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An analytical model for predicting growth rate and departure diameter of a bubble in subcooled flow boiling

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ABSTRACT

Bubble formation in flow boiling undergoes an ebullition cycle in which nucleation is followed by bubble growth, departure and a waiting period. Bubble growth rate plays an important role in bubble dynamics and also affects the whole ebullition cycle. It is difficult to make analytical calculation of bubble growth rate and departure diameter due to involvement of various forces and heat transfer processes on a nucleating bubble. In this paper, an analytical technique is proposed to calculate the growth rate and departure diameter of a nucleating bubble in subcooled flow boiling. Both force and energy balance approaches have been applied to calculate the growth and departure diameter of the bubble. Heat transfer contributions from evaporative microlayer beneath the bubble, superheated liquid surrounding the bubble and condensation from the bubble cap have been considered to calculate the bubble growth rate. In place of using a constant coefficient to represent the fraction of bubble in subcooled bulk liquid by existing analytical models, the present model correlates the coefficient with the operating parameters of flow boiling. An effort has also been made for accurate calculation of temperature distribution in heated surface and flowing liquid. Bubble growth rate and departure diameter have been calculated for different values of coolant mass flux, system pressure, applied heat flux, surface orientation angle and liquid subcooling. The heat transfer contribution from individual layer towards the growth rate of the bubble has been quantified and analyzed. The present analytical model has been validated with a wide range of experimental data and it produces better agreement with the experimental data compared to existing analytical models.

1. Introduction

Flow boiling is an efficient mechanism for heat transfer in several applications due to involvement of latent heat. The process is widely used in various applications, ranging from chemical and process industries to boiling water reactors and steam power plants etc. Bubble dynamics plays an important role in flow boiling heat transfer. Analysis of bubble ebullition cycle and mechanism of bubble detachment in flow boiling have always been fascinating and challenging topics of research for several decades. Several attempts have been made to calculate bubble growth rate and departure diameter considering various forces that act on a growing bubble from a heated surface. However, compared to pool boiling, number of investigation of bubble dynamics in flow boiling is limited. This might be due to complexity involved in dealing with turbulent bulk convection, complex thermo-hydrodynamic interaction between liquid and vapor phases [1]. Moreover, bubble growth and its departure are controlled by different forces that act on the bubble. Chang [2] developed a mechanistic model to predict departure diameter of vapor bubble considering balance of buoyancy, surface tension and inertia force. Bubble departure diameter in subcooled flow boiling in an upward direction was calculated by Levy [3] considering the balance of surface tension, buoyancy and drag forces. For calculating temperature distribution of coolant, an approximation of thermal boundary layer in a single phase (liquid) turbulent flow was assumed. Koumoutsos et al. [4] investigated the nucleation and evolution a bubble from a heated surface. They observed sliding of the growing bubble along the heated surface before its lift off. They also developed a correlation for calculating bubble departure diameter based on force balance method and validated their results with experimental data. Cooper et al. [5] analyzed the individual motion of *n*-hexane vapor bubbles over a flat surface and concluded that the point of bubble departure in a flow boiling cannot be calculated exactly. They also observed that analytical results from force balance model were unable to produce good agreement with the experimental data. Reliability of the force balance approach largely depends on how

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Nomenclature

a	thermal diffusivity $\left(\frac{K_l}{\rho_l C_{pl}}\right)$
C	constant
C_p	specific heat
d_b	departure diameter
D_h	hydraulic diameter
d_w	wall contact diameter
G	mass flux
G_s	dimensionless shear rate
g	gravitational acceleration
h	heat transfer coefficient
i	enthalpy
ja	Jacob number
K	thermal conductivity
Pr	Prandlt number $\left(\frac{\mu_l C_{pl}}{K_l}\right)$
p	pressure
ΔP	pressure difference
q''	heat flux
R	radius
Re	Reynolds number
S	suppression factor
T	temperature
T_τ	frictional temperature, $T_\tau = \frac{q''}{\rho c_p u^*}$
ΔT	temperature difference
t	time
u^*	frictional velocity, $u^* = \sqrt{\tau/\rho}$
U	velocity
y	wall distance
y^+	non-dimensional wall distance

