to become relaxative.

From the above results, the falling film evaporation on the heat pipe in the negative pressure has good heat transfer characteristics. Furthermore, using heat pipes, all kinds of low quality heat resources could easily be utilized and make the structure of desalination system simpler. So this technique could be widely utilized in desalination, distillation, etc.

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Symbols

g	—	Acceleration of gravity, m/s^2
m	—	Flow density, kg/(m·s)

Pr — Prandtl number
t — Temperature, ºC
u, v–x, y — Direction velocity, m/s
δ — Thickness of liquid film, m
μ — Dynamical viscidity
ρ — Density, kg/m^3

Subscripts

f — Hydro-
l — Liquid
t — Thermal boundary layer
v — Gas
w — Wall

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