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On the Partitioning of Wall Heat Flux in Subcooled Flow Boiling

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1. Introduction

Modeling of subcooled flow boiling is crucial to the design and safe operation of thermal-hydraulic systems in which a high heat-transfer rate is anticipated, e.g. nuclear reactors. Regarding this topic, two regions of interest have been investigated intensively [1]. The first region is two-phase flow and bubble behaviors in a bulk subcooled flow away from the heated wall. This region has been treated successfully by two-fluid model coupled with a population balance model or interfacial area transport equation (IATE). The second region is near-wall heat transfer which has been commonly described by a wall heat flux partitioning model coupled with models of nucleation site density (NSD), bubble departure diameter and bubble release frequency. Since the phase change process in the near-wall heat transfer is really complex, comprising different heat transfer mechanisms, bubble dynamics, bubble nucleation and thermal response of heated surface, the modeling of the second region is still a great challenge despite intensive efforts.

Numerous models and correlations have been proposed to aim for computing the near-wall heat transfer. These models and correlations, however, are quite limited in application. Cheung et al. [1] conducted an assessment of the existing models and correlations, and found that not one single combination of the models and correlations can provide satisfactory predictions covering different flow conditions. Also, according to this study, the model of heat flux partitioning that plays a central role in the near-wall heat transfer should be investigated thoroughly. Indeed, a heat flux partitioning model separates the heat flow from the heated wall into different components going through liquid and vapor phases following certain mechanisms. And the models of nucleation site density, bubble departure diameter and bubble release frequency are used to quantify these components. The models closely related to each other. The heat flux partitioning model controls the wall and liquid temperatures. Then, it turns to control the boiling parameters, i.e. nucleation site density, bubble departure diameter and bubble release frequency.

In this study, the partitioning of wall heat flux is taken into account. The existing issues occurred with previous models of the heat flux partitioning are pointed out and then a new model which considers the heat transfer caused by evaporation of superheated liquid at bubble boundary and the actual period of transient conduction term is formulated. The new model is then validated with a collected experimental database.

2. Previous Models and Existing Issues

The heat flux partitioning model provides the information regarding the partitioning of wall heat flux between liquid and vapor phases. It shows the factions of the wall heat flux used for vapor generation and for raising liquid temperature. Many heat flux partitioning models have been proposed, and they can be categorized into two primary groups [2]. One group consists of empirical correlations and the other group consists of mechanistic models. The models/correlations of both these groups have been formulated based on the heat transfer mechanism. However, the heat flux components in the empirical correlations are not independent and can be determined once the wall heat flux and the ratio between the components are given. This means that the wall heat flux cannot be calculated by such a correlation. In contrast, the heat flux components in the mechanistic models are calculated independently through boiling parameters like NSD, bubble departure diameter and bubble release frequency. Therefore, not only the partitioning of heat flux but also the wall heat flux can be determined by a mechanistic model. In this study, we pay attention on the second group only.

Regarding the mechanistic models, an adequate description of all heat transfer terms via the boiling parameters is required. However, this work faces with many considerable difficulties in respects of the measurement and modeling because of the complexity of the vapor change process in the near-wall heat transfer. The followings present the existing issues of the heat flux partitioning models and suggestions for model improvement.

2.1 Heat Transfer Mechanisms

In common, most previous models comprise three main elements: sing-phase convection (q_{sp}), latent heat transport by microlayer evaporation (q_{lt}) and transient conduction (q_{tc}) induced by departing and/or sliding bubbles [2]. The latent heat transport normally takes a small fraction of overall heat transfer. It is true if only the evaporation of the microlayer at the bubble base is the sole path of the latent heat transport. However, this is definitely insufficient because the evaporation of

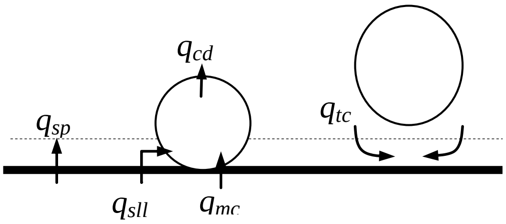

Fig. 1. Heat transfer mechanisms in subcooled flow boiling.

superheated liquid at the bubble boundary, as illustrated in Fig. 1, is another primary path of the latent heat transport. The energy transferred by this path is about four times larger than that transferred by the microlayer evaporation, and it takes a big role in controlling the bubble growth. Hence, the adequate energy balance at the bubble must be

$$q_{sll} + q_{mc} = q_{ev,t} + q_{cd,t} \qquad (1)$$

and the wall heat flux partitioning is expressed by

$$q_w = q_{sp} + \left(q_{ev} + q_{cd}\right) + q_{tc} \qquad (2)$$

where q is heat flux, and the subscripts w, sp, ev, cd, sll, mc, tc and t denote wall, single-phase, evaporation, condensation, supper heated liquid, microlayer, transient conduction and time averaged, respectively.