Greek symbol

α	advancing contact angle
β	receding contact angle
φ	bubble inclination angle
δ	boundary layer thickness
σ	surface tension
μ	dynamic viscosity
υ	kinematic viscosity
ρ	density
τ	frictional

Subscripts

B	bubble
$cond$	condensation
$conv$	convection
d	departure
l	liquid
nb	nucleate boiling
o	superheated liquid
sat	saturation
sub	subcooling
tp	two phase
v	vapor
w	wall
x	x-direction
y	y-direction

accurately different forces are formulated on a growing vapor bubble. On the other hand, demarcation of different heat transfer layers across the bubble is difficult because of non-uniform temperature distribution in the flow field. Besides this, bubble growth is controlled by both inertia force at initial stage and later on by heat transfer [6] from different layers. Different heat transfer phenomena that contribute for growth of the bubble are: evaporation from a microlayer (evaporative microlayer) beneath the bubble, heat transfer from the superheated region (above the microlayer) and condensation at the bubble cap where the bubble is exposed to bulk subcooled fluid. Several researchers have observed that during early stage of bubble growth, a thin liquid microlayer is trapped between lower portion of the bubble interface and the heated surface. This layer is termed as evaporative microlayer [6–8]. This layer is wedge shaped and evaporates completely when nucleation is initiated, resulting an increase in fluctuating wall temperature. As the bubble grows the liquid region adjacent to the interface is gradually depleted because of its superheat. This layer is referred as relaxation microlayer or superheated layer [8]. Contrary to heat addition to the bubble from these two regions, condensation takes place from the top portion of the bubble i.e. bubble cap which is in contact with subcooled liquid. A schematic view of all these three heat transfer regions is shown in Fig. 4 and details of their contributions are discussed in Section 2.3.

From literature review, it has been observed that there is no any general consensus on the contribution of heat transfer from each of these three layers towards the growth of a nucleating bubble in flow boiling. Several propositions are found without a convergence. Table 1 presents an overview of heat transfer contributions towards the growth of a vapor bubble reported by several researchers. Kim [9] has pointed out that microlayer evaporation accounts for less than 25% of the overall heat transfer to the bubble. On the other hand microlayer formation beneath the bubble depends on various other factors such as amount of subcooling and nature of coolant fluid [10].

Table 1
Sources of heat addition to bubble growth.

Authors	Contribution		Mode of study
	Superheated/ relaxation microlayer	Evaporative microlayer	
Gerardi et al. [11]	–	Major	Experimental
Chen and Utaka [12]	–	Major (40%)	Simulation
Zhao et al. [13]	–	Major	Experimental
Jung and Kim [14]	Major	Minor	Experimental
Demiray and Kim [15]	Major	Minor (12.5%)	Experimental
Kim [9]	Major	Minor (<25%)	Experimental and analytical

It can also be seen that superheated region has been considered as major source of heat transfer to the growing bubble by most of the researchers. On the other hand, the effect of condensation from bubble cap on bubble growth has not been considered in these investigations. Based on heat transfer contribution from single or two/three regions towards the bubble growth, several analytical models for calculating bubble growth rate have been reported in the literature and few of them have been presented in Table 2. The analytical models proposed by Plesset and Zwick [16] and Foster and Zuber [17] were formulated based on the heat diffusion from superheated layer surrounding the bubble dome. Besides heat diffusion from the superheated layer, Yun et al. [18] incorporated the effect of condensation at the bubble cap for calculating bubble growth rate. Cooper and Lloyd [19] and van Stralen et al. [20] proposed the bubble growth rate model considering evaporation layer as major source of heat addition to the bubble. From the formulations presented in Table 2, it can be seen that bubble growth rate