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On heat transfer and evaporation characteristics in the growth process of a bubble with microlayer structure during nucleate boiling

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ABSTRACT

We have previously observed and experimentally measured a microlayer formed beneath a growing bubble during nucleate pool boiling. The initial microlayer thickness was of micrometer order and increased linearly with distance from the bubble inception site. The quantitative degree of contribution of the microlayer evaporation to bubble growth was still not elucidated, although a large number of experimental studies have been conducted on the distribution and evaporation characteristics of the microlayer. To clarify the heat transfer characteristics, especially the contribution of microlayer evaporation in nucleate pool boiling, numerical simulations are performed here for two phase vapor–liquid flow induced by the growth of a single bubble using the volume of fluid method. Furthermore, a special model is proposed to combine the microlayer and bulk liquid regions, the scales of which are extremely different in the simulations. The microlayer was neglected in the volume fraction calculation, while the evaporation from the microlayer was included by applying the source terms of the basic equations for the presence of a virtual microlayer. Similar tendencies were observed between the calculated and experimental results on the variations in the microlayer radius and bubble volume. The proportion of microlayer evaporation to total bubble volume was generally in agreement with the previous results, and the ratio of microlayer evaporation to the change in the total bubble volume was approximately 40 percent.

1. Introduction

Several mechanisms for nucleate boiling have been previously proposed that can be classified into two categories; convective heat transfer and latent heat transport. The latent heat transport mechanism involves the microlayer evaporation mechanism; a thin liquid film (microlayer) exists between a growing bubble and the heat transfer surface, from which a large amount of heat is transported by vaporization of the microlayer. The existence and distribution of the microlayer was confirmed by utilizing several different methods in recent experimental studies, such as laser interferometry [1,2], laser extinction [3–5], and indirect inference of the microlayer thickness based on the measured temperature variation in the heat transfer surface [6]. The initial microlayer thickness was found to increase linearly with the distance from the bubble inception site. Furthermore, Utaka et al. [7] conducted a two-dimensional (2D) numerical calculation on the transient heat conduction of a heat transfer plate with the heat flux of microlayer evaporation as the boundary condition on the backside of the heat transfer surface, which is calculated based on the surface superheat at bubble inception ΔT_i, and the distribution of initial microlayer thickness δ_0, measured from experiments with water and ethanol. Evaporation of the microlayer and the consequent decrease in its thickness were discussed; however, instead of calculating the evaporation from the superheated liquid layer, the bubble volume acquired from a recorded image of the bubble was adopted to determine the contribution of microlayer evaporation to the total amount of evaporation during the bubble growth process. As a result, the proportion of evaporation from the microlayer to the bubble volume was approximately 20–70%, as shown in Fig. 1, and this increased with the surface superheat at bubble inception, ΔT_i. It was demonstrated that both evaporation from the microlayer and the superheated liquid layer are closely related to the bubble growth in saturated nucleate boiling. Therefore, it is necessary to quantitatively evaluate both the evaporation from the microlayer and that from the superheated liquid layer to elucidate the mechanism of nucleate boiling.

In the growth process of a boiling bubble, the temperature distribution in the vicinity of the vapor–liquid interface changes rapidly due to evaporation and the extremely fast movement of the interface with growth of the bubble. In this study, the heat transfer

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Nomenclature

A	area (m^2)
c	specific heat (J/kg K)
C_r	Courant number
F	volume fraction of fluid
f_r	source term of Navier–Stokes equation in radial direction
f_z	source term of Navier–Stokes equation in axial direction
g	acceleration of gravity (m/s^2)
h_i	evaporation heat transfer coefficient (W/m^2 K)
L	latent heat of vaporization (J/kg)
ΔL	normal distance from superheated liquid cell to interface (m)
p	pressure (Pa)
p_s	set value of pressure (Pa)
$\dot{m}$	mass flux (kg/s)
q	heat flux (W/m^2)
q_s	source term of energy equation
r	radial direction (distance from bubble inception site in radical direction; mm)
R_{M}	microlayer radius on heat transfer surface (mm)
R_{B}	bubble radius (mm)
R_{Mmax}	maximum microlayer radius (mm)
s_f	source term of volume fraction equation
s_m	source term of continuity equation
T	temperature (K)
ΔT_i	surface superheat temperature at bubble inception (K)
t	time (s)
t_{B}	elapsed time from bubble inception (ms)
t_{Bd}	elapsed time from bubble inception to completion of bubble departure (ms)
Δt	time step (s)
V_{ML}	evaporation from microlayer (mm^3)
V_{B}	bubble volume (mm^3)
v_r	radial velocity (m/s)
v_z	axial velocity (m/s)
z	axial direction (distance from bubble inception site in axial direction; mm)

