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The Modeling of Bubble Lift-Off Diameter in Vertical Subcooled Boiling Flow

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Abstract: Bubble lift-off diameter is characterized as the size of a bubble rising from a wall, which is vital in the boundary condition of heat transfer model and interfacial area transport equation. In this paper, mechanistic force analysis was conducted to explore a predictive model for bubble lift-off diameter in a vertical channel of subcooled boiling flow. Specifically, the component of growth force normal to the wall and the shear lift force lead to the lift-off of a bubble on the vertical surface. Through force analysis, we found that bubble lift-off diameter is arranged to be related to wall superheat, latent heat, liquid velocity, fluid properties, bulk liquid subcooling, etc. To account for the contribution of the influencing factors, the dimensionless bubble lift-off diameter was correlated with dimensionless parameters, including the Prandtl number, the Reynolds number, the Jacob number, and dimensionless subcooling. The proposed correlation was assessed according to experimental data and the predictions showed good agreement with the data.

Keywords: bubble lift-off diameter; force analysis; subcooled boiling flow

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1. Introduction

Subcooled boiling flow is a relatively effective way of removing heat from heat source by utilizing the additional latent heat of a working fluid. It is a promising method of improving heat transfer efficiency in the application of high-power devices, such as nuclear reactors and boilers. To understand the mechanism of flow boiling, many researchers have carried out experimental or theoretical studies to quantitatively describe heat transfer in flow boiling [1–5]. Mechanistic models or empirical correlations have been developed to explain the relationship between input heat flux and wall temperature and bubble diameter is vital in preparing these models.

Generally, two kinds of diameters are commonly proposed to characterize bubble size, including bubble departure diameter and bubble lift-off diameter [6]. In a typical period of bubble growth, a bubble grows until it leaves the nucleation site. The diameter of the bubble at this point is regarded as the bubble departure diameter. Thereafter, the bubble may slide along the wall and keep growing until it lifts off the wall. Another possibility is that the bubble may grow on the nucleation site and lift directly off the wall to the bulk liquid. In these two situations, the bubble lift-off diameter is defined as the size of the bubble rising from the wall, which marks the start of its entry to the bulk liquid.

Mechanistic models have been widely applied in boiling systems. The traditional wall heat flux partitioning model [4] divides wall heat flux into three parts: latent heat of evaporation, liquid-phase convection, and sensible heat due to quenching. Bubble departure diameter is usually used to characterize latent heat of evaporation. However, the growth of a bubble during sliding enhances heat transfer, due to the disturbance of the thermal boundary layer that is induced by bubbles [7–11]. Recently, a wall heat flux partitioning model was modified by considering sliding bubbles and introducing the concept of bubble lift-off diameter [12]. The result performed better than the original model, which indicated that the introduction of the concept of bubble lift-off diameter is necessary and essential.

In two-phase flow models, after a bubble lifts off the wall and enters bulk flow, fluid flow coupled with heat transfer is considered. Bubble lift-off diameter is the initial size of bubble that slips into the bulk liquid. Interfacial heat and mass transfer between liquid and vapor are determined by the interfacial area concentration and the driving force. The interfacial area transport equation, which predicts the interfacial area concentration dynamically, requires the bubble lift-off diameter as the boundary condition of wall nucleation terms [13]. Therefore, bubble lift-off diameter plays a significant role in both the wall heat flux model and the interfacial area transport equation.

A review of the relevant literature indicates that very few studies have focused on the modeling of bubble lift-off diameter, compared with studies on bubble departure diameter [14–16]. Generally, force analysis and semi-empirical correlations are commonly adopted in the prediction of bubble lift-off diameter [17–22]. Situ et al. [17] considered bubble growth force and shear lift force that are normal to the wall to predict bubble lift-off diameter. Their model required consideration of bubble sliding velocity, which introduced uncertainty in their experiments. Cho et al. [18] applied a force-balance model in low heat flux and low flow velocity conditions to predict both bubble departure and bubble lift-off diameter. Their model was derived by the elimination of quasi-steady drag force and growth force, which is applicable only when the fluid's velocity is sufficiently low.

In addition to force analysis, semi-empirical correlations are also used to calculate bubble lift-off diameter. Prodanovic et al. [20] carried out experiments with flow boiling to capture bubble behaviors in a vertical annulus. New correlations for a bubble's ejection diameter were proposed by his experimental data. Chu et al. [21] modified bubble lift-off diameter correlations that were proposed by Unal [22] and Prodanovic [20] et al. Their results slightly overpredicted experimental data, with an error of 41.4%. Basu [23] performed subcooled boiling experiments in a square channel and correlated the bubble lift-off diameter empirically with significant-effect parameters. The details of the above bubble lift-off diameter models are listed in Table 1.