2.2 Quantification of Heat Fluxes

The accurate quantification of the heat flux terms is really challenging since the heat transfer mechanisms and bubble behaviors are very different at different flow conditions, especially at high heat flux conditions. One of the difficulties is to determine the influential area of a bubble – the area over which the transient conduction is active. The bubble behavior at a nucleation site can be observed by visualization, but actual influential area of the bubble is not known by this way. In common, it is assumed to be two times of the bubble departure diameter. This assumption is, however, valid for the region of separated bubbles only. When the number of bubbles increases, the influential area of neighbor bubbles becomes overlapped, leading to a change in the fraction of heat flux components. This effect is evident, but its quantification is difficult. Del Vale and Kenning [3] attempted to quantify the degree of the overlap by drawing circles around the known positions of active nucleation sites, but a general estimation has not been obtained yet.

Another difficulty is to quantify the contribution of bubble merger, bubble sliding and micro-convection effects to the overall heat transfer. Basu et al. [2] developed a new model of wall heat flux partitioning in which the bubble sliding acts to enhance the transient conduction whereas the bubble merger results in a reduction in the number of active nucleation sites. However, the criteria by which a bubble will slide or merge with another bubble are very uncertain since they were expressed in terms of the nucleation site density–a greatly uncertain parameter. Therefore, the partitioning of wall heat flux might be not close to the actual process. Otherwise, it is doubted that whether the bubble sliding acts to enhance the transient conduction or enhance the convection heat transfer. A bubble slides along the surface inducing turbulence near the surface, hence enhancement of heat transfer. The cold liquid can replace the bubble once it is detaching from the surface. Iman Haider and Webb [4] attempted to quantify the micro-convection effect as an enhancement of the transient conduction. The analytical form was obtained by summation of transient and steady-state conduction solutions. However, the model proposed is based on the boiling phenomenon observed on an enhanced heat-transfer surface. This model might be therefore overestimated for other surface conditions.

The other issue relates to the determination of the boiling parameters used. The measurement and prediction of all these parameters even have a significant uncertainty, especially of the nucleation site density and bubble release frequency. Most the measurements and correlations are for low heat flux conditions at which vapor bubbles remain isolated. However, the region of interest is high heat flux conditions at which bubble interference is significant and the boiling parameters, i.e. nucleation site density, bubble departure diameter and bubble release frequency, are really difficult to measure. Until now, it is a big challenge to improvement of the modeling of the subcooled flow boiling.

3. Model Development and Assessment

In the scope of this study, we attempt to model the partitioning of wall heat flux with the consideration of the additional heat transfer by means of the evaporation of superheated liquid at the bubble boundary and the active period of the transient conduction. The new model obtained is validated with the experimental data measured by Phillips [5].

3.1 Model Development

Assume that vapor bubbles are spherical in shape and partially immersed in the thermal boundary layer, as illustrated in Fig. 1. The latent heat transport term in Eq. (1) is expressed as follow:

$$\begin{aligned} q_{lt,t} &= q_{mc} + q_{sll} = q_{ev,t} + q_{cd,t} \\ &= \rho_g h_{fg} \frac{d}{dt}\left(\frac{\pi}{6} D_b^3\right) + h_{cd}\left(m\pi D_b^2\right)\left(T_{sat} - T_l\right) \end{aligned} \qquad (3)$$

where $h_{cd} = C\phi h_{fg} D_b \big/ 2\left(1\big/\rho_v - 1\big/\rho_g\right)$ and

$$m = \frac{\delta_{cd}}{D_b} = 1 - \frac{\delta_{tbl}}{D_b} = 1 - \frac{\sqrt{\pi\alpha_l\left(t_w + t\right)}}{4b\big/ Ja\sqrt{\pi\alpha_l t}} \le 0.5 .$$