Greek

θ	non-dimensional temperature (–)
θ_a	apparent contact angle (°)
θ_c	angle of reference position on the vapor–liquid interface (°)
δ	microlayer thickness (μm)
ρ	density (kg/m^3)
λ	thermal conductivity (W/m K)
μ	viscosity (Pa s)
σ	evaporation coefficient (–)
η	non-dimensional distance in axial direction (–)

Subscripts

BK	bulk liquid
cell	calculation cell
ex	experimental value
ML	microlayer
L	liquid
V	vapor
sat	saturation state
surface	vapor–liquid interface
w	heat transfer surface

Superscript

0	initial

characteristics of the bubble growth process during nucleate boiling are investigated numerically. The volume of fluid (VOF) method developed by Hirt and Nichols [8] is an effective approach for interface capturing of free surface flow and its modified versions have been widely adopted in research on two-phase flow (e.g. boiling). Stephan and coworkers [9,10] established a new steady state model for calculating the evaporation from a liquid microfilm and performed numerical simulations on nucleate pool boiling. The microfilm referred to here is a thin liquid film between the bulk liquid and absorbed film on the heat transfer surface. The absorbed film is extremely thin (a few molecular layers thick). The evaporation from this microfilm region was calculated and the heat transfer characteristics during the growth of a single bubble were investigated. A large amount of evaporation was determined to occur in the microfilm region during the boiling process. However, the microfilm region in the simulations is extremely narrow and was different from the experimentally measured microlayer region examined in the study. Therefore, the experimentally elucidated microlayer was not included in the numerical simulation. Ose et al. [11] conducted a numerical simulation on the bubble behavior in subcooled boiling by utilizing an improved phase-change model based on the temperature-recovery method [12]. It was concluded that a model with consideration of the relaxation time based on unsteady heat conduction could predict the bubble growth and condensation processes in the subcooled pool boiling phenomena. Jiang et al. [13] performed a numerical simulation on the bubble growth and heat transfer in nucleate boiling using a hybrid scheme [14] that combined the mechanical boiling model with a computational fluid dynamics (CFD) simulation. However, a similar structure to that from the simulation of Stephan et al. [9] was adopted for the liquid film between the bubble and heat transfer surface. The calculation results for bubble growth (bubble radius) were then approximated in accordance with the experimental results. For the various research summarized here, although the calculation results were compared with the experimental results, the experimentally measured microlayer was not considered in the numerical simulations. Therefore, it is necessary to acquire qualitative knowledge regarding microlayer evaporation and its contribution to bubble growth to elucidate the mechanisms and heat transfer characteristics of nucleate pool boiling.

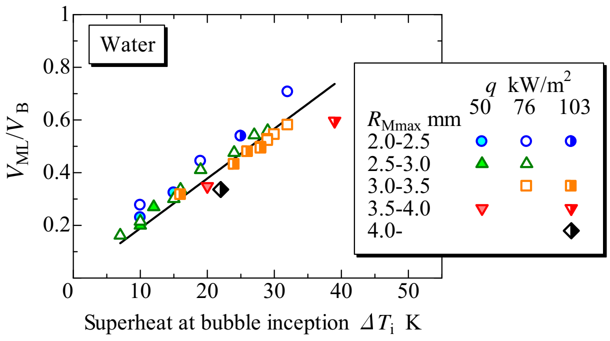

Fig. 1. Contribution of evaporation from the microlayer as a function of surface superheat at bubble inception.

In this study, the microlayer present between a growing bubble and the heat transfer surface is extremely thin compared with the