Heat Transfer Performance Prediction of Confined Thin Film Boiling

Yang Shi, Yingxue Yao*

School of Mechanical Engineering and Automation, Harbin Institute of Technology (Shenzhen), Shenzhen, 518055, China

Corresponding author: shiyanghitchina@outlook.com

Abstract. The liquid-vapor phase change is considered as one of the most effective way to transfer heat flux. Improving the heat transfer efficiency and critical heat flux (CHF) is crucial to face our energy-intensive and energy-deficient plight. Pool boiling in a confined thin liquid film is known to have the ability improve the heat transfer efficiency. This work theoretically predicted the heat transfer performance of the confined thin film boiling using non-vapor permeable gap through the thermal resistance analysis. The model showed the same trend as the practical situation that the thermal resistance can be reduced by the reducing the liquid thickness but the vapor leaving resistance was increased at the same time. The heat transfer efficiency can be increased by the decrement of both the liquid layer conduction resistance and convection resistance at the bubble interface because of the smaller bubble size and higher efficiency inside the confined thin liquid layer with higher temperature. But both the CHF and efficiency will be influenced a lot by the vapor leaving resistance from the gap. This work demonstrated the influence of superheat, gap size and gap length, also showed the potential to further increase the heat transfer efficiency and CHF if the vapor leaving resistance can be further reduced when using the vapor-permeable gap.

1. Introduction

Vaporization, including boiling and evaporation, is widely used in heat transfer applications of both industry and daily life, such as air conditioner, water desalination and power plant. A sharp increase of the heat dissipation demand, such as cooling of electron hotspot, makes the heat transfer with high efficiency being very imperative. Thin film boiling using a confined space was noticed due to its potential to increase the heat transfer coefficient (HTC) by reducing the thermal resistance. It can be easily used in many practical conditions like immerse cooling of electron device with highly packing density. Many researchers have studied pool boiling with confined gap of different gap sizes and confirmed that the heat transfer efficiency can be improved when the liquid film was confined under certain level usually in a few mm size of water, such as Fujita[1], Liu[2] and Unno[3], but the CHF will be sacrificed a lot. The dielectric fluid, such as HFE7100, FC-72, FC-73 by Cardoso[4], Passos[5], Misale[6] were also studied and got the same trend. Although some researchers modified the heating surface, like Xie[7], Utaka[8], to manipulate the bubble nucleation, the heat transfer performance, especially CHF, is not enhanced a lot. The low CHF mainly results from the high vapor resistance added by the confined lid. High speed images from Passos[5], Li [9] showed that when the small gap thicknesses impede the bubble departure, the bubble will grow radially along the gap, until reaching the confinement boundary to escape.
To further improve both the CHF and HTC, and reduce the thermal resistance from bubble nucleation, growth and departure of thin film boiling other than the confinement size, Xie[7] and Alsaati[10] studied the influence of confinement area that smaller confinement window can increase the CHF; Misale[6] studied the surface orientation and found it does not have special interface to the thin film boiling. To predict the heat transfer performance, Zhao[12] modelled the CHF of boiling in a confined space by the dry-out mechanism of microlayer under bubble; people also correlate with the experimental data based on the classical pool boiling equation of Zuber equation by Misale[6] and Katto[13] or the Kutateladze correlation by Su[14] and Wu[15], and the gap thickness effect was coalesced by the ratio of the gap size and capillary length.

In this paper, we predicted the CHF and HTC of the confined thin film boiling by modelling the thermal and vapor leaving resistance. The smaller gap sizes can reduce the thermal resistance of not only liquid layer conduction but also liquid-vapor convection of bubble interface, especially the evaporation of microlayer under the bubble can be largely enhanced. However, a higher vapor leaving resistance resulted from the thinner gap where vapor bubbles were harder to escape. If vapor-permeable lid can be used as the gap confinement to reduce the vapor leaving resistance, the CHF and HTC can be further improved. Comparing with pool boiling, the thin film boiling using confined gaps can sustain the low liquid level to greatly improve the heat transfer efficiency, and it can achieve both higher CHF and HTC when it can be accompanied with small vapor leaving resistance and sufficient liquid supply.