Table 1. Models of bubble lift-off diameter in vertical subcooled boiling flow.

Authors	Correlations	Applications
Situ et al. [17]	$D_{lo}^{*} = \frac{4\sqrt{22/3}b^2}{\pi} Ja_e^2 \mathrm{Pr}^{-1}$ $D_{lo}^{*} = \sqrt{C_l}\frac{U_r D_{lo}}{\nu_f}, Ja_e = \frac{\rho_l c_{pl} S(T_w - T_{sat})}{\rho_g h_{fg}}$	$P: 0.101$ MPa $U_l: 0.487$–0.939 m/s $T_{in}: 80.0$–98.5 °C
Cho et al. [18]	$D_l = D_d(1 + 2.073Lo^{-0.505})$ $D_d = 2\left(\frac{3(2\sin\theta_m)\sigma\frac{\theta_d}{\pi^2-\theta_d^2}(\sin\theta_a + \sin\theta_r)}{g\Delta\rho}\right)^{0.5}$	$Ja_e \leq 20$ $q_w: 2750$–6570 W/m^2 $U_l: 0.02$–0.05 m/s $\Delta T_{sub}: 2$–11.8 K
Prodanovic et al. [20]	$D_{ejc}^{+} = 440.98 Ja^{-0.708}\Theta^{-1.112}(\rho_l/\rho_v)^{1.747} Bo^{0.124}$ $D_{ejc}^{+} = \frac{D_{ejc}\sigma}{\rho_l a_l^2}, \Theta = \frac{T_w - T_l}{T_w - T_{sat}}, Bo = \frac{q_w}{G h_{fg}}$	$P: 0.105$–0.3 MPa $U_l: 0.08$–0.84 m/s $\Delta T_{sub}: 10$–30 K
Chu et al. [21]	$D_{lo}^{+} = 12788.5 Ja^{-0.28}\Theta^{-1.07}\left(\frac{\rho_f}{\rho_g}\right)^{1.36} Bo^{0.35}$	$P: 0.139$–0.152 MPa $q_w: 133.4$–355.6 kW/m^2 $U_l: 0.31$–0.733 m/s $\Delta T_{sub}: 1.1$–24 K
Basu et al. [23]	$D_{lo}^{*} = (0.24\exp(-1.1U_l) + 0.005) Ja_{\mathrm{sup}}^{0.45}\exp(-0.0065 Ja_{sub})$ $D_{lo}^{*} = \frac{D_{lo}}{Lo}, Ja_{\mathrm{sup}} = \frac{\rho_l c_{pl}\Delta T_w}{\rho_v h_{fg}}, Ja_{sub} = \frac{\rho_l c_{pl}\Delta T_{sub}}{\rho_v h_{fg}}$	$Ja_{\mathrm{sup}}: 14$–56 $Ja_{sub}: 1$–138 $\mathrm{Re}_l: 0$–7980 $\varphi: 30^{\circ}$–90°

Based on the above discussion, we concluded that bubble lift-off diameter is significant in subcooled boiling flow as the boundary condition of heat transfer model and interfacial area transport equation. However, investigations of bubble lift-off diameter are limited and existing models require further assessment. The popular methods for bubble lift-off diameter are force analysis and correlations. In this study, we aimed to benefit from both force analysis and empirical correlation to establish a model for investigating bubble lift-off diameter in a vertical channel. Through force analysis, bubble lift-off diameter was correlated with dimensionless parameters, including the Prandtl number, the Reynolds number, the Jacob number, and dimensionless subcooling. The uncertain coefficients were determined empirically. The accuracy of present correlation was evaluated by comparing with experimental data.

2. Modeling of Bubble Lift-Off Diameter

2.1. Force Analysis

Generally, bubble nucleation occurs spontaneously at a nucleation site which has pre-existing vapor when the wall temperature is superheated. After nucleation, a bubble keeps growing at the nucleation site as forces acting on the bubble are balanced. Once the forces acting on the bubble are broken, the bubble may lift off the wall directly or slide along the wall for a distance [24]. According to the force analysis undertaken in our previous work [25], the forces can be divided into those that are parallel to the wall and those that are normal to the wall, as shown in Figure 1. The lift-off of a bubble can be ascribed to the disruption of the balance in forces that are normal to the wall.

