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Multi-jet flows and bubble emission during subcooled nucleate boiling of aqueous n-butanol solution on thin wire

Leping Zhou [a,*], Yuanyuan Li [a], Longting Wei [a], Xiaoze Du [a,*], Yongping Yang [a], Peixue Jiang [b], Buxuan Wang [b]

[a] Key Laboratory of Condition Monitoring and Control for Power Plant Equipment of Ministry of Education, School of Energy, Power and Mechanical Engineering, North China Electric Power University, Beijing 102206, China

[b] Department of Thermal Engineering, Tsinghua University, Beijing 100084, China

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ABSTRACT

Jet flow phenomenon is important in enhancing the nucleate boiling heat transfer processes. When heater sizes scale down, jet flow can be observed due to the thermocapillary convection around bubbles attached on microscale heated surface. In this paper, a self-rewetting fluid, aqueous n-butanol solution, was employed for demonstrating the effect of thermocapillary convection on bubble behaviors during subcooled nucleate boiling on thin wire, comparing with deionized water. Bubble-top jet flow for water and multi-jet flows for n-butanol solution were observed around a platinum micro heating wire by high speed CCD camera. Corresponding numerical simulation proved that it is the thermocapillary convection that attracts the subcooled water to flow from the superheated microlayer at the base to the top of a stationary bubble. For n-butanol solution, however, the thermocapillary convection can induce it to flow oppositely, causing the subcooled solution to flow onto the heated surface. The simulation for the solution was in good agreement with the experiment where the subcooled liquid near the bubble top flow towards the bubble base, or the heated surface, and hence the multi-jet flows occur. The multi-jet flows can sustain for a long period and cause bubble emission at the superheated thin liquid layer near the heated surface. The temperature around the bubble presented sharp temperature gradient and the velocity in the near-wall region was almost vertical to the wall. The experimental and numerical studies on the effect of surface tension and thus thermocapillary convection are crucial to the mechanisms of subcooled nucleate boiling of fluids.

1. Introduction

Nucleate boiling phenomenon was investigated extensively since the boiling curve for saturated pool boiling was first introduced by Nukiyama [1]. Bubble dynamics, bubble-induced convection, microlayer evaporation, thermocapillary flow, boiling nonlinearity, etc., are possible mechanisms for the high heat transfer coefficient in nucleate boiling [2–5]. Bubble dynamics is critical among the other boiling heat transfer mechanisms. However, there remains many unsolved problems in bubble dynamics and bubble interaction needed for further investigation [6–9].

For microscale nucleate boiling, there are many interesting phenomena observed in the experiments. For example, Wang et al. [10–12] observed bubble sweeping and bubble-top jet flow phenomena in subcooled nucleate boiling on microwires. Lu et al. [13–15] analyzed the role of interfacial thermocapillary force on bubble dynamics during subcooled nucleate boiling of water on platinum microwires. Christopher et al. [16,17] pointed out that these phenomena can be explained by the asymmetric temperature, pressure or surface tension distribution on both sides of the bubble, and suggested that the reduced wire temperatures around the stationary bubble cause the sweeping bubble to decelerate and reverse direction before colliding with the stationary bubble. It was well recognized that the Marangoni or thermocapillary effect is a crucial factor that influences the bubble interactions. The thermocapillary effect is the mass transfer along an interface due to the temperature-dependent surface tension gradient. The thermocapillary effect always causes liquid convection from high surface tension region to lower one. The self-rewetting working fluids, i.e., dilute aqueous alcohol solutions, have unique properties, such as surface tension in the high temperature region that increases with increasing temperature. It can exhibit a reverse thermocapillary flow along the bubble interface, resulting in a strong liquid flow

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* Corresponding authors. Tel.: +86 1061773873.
E-mail addresses: lpzhou@ncepu.edu.cn (L. Zhou), duxz@ncepu.edu.cn (X. Du).

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Nomenclature

a,b,c	constants
E	internal energy (J)
F	bulk force (N)
g	gravitational acceleration (m s^{-2})
k	thermal conductivity (W m^{-1} K^{-1})
k_{eff}	effective thermal conductivity (W m^{-1} K^{-1})
L	latent heat (J/kg)
p	static pressure (Pa)
q''	heat flux (W m^{-2})
R	electric resistor (Ω)
S_{α_g}	mass source term in the vapor phase (kg m^{-3} s^{-1})
S_{α_l}	mass source term in the liquid phase (kg m^{-3} s^{-1})
S_{α_s}	mass source term of the liquid-vapor interface (kg m^{-3} s^{-1})
S_E	energy source term in the energy equation (W m^{-2})
S_h	volumetric heat source (W m^{-2})
t	time (s)
T	absolute temperature (K)
u,v,w	x-, y- and z-component of velocity (m s^{-1})
V	velocity vector (m s^{-1})
x,y,z	dimensional coordinates (m)

