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Validation of a dynamic model for vapor bubble growth and collapse under microgravity conditions

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ABSTRACT

A complete set of ordinary differential equations, based on modifications of existing models, is used to investigate bubble growth and collapse under microgravity conditions in this paper. As in previous work, effects of inertia, surface tension and viscosity are taken into consideration in the momentum equation of the liquid phase outside of vapor bubble, while effects of "moving interface", interface curvature and thermal resistance of surrounding liquid are considered in the evaporation of the vapor bubble. A dimensionless fitting constant b is introduced to account for area change of the moving vapor/liquid interface and the diffusive nature of the interface layer. The values of these fitting constants for bubble growth and bubble collapse in water and ethanol are obtained by matching predicted temporal variations of bubble radii with experimental data. The predicted interfacial dynamics during bubble growth and bubble collapse is analyzed. Different stages during the bubble growth process are characterized. During the early stage of bubble collapse, the simulated bubble radii show some "fluctuations", which can be attributed to the "rebound effect" of pressure balance in the bubble owing to the initial condition of a sudden drop in temperature.

1. Introduction

Bubble growth and/or collapse in fluids are fundamental phenomena in many problems, such as in subcooled boiling, condensation, cavitation, bubble sonoluminescence and sonofusion [1–5]. The processes are inherently complex because phase-change heat transfer takes place at a moving interface where the bubble radius is changing with time. In the past, although much theoretical modeling [6–13] and experimental investigations [14–16] have been performed to study bubble growth, only a few experimental studies have been carried out for bubble collapse [16–18]. Moreover, few dynamical modeling work has been published on bubble collapse because of numerical instabilities [5,16].

It is known that the dynamics of bubble growth can be characterized in terms of three different mechanisms: inertia-controlled, thermal diffusion controlled and mass diffusion controlled mechanisms [19]. Approximate analytical solutions for bubble radius as a function of time for bubble growth based on different assumptions have been derived [20–23]. However, these analytical solutions show significant deviations from reality under certain conditions, such as in the very early stage of bubble growth when the superheat is small (or the Jacob number is small) or when the operating pressure is extremely low [8,24].

In our previous paper [24], a modified version of existing models based on many approximations was proposed to study bubble growth in a superheated liquid. Although the model shows good accuracies but several questions remain unresolved. First, the model was built under zero gravity condition but it was only partially validated with experimental data obtained under normal gravity. The effect of the buoyance force in a normal gravitational field may induce appreciable translational velocities and deformation of a bubble [14,15,25], which obscures the process of growth/collapse, and brings difficulties to confirm the validity of the model. Secondly, problems of bubble growth and bubble collapse, which should be solved with the same set of governing equations, have not been verified. In this paper, we study the problems of bubble growth and bubble collapse under the following considerations: (i) a set of ordinary differential equations for bubble radius is derived which are applicable for both bubble growth and bubble collapse processes. (ii) The curvature effect of the heat flux through the interface of the bubble is taken into consideration. (iii) A dimensionless

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Nomenclature

P	pressure, Pa
T	temperature, K
R	bubble radius, m
R_v	ideal gas constant, J/(kg·K)
r	radial distance from the bubble center, m
u	radial velocity, m/s
t	time, s
h_{lv}	latent heat of evaporation, J/kg
C_p	specific heat at constant pressure, J/(kg·K)
Δt	time step, s

Greek symbols

ρ	density, kg/m^3
σ	surface tension, N/m
μ	viscosity, kg·m/s
λ	thermal conductivity, W/(m·K)
α	thermal diffusivity, m^2/s, $\alpha = \lambda/(\rho C_p)$
δ	characteristic length of heat conduction, m

Subscripts

v	vapor
l	liquid
R	liquid vapor interface
∞	infinity
c	critical
0	initial
sat	saturation
sup	superheat level
sub	subcooling level
hd	hydrodynamic
vis	viscosity
st	surface tension
g	gas

Superscripts

$\cdot$	first-order differential
$\cdot\cdot$	second-order differential
s	stationary
m	moving

Dimensionless numbers

b	dimensionless fitting constant for moving interface $b = \delta_T{}^s/\delta_T{}^m$
φ	dimensionless temperature, $\varphi = 1 - T_{sat}/T_c$
Ja	Jacob number, $Ja = \frac{C_{pl}\rho_l(T_\infty - T_v)}{\rho_v h_{lv}}$

parameter is introduced to account for effects of area change of the moving vapor/liquid interface and the diffusive nature of the interface, and the role of this parameter is demonstrated explicitly. (iv) The model is built under zero gravity conditions which is validated with existing experimental data obtained in a free fall condition [17,25], where buoyancy-induced translational motion and deformation of a bubble can be neglected in the model validation.