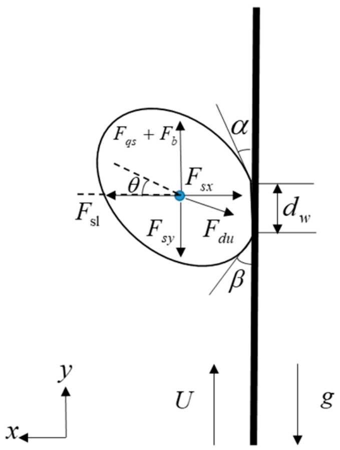

Figure 1. The analysis of forces in vertical surface.

Before the bubble rises from the wall, forces normal to the wall are balanced in the x-direction:

$$\sum F_x = F_{sx} + F_{dux} + F_{sl} = \rho_g V_b \frac{dU_{bx}}{dt} \tag{1}$$

where F_{sx}, F_{dux}, F_{sl}, ρ_g, V_b, U_{bx}, t stand for the surface tension force in the x-direction, the bubble growth force in the x-direction, the shear lift force, the gas density, the bubble volume, the bubble velocity in the x-direction, and time, respectively. The left side of Equation (1) represents the components of forces in the x-direction, while the right side of the equation accounts for the acceleration of bubble, which approaches zero at the point of lift-off. The surface tension force component can be derived from Klausner et al. [11] as follows:

$$F_{sx} = -D_w \sigma \frac{\pi}{\alpha - \beta} (\cos\beta - \cos\alpha) \tag{2}$$

where D_w is the diameter of the bubble contacting the wall, σ is the surface tension, and α and β are the advancing and receding contact angles, respectively. The bubble contact diameter is nearly zero at the point of lift-off, due to a necking effect [26], which means that the contribution of the surface tension is negligible at this moment.

The formation of bubble growth force originates from the difference between pressures inside and outside the bubble. The component of growth force in the x-direction is expressed as follows [11]:

$$F_{dux} = \pi R^2 \rho_l (R\ddot{R} + \frac{3}{2}R^2) \cos\theta \quad (3)$$

where R and θ are the bubble radius and the inclined angle, respectively. The inclined angle is treated as an empirical constant, $\frac{\pi}{18}$ [11]. The bubble growth model of Zuber [27] is recommended by many researchers [16,17] to calculate the growth rate of the bubble:

$$\begin{gathered} R = \frac{2b}{\sqrt{\pi}} Ja\sqrt{a_l t} \ \ (1 < b < \sqrt{3}) \\ Ja = \frac{\rho_l c_{pl}(T_w - T_{sat})}{\rho_v h_{fg}} \end{gathered} \quad (4)$$

where Ja, a_l, ρ_l, ρ_v, c_{pl}, T_w, T_{sat}, h_{fg} are the Jacob number, the thermal diffusivity, the liquid density, the vapor density, the specific heat of the liquid, the wall temperature, the saturated temperature, and the latent heat, respectively.

The shear lift force due to the relative velocity on the spherical bubble can be derived from Mei and Klausner [28], as follows:

$$F_{sl} = \frac{1}{2} C_l \rho_l \pi R^2 {U_r}^2 \quad (5)$$

$$C_l = 3.877 G_s^{1/2} \left(\mathrm{Re}_b^{-2} + 0.014 G_s^2 \right)^{1/4} \quad (6)$$

where U_r stands for the relative velocity between the bubble and the fluid at the center of the bubble and C_l is the shear lift coefficient. Re_b represents the Reynolds number and G_s is defined as follows:

$$G_s = \left| \frac{dU_l}{dx} \right| \frac{R}{U_r}, \quad \mathrm{Re}_b = \frac{U_r D}{\nu_l} \quad (7)$$

where U_l, D and ν_l are the liquid velocity, the bubble diameter, and the kinematic viscosity of the liquid, respectively.

