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A modified model for bubble growth rate and bubble departure diameter in nucleate pool boiling covering a wide range of pressures

Jingyu Du, Chenru Zhao, Hanliang Bo*

Institute of Nuclear and New Energy Technology, Tsinghua University, Key Laboratory of Advanced Reactor Engineering and Safety of the Ministry of Education, Beijing 100084, China

HIGHLIGHTS

- A modified model is proposed to predict bubble growth rate in a wide range.
- The force-balance model is improved by present bubble growth rate model.
- The results of present model perform better than several other existed models.

ARTICLE INFO

Keywords:
Bubble growth rate
Superheated layer
Bubble departure diameter
Pool boiling

ABSTRACT

Based on the assumption of superheated layer and experimental data from literature, a modified model for bubble growth rate in saturated pool boiling is developed to cover a wide range of boiling conditions at pressures from 0.00204 MPa to 9.57 MPa and Jakob numbers from 0.0904 to 2689. In this paper, the bubble growth rate is non-dimensionalized to follow a power curve and the expression is modified as a function of growth exponent and growth coefficient. According to the analysis of the available experimental data, the growth exponent of bubble appears to change with the system pressure while the growth coefficient vary with the Jakob number. By analyzing the relationships between bubble growth rate and system pressures and Jakob numbers, a modified bubble growth rate model is developed in this paper. The predictions by present model agree better with the experimental data than those by several other models. Based on the developed bubble growth rate model, the force-balance model to predict the bubble departure diameter in nucleate pool boiling is accordingly modified in this paper. The modified bubble departure diameter model predicts more than 90% of the experimental data within ± 50%.

1. Introduction

Due to its high efficiency, nucleate boiling has been widely applied in nuclear reactors, chemical reaction and so on [1–3]. The growth rate and departure diameter of vapor bubble are two key issues in understanding the mechanism of nucleate boiling. Considering the heat diffusion to be the motivation for bubble growth, there are several heat transfer mechanisms, such as the microlayer between the base of the bubble and heating wall, the superheated layer surrounding the bubble and evaporation at the three-phase contact line when a dry patch forms on the surface [4].

Plesset and Zwick [5] assumed a spherical bubble growing in superheated liquid and its growth was controlled by inertia of the liquid, surface tension and the vapor pressure. Zuber [6] extended the bubble growth model to non-uniform temperature field. Han and Griffith [7,8] considered the superheated layer to control bubble growth and divided the process of bubble growth into three stages: waiting period, unbinding period and departure period. Later, Cooper and Lloyd [9,10] measured the fluctuation of wall temperature and inferred the existence of a thin liquid layer called microlayer beneath the bubble. However, the structure of microlayer was not observed directly due to the limitation of experimental techniques. The shape and thickness of microlayer were assumed in theoretical models to determine the heat transfer through microlayer and bubble growth rate [11,12]. Therefore, bubble growth models considering both superheated layer and microlayer were suggested by many researchers [13–15], while the portion of each heat transfer mechanism contributed to bubble growth remains to be unclear. Although there are some debates on the contribution of heat transfer, for instance, the debate between superheated layer surrounding the bubble and microlayer beneath the bubble as mentioned

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* Corresponding author.
E-mail address: bohl@tsinghua.edu.cn (H. Bo).

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Nomenclature

Ja	Jakob number
R	bubble radius (m)
P	pressure (MPa)
T	temperature (K)
$f(Ja)$	bubble growth coefficient
n	bubble growth exponent
t	time (s)
r	radial coordinate
u	velocity (m/s)
a	thermal diffusivity (m^2/s)
k	thermal conductivity (W/(m·K))
c_p	heat capacity (J/(kg·K))

Greek symbols

Δ	difference
ρ	density (kg/m^3)
μ	kinetic viscosity (Pa·s)

Subscripts

w	wall
sat	saturated
l	liquid
v	vapor
h_{fg}	latent heat (J/kg)
F_b	buoyancy force (N)
F_{sl}	shear lift force (N)
F_{cp}	contact pressure force (N)
F_s	surface tension (N)
F_{du}	growth force (N)
D	diameter(m)
d_w	contact diameter (m)
U	relative velocity (m/s)
V	volume (m3)
H	Height (m)
σ	surface tension (N/m)
α	contact angle (rad)
∞	infinite
b	bubble
d	departure
x	x-direction
y	y-direction

above, the assumptions help us to have a deep understanding of heat transfer mechanism in bubble growth and nucleate boiling.

