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Thermocapillary effect on bubble sweeping and circling during subcooled nucleate pool boiling of water over microwire

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ABSTRACT

Bubble dynamics on a microscale heating source is crucial to the understanding of heat transfer mechanisms in nucleate boiling. In this investigation, the effect of thermocapillary convection, along with other contributors such as viscous force, on the bubble sweeping and circling phenomena observed in the experiment of subcooled nucleate boiling of deionized water over a micro platinum wire was investigated by numerical simulation and theoretical analysis. The simulation indicates that occurrence of sweeping is mainly due to the thermocapillary effect between the sweeping bubble and a neighboring bubble with a temperature drop caused by the bubble-top jet flow. Based on the parabolic interfacial temperature profile, a simplified dimensional analysis was conducted for the characteristic velocities and lengths along the heating wire and along the bubble interface. The theoretical analysis and the simulation show that the thermocapillary force and the viscous force play important roles in the bubble circling phenomenon. This work may be helpful for better understanding the interfacial force effects on the bubble behaviors and hence the boiling heat transfer at the microscale.

1. Introduction

Nucleate pool boiling over micro heat source is important for heat transfer problems in industries such as thermal management in electronics. The bubble dynamics during nucleate pool boiling on micro objects is the key for studying the heat transfer process. Kim et al. [1] first observed that small bubble can leave from the nucleation site and move towards an adjacent bubble along the heated surface, and then merge with the adjacent bubble into a larger bubble or depart from the bubble and repeatedly move along the surface. Qiu et al. [2] observed the increased heat transfer due to the bubble sliding on a heated surface. For typical micro heat source such as thin heating wire, there exists many interesting phenomena, including bubble-top jet flow, bubble sweeping, bubble circling, bubble coalescence, bubble leaping, etc., during subcooled nucleate pool boiling [3–10]. Although obvious enhancement of boiling heat transfer can be achieved by bubble motion which is mainly due to the thermocapillary effect (or Marangoni effect) [11–13], the mechanisms of the bubble behaviors still need for further investigation.

The temperature-dependent thermocapillary effect is the mass transfer along the interface between two fluids due to surface tension gradient. For bubble motion and interaction along a thin wire during subcooled nucleate pool boiling, the interfacial thermocapillary force is thought to be the main contributor for the observed phenomena such as bubble coalescence and departure [6–13]. When a bubble slides with constant velocity, the thermocapillary force should be balanced by other forces, including the contact line force acting on a sweeping bubble [11] and the drag force due to the fluid viscosity [14,15]. For bubble circling phenomenon observed in our previous investigation, the thermocapillary force along the larger bubble interface is balanced by the buoyancy force on the small bubble, the viscous force, and the temperature-dependent surface tension [9]. When two bubbles approach to each other, the balance between these forces should be broken and hence the bubbles coalesce or depart. However, it needs to verify the critical distance between two bubbles where the balance tends to be broken, e.g., for leading a small neighboring bubble to circling around a stationary larger bubble.

The thermocapillary force strongly depends on the temperature distribution along the bubble interface. The temperature distribution along the wire can affect the interfacial temperature due to the heat conduction between the solid and vapor phases and the evaporation from the liquid layer at a bubble base [11,16]. For

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Nomenclature

a	thermal diffusivity ($m^2\, s^{-1}$)
C_v	heat capacity under constant volume ($J \cdot K^{-1}$)
d	wire diameter (m)
d_a	bubble diameter (m)
E	internal energy (J)
f_d	viscous force (N)
f_M	thermocapillary force (N)
F	bulk force (N)
g	gravity acceleration ($m\, s^{-2}$)
h	heat transfer rate ($W\, m^{-2}\, K^{-1}$)
h_{fg}	phase change latent heat ($J\, kg^{-1}$)
k	thermal conductivity ($W\, m^{-1} \cdot k^{-1}$)
l	characteristic length (m)
L	latent heat ($J \cdot kg^{-1}$)
$\bar{M}$	relative molecular weight
n	normal direction
Nu	Nusselt number
p	pressure (Pa)
Pe	Peclet number
q, q''	heat flux ($W \cdot m^{-2}$)
r	radial distance (m)
R	bubble radius (m)
$\bar{R}$	gas constant ($J \cdot mol^{-1} \cdot K^{-1}$)
Re	Reynolds number
s	tangential direction
$S_{a,12}$	mass source term of the liquid–vapor interface ($kg \cdot m^{-3} \cdot s^{-1}$)
$S_{a,g}$	mass source term in the vapor phase ($kg \cdot m^{-3} \cdot s^{-1}$)
$S_{a,l}$	mass source term in the liquid phase ($kg \cdot m^{-3} \cdot s^{-1}$)
S_E	energy source term in the energy equation ($W \cdot m^{-2}$)
S_h	volumetric heat source ($W \cdot m^{-2}$)
t	time (s)
T	temperature (K)
u	velocity ($m \cdot s^{-1}$)
V	velocity ($m \cdot s^{-1}$)
x	interface
x, y, z	dimensional coordinates (m)