Taking average of the latent heat transport term over a bubble cycle yields

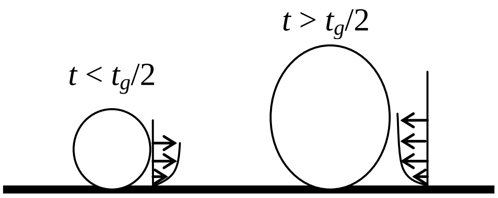

Fig. 2. Transient heat conduction

$$q_{lt} = \frac{1}{t_w + t_g} \int_{t_w}^{t_g} q_{lt,t} dt \cdot N_a = N_a f_b \left(\frac{\pi}{6} D_b^3 \right) \rho_v h_{fg} + \frac{m\pi}{2(3x+1)} \frac{C\phi h_{fg} \Delta T_{sub} D_b^3}{1/\rho_v - 1/\rho_l} \frac{t_g}{t_w + t_g} N_a \tag{4}$$

Note that the second term on the RHS of Eq. (4) is derived using the assumption of $D_b = b_g t^x$. Typically, the exponent x takes a value of 1/2.

For the transient conduction term, the active period should be the latter half of bubble growth period when the bubble starts to lift up and shrinks at its leg gradually. As illustrated in Fig. 2, the bubble grows during the first half and pushes the liquid away from its leg, hence no chance for the cold liquid to reach the heated surface. However, the liquid velocity will change to reversed direction during the latter half and the transient conduction is possible to happen.

$$\begin{aligned} q_{tc} &= \frac{1}{t_w + t_g} \int_{t_w + \frac{1}{2}t_g}^{t_w + t_g} \frac{k(T_w - T_l)}{\sqrt{\pi \alpha t}} dt \cdot (A_{2f} N_a) \\ &= \frac{2}{\sqrt{\pi}} \sqrt{k \rho_l c_{pl}} f_b (A_{2f} N_a)(T_w - T_l) \\ &\times \left(\sqrt{t_w + t_g} - \sqrt{t_w + t_g/2} \right) \end{aligned} \tag{5}$$

The remaining term, i.e. single-phase heat transfer, is computed similarly to that of Kural and Podowski's model. This is

$$q_{sp} = A_{1f} \rho_l c_{pl} U_l St (T_w - T_l) \tag{6}$$

where $A_{2f} = K(\pi D_b^2/4)$, $A_{1f} = 1 - A_{2f}$ and St is Stanton number. The value of influential factor K is 4.

The final expression of the new heat flux partitioning model is

$$q_w = q_{sp} + q_{lt} + q_{tc} \tag{7}$$

where q_{lt}, q_{tc} and q_{sp} are given by Eqs. (4–6), respectively.

3.2 Model Assessment

The new model presented above is validated with the experimental data measured for subcooled flow boiling of water over an ITO heated surface attached to one side of a vertical rectangular channel by Phillips [5]. The experimental conditions of this database are:

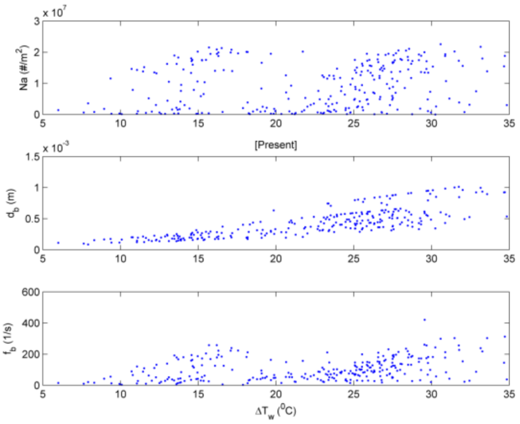

Fig. 3. Boiling parameters.

