Development of Bubble Lift-off Diameter Model for Subcooled Boiling Flows

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1. Introduction

The high heat transfer rate under the subcooled boiling condition is of great interest in industrial applications, especially nuclear reactors, during several past decades. The formation and detachment of vapor bubbles on/from a heated surface that is subjected to a high heat flux accompanied by a large amount of heat taken away from the surface. Therefore, the size of bubbles during their growth and at lift-off points is an important parameter needed to evaluate the performance of this heat transfer process.

A lot of models and correlations for predicting the bubble departure/lift-off diameter are available in the literature [1]. Most of them were developed based on a hydrodynamic principle, which balances forces acting on a bubble at the departure/lift-off point. One difficulty of these models is lack of essential information, such as bubble front velocity, liquid velocity, or relative velocity, to estimate the active force elements [2]. Hence, the lift-off bubble diameter predicted by these hydrodynamic-controlled models may be suffered a large uncertainty. In contract to the hydrodynamic approach, there are few models developed based on the heat transfer aspect. By balancing the heat conducted through a microlayer underneath a bubble with the heat taken away by condensation at the upper part of the bubble, Unal derived a heat-controlled model of the bubble lift-off diameter [3]. This model did not consider the role of superheat liquid layer surrounding the bubble as well as the effect of liquid properties on the heat transfer process. Beside these two approaches, several empirical correlations have been proposed based on dimensionless analyses for measured experimental databases [1,4]. The application of these correlations to different experiments conditions is, of course, questionable because of the lack of physical bases.

Regarding the heat transfer accompanied by a vapor bubble, four involved heat transfer regions surrounding this bubble can be defined as in Fig. 1. These are dry region, microlayer, superheated liquid layer (SpLL) and subcooled liquid layer (SbLL). The existing of the microlayer is confirmed by experiments, and it is considered to be very effective in the heat transfer [5]. Sernas and Hoper defined five types of the microlayer and indicated that the microlayer acting as a very thick liquid layer gives a best prediction for the bubble growth [6]. However, beside the microlayer, the SpLL might play an important role in the heat transfer if its effective heat transfer area is large. To the best of our understanding, the SpLL must be involved in the growth of the bubble, and its contribution to the bubble diameter at the lift-off point should be qualified.

In this paper, a new bubble lift-off diameter model, in which the SpLL contribution is incorporated, is proposed and adopted to analyze two available experimental databases measured by Prodanovic et al. and Situ et al. [2,4]. Three existing models/correlations, i.e. Unal's model, and Prodanovic and Chu's correlations are also applied to these databases to give a comparison with the proposed model.

2. Bubble lift-off diameter model

To qualify the heat transferred though the microlayer, SpLL, and SbLL, the thickness of these regions need to be determined. Then, a heat balance equation is derived and solved to obtain the lift-off bubble diameter.

2.1 Dimension of heat transfer regions

- *Dry area*: According to [3], the dimension of the dry region can be determined as a function of pressure *p*, given by:

$$l_w = \frac{d_w}{D} = \begin{cases} \left[1-0.07p^{0.709}\left(67.69-5.69p\right)^{1/2}\right]^{1/2} & 1\le p\le 10 \\ 0 & p>10 \end{cases} \quad (1)$$

where the unit of *p* is bar. This expression was obtained by interpolating a collected experimental database [3].

