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Bubble growth and departure trajectory under asymmetric temperature conditions

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ABSTRACT

The sudden expansion of an evaporating mass during a phase change process like boiling causes the liquid–vapor interface to experience a reactionary force known as evaporation momentum force. Previous publications have illustrated that by creating a non-uniform liquid temperature distribution around a bubble, the resultant evaporation momentum force acting on the nucleating bubbles can be used to generate separate liquid–vapor pathways during boiling. This paper presents an analytical investigation on the distribution of evaporation momentum force experienced by a nucleating bubble, its effect on bubble growth rate and its role in determining the bubble departure trajectory. An analytical model is developed by incorporating evaporation momentum force into a widely accepted bubble growth model (Mikic et al., 1970) to determine the effect of evaporation momentum force on bubble growth rate. Furthermore, the horizontal displacement of a bubble when the liquid around the bubble is superheated in an asymmetric manner is determined. Experiments are designed to produce an asymmetric temperature condition around a nucleating bubble by creating a temperature gradient over the heater surface and the departure trajectory of the bubbles is observed using a high speed camera. The results indicate that the bubble departure trajectory is significantly altered under asymmetric temperature conditions and the analytical model developed shows good agreement with the experimental observations.

1. Introduction

Evaporation momentum force (vapor recoil) is an interfacial force experienced during liquid to vapor phase change because of the sudden expansion of the evaporating liquid. Due to the difference in the densities of the liquid and vapor phases, the evaporating mass at the interface experiences an increase in momentum causing an equal and opposite force, evaporation momentum force, to act on the interface. Researchers have studied the effect of evaporation momentum force on various aspects of phase change but it is especially relevant in the case of boiling. Interfacial instabilities [1], onset of critical heat flux (CHF) [2], [3] and lateral displacement of bubbles during nucleation [4] are some of the phenomenon where the effect of evaporation momentum force have been studied. Kandlikar [4] showed significant improvement in boiling performance of a surface by using evaporation momentum force to control the trajectory of the bubble along the heater surface. The role played by evaporation momentum force on many aspects of boiling, and the possibility of exploiting it to control bubble trajectory and create separate liquid vapor pathways, illustrate the need to better understand the nature of the force and its role in bubble growth and bubble trajectory. In the current paper, the effect of evaporation momentum force on bubble growth rate and the effect of asymmetric temperature distribution around a bubble on the bubble trajectory is investigated.

The underlying heat transfer mechanisms responsible for bubble nucleation and growth have been studied by many researchers. The main modes of heat transfer that have been proposed are transient conduction, microconvection and microlayer evaporation [5–8]. In both the transient conduction and microconvection modes, heat is transferred from the heater to the liquid and evaporation takes place at the liquid vapor interface. Microlayer evaporation is observed under the bubble as a result of the evaporation of a thin liquid layer present between the bubble and the heater surface and accounts for under 20% of the total heat transferred at high heat fluxes [9–11]. The relative contributions of each of the modes of heat transfer especially near CHF are still unclear with varying values being proposed. However, it is widely accepted that most of the evaporation occurs near the base of the bubble (near the heater surface) as the liquid superheat in this region is higher than at the top of the bubble [12].

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Nomenclature

A	non dimensional constant used by Mikic et al. [19]
A_b	cross sectional area of bubble (m^2)
b	shape factor used by Mikic et al. [19]
c	constant of proportionality (kg/m^2-s-K)
C_D	coefficient of drag
F_M	evaporation momentum force (N)
H_b	height of bubble (m)
h_{fg}	latent heat of evaporation (J/kg)
P_M	evaporation momentum pressure (N/m^2)
q_I	interfacial heat flux (W/m^2)
R	radius (m)
$\dot{R}$	rate of change of radius (m/s)
Re	Reynolds number
T	temperature (K)
ΔT	temperature difference (K)
v	velocity (m/s)
w	width of the bubble (m)
δ	boundary layer thickness (m)
η	evaporative mass flux (kg/m^2-s)
θ_c	contact angle
ρ	density (kg/m^3)

Subscripts

l	liquid
Sat	saturation temperature
v	vapor

Bubble growth is another important topic where significant amount of research has been conducted. Bubble growth can be divided into two main phases. In the first phase, the factor limiting bubble growth rate is the inertia of the liquid around the bubble. Rayleigh [13] proposed a bubble growth equation which is applicable to inertia controlled phase of bubble growth. This equation predicted bubble growth as a function of pressure difference across the bubble interface and did not include any heat transfer term. The second phase of bubble growth is observed as the bubble gets bigger and the bubble growth rate is controlled by heat diffusion into the bubble. Many researchers have proposed correlations which described bubble growth during the heat diffusion controlled phase. Some of the significant contributions include those by Plesset and Zwick [14], as well as Forster and Zuber [15]. These works were extended to include non-uniform temperature distribution by Griffith [16], Zuber [17], and Mikic and Rohsenow [18] among others. Mikic et al. [19] later proposed an integrated approach which describes bubble growth during both the inertia controlled and heat diffusion controlled phases.