Greek symbols

α	volume fraction
φ	azimuthal angle (rad)
γ	positive constant
κ	curvature (m^{-1})
ν	kinetic viscosity ($m^2 \cdot s^{-1}$)
ρ	density ($kg \cdot m^{-3}$)
μ	dynamic viscosity ($Pa \cdot s$)
θ	angle (rad)
σ	surface tension ($N \cdot m^{-1}$)
$\hat{\sigma}$	accommodation coefficient

Subscripts

0	reference point
1	liquid
2	vapor
b	bubble
	bubble bottom
d	viscous
g	gas
i	interface
l	liquid
t	top
x	horizontal
v	vapor
θ	tangential

example, Christopher et al. [11] proposed a phenomenological model of the temperature distribution around the bubble and the force acting on the bubble. It was concluded that the asymmetric temperature, pressure or surface tension distribution on both sides of the bubble can cause the unusual bubble dynamics. However, the wire temperature itself is influenced by many factors, such as wire material, wire diameter, fluid type, and heating power. These have made the model and the analysis very complicated. In order to investigate the thermocapillary effect around a bubble, Mareka and Straub [17] derived analytical solutions for the corresponding thermocapillary force using several interfacial temperature profiles (linear, parabolic, hyperbolic, power law, etc.) and compared to a numerical solution. The comparison shows that the parabolic profile is suitable for sufficiently representing the temperature distribution of the bubble interface. Therefore, a simple and comprehensive understanding of the mechanisms of force effects on the bubble behaviors and hence the heat transfer could be obtained based on the parabolic temperature profile.

In this paper, we will first numerically investigate the effect of surface tension gradient induced thermocapillary force on bubble sweeping and circling during subcooled nucleate boiling of deionized water on a microscale heating wire, based on the corresponding experimental investigation. The simulation will be compared with the observation to analyze the roles of various forces, i.e., the viscous force and the thermocapillary force, in bubble motion, especially the sweeping and circling phenomena. We will then theoretically study the relation between the characteristic velocities of bubble sweeping and circling which is important for the correlation of heat transfer coefficient by dimensional analysis of the conservation equations. The characteristic length for leading a small neighboring bubble to circling around a stationary larger bubble can then be given. The horizontal thermocapillary effect between a sweeping bubble and a neighboring bubble with a temperature drop due to bubble-top jet flow will be analyzed for its contribution to the bubble sweeping phenomenon.

2. Bubble sweeping and circling

A bubble may interact with other bubbles when it moves by the forces imposed on its interface. These forces may include the inertial force, the viscous force, the gravity force, the buoyancy force, and the thermocapillary force. The thermocapillary effect which is the mass transfer along the interface between the liquid and the vapor phases is caused by the temperature-dependent surface tension gradient. When the size of heated surface scales down, the thermocapillary force may be dominant to create unique bubble interaction phenomenon. In this investigation, various types of bubble behaviors during subcooled nucleate pool boiling of deionized water on platinum microwires were systematically revisited to explore the major mechanisms of the unique bubble behaviors and hence the enhanced heat transfer [18,19].

The bubble sweeping phenomenon can be frequently observed during subcooled nucleate pool boiling when the heat flux is relatively high [4,12]. It is one of the interesting phenomena in the