The expressions of bubble growth force and shear lift force can be substituted to Equation (1) and the bubble lift-off diameter D_{lo} can be arranged into a function of dimensionless numbers, as follows:

$$D_{lo}^* = \frac{2b^2\sqrt{2\cos\theta}}{\pi\sqrt{C_l}C_r} \mathrm{Re}_{lo}^{-1} \mathrm{Pr}^{-1} Ja^2 \quad (8)$$

$$D_{lo}^* = \frac{D_{lo}}{Lo}, Lo = \sqrt{\frac{\sigma}{(\rho_l - \rho_v)g}} \quad (9)$$

$$C_r = \frac{U_r}{U_l}, \ \mathrm{Re}_{lo} = \frac{U_l Lo}{\nu_l}, \ \mathrm{Pr} = \frac{\nu_l}{a_l} \quad (10)$$

where σ and C_r are the surface tension force and the relative velocity coefficient, respectively. The Laplace number, La, is introduced to nondimensionalize the bubble lift-off diameter [17,23]. Based on Equations (6) and (7), it is concluded that the shear lift coefficient C_l is related to the Reynolds number and to the relative velocity between fluid velocity. The above dimensionless analysis suggests that the bubble lift-off diameter is correlated to the Prandtl number, the Jacob number, and the Reynolds number. The influence of the relative velocity coefficient can be determined via the empirical constant coefficient. In addition, we observed that the diameter of the bubble decreases slightly during sliding until the bubble lifts from the wall, as the condensation due to subcooling works on the top of the bubble [29,30]. To account for the effect of subcooling, the dimensionless subcooling T^* is introduced, as follows:

$$T^* = \frac{T_w - T_l}{T_w - T_{sat}} \quad (11)$$

Thus, the bubble lift-off diameter in vertical subcooled flow boiling is a function of multiple variables:

$$D_{lo} = f(\mathrm{Re}_{lo}, \mathrm{Pr}, Ja, T^*) \tag{12}$$

2.2. Experimental Data Source from the Literature

According to the above analysis, bubble lift-off diameter is a function of the Prandtl number, the Jacob number, and the Reynolds number. The unsettled coefficients of a bubble lift-off diameter are correlated empirically with experimental data that are collected from the literature. The database from the six groups shown in Table 2 covers a broad range of operating conditions at low pressures in subcooled boiling flow. Specially, the data from Zeng et al. [10] in horizontal flow boiling were not included in the correlated coefficient, as the force analysis in this study focused on bubbles in a vertical channel. In addition, it should be pointed out that wall temperature was not provided in the experiments of Situ et al. [17], Prodanovic et al. [20], and Chu et al. [21]. The correlation of Gungor and Winterton [2] was chosen to resolve the wall temperature, which was validated in our previous work [25].

Table 2. Detailed experimental parameters.

Parameters	Situ et al. [17]	Zeng et al. [10]	Prodanovic et al. [20]	Chu et al. [21]	Okawa et al. [30]	Ahmadi et al. [24]
Direction	Vertical	Horizontal	Vertical	Vertical	Vertical	Vertical
Channel	Annulus	Square	Annulus	Annulus	Pipe	Rectangle
Hydraulic Diameter (mm)	19	25	9.3	22.25	20	13.33
Fluid	Water	R113	Water	Water	Water	Water
Material	Stainless steel	Nichrome	Stainless steel	NCF600	Sapphire glass	Stainless steel
Contact angle (°)	-	-	-	89.9	45	18
Pressure (MPa)	0.101	0.146–0.165	0.105–0.3	0.145	0.121–0.125	0.096–0.113
Heat flux (kW/m^2)	60.7–206	5.8–16.8	100–1200	135–201	67–549	160–318
Mass flow rate (kg/m^{2}s)	466.75–899.96	149–315	74.54–804.43	301–702	85.89–1421.97	169–497
Subcooling (°C)	3–20	Saturated	10–60	3.4–22.6	9.2–20.8	6.5–20.6
Measured D_{lo} (mm)	0.14–0.60	0.46–0.19	0.31–2.68	0.51–1.71	0.50–3.02	0.31–3.90
Data points	90	38	54	14	30	14

With the force analysis and the experimental data, the multiple linear regression method was capitalized to correlate the lift-off diameter of a bubble, with the following variables:

$$D_{lo}^* = 0.984\mathrm{Re}_{lo}^{-0.286}\mathrm{Pr}^{-0.424}Ja^{0.663}{T^*}^{-0.638} \tag{13}$$

3. Results and Discussion

3.1. Assessments of Existed and Present Models

As discussed in the introduction, many bubble lift-off diameter models have been proposed, based on force analysis or empirical correlation, such as the models of Situ et al. [17], Basu et al. [23], and Prodanovic et al. [20]. The expressions and applications of these models are shown in Table 1. To check the performances of above models, the predictions were compared with experimental data in Table 2.