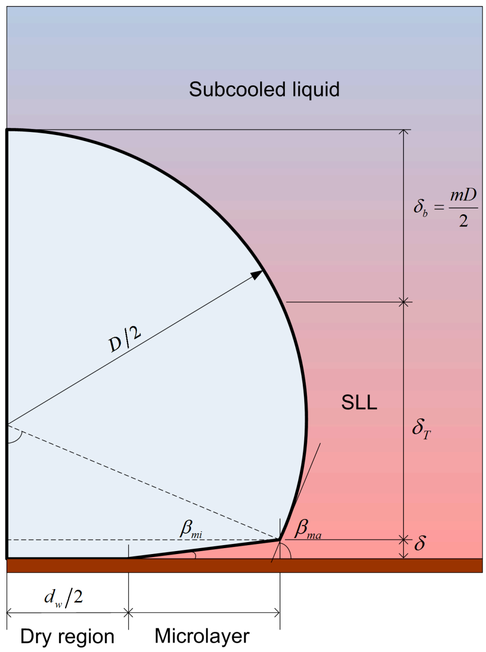

Fig. 1 Bubble heat transfer regions

- *Microlayer thickness*: Cooper (1969) derived theoretically expressions for the growing bubble diameter and initial microlayer thickness [5]. These parameters were indicated to be proportional to $t^{1/2}$,

$$\delta = 0.8\sqrt{v_l t} \quad (2)$$

$$D = \begin{cases} 5\dfrac{Ja}{\Pr}\sqrt{\alpha_l t} & T_w = const. \\ 2.24\gamma Ja\sqrt{\alpha_l t} & T_w \to T_{sat} \end{cases} \quad (3)$$

Therefore, one gets

$$l_m = \frac{\delta}{D} \sim \begin{cases} 2.5\dfrac{\Pr^{3/2}}{Ja} & T_w = const. \\ 0.375\dfrac{\Pr^{1/2}}{\gamma Ja} & T_w \to T_{sat} \end{cases} \quad (4)$$

- *Superheated liquid layer thickness*: If the contact angle of the microlayer is β_{mi}, the dynamic contact angle of the SpLL, β_{ma}, can be determined as follows:

$$\beta_{ma} = \sin^{-1}\left(l_w + \frac{2l_m}{\tan\beta_{mi}}\right) \quad (5)$$

The thickness of the SpLL can be obtained once the dynamic contact angle and other thickness are obtained.
- *The subcooled liquid layer thickness*: In this study, the SbLL is assumed to cover the top-half of the bubble, and its thickness is given by:

$$\delta_b = mD/2 \quad (6)$$

where the value of m can be selected to be equal to 0.9 for two these databases mentioned above.

2.2 Lumped heat balance approach

As described in Fig. 1, the dry region on the heated surface is covered by vapor, and the heat transfer through it is almost zero. Thus, the heat conducted through the microlayer and SpLL, q_{mi} and q_{ma}, is used to growth, and the heat balance can be written as follow:

$$\rho_v h_{lv}\frac{dV}{dt} = q_{mi} + q_{ma} - q_b \quad (7)$$

If assuming that the microlayer acts as a semi-infinite medium, the heat flow conducted though this layer is

$$q_{mi} = \frac{k_s\Delta T_{sat}}{\sqrt{\pi\alpha_s t}}\frac{\pi D^2}{4}\left(\sin^2\beta_{ma} - l_w^2\right) \quad (8)$$

According to [6], the liquid temperature in the SpLL drops to saturated temperature on the bubble interface, and the heat transfer through this layer is governed by a transient conduction. Therefore, the heat flow fed by the SpLL can be estimated by:

$$q_{ma} = b_z\frac{k_l\Delta T_{sat}}{\sqrt{\pi\alpha_l t}}\frac{\pi D^2}{2}\left(1 + \cos\beta_{ma} - m\right) \quad (9)$$

where b_z is a growth constant.

