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Study on bubble dynamics for pool nucleate boiling

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Abstract

A characteristic length scale and a time scale are proposed to describe the dynamic growth and departure process of bubbles. A correlation between bubble departure diameter and bubble growth time is established thereby, and a predication formula for bubble departure diameter is suggested by considering the analogue between nucleate boiling and forced convection. © 1999 Published by Elsevier Science Ltd. All rights reserved.

Keywords: Nucleate boiling; Bubbles; Departure diameter; Departure frequency

1. Introduction

Nucleate boiling has achieved worldwide interest and received comprehensive researches, since it is a highly efficient heat transfer process favored in many industrial applications. Bubble departure diameter, D_b, and frequency, f, are two important parameters of bubble dynamic process. Bubble departure frequency was predicted generally by the expression relating departure frequency to departure diameters. We present this work to put forward the characteristic length scale and the time scale for describing the dynamic process of bubble growth and departure.

2. Basic considerations

The well-known Fritz equation [1] was presented as:

$$D_\mathrm{b} = 0.0208\theta\sqrt{\frac{\sigma}{g(\rho_\mathrm{l}-\rho_\mathrm{v})}} \tag{1}$$

This agreed well with the experimental data at atmospheric pressure, but did not agree well with the experimental data at subatmospheric and superatmospheric pressures. Latter, Cole found that, if $D_\mathrm{F} = \sqrt{\sigma/g(\rho_\mathrm{l}-\rho_\mathrm{v})}$ for a contact angle of 48°, $\bar{D}_\mathrm{b} = D_\mathrm{b}/D_\mathrm{F}$, is a function of pressure and according to the experimental data for water, Cole [2] obtained:

$$\bar{D}_\mathrm{b} = \frac{1000}{P} \tag{2}$$

where P is in mm Hg. Furthermore, Cole [3] proposed that the effect of system pressure, p, is accounted with a modified Jacob number $Ja^* = \rho_\mathrm{l}C_\mathrm{pl}T_\mathrm{s}/\rho_\mathrm{v}H_\mathrm{fg}$, and obtained:

$$\bar{D}_\mathrm{b}^{1/2} = C_1 Ja^{*5/4} \tag{3}$$

The proportion factor C_1 of Eq. (3) was found different for water and organic liquids and the influence of degree of superheat on departure diameter could not be explained.

Recently, Zeng et al. [4] proposed that the dominant forces leading to bubble detachment would be the unsteady growth force and the buoyancy force. They

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Nomenclature

C	bubble shape coefficient
C_s	bubble growth constant
D_b	bubble departure diameter (m)
D_F	bubble departure diameter for a contact angle of 48° predicted by equation of Fritz (m)
$\bar{D}_b$	dimensionless bubble departure diameter
D_b^+	dimensionless bubble departure diameter
f	bubble departure frequency (s^{-1})
$f(c)$	bubble volume factor
g	gravitational acceleration (m/s^2)
H_{fg}	latent heat of vaporization (J/kg)
Ja	Jacob number
Ja^*	modified Jacob number, $\frac{\rho_l C_{pl} T_s}{\rho_v H_{fg}}$
L_0	the characteristic length scale
N_b	Nusselt number
n	bubble growth exponent
P	system pressure (mm Hg)
Pr_l	liquid Prandtl number
Re_b	Reynolds number
R	bubble radius (m)
R_b	radius of the liquid microlayer underneath the bubble (m)
T_s	saturated temperature (K)
U_0	the characteristic speed scale
ΔT	superheat (K)
θ	contact angle
σ	surface tension (N/m)
ρ_l	liquid density (kg/m^3)
ρ_v	vapour density (kg/m^3)
a_l	liquid thermal diffusivity (m^2/s)
ϕ	modified factor of bubble growth for high pressure
R^+	bubble dimensionless radius (m)
τ^+	bubble dimensionless time (s)
τ_g	bubble growth time (s)
τ_g^+	dimensionless bubble growth time
τ_0	the characteristic time scale
μ_l	liquid dynamic viscosity (kg/m s)
ψ	a parameter defined by Eq. (18)
η	a parameter in Eq. (19), $\psi Ja^{0.3}$

based on the empirical correlation of bubble growth radius, R_t, to time, τ_g, as:

$$R_t = K\tau_g^n \tag{4}$$

and obtained an expression for predicting bubble departure diameter:

$$D_b = 2\left\{\frac{3}{4}\frac{K^{2/n}}{g}\left[\frac{3}{2}C_s n^2 + n(n-1)\right]\right\}^{n/(2-n)} \tag{5}$$

