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Force analysis and bubble dynamics during flow boiling in silicon nanowire microchannels

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ABSTRACT

In microchannel flow boiling, bubble nucleation, growth and flow regime development are highly influenced by channel cross-section and physical phenomena underlying this flow boiling mechanism are far from being well-established. Relative effects of different forces acting on wall-liquid and liquid–vapor interface of a confined bubble play an important role in heat transfer performances. Therefore, fundamental investigations are necessary to develop enhanced microchannel heat transfer surfaces. Force analysis of nucleating bubble and bubble dynamics in flow boiling silicon nanowire microchannels have been performed based on theoretical, experimental and visualization studies. The relative effects of different forces on flow regimes, instabilities and heat transfer performances of flow boiling in silicon nanowire microchannels have been identified. Inertia, surface tension, shear, buoyancy, and evaporation momentum forces have significant importance at liquid–vapor interface as discussed earlier by other researchers. However, no comparative study has been done for different surface properties till date. Detail analyses of these forces including contact angle effect, channel dimension effect, heat flux effect and mass flux effect in flow boiling microchannels have been conducted in this study. A comparative study between silicon nanowire and plainwall microchannels has been performed based on force analysis in the flow boiling microchannels. Compared to plainwall microchannels, enhanced surface rewetting and CHF are owing to higher surface tension force at liquid–vapor interface and Capillary dominance resulting from silicon nanowires. Whereas, low Weber number in silicon nanowire helps maintaining uniform and stable thin film and improves heat transfer performances. Moreover, results from these studies are compared with the literatures and great agreements have been observed.

1. Introduction

Flow boiling in microchannels is a highly efficient mode of heat transfer for a variety of applications including cooling high power microelectronics [1–3], compact heat exchangers, and chemical reactors [4–7]. In recent years, microscale flow boiling has been paid extensive attention due to its large surface to volume ratio, high heat transfer capacity, uniform temperature distribution and low mass flux requirements [8–10]. In spite of these positive attributes, flow boiling in microchannels encounters some major problems including flow instabilities, which degrades their reliability (non-uniform wall temperatures distribution, premature dry out, critical heat flux limitation and flow reversal) and heavy pressure drop penalty than its single-phase equivalent [8,11–14]. Flow boiling instabilities can be controlled or mitigated by controlling flow regime development. A flow boiling cycle includes bubble nucleation, growth, separation, interaction, development of two-phase flow regimes and rewetting for a given channel geometry and working conditions; and these are primarily influenced by surface properties. A number of studies have been performed to enhance heat transfer in microchannels by controlling bubble nucleation site density and wettability via changing surface properties [15–17]. Artificial nucleation cavities were formed on the boiling surfaces to enhance nucleate boiling by various methods, such as micromachining [18–21], nanostructured surfaces [22–26], porous metal coating [27–29], and chemical etching [30,31]. Recently, nanowires (NWs) [32,33] and carbon nanotubes (CNTs) [34–36] were used to enhance nucleate pool boiling and convective boiling in microchannels [23,25,26,34,37,38] and improved heat transfer

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Nomenclature

A_c	channel cross-sectional area, m^2
A_i	bubble interface area, m^2
A_{pl}	shear plane area, m^2
Bo	Bond number $((\rho_l - \rho_v) \cdot g \cdot \cos\varphi \cdot D^2/\sigma \cdot \cos\theta)$
Bl	Boiling number $(q''_{eff}/G \cdot h_{lv})$
Ca	Capillary number $(\mu \cdot U/\sigma \cdot \cos\theta)$
D	relevant dimension, m
D_h	channel hydraulic diameter, µm
d	bubble diameter, µm
F_b	buoyancy force, N
F_i	inertia force, N
F_M	evaporation momentum force, N
F_s	surface tension force, N
F_τ	shear force, N
G	mass flux, kg/m^{2}s
g	gravitational acceleration, m/s^2
H	channel height, µm
h	heat transfer coefficient, kW/m^{2}K
h_{lv}	latent heat of vaporization, kJ/kg
q''_{eff}	effective heat flux, W/cm^2
q''_{EV}	evaporative heat flux at the interface, W/cm^2
Re	Reynolds number $(\rho \cdot U \cdot D/\mu)$
t	time, s
U	fluid mean velocity, m/s
V	volume of bubble, m^3
We	Weber number $((\rho \cdot U^2 \cdot D/\sigma \cdot \cos\theta))$
x_e	exit vapor quality
Greek symbols	
α	void fraction
δ	film thickness, µm
θ	contact angle
ρ	fluid average density, kg/m^3
ρ_l	liquid density, kg/m^3
ρ_v	vapor density, kg/m^3
σ	surface tension, N/m
μ	fluid viscosity, kg/ms
φ	heating surface orientation

coefficient and critical heat flux were reported owing to the higher nucleation site density and enhanced wettability. However, optimization of surface properties to control bubble size, forces acting on bubble and flow patterns/ regimes has not yet been well resolved.