Greek symbols

α	volume fraction
β	proportional constant
ϕ	concentration (%)
ν	kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})
σ	surface tension (N/m)
μ	dynamic viscosity (Pa s)

Subscripts

0	reference point
g	vapor
l	fluid
s	solid

towards the hot side. When a self-rewetting fluid, namely 3.0 wt% n-butanol aqueous solution, was used as working fluid, bubble circling phenomenon can also be observed, with extremely small diameter of the circling bubbles, e.g., one order of magnitude lower than those of the deionized water [18]. The critical heat fluxes of these unique fluids were also investigated recently and indicated prominent capability for improvement of the thermal endurance in high heat-load equipments [19]. However, it is unclear if there exists the jet-flow phenomenon for self-rewetting fluids.

Bubble emission phenomenon can be observed during subcooled boiling under either gravity or microgravity conditions for pure liquid flowing in microchannel or over micro heated surface [20–23]. In these studies, bubble emission could greatly enhance the heat flux up to 144.1 W/cm^2 due to bubble collapse and explosion, proving a promising method for microelectronic chips cooling [22]. The mechanism for the bubble emission behavior in the liquid, however, is yet unclear. The emission phenomenon can also be observed for low-concentration aqueous high-carbon alcohol solution during subcooled boiling on micro heated surface [24–27]. These researches showed large critical heat flux (CHF) values, up to 2–3 times that of water, can be achieved under the small bubble emission mode. Hence it makes itself a potential choice for many microscale applications in the field of thermal engineering. But the insufficiency in explanation for the emission phenomenon makes it difficult to engineer the enhancement effect. Recently, Tang et al. [28] reported their observation of bubble emission phenomenon in subcooled pool boiling of water on a cone copper block with an upper cylindrical section of 10 mm in diameter. It showed that a heat flux up to 90 W/cm^2 can be obtained at the liquid subcooling of 60 K, when remarkable bubble emission phenomenon could be observed. The subcooling and noncondensable gas have significant effects on bubble emission phenomenon and hence the heat transfer rate. Their numerical simulation showed that strong thermocapillary convection as well as condensation and evaporation at the interface result in the collapse of the vapor film, resulting in the occurrence of bubble emission phenomenon.

For subcooled boiling of pure fluid such as water and ethanol, the bubble emission phenomenon could be created by the rupture of bubble interface. At the interface of a bubble attaching to a heated surface, evaporation happens at especially near the vapor film underneath the bubble, and condensation into the subcooled liquid happens at the upper part of the bubble [29]. During the phase change at the interface, noncondensable gas on the vapor side of the bubble can be accumulated nonuniformly along the interface, inhibiting vapor condensation and creating saturation pressure gradients and hence temperature gradients along bubble interface [30]. The increased saturation pressure gradient and temperature gradient can induce thermocapillary convection on the liquid side of the bubble, impeding bubble detachment by a reaction force due to the flow. However, the surface tension gradient along bubble interface, induced by the temperature difference in the liquid film around the bubble, creates tangential stresses on both sides of bubble interface. The created thermocapillary force is acting to the heated surface along bubble interface and thus could lead to bubble collapse, limited by the bubble growth process or the condensation into the subcooled liquid. The rupture of bubble interface and the folding of vapor film can create numerous small bubbles due to vapor entrapment [31], and apparently, the induced turbulence by these microbubbles could greatly enhance the heat transfer. Tang et al. [28] observed in their experiment that, especially on the periphery of the vapor film, obvious film collapse phenomenon existed for high subcooling of water and concluded that it was caused by the thermocapillary convection near the periphery where the tangential force is considerably stronger than other regions. Therefore, a schematic diagram of thermocapillary convection for pure fluid can be referred to Fig. 1, where thermocapillary flow results in a recirculating fluid flow from the warmer to the colder regions. From this diagram, one can also understand the possible mechanisms for various bubble behaviors during subcooled nucleate boiling on a micro heated wire, including bubble sweeping, bubble circling and staying at the bubble top.

In the current investigation, the jet flow phenomena on micro heated wire immersed in n-butanol solution will be revealed using high-speed CCD camera system. Differences in the jet flow phenomena for n-butanol solution and deionized water will be demonstrated by experiment and corresponding simulation using the FLUENT software package. The effects of surface tension and hence the thermocapillary force on the mechanisms of jet flow and bubble behaviors will be discussed by obtained temperature and velocity fields around the stationary bubbles on a thin heated wire.

2. Experimental apparatus

The experimental setup for observing the jet flow and bubble behavior during subcooled nucleate pool boiling on a micro