2. Models

2.1. Thermal resistance analysis

Fig. 1 is the schematics of confined thin film boiling. The bubbles expand along the confined thin gap when the gap thickness is thinner than the bubble departure diameter. Fig. 2 shows the thermal resistance diagram and the heat flux distribution. The heat flux taken from the heating surface should be balanced with the heat flux taken away by the vapor bubbles leaving from the gap side. During the boiling process, the applied heat flux goes through the resistance of solid-liquid interface then overcomes the liquid-vapor interface resistance from the bubbles and liquid surface, meanwhile, the conduction resistance of liquid layer. For water pool boiling in bulk liquid with thick liquid layer in or more than cm scale, the HTC is usually less than 10 W/cm²K which gives thermal resistance more than 10⁻⁵ m²K/W. The resistance of the solid-liquid interface which is also called the Kapitza resistance is usually in 10⁻⁹ m²K/W order of magnitudes between metal and water, which is very small compared to the boiling thermal resistance. Since solid-liquid resistance is in series with other thermal resistance, so it can be neglected in the violent boiling process. The conduction resistance from the liquid layer is given by the Fourier’s law which is the ratio of liquid thickness δ and water thermal conductivity λ within 0.5 ~ 0.7 W/m K. Assuming 1 cm thick water layer, the conductance ~10⁻² m²K/W is very big comparing with the boiling thermal resistance and it is in parallel with the liquid vapor interfacial resistance, so it will be minor comparing to the smaller one. Thus the thermal resistance of the phase change will be dominated by the liquid-vapor interface resistance.

![Figure 1. Schematics of confined thin film boiling](image1)

![Figure 2. Thermal resistance and heat distribution](image2)
2.2. The velocity of vapor bubble growth

Fig 3 shows the schematics of the heat flux absorbing from both evaporation and relaxation layer. For a single expanding bubble, the absorbed heat flux from both the microlayer under the bubble and the relaxation layer around the bubble cap are all applied to the bubble growth:

\[ q''_{\text{in}} = \frac{\rho_v(2\pi R \Delta s) h_{lv}}{\pi R^2} = \rho_v h_{lv} \frac{2s}{R} \]

(1)

\[ \rho_v h_{lv} \frac{2s}{R} = k \frac{T_w - T_v}{0.8 \sqrt{\gamma \Delta t}} + k \frac{T_l - T_v}{\sqrt{\pi a \Delta t}} \]

(2)

where \( A = \frac{k(T_w - T_v)}{\rho_v h_{lv}} \), and integral from \( t_s \), the time when the bubbles first grow spherically to the top lid to get the relationship of the radius of microlayer under the bubble with time:

\[ \int_{t_s}^{t_s} A \sqrt{R} dt = \int_0^R \frac{1}{R} \frac{1}{1.6 s \sqrt{\gamma} + \sqrt{\pi a}} dR \]

(3)

\[ R = (e^{0.8 s \sqrt{\gamma}} (t - t_s) - 1) \frac{1.6 s \sqrt{\gamma}}{\sqrt{\pi a}} \]

(4)

\[ v = \dot{R} = \frac{A}{\sqrt{t - t_s \sqrt{\pi a}}} (e^{0.8 s \sqrt{\gamma}} (t - t_s) - 1) \]

(5)

Here, \( t_s \) can be estimated by the pool boiling bubble radius equation, where bubble radius \( r = \frac{s}{2} = C_s J a \sqrt{a t_s} \), \( J a = \frac{\rho_v C_p\Delta T}{\rho_v h_{lv}} \), so \( t_s = \frac{1}{a} (\frac{s}{2C_s J a})^2 \). \( \delta_s = 0.8 \sqrt{\gamma t_s} \). As Fig. 4 shows the radius of attaching area at the bottom of bubbles grow with time exponentially from the \( t_s \). Thinner gap thickness and higher superheat grows faster obviously.

![Figure 3. Schematics of heat flux from both evaporation and relaxation layer.](image1)

![Figure 4. The relationship of growing time and radius.](image2)

2.3. The heat flux predicted by the vapor leaving resistance model

The thermal resistance can decide how much heat flux can be absorbed \( q''_{\text{in}} \), while the vapor leaving resistance representing the vapor leaving rate can decide the outflow heat flux \( q''_{\text{out}} \). For unconfined pool boiling, there is no extra vapor leaving resistance when the bubble vapor pressure \( P_v \) reach the ambient chamber pressure \( P_\infty \). For thin film boiling confined by solid gap, the vapor volumetric flux is \( \dot{Q} = \frac{P_v - P_\infty}{R_v} \), so the heat flux is:
The vapor leaving resistance is from both the gap side $R_{v,\text{side}}$ and top $R_{v,\text{top}}$ in parallel, which is:

$$R_v = \frac{1}{\frac{1}{R_{v,\text{side}}} + \frac{1}{R_{v,\text{top}}}}$$  \hspace{1cm} (7)

For solid lid with vapor permeability is zero, $R_{v,\text{top}} = 0$ then $R_v = R_{v,\text{side}}$. We assumed the vapor flow along the gap as fully developed Poiseuille flow between two parallel plates so the vapor resistance is $R_{v,\text{side}} = \frac{12\mu}{s^3}$, and it is increased when the gap thickness is reduced. The relationship between the pressure difference on the bubble surface and the heat flux can be estimated based on the momentum theorem $F = \dot{m} \times \nu$, where the velocity of vapor bubble is $\dot{R}$, mass flux is $\dot{m} = \frac{q^*A_w}{h_{lv}}$ and the projected area for bubble interface pressure difference is $s\ell$ with $l = 2R$, and $A_w = \pi R^2$, so the vapor pressure inside the bubble will be:

$$(P_v - P_l)sl = \frac{q^*A_w}{h_{lv}}\dot{R}$$  \hspace{1cm} (8)

$$P_v = \frac{1}{2}\rho_l g s + \frac{q^*\dot{R}}{2sh_{lv}}\pi R$$  \hspace{1cm} (9)