2. Mathematical model

The problem of bubble growth in a superheated liquid is sketched in in Fig. 1(a) where $P_v > P_\infty$ while the problem of bubble collapse in a subcooled liquid is sketched in Fig. 1(b) where $P_v < P_\infty$, both of which are assumed under microgravity conditions. In these figures, variations of pressure and temperature in the radial distance refer to the real situation where the pressure has a discontinuity at the vapor/liquid interface while the temperature has a smooth and continuous variation across the interface (denoted by the dashed line) between vapor bubble and liquid outside of the bubble. In the following, we present a zero-order solution [7,8] for bubble growth/collapse under the following assumptions: (i) Under microgravity conditions, where the bubble is assumed to be spherically symmetric during its growth and collapse processes. (ii) The liquid of infinite extent is static and *incompressible* at a uniform temperature at T_∞ and a uniform pressure at P_∞. (iii) The vapor bubble is a *perfect gas* at a uniform temperature at T_v and a uniform pressure P_v. (iv) A sharp interface exists between the vapor and the liquid. In other words, the interface thickness is zero for the zero-order approximation, where both pressure and temperature are discontinuous at the interface.

Based on these assumptions, an ordinary differential equation for the variation of bubble radius R as a function of time for bubble growth/collapse can be derived from the momentum equation in a spherical coordinate [20] for the liquid phase as follows

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{P_v(T) - P_\infty}{\rho_l} - \frac{2\sigma(T)}{\rho_l R} - 4\frac{\mu_l \dot{R}}{\rho_l R} \quad (1)$$

Eq. (1) is obtained by integrating the momentum equation in the radial direction from the vapor/liquid interface to infinity with the assumption of an incompressible flow, which is a zero-order

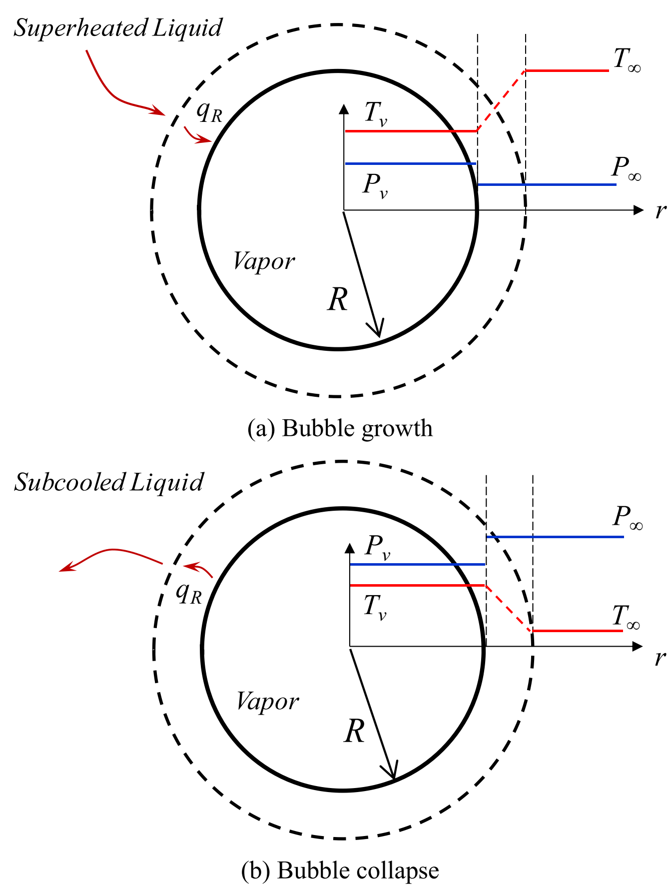

Fig. 1. Sketches of bubble growth in a superheated liquid and bubble collapse in a subcooled liquid.