The bubble growth constant, C_s, was found empirically as $C_s = 20/3$. Then, the influence of many factors on bubble growth and departure are reflected in the proportional constant, K, and exponent, n. Therefore, Eq. (5) is useful only when specific information on the vapor bubble growth (K and n) is available.

Zeng and Klausner [5] proposed an empirical correlation of computing the bubble volume:

$$V_b = \frac{4\pi}{3}f(c)R_t^3 \tag{6}$$

with

$$f(c) \approx 1 - \frac{3}{4}\left[1-\sqrt{1-c^2}\right]^2 + \frac{1}{4}\left[1-\sqrt{1-c^2}\right]^3 \tag{7}$$

where parameter $c = R_b/R_t$, with R_b and R_t shown in Fig. 1.

It is of interest to note that, if Eq. (4) is valid at the time of bubble departure, then substituting it into Eq. (5) yields:

$$D_b t_g^{-2} = 2\left\{\frac{3}{4g}\left[\frac{3}{2}C_s n^2 + n(n-1)\right]\right\}^{-1} \tag{8}$$

For the case that the departure time is just one-half the time period, $1/f$, Eq. (8) can be expressed as:

$$f D_b^{1/2} = \sqrt{2}\left\{\frac{3}{4g}\left[\frac{3}{2}C_s n^2 + n(n-1)\right]\right\}^{-1/2} = C\sqrt{g} \tag{9}$$

which is same as suggested by McFadden and Grassmen [6].

The prediction of the growth rates of vapor bubbles in boiling has been a basic problem in the study of nucleate boiling heat transfer Labuntsov suggested that C_s could be computed by the fitted correlation [7]:

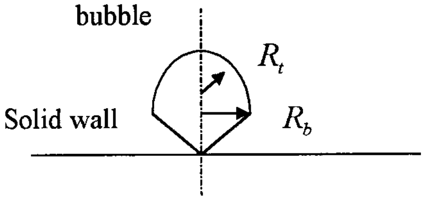

Fig. 1. Sketch for the growing bubble.

$$C_s = Ja\sqrt{\frac{3}{\pi}}\phi^{1/2} \tag{10}$$

where

$$\phi = \left[1 + \frac{1}{2}\left(\frac{\pi}{6Ja}\right)^{2/3} + \frac{\pi}{6Ja}\right] \tag{11}$$

3. New correlation proposed

We introduce the following dimensionless form characteristic length scale and time scale:

$$D_b^+ = \frac{D_b}{L_0} = \frac{AD_b}{\phi B^2};\quad \tau_g^+ = \frac{1}{\phi}\left(\frac{A}{B}\right)^2\tau_g \tag{12}$$

where

$$A = \sqrt{\frac{2\rho_v \Delta T_s H_{fg}}{3\rho_l T_s}};\quad B = Ja\sqrt{\frac{12}{\pi}}a_l \tag{13}$$

Fig. 2 shows the relationship between the dimensionless bubble departure diameter, D_b^+ and growth time, τ_g^+, according to the experimental results of Cole [8], Han and Griffith [9], Stralen [10] and Stainszewski [11] etc. A straight line in the double logarithmic plots and can be expressed as:

$$D_b^+ = C_\tau\left(\tau_g^+\right)^{2/3} \tag{14}$$

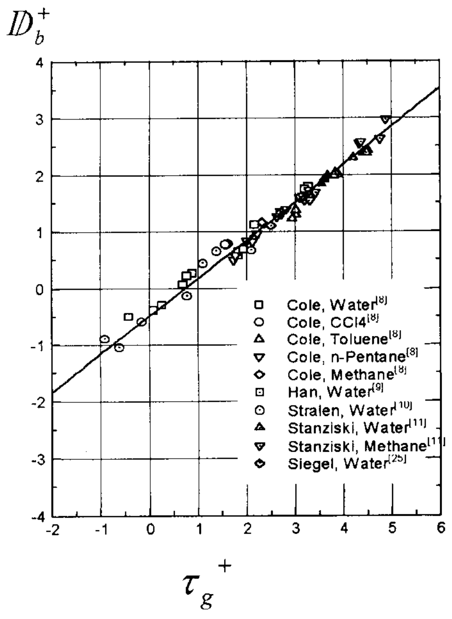

Fig. 2. Relationship between dimensionless growth time and departure diameter.

Taking into account the different liquids and the wide range of pressure and superheat, it seems to us that the length scale and time scale can correctly describe bubble dynamic growth process. The bubble departure diameter is correlated only with bubble growing time.

As proposed by Rohsenow [12]:

$$\frac{Re_b Pr_l}{Nu_b} = C_b Re_b^m Pr_l^n \tag{15}$$

We have

$$Nu_b = \frac{2f(c)}{3c^2}\frac{D_b A}{a_l Ja}\quad Re_b = \phi\frac{\rho_l B^2}{\mu_l} \tag{16}$$

and Eq. (15) becomes:

$$D_b^+\psi = \frac{3}{2C_b}\left(\frac{\pi}{12}\right)^m Ja^{1-2m}Pr_l^{m-n} \tag{17}$$

where

$$\psi = \frac{c^2}{\phi^{m-1}\left[f(c)\right]^{2/3}} \tag{18}$$

This provides a unified model of predicting bubble departure diameter.

Fig. 3 presents the relationship between modified factor, ψ and Jacob number, Ja. Figs. 4 and 5 presents the comparison between the measured departure diameter and the result predicted by using Eq. (17) (see also Tables 1 and 2). It is noted that the measured data of both organic liquids and water can be correlated with

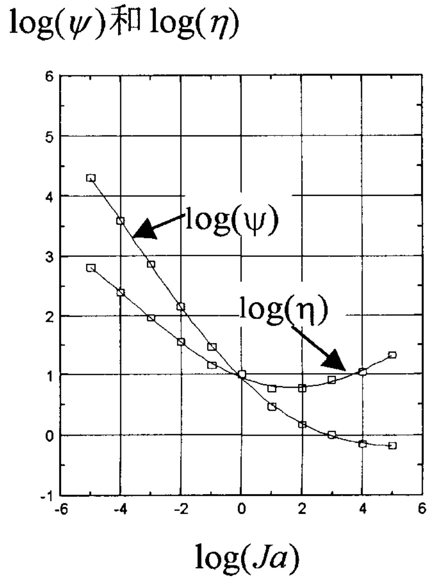

Fig. 3. Relationship between modified factor ψ and Jacob number Ja.

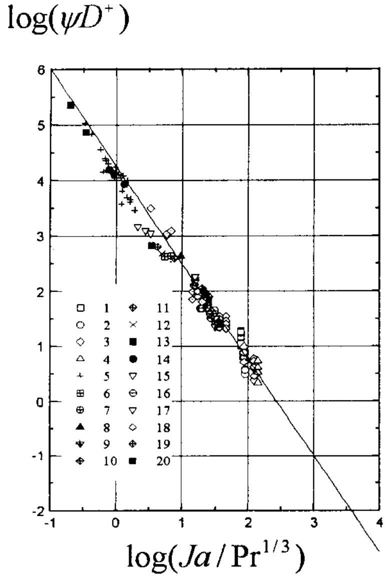

Fig. 4. Comparison of predicted and measured bubble departure diameter for organic liquids.

the same equation with $m = 1.4$; $n = 0.8$ for the entire range of experimental condition. Eq. (17) settles the puzzle of Cole [3] that C_1 in Eq. (4) would be different for water and organic liquids.