Equation (10) shows the outflow heat flux estimated by the vapor leaving resistance and can be simplified to be equation (11).

$$q''_{out} = \frac{1}{2}\rho_l g s + \frac{q''_{out}\dot{R}}{2sh_{lv}}\pi R$$  \hspace{1cm} (10)

$$q''_{out} = \frac{1}{2}\rho_l g s - \frac{P_\infty}{\rho_v h_{lv}}$$ \hspace{1cm} (11)

3. Results and Discussion

3.1. The heat flux contribution from the microlayer and relaxation layer

The bubbles of boiling in a confined gap grow as the same as pool boiling from the nucleation to the bubble diameter reaches the gap size, then it expands along the gap until reaching the gap size to escape. The bubble growth is first limited by the heat diffusion of relaxation layer when the microlayer area under the bubble is relatively small, but as the bubble expands, the heat flux will be mainly limited by the microlayer under bubble. The ratio of heat flux contribution between the microlayer and relaxation layer can be calculated by:

$$k = \frac{q_m}{q_{side}} = \frac{k}{k} \frac{T_w - T_v}{1.6s\sqrt{Y}} = \frac{\sqrt{\pi a}}{1.6s\sqrt{Y}}$$  \hspace{1cm} (12)

Here we assumed the bubble leaving radius $R$ is the same size of the gap length $l$. The ratio increases with the gap length and the contribution from microlayer will be larger at smaller gap sizes and higher saturation pressure, as showed in Fig. 5. It demonstrates that the heat flux contribution from the
microlayer is larger than the relaxation layer when the gap length is larger than around 1mm or less, but within the gap length of 10 cm, the ratio is less than 100 times so the heat flux of both the relaxation and micro layer should not be ignored when boiling in a confined thin liquid film. Fig. 6 also shows that boiling at lower saturation pressure will increase the relaxion limit from the bubble interface.

Figure 5. The heat flux contribution of the microlayer and relaxation layer with the gap length l.

3.2. The CHF of thin film boiling confined with vapor non-permeable gap

Bubbles can only leave when reaching the side of the confinement gap as the top solid lid is not vapor permeable, and the vapor pressure inside the gap will push the bubble interface growing along the gap until the gap’s boundary. Here we assume the bubble radius attaching with the heater area is \( R \), bubble expanding rate is \( \dot{R} = \frac{dR}{dt} \) and the bubbles can leave the gap when the diameter equals to the gap length. The corresponding heating time \( t_d \) can be estimated by equation (4), with \( R \) is half of the gap length:

\[
t_d = \left[ \frac{0.8s\sqrt{\gamma}}{A} \ln\left( \frac{\sqrt{\pi a}}{1.6s\sqrt{\gamma}} \frac{1}{l+1} \right) \right]^2 + t_s
\]  

(13)

The heat flux was estimated when the single bubble grows to the confinement boundary. The absorbing heat flux \( q''_{\text{in}} \) (equation 14) is calculated based on equation (1) of the microlayer and relaxation layer heat conduction. The taken-away heat flux \( q''_{\text{out}} \) (equation 15) is estimated by the vapor leaving resistance of equation (11). We the Bo number to describe the influence of gap size to the bubble departure and study its relationship with heat flux.

\[
q''_{\text{in}} = k \sqrt{t_d} \theta_w \left( \frac{1}{0.8\sqrt{\gamma}} + \frac{1}{\sqrt{\pi a}} \frac{2s}{l} \right)
\]  

(14)

\[
q''_{\text{out}} = \frac{1}{2} \rho_l g s - P_\infty
\]  

(15)
As shown in Fig. 6, we took an example of boiling at the gap length of 2 cm of superheat of 20℃. As the Bo number decreased, the $q'''_{in}$ was decreased and the decreasing rate slowed down at higher Bo number which is also larger gap size; but the $q'''_{out}$ was increased. It verified our assumption that it will be a trade-off that the thermal resistance is decreased at smaller liquid thickness but the vapor leaving resistance is larger. The CHF based on $q'''_{out} = q'''_{in}$, we take the minimum value of the heat flux and shows the prediction of CHF at Fig. 7. The CHF first increased then decreased which shown a similar trend as the experimental results of dielectric fluid. The model also shows that the smaller gap sizes will have larger CHF value.

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