- *Pressure*: 1.05, 1.5 and 2.0 bars
- *Liquid flow rate*: 150, 250, 500, 750, 1000 and 1250 kg/m^{2}s
- *Subcooling*: 5, 10 and 15 K
- *Heat Flux*: 0 – 1.8 MW/m^2

Since the database did not provide the information on the bubble departure diameter, a model to estimate the bubble departure diameter is used. In this study we use our developed model given below.

$$D_b = 1.21 a b^{-1/2} \tag{8}$$

where $a = \dfrac{(1-m) k \Delta T_{sat}}{\rho_v h_{fg} \sqrt{\pi \alpha}}$ and $b = \dfrac{m C \phi \Delta T_{sub}}{1 - \rho_v / \rho_l}$. This model was derived based on the assumption that only the evaporation of the superheated liquid at the bubble boundary contributes to the bubble growth during the latter half of the growing period. As shown in Fig. 3, the bubble departure diameter predicted by our model is in the range of the bubble diameter measured by Phillips [5], 0.1 – 0.5 mm. The other plots in Fig. 3 present the measured NSD and bubble release frequency.

A comparison between Kural and Podowski's model and the new model based on Phillips' data is presented in Figs. 4 and 5. The new model closely matches the experimental data with an average error of 95.9%. It is much better than the prediction with Kural and Podowski's model, which suffers a really larger error of 1061.3%. The prediction error of both these models can be reduced if using smaller value of K.

To gain insight of the boiling phenomenon, detailed heat flux partitioning based on these models was plotted also. As seen in Fig. 4, Kural and Podowski's model showed the dominance of the transient conduction heat flux over the others for each bubble case. The evaporation heat flux nearly equals zero. Meanwhile, the new model showed that the evaporation heat flux is about 15 to nearly 40 % of the overall heat flux, and the contribution of the transient conduction is reduced to about 60 – 70 %. If considering the evaporation of superheated liquid at the bubble boundary, the latent

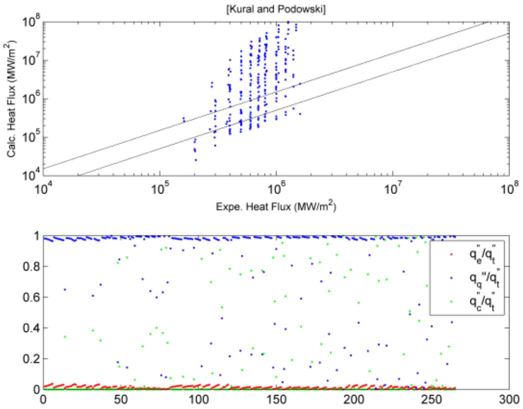

Fig. 4. Partitioning of wall heat flux predicted by Kural and Podowski's model (K = 4).

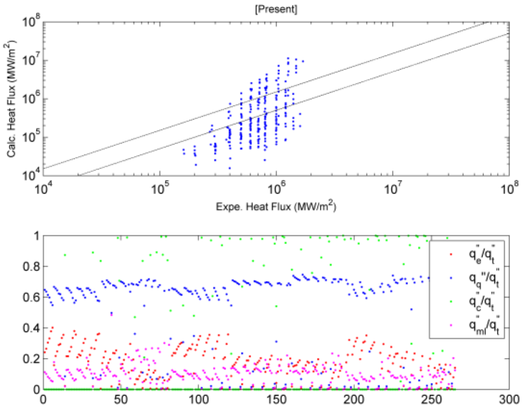

Fig. 5. Partitioning of wall heat flux predicted by the present model (K = 4).

heat can contribute up to 50% of the overall heat flux. The results show the reason accounting for the agreement of the new heat flux partitioning model. It is evident that the transient conduction term in Kural and Podowski's model is overestimated and it leads to the overestimation of this model. Meanwhile, if assume that the transient conduction is active over the latter half of the bubble growth, the relevant heat flux reduces significantly. On the other hand, the addition of the evaporation of the superheated liquid to the overall heat transfer leaded to an increase in the latent heat transport to a degree comparable with the actual experimental range reported.

4. Conclusions

This paper presented a new heat flux partitioning model in which the heat transfer by evaporation of the superheated liquid at the bubble boundary and the active period of the transient conduction were considered. The new model was validated with the experimental data of the subcooled flow boiling of water obtained by Phillips [5]. The new model showed a good agreement with the experimental data, and it is much better than Kural and Podowski's model – a model adopted frequently in CFD codes. Nevertheless, some unsolved issues related to the overlaps of influential areas and the effect of bubble sliding and bubble merger are still remained. Such an issue might be solved by means of an empirical correlation instead of a mechanistic model because of difficulties in the aspect of measurement and modeling.

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