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Numerical simulation of thermal property effect of heat transfer plate on bubble growth with microlayer evaporation during nucleate pool boiling

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ABSTRACT

It is well known that during nucleate boiling, a large amount of energy can be transferred under relatively small temperature difference between the heat transfer surface and fluid, indicating that high efficiency of heat transfer can be achieved. However, the mechanism of nucleate boiling is still not well elucidated owing to the complexity of the phenomenon. The thermal properties of heat transfer plate, which is directly in contact with the microlayer, may have a significant impact on heat transfer and evaporation characteristics of the microlayer. A volume of fluid (VOF) method based algorithm, in which the experimentally measured microlayer structure was taken into account, has been developed to simulate microlayer evaporation and single bubble behavior. The influence of thermal conductivity of heat transfer plates on the contribution of microlayer evaporation was examined. It was concluded that more efficient heat supply to the heat transfer surface can be achieved for the heat transfer plate with higher thermal conductivity. Microlayer evaporation occupied approximately 30–70% of the bubble volume, indicating that microlayer evaporation is a principal mechanism of boiling heat transfer.

1. Introduction

As a widely applied phenomenon in industry, a large amount of energy can be transferred under a small temperature difference between fluid and heat transfer surface during nucleate boiling, which means that high efficiency heat transfer can be achieved. However, the mechanism of nucleate boiling has not been well elucidated owing to its complexity. In recent decades, it has been experimentally confirmed that there is a thin liquid film (microlayer) beneath the boiling bubble using different methods, such as indirect measurement based on temperature variation of heat transfer plate [1–3], laser extinction method [4–7], and laser interferometric method [8–11]. By applying indirect measurement on temperature variation, Moore and Mesler [1] was firstly demonstrated the formation of a microlayer under bubble during nucleate boiling of water. After that, Cooper and Lloyd [2] confirmed the existence of a microlayer for various organic liquids and predicted the thickness based on a simplified hydrodynamic analysis. Recently, Yabuki and Nakabeppu [3] predicted the distribution of microlayer thickness for water by measuring the temperature variation of the heat transfer surface with microelectromechanical systems (MEMS) sensors. By using the laser extinction method, Utaka et al. [4–7] systematically conducted measurements on the variation of microlayer thickness and determined the distribution of initial microlayer thickness for water and ethanol. Koffman and Plesset [8] measured microlayer thickness for water and ethanol during subcooled boiling using the laser interferometric method. MacGregor and Jawurek [10] measured the microlayer thickness for methanol, and specifically analyzed experimental errors of the laser interferometry technique. Gao et al. [10] and Chen et al. [11] adopted a similar method with Koffman and Plesset [8]; they measured and analyzed the microlayer formation process for ethanol and water, respectively. Based on these existing studies, it was confirmed that initial microlayer thickness increases linearly with the distance from the bubble inception site. Typically, slopes of the initial microlayer thickness were experimentally obtained for water and ethanol and consistent results were obtained from different studies [3,7,8]. Furthermore, a special convex structure of microlayer appearing near the commencement of bubble departure was also observed [11].

Based on the knowledge of microlayer structure, studies on the characteristics of microlayer evaporation were also carried out. MacGregor and Jawurek [9] obtained the contribution of microlayer evaporation based on laser interferometric measurement of the microlayer thickness. The results showed that the contribution of microlayer evaporation to bubble detachment volume was