In addition, it should be noticed that the data from Zeng et al. [10] in horizontal flow boiling participate in the comparison between the models and the measured values. The performances of existing and present models are presented in Figure 2. We concluded that Prodanovic's correlation [20] can well predict the values from Chu et al. [21], Okawa et al. [30], and Ahmadi et al. [24], but it fails to compare with the data of the other three groups. The mechanistic model of Situ et al. [17] overpredicts most of the experimental data. The error may be due to the empirical constant of relative velocity coefficient, with respect to which the results were very sensitive. To replicate the results of Situ's model, the modified correlation of Chen et al. [1] was utilized to compute the unavailable wall temperature, as suggested in the original article. Although Basu's model [23] performs much better than the other two models, it slightly overpredicts the data from Situ et al. [17] and Zeng et al. [10]. Based on a mechanistic analysis and empirical modifications, the present model provides comparatively precise predictions of bubble lift-off diameter in subcooled flow boiling.

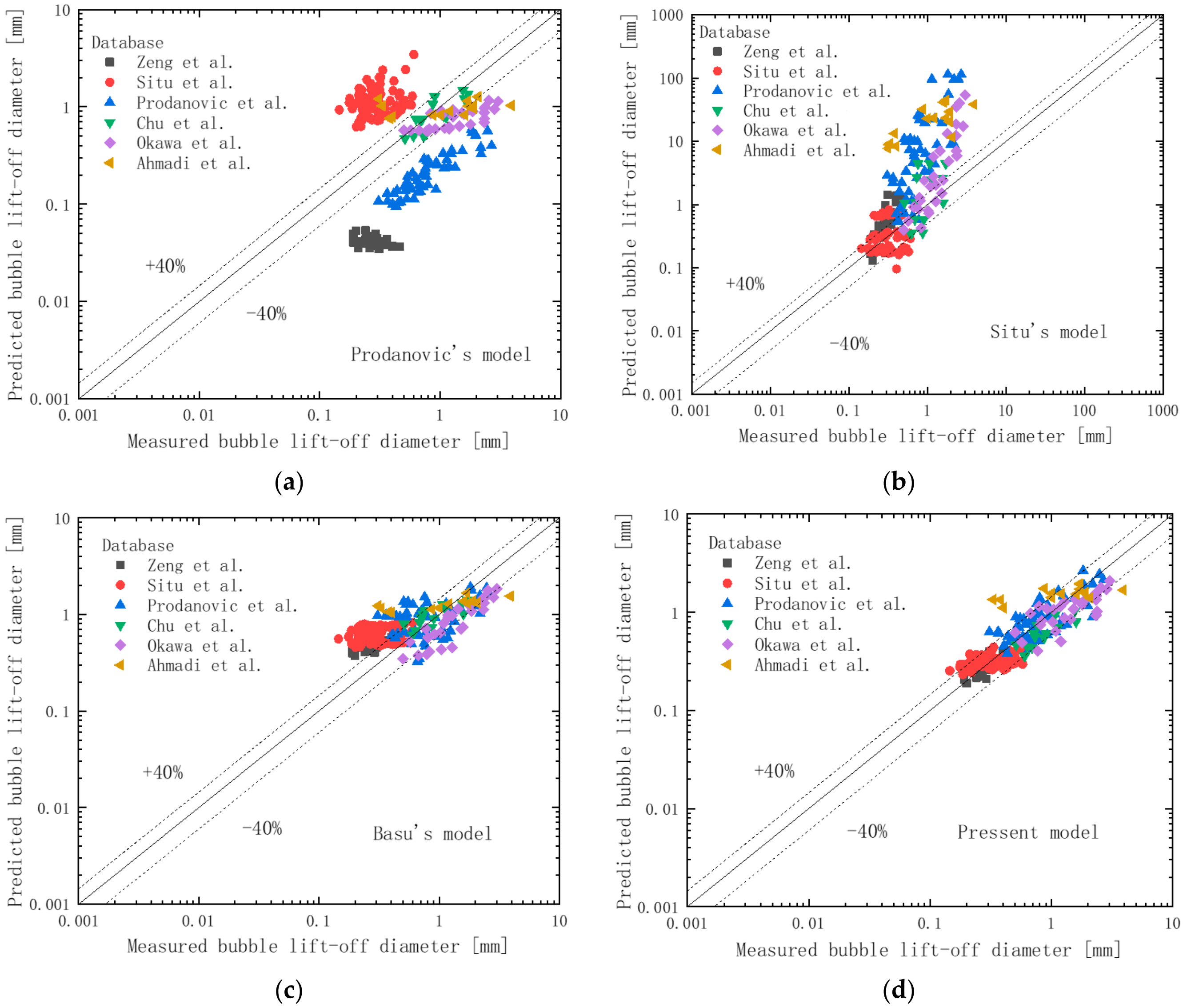

Figure 2. The evaluation of predictive models against experimental data. (**a**) The comparison with Prodanovic's model; (**b**) The comparison with Situ's model; (**c**) The comparison with Basu's model; (**d**) The comparison with the present model [10,17,20,21,24,30].

To concretely assess the performances of these theoretical or empirical models, the comparisons between the predictive models and the experimental data were calculated quantitively. The mean relative error was defined as:

$$\varepsilon = \frac{1}{n}\sum_{i=1}^{n} \frac{\left| D_{lo,predicted} - D_{lo,measured} \right|}{D_{lo,measured}} \tag{14}$$

where n stands for the data points in the database. Table 3 lists the mean relative errors between the values calculated by the four predictive models and the values measured in the experiments.

Table 3. Evaluated relative errors between the models and the experiments.

Predictive Models	Experiments						
	Zeng et al. [10]	Situ et al. [17]	Prodanovic et al. [20]	Chu et al. [21]	Okawa et al. [30]	Ahmadi et al. [24]	Total
Prodanovic et al. [20]	85.53%	237.65%	73.57%	20.19%	41.11%	56.82%	122.70%
Situ et al. [17]	84.67%	40.22%	736.53%	129.24%	318.66%	894.57%	258.81%
Basu et al. [23]	69.54%	102.53%	44.63%	21.71%	36.77%	73.61%	69.92%
Present study	12.15%	25.44%	30.14%	27.26%	29.90%	45.91%	26.95%