And the heat taken away by the condensation, q_b, can be calculated as [3]:

$$q_b = h_c\Delta T_{sub}\frac{\pi m D^2}{2} \quad (10)$$

where

$$h_c = \frac{C\Phi h_{lv}D}{2\left(1/\rho_v - 1/\rho_l\right)} \quad (11)$$

C and Φ is coefficients depending on the pressure and liquid velocity [3]

Substituting Eqs. (8 – 10) into the Eq. (7) yields

$$\frac{dD}{dt} = at^{-1/2} - bD \quad (12)$$

where

$$a = \frac{k_l\Delta T_{sat}}{\rho_v h_{lv}\sqrt{\pi\alpha_l}}\frac{\gamma\left(\sin^2\beta_{ma} - l_w^2\right) + 2b_z\left(1 + \cos\beta_{ma} - m\right)}{1 + 3/2\cos\beta_{ma} - 1/2\cos^3\beta_{ma}} \quad (13)$$

$$b = \frac{mC\Phi\Delta T_{sub}}{1 - \rho_l/\rho_v}\frac{1}{1 + 3/2\cos\beta_{ma} - 1/2\cos^3\beta_{ma}} \quad (14)$$

As shown in equations (8), (9) and (13), the superheat, ΔT_{sup}, is needed to determine the coefficient a, and the heat flow rate through the microlayer and SpLL. To calculate the superheat, Unal used the Rohsenow's correlation [3], and Chu et al. used the Chen's correlation [1]. According to [1], using the Chen's correlation gave a better prediction for the lift-off bubble diameter compared with using the Rohsenow's correlation. Therefore, the Chen's correlation is employed to predict the superheat in this study.

Since the bubble grows very quick over a short period, the product bt is less than unity, and the approximated solution of Eq. (13) can be obtained as:

$$D(t) = \frac{2at^{1/2} + bt/3}{1 + bt} \quad (15)$$

As indicated in Eq. (7), the bubble will stop growing when the heat taken away by condensation equals the heat supplied by the microlayer and SpLL, and the condition for the bubble detachment is

$$dD/dt = 0 \quad \text{at} \quad t = t_m \quad (16)$$

From equations (15) and (16), the bubble lift-off diameter obtained is

$$D_m = at_m^{-1/2}/b \quad (17)$$

where

$$t_m = 0.686/b \quad (18)$$

3. Results and discussion

3.1 Experimental data collection

To evaluate the proposed lift-off bubble diameter model, two available experimental databases for subcooled boiling flows measured by Prodanovic et al. and Situ et al. are used [2,4]. The Prodanovic's database includes 54 data points measured for a subcooled boiling flow of water in a vertical annulus channel under pressures of 1.05, 2.0 and, 3.0 bar. And the Situ's database includes 91 data points measured for a similar system configuration, but at the atmospheric pressure. The experimental conditions corresponding to these databases are summarized in Table I.

Table I: Experimental conditions

	Prodanovic et al. (2002)	Situ et al. (2005)
Fluid	Water	Water
Channel	Annulus	Annulus
D_h (mm)	22.25	9.3
p_{in} (bar)	1.06, 2.02, 3.03	~ 1.3 (estimated)
u_l (m/s)	0.08 – 0.84	0.49 – 0.94
q_w (MW/m^2)	0.1 – 1.2	0.61 – 2.06
ΔT_{sub} (^0C)	10 – 60	6.1 – 24.0

3.2 Bubble lift-off diameter prediction

For compression between the proposed model and the existing models/correlations, the Unal's model and Prodanovic and Chu's correlations are employed together with the proposed model to predict the bubble lift-off diameter for two these experimental databases. These model and correlations are listed in Table II.

Figures (2) and (3) show a comparison between the bubble lift-off diameters predicted by these models/ correlation and the experimental values. For the Prodanovic's database, the bubble lift-off diameter predicted by the Unal's model, Chu's correlation and proposed model agrees well with the experimental data with average errors less than 35 %, and underestimates with 44.2 % average error when predicting with the Prodanovic's correlation. For the Situ's database, the proposed model gives a best prediction with an average error of 25.2 %; the Unal's model is slightly overestimated with 31.2 % average error; and the Prodanovic and Chu's correlations are all significantly overestimated with the 191.7 % and 95.6 % average error, respectively. In general, these results show that the proposed model is better than these other model/ correlations in predicting the bubble lift-off diameter for both these databases. The improvement of the proposed model compared with these others can be explained as follows:

The proposed model and the Unal's model, in principle, were all developed based on a heat balance. However, the proposed model considers additionally the contribution of the SpLL, while the Unal's model considers the contribution of the microlayer only. If only the microlayer is taken into account, the effect of fluid properties are not included as indicated in Eq. (8). This might lead to a slight overestimation of the Unal's model because the thermal properties of the solid surface are usually higher than the thermal properties of fluid (see Fig. 2a). Otherwise, the contribution of the SpLL might be large compared with the contribution of the microlayer, but not small as assumed by Unal [3].