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Nomenclature

A_s	surface area of vapor-liquid interface in a calculation cell (m^2)
c	specific heat (J/kg·K)
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 ($W/m^2{\cdot}K$)
L	latent heat of vaporization (J/kg)
ΔL	normal distance from superheated liquid cell to interface (m)
p	pressure (Pa)
q	heat flux (W/m^2)
q_s	source term of energy equation
r	radial axis (distance from origin at bubble inception site; mm)
R_M	microlayer radius on heat transfer surface (mm)
s	source term
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)
Δt	time step (s)
t_B	elapsed time from bubble inception (ms)
t_d	bubble departure time (ms)
V_{ML}	evaporation from microlayer (mm^3)
V_B	bubble volume (mm^3)
V_{cell}	volume of calculation cell (m^3)
v_r	radial velocity (m/s)
v_z	axial velocity (m/s)
Greek	
δ	microlayer thickness (μm)
ρ	density (kg/m^3)
λ	thermal conductivity (W/m·K)
μ	viscosity (Pa·s)
σ	evaporation coefficient (–)
Subscript	
BK	bulk liquid
h	heating
intV	vapor side of vapor-liquid interface
intL	liquid side of vapor-liquid interface
ML	microlayer
L	liquid
V	vapor
sat	saturation state
w	heat transfer surface
ref	reference
Superscript	
0	initial

approximately 4 l%, which is significant and cannot be ignored for bubble growth. Myers et al. [12] measured the temperature distribution using a 10 × 10 micro-heater array with 100 μm resolution under bubbles during nucleate boiling of FC-72. They concluded that microlayer evaporation is not a major heat transfer mechanism for bubble growth since microlayer evaporation accounted for no more than 23% of the total heat transferred from the surface. Furthermore, by utilizing experimentally measured slope of microlayer thickness distribution for water, Chen and Utaka [13] performed numerical simulations on the growth of isolated bubbles during nucleate boiling to reveal the contribution of microlayer evaporation. As a result, the proportion of microlayer evaporation to total bubble volume was approximately 40% for a quartz glass heat transfer plate. Sato and Niceno [14,15] carried out numerical simulations on nucleate boiling for single and multiple nucleation sites using a similar method. It was concluded that microlayer evaporation approximately occupied 40–60% of the total mass transfer (phase change) on copper heat transfer plate for different heat flux of heating, indicating that microlayer evaporation during nucleate boiling is very important and cannot be ignored.

However, the knowledge of the characteristics and importance of microlayer evaporation during nucleate boiling is still quite insufficient since both experimental and simulation conditions were limited. It is considered that the thermal properties of the heat transfer plate, which is directly in contact with the microlayer, may have a significant impact on heat transfer and evaporation characteristics of the microlayer. To the authors' knowledge, the effects of thermal properties of heat transfer plate on microlayer evaporation have not been systematically studied. In a previous study conducted by the authors [13], quartz glass was adopted as the heat transfer plate in order to compare simulation results with experimental results obtained by the laser extinction method. However, a metal heat transfer plate with a significantly higher thermal conductivity than quartz glass is widely used in the industry. In this study, by utilizing the simulation method developed by the authors [13], numerical simulations were carried out and the characteristics of microlayer evaporation were analyzed for heat transfer plates with different thermal properties during nucleate pool boiling of water.

2. Numerical simulation model

The volume of fluid (VOF) based algorithm of numerical simulation [13] developed by the authors was adopted in this study for the simulation of microlayer evaporation of single bubble behavior during nucleate boiling. The simulation model is briefly introduced in this section and a more detailed description can be found in [13].

In the algorithm, two-phase vapor-liquid flow induced by bubble growth and expansion was simulated by the VOF method using a commercial software, Fluent. Special handling was performed such that the microlayer was ignored in the simulation of flow field, since the volume of the microlayer is negligible compared with that of the bulk liquid. In addition, the evaporation of the microlayer was considered by applying the source terms of the governing equations (mass, momentum, and energy). The heat flux and the corresponding mass flow rate of microlayer evaporation were determined based on a one-dimensional thermal conduction in a virtual microlayer on the heat transfer surface, on the basis of the experimentally measured initial distribution of microlayer thickness by the authors [7]. The initial distribution of microlayer thickness adopted here has a unique linear distribution (wedge shape) for a certain test liquid (e.g. water) under different experimental conditions. In addition, quantitatively similar distribution of initial microlayer thickness was also confirmed on different heat transfer surfaces by using different measuring methods [3,7,8] for water. It is considered that the general distribution of initial microlayer thickness was adopted for the numerical simulation. Further-