With the development of advanced techniques such as the infrared thermometry and laser interferometry, the existence of microlayer was proved and the detailed structure of microlayer was observed during the growth of vapor bubble [16–18]. The portion of heat transfer through microlayer can be obtained by temperature distribution measured by infrared thermometry. However, Demiray [19] pointed that only 12.5% of the energy required to produce the bubble came from the microlayer and the rest came from the superheated layer surrounding the bubble. Jung and Kim [16] estimated that the contribution of the heat transferred through the liquid microlayer was less than 17% and the fraction of the heat transferred through the dry spot area was negligible. Therefore, it can be inferred that the growth of a single bubble was primarily due to the superheated layer surrounding the bubble. Based on the assumptions or available experimental data, several previous models for bubble growth rate are proposed in Table 1.

From Table 1, we can see that most of bubble growth rates changing with time follow power curve, where the growth exponent is 1/2 and the coefficient is determined by Jakob number which is the ratio of the

Table 1
Various models for bubble growth rate.

Author	Growth model	Consideration	Application
Plesset (1954) [5]	$R(t)=\left(\frac{12}{\pi}\right)^{1/2}Ja(at)^{1/2}$	Superheated layer	Uniform temperature field
Forster (1954) [20]	$R(t)=\sqrt{\pi}Ja(at)^{1/2}$	Superheated layer	Uniform temperature field
Zuber(1961) [6]	$R(t)=\frac{2b}{\sqrt{\pi}}Ja(at)^{1/2}$	Superheated layer	Uniform temperature field
	$R(t)=\frac{2b}{\sqrt{\pi}}Ja(at)^{1/2}\left[1-\frac{q_b\sqrt{\pi at}}{2k\Delta T}\right]$		Non-uniform temperature field
Labunstov (1964) [21]	$R(t)=\sqrt{2\beta\cdot Ja}\,(at)^{1/2}$ $\beta=2\cos(\theta/2)\ln\frac{\Delta}{y_A}[(1+\cos\theta)^2(2-\cos\theta)]^{-1}$	Microlayer	Pressure: 1–100 bar
Cole (1966) [22]	$R(t)=\frac{5}{2}J_a{}^{3/4}(at)^{1/2}$	Experiment	High Jakob number
Cooper (1969) [9]	$R=2.5\frac{Ja}{\mathrm{Pr}_l^{0.5}}(at)^{1/2}$	Microlayer	–
Mikic (1970) [23]	$R^+=\frac{2}{3}[(t^++1)^{3/2}-(t^+)^{3/2}-1]$ $R^+=\frac{R}{B^2/A},\ t^+=\frac{t}{B^2/A^2}$ $A=\left[b\frac{\Delta Th_{fg}\rho_v}{T_{sat}\rho_l}\right]^{1/2},\ B=\left[\frac{12}{\pi}Ja^2a_l\right]^{1/2}$	Superheated layer	–
Akiyama (1969) [24]	$R=Ja^{3/5}a^{1/2}t^n$	Experiment	Jakob number: 2–1040
Chen (2011) [25]	$R^*=Kt^{*n}$ $R^*=\frac{R}{La/2},\ t^*=\frac{t}{\xi}$	Experiment	Pressure: 1–10 bar
Hoang (2016) [26]	$\frac{dR}{dt}=\frac{1-m}{2}Ja\sqrt{\frac{a_l}{\pi}}t^{-1/2}-mh_c\Delta T_b$	Superheated layer Condensation	Subcooled flow boiling
Raj (2017) [15]	$\frac{dR}{dt}=\frac{1}{C}(\mathrm{Pr}^{-0.5}\times Ja\times a^{0.5})t^{-0.5}+\sqrt{\frac{3}{\pi}}\frac{K_l(T_0-T_b)}{a^{0.5}\rho_lh_{lv}}t^{-0.5}(1-f_{ra})$ $-\left(\frac{K_l}{\rho_lh_{lv}d_b}(2+0.6\mathrm{Re}^{0.5}\mathrm{Pr}^{0.3})(T_{sat}-T_{bulk})\right)f_{ra}$	Superheated layer Microlayer; Condensation	Subcooled flow boiling