For the Prodanovic and Chu's correlations, the overestimation for the Situ's database might be attributed to the difference in the experimental conditions. The Chu's correlation has a same form with the Prodanovic's correlation, but different coefficients and powers, which are obtained based on their experimental databases. Therefore, these correlations might be not good in prediction for other databases. Moreover, these correlations depend strongly on the fluid properties, superheat and experimental conditions, which were not given sufficiently in the Situ's database. Hence, the overestimation as shown in Figs. 2a and 2b is possible to happen.

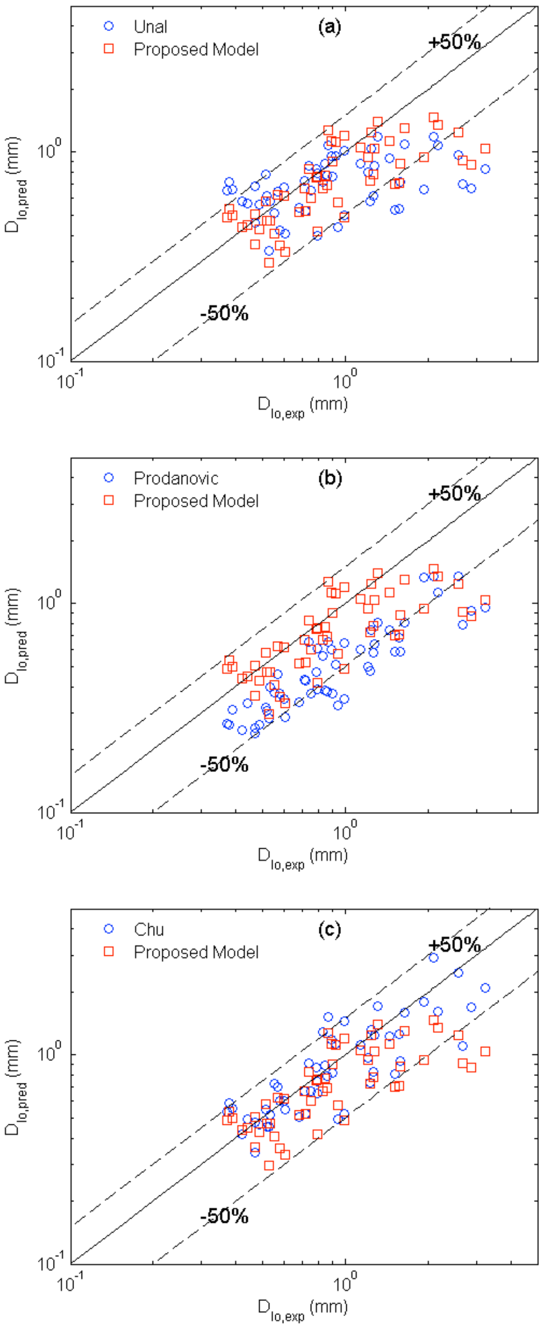

Fig. 2 Prodanovic's database

Table II: Compared models/correlation of the bubble lift-off diameter

	Models, or Correlations
Unal (1967)	$D_{lo} = 2.42\times10^{-5} p^{0.709} a\left(b\Phi\right)^{-1/2}$
	$a = \frac{\Delta T_{sat} k_l \gamma}{2\rho_v h_{lv}\left(\pi\alpha_l\right)^{1/2}},\ b = \frac{\Delta T_{sub}}{2\left(1-\rho_v/\rho_l\right)}$
Prodanovic et al. (2002)	$D_{lo}^{+} = 440.98\cdot Ja^{-0.708}\theta^{-1.112}\left(\rho_l/\rho_v\right)^{1.747} Bo^{0.124}$
Chu et al. (2011)	$D_{lo}^{+} = 12788.5\cdot Ja^{-0.28}\theta^{-1.07}\left(\rho_l/\rho_v\right)^{1.36} Bo^{0.35}$