It can be concluded from Table 3 that Prodanovic's model and Basu's model provide acceptable predictions for most of the experimental data except for the data from Situ et al. [17]. The predictions of Situ's model accord with their own experimental data, and were well within a relative error of 40.22%, which is similar to the value stated in their paper. The mean relative error of the present model was 26.95%, which showed better agreement than that of the other models. In addition, it was surprising to find that the predictions of the present model in horizontal flow boiling had a great performance when compared with data from Zeng et al. [10], whose mean relative error was 12.15%. The force analysis in a horizontal surface [25] indicated the buoyancy force, which is due to the density difference and gravity, makes a contribution to the rise of a bubble. In Equation (11), the Laplace length, which is a function of gravity and the density difference, is assumed to nondimensionalize the bubble lift-off diameter. According to the definition, it can be inferred that the effect of the buoyancy force is embodied in the value of the Laplace length. Therefore, the extension of the bubble lift-off diameter models from vertical channels to horizontal channels is reasonable.

3.2. The Effects of Dimensionless Parameters

In Equation (13), the bubble lift-off diameter is determined by a combination of the Prandtl number, the Jacob number, the Reynolds number, and dimensionless subcooling. Based on the experimental data shown in Table 2, the change tendencies of dimensionless diameters with dimensionless parameters are analyzed and presented in Figure 3, which shows that bubble lift-off diameter increases with the Jacob number and the Prandtl number, while it decreases with the Reynolds number and dimensionless subcooling. The change tendency can be explained by force analysis or by physical mechanisms.

3.2.1. Jacob Number

The physical meaning of the Jacob number is the available sensible heat divided by the latent heat of vaporization. Available sensible heat is determined by wall superheat, which reflects external energy from the wall. The growth of a bubble is mainly generated by the superheated layer surrounding the bubble and by the microlayer beneath the base of the bubble [22]. The rise of wall superheat may thicken the superheated layer and the microlayer, contributing to the bubble growth on the nucleation site. The latent heat of vaporization rises linearly with system pressure. Because the experimental data varies within a limited range of system pressure, available sensible heat changes more obviously. The bubble lift-off diameter is enlarged with the rise in the Jacob number, which boosts the sensible heat.

On the other hand, in the force analysis, the Jacob number affects the bubble growth force. The bubble growth force originates from the pressure difference inside and outside the bubble and the direction points to the wall, which keep the bubble growing on the wall. The increase in the Jacob number stands for the rise in bubble growth force, which contributes to bubble growth.