In order to study the effect of superheat on bubble departure diameter, the value of m and n and Eq. (13) were introduced into Eq. (17), then we obtain:

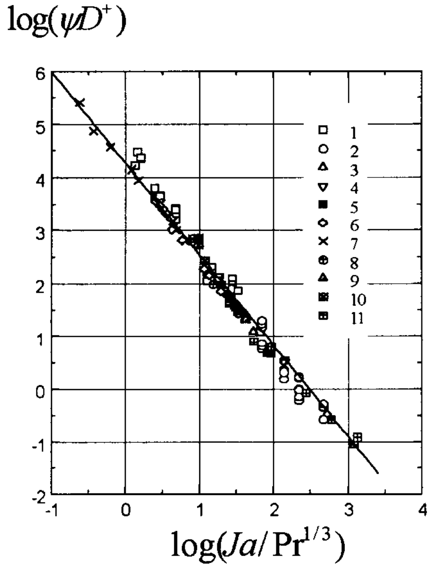

Fig. 5. Comparison of predicted and measured bubble departure diameter for water.

$$D_b = 3.0557 \times 10^3 \frac{\rho_l}{\rho_v} \frac{\sqrt{C_{pl} T_s}}{H_{fg}} \frac{\alpha Pr_l^{3/5}}{\eta} \tag{19}$$

where $\eta = \psi Ja^{0.3}$. According to Eq. (19), the effect of superheat on bubble departure can be represented by the effect of superheat on η. Fig. 3 also shows the effect of superheat on η. It is noted that η varied very little with Ja ranging from 1 to 1000. This indicates

Table 1
Means of the icons in Fig. 4

No. of icons	Source of data	Pressure (atm)	Boiling liquids
1	Cole [8]	0.3	Acetone
2	Cole [8]	0.1816	Carbon tetrachloride
3	Cole [8]	0.18, 0.27, 0.4, 0.52, 0.71	Methane
4	Cole [8]	0.6895, 1.0	*n*-Pentane
5	Cole [8]	0.0632	Toluene
6	Haider [13]	1.0	R-123
7	Judd [14]	0.5, 0.6, 0.8, 1.0	Carbon tetrachloride
8	Tolubinsky [15]	1.0	Benzene
9	Tolubinsky [15]	1.0	Carbon tetrachloride
10	Tolubinsky [15]	1.0	Ethanol
11	Tolubinsky [15]	1.0	Glecerine
12	Tolubinsky [15]	1.0	Methanol
13	Tolubinsky [15]	1.0	*n*-Butanol
14	Tolubinsky [15]	1.0	R-12
15	Wanninger [16]	1.0	Methyl pentane
16	Wanninger [16]	8.5, 11.0, 14.0	Propane
17	Perkins [17]	1.0	Methanol
18	Staniszewski [11]	2.72	Methanol
19	McFaden [6]	1.0	He (liquid)
20	Nakayama [18]	1.0	R-11

Table 2
Means of icons in Fig. 5

No. of icons	Source of data	Pressure (atm)
1	Akyiama [19]	0.2–15
2	Cole [8]	0.0658, 0.0855, 0.1289, 0.2566, 0.4737
3	Gaertner [20]	1.0
4	Han [9]	1.0
5	Nishikawa [21]	0.4, 0.423, 0.7, 0.9, 1.0
6	Tolubinsky [22]	0.2, 0.5, 0.8, 1.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0
7	Semeria [23]	1.0, 4.0, 5.75, 10.0, 20.0, 27.5, 50.0, 75.8, 132.0
8	Siegel [24]	1.0
9	Siegel [25]	1.0
10	Stanizewski [11]	1.0, 1.92, 2.72
11	Stralen [10]	0.0204, 0.0408, 0.1321, 0.2028, 0.2672, 1.0

that the effect of superheat on bubble departure diameter is very small.

4. Conclusion

The following conclusions can be drawn:

1. The characteristic length scale and time scale can correctly describe the dynamic growth process of bubbles.
2. Bubble departure diameter could correlate with bubble growth time.
3. The unified model of bubble departure diameter is in satisfactory agreement with the reported experimental results.
4. The proposed model for correlating and predicting bubble dynamics could be applied in earth gravity pool boiling. Further study is needed to introduce the effect of gravity on bubble departure diameter into the model.

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