Evaporation momentum force was initially studied by Palmer [1] on an evaporating flat interface as a precursor to the formation of surface waves. The influence of these waves in causing instability at the evaporating surface, called recoil instability, was postulated to be a basis for CHF by Sefiane et al. [20]. During bubble growth, evaporation momentum force pushes the bubble outwards in all directions but has no net effect along the heater surface as the forces act symmetrically in all directions and cancel each other out. Kandlikar [2] and Nikolayev et al. [3] postulated that evaporation momentum force is the driving force behind boiling crisis and that CHF is reached when evaporation momentum force on a bubble overcomes the forces which resist bubble growth such as surface tension and gravitational force. Nikolayev et al. [3] expressed evaporation momentum pressure (P_M) as a function of mass flux at the bubble interface as

$$P_M = \eta^2(\rho_v^{-1} - \rho_l^{-1}) \quad (1)$$

where η is the evaporative mass flux across the liquid–vapor interface, and ρ_l and ρ_v are the densities of the liquid and vapor phases respectively. Kandlikar [2] proposed a force balance model along the contact line to predict CHF. The horizontal component (parallel to the heater surface) of the evaporation momentum force was expressed as a function of the interfacial heat flux and the cross sectional area of the bubble to obtain an expression for evaporation momentum force (F_M) given by

$$F_M = \frac{q_I H_b 1}{h_{fg}} \frac{q_I}{h_{fg}} \frac{w}{\rho_v} = \left(\frac{q_I}{h_{fg}}\right)^2 \frac{w}{\rho_v} H_b \quad (2)$$

where q_I is the interfacial heat flux, h_{fg} is the latent heat of vaporization, H_b is the height of the bubble above the heater surface and w is the width of the bubble. The ability of the model to predict the critical heat flux for multiple fluids and under a wide range of conditions highlighted the importance of evaporation momentum force acting on a nucleating bubble. For a bubble on a flat uniformly heated surface, the evaporation momentum force acts symmetrically along the vertical axis (normal to the heater surface) and hence the net force on the bubble is zero. But when a bubble is subjected to an asymmetric temperature condition on two of its sides, the evaporation momentum force experienced on the hotter side of the bubble is greater than the cooler side due to increased evaporation rate, and hence the bubble experiences a net force towards the hotter side. Kandlikar [4] proposed that this mechanism can be used to control the horizontal trajectory of the bubble and hence establish separate liquid and vapor pathways during boiling. Kandlikar proposed a microstructure with a contoured fin and artificial nucleation sites at the base of the fin as shown in Fig. 1. The resultant CHF of 3 MW/m^2 and heat transfer coefficient of 629 kW/m^2-K were significantly greater than the corresponding values of 1.2 MW/m^2 and 70 kW/m^2-K on a flat surface respectively. Better understanding of the evaporation momentum force can help effectively exploit it further to create separate liquid vapor pathways during boiling.

2. Modeling effect of evaporation momentum force

In the first part of the present work, the effect of evaporation momentum force on bubble growth under uniform temperature conditions is modeled by modifying the bubble growth equation derived by Mikic et al. [19]. To account for the effect of evaporation momentum force on bubble growth, it is first expressed in terms of bubble growth rate. Subsequently, a first order approximation of

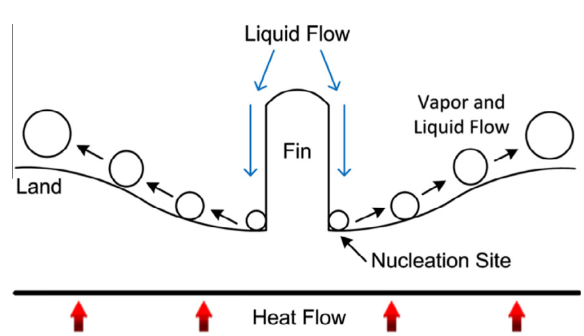

Fig. 1. Schematic of the contoured fin depicting independent liquid and vapor pathways [4].