$\left(D_{lo}^{+} = D_{lo}\sigma/\rho_l\alpha_l^2,\ \theta = \left(T_w - T_{bulk}\right)/\left(T_w - T_{sat}\right),\ Bo = q_w''/Gh_{lv} \right)$

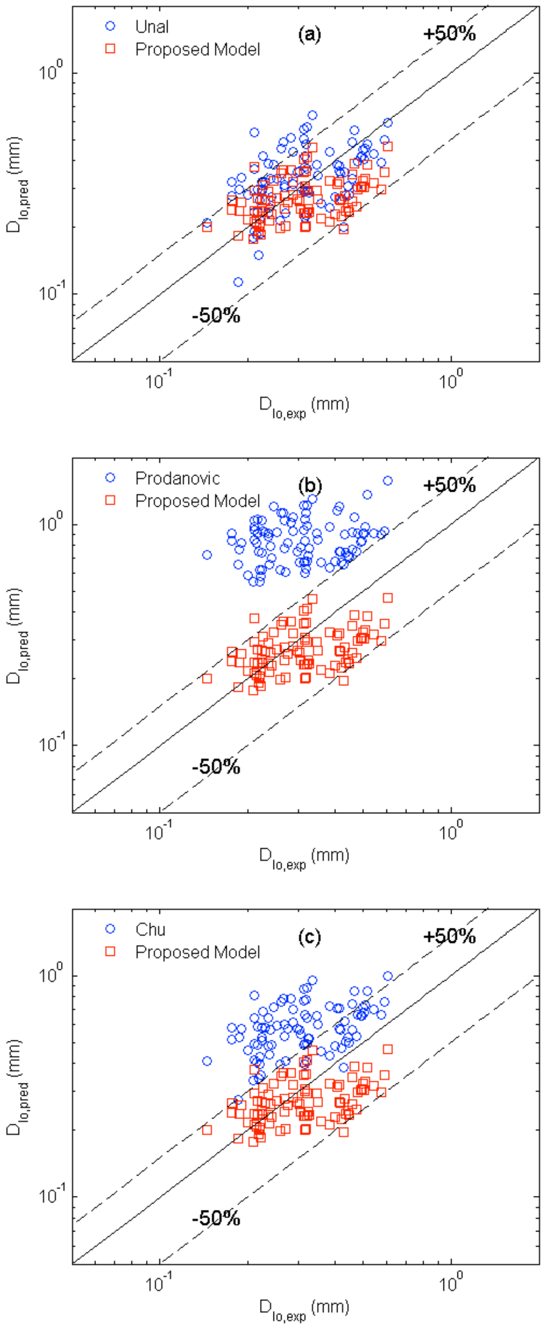

Fig. 3 Situ's database

3. Conclusions

In this paper, a bubble lift-off diameter model for subcooled boiling flows was developed considering the contribution of the superheated liquid layer. The effect of liquid wettability and liquid thermal properties, therefore, was included in this model.

In comparison with the existing models/correlations, i.e., Unal's model, and Prodanovic and Chu's correlations, the proposed model shows a better prediction of the bubble lift-off diameter for the Prodanovic and Situ's databases with average errors less than 30 %.

In the future, a detail analysis used the same approach will be performed to investigate the bubble growth rate, bubble growth time, and other heat transfer characteristics, which are involved in the growth and detachment of a bubble under the subcooled boiling conditions.

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