Enhanced flow boiling performances and reduced instabilities can be achieved by controlling flow regime development without having large pressure drop penalties and introducing complex geometries as demonstrated in our previous studies [39–41]. A novel boiling surface with submicron pores formed by NW bundles and nanoscale pores created by individual NWs were developed by our team [39]. This silicon nanowire (SiNW) microchannels configuration reduced the transitional flow boiling regimes in plainwall microchannels to a single annular flow starting from onset of nucleate boiling (ONB) to critical heat flux (CHF) conditions by controlling the flow structure in two aspects: reducing bubble size and transforming the direction of the surface tension force from the cross-sectional plane to the inner-wall plane [39–41]. An enhanced heat transfer, CHF and reduced pressure drop and instabilities were observed from these studies. Efforts have been made to understand the heat transfer mechanisms and other relevant problems including flow patterns, instabilities, and CHF etc on flow boiling occurring in SiNW microchannels. However, there are still many unexplained physical phenomena underlying the observed behaviors.

Understanding conjugated effects of various forces acting on bubble and liquid–vapor interface in SiNW microchannels are necessary to understand the flow boiling phenomena inside the channels and are also a key to develop enhanced heat transfer surfaces. A number of research efforts on flow boiling in microchannels were focused on understanding the underlying mechanisms [20,42–47]. Recently, Kandlikar [48] provides excellent discussion on the effects of different forces acting on liquid–vapor interface and settles on the inertia, surface tension, shear, buoyancy, and evaporation momentum forces as the candidates for significance. Although there are a number of researches have been focused on the force analysis of bubble and liquid–vapor interface in microchannel flow boiling, the investigation of forces in SiNW microchannels including contact angle, channel dimension and operating conditions are still deficient to the best of the authors' knowledge. Moreover, validation of force analysis with the experimental observations and literatures are also unavailable. The objective of this paper is to study the forces acting on the vapor bubble and liquid–vapor interface in flow boiling SiNW microchannels based on theoretical, experimental and visualization studies.

2. Analysis of forces acting on a liquid–vapor (L–V) interface

Inertia, surface tension, shear, buoyancy, and evaporation momentum forces are of significant importance at liquid–vapor interface and their relative effects of these forces play a major role in establishing different two-phase flow regimes in microchannels. Forces acting on a liquid–vapor interface of a bubble inside the microchannel are schematically shown in Fig. 1. The normalized forces with respect to channel unit cross-sectional area are used to understand the relative effects of these forces over bubble behaviors. Adopting simplified equations from Kandlikar [48] and incorporating static contact angle and heating surface orientation, forces are calculated in this study.

The surface tension force is expressed as,

$$F_s = \sigma \cdot \cos\theta \cdot D \tag{1}$$

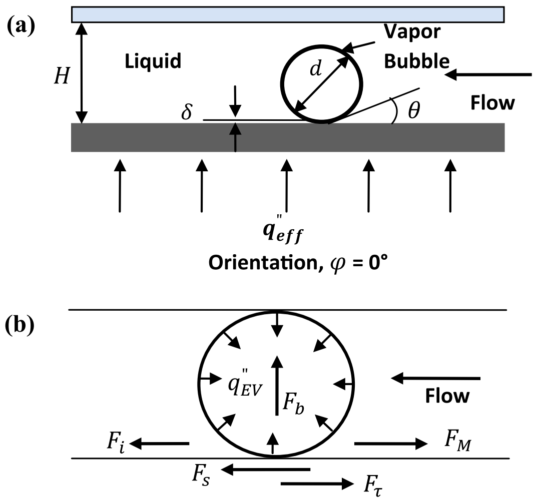

Fig. 1. Forces acting on a liquid–vapor interface of a growing bubble in a microchannel cross-section.