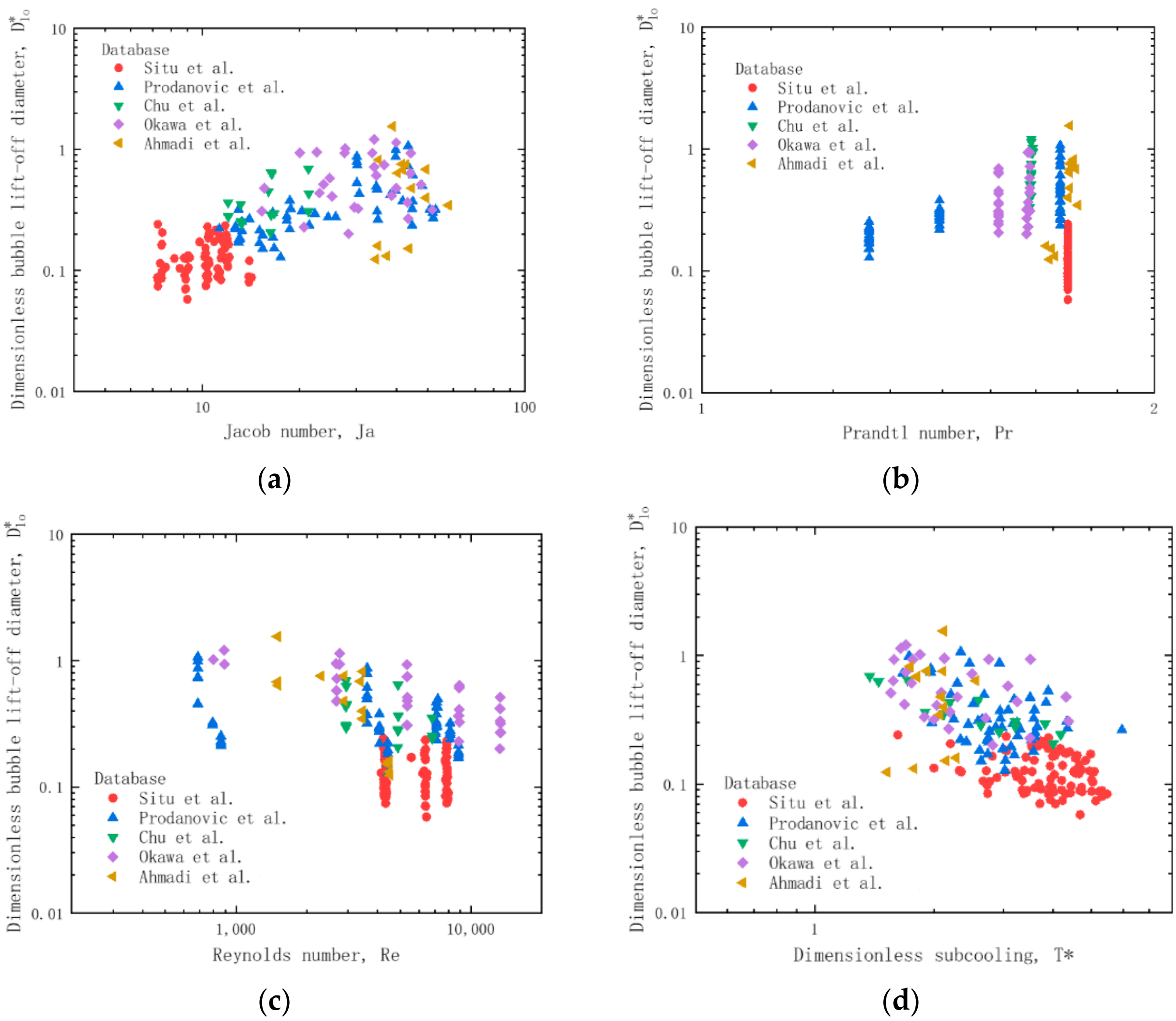

Figure 3. Non-dimensional lift-off diameters changing with dimensionless parameters. (**a**) The effect of the Jacob number; (**b**) The effect of the Prandtl number; (**c**) The effect of the Reynolds number; (**d**) The effect of dimensionless subcooling [17,20,21,24,30].

3.2.2. Prandtl Number

The Prandtl number represents the proportion of kinematic viscosity to thermal conductivity, which is determined by the properties of the working fluids and elucidates the relationship between the velocity boundary layer and the thermal boundary layer [25]. Water only was selected as the working fluid in the experimental data available in the empirical coefficients. The Prandtl number can be regarded as the ratio of the velocity boundary layer and the thermal boundary layer of water. The increase in the Prandtl number indicates that the velocity boundary layer thickens faster than the thermal boundary layer, which prevents the bubble from being sheared by fluid turbulence; the bubble may keep growing during its sliding distance before leaving the wall. As shown in Figure 3, the bubble lift-off diameter increases with the Prandtl number.

3.2.3. Reynolds Number

The Reynolds number is related to liquid velocity, characteristic length, and kinematic viscosity, which reflects the flow condition of the working fluid. To account for the characteristic length of a bubble's lift-off diameter, the Laplace number (La) was introduced into the definition of the Reynolds number. The rise in liquid velocity signified that the liquid turbulence was strengthened, accelerating the process of bubble lift-off and reducing the bubble's size. Moreover, the intensity of the liquid turbulence can boost the liquid convection around the bubble, which can enhance heat transfer. According to the wall heat flux partitioning model, more heat transfer convection means less latent heat for bubble growth.

In the force analysis, the Reynolds number affects the bubble shear lift force. With the increase in liquid velocity, the velocity gradient near the wall grows steeper and the shear lift force acting on the bubble becomes stronger. Consequently, the rise in the Reynolds number leads to a decrease in the bubble lift-off diameter.

3.2.4. Dimensionless Subcooling

Dimensionless subcooling is defined as the ratio of subcooling to superheat. In terms of energy, the superheated layer contributes to the growth of the bubble near the wall. With an increase in liquid subcooling, the superheated layer may become thinner and the temperature gradient becomes steeper, which may retard bubble growth and allow the top of the bubble to be condensed. In addition, the liquid subcooling enhances the convection heat transfer between the wall and the bulk fluid and, consequently, decreases the wall temperature. The input wall heat flux for latent heat decreases as well. Therefore, the bubble lift-off diameter decreases with dimensionless subcooling.

4. Conclusions

A bubble's lift-off diameter is essential as the boundary condition of wall heat transfer model and interfacial area transport equation. Force analysis and dimensionless analysis were conducted to develop a predictive model of bubble lift-off diameter. Based on force analysis, the bubble growth force and the shear lift force, which control bubble lift-off, are arranged as a combination of the Jacob number, the Prandtl number, and the Reynolds number. Considering the effect of bulk liquid subcooling, the dimensionless subcooling was introduced into the correlation.

Based on our analysis, bubble lift-off diameter is correlated with the measured data from the relevant literature. The proposed model is applicable in pressures from 0.101 MPa to 0.3 MPa, mass flow rates from 85.89 to 1421.97 kg/(m^2·s), heat flux from 60.7 to 1200 kW/m^2, and subcooling from 3 K to 60 K. To assess the performance of present model, comparisons between predictive models and experimental data were performed quantitively. The mean relative error of present model was 26.95%. The change tendencies of bubble lift-off diameter with dimensionless parameters were analyzed and discussed by force analysis or with reference to physical mechanisms. Bubble lift-off diameter increases with the Jacob number and the Prandtl number, while it decreases with the Reynolds number and dimensionless subcooling.

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Nomenclature

F_s	surface tension force (N)
F_{du}	bubble growth force (N)
F_{sl}	shear lift force (N)
ρ	density (kg/m^3)
V	volume (m^3)

U	velocity (m/s)
t	time (s)
F_{qs}	quasi-steady drag force (N)
F_b	buoyancy force (N)
R	bubble radius (m)
D	bubble diameter (m)
U_r	relative velocity (m/s)
C_l	shear lift coefficient
G_s	dimensionless shear rate
λ	thermal conductivity (W/(m·K))
ε	mean relative error
c_p	heat capacity (J/(kg·K))
T	temperature (K)
h_{fg}	latent heat (J/kg)
C_r	relative velocity coefficient
Pr	Prandtl number
Re	Reynolds number
Ja	Jacob number
T^*	dimensionless subcooling
Lo	Laplace length (m)
σ	surface tension (N/m)
α	advancing contact angle
β	receding contact angle
θ	inclined angle
a	thermal diffusivity (m^2/s)
ν	kinematic viscosity (m^2/s)
n	data points
Subscripts	
w	wall
sat	saturated
l	liquid
v	vapor
g	gas
b	bubble
lo	lift-off
x	x-direction
y	y-direction

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