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Transient force analysis and bubble dynamics during flow boiling in silicon nanowire microchannels

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ABSTRACT

A study on bubble growth mechanisms and underlying physical phenomena of flow boiling in silicon nanowire (SiNW) microchannels has been performed and compared these results with plainwall microchannels. A new approach in studying bubble dynamics and forces acting on liquid–vapor (L–V) interface of growing bubble has been proposed based on theoretical, experimental and visual studies. Bubble size, liquid film thickness, interfacial properties are measured and L–V interfaces are detected from high speed visualization data and results are analyzed by vision-based approach. Force analysis during instantaneous bubble growth from bubble nucleation to formation of annular flow regime has been performed for both the SiNW and plainwall microchannel configurations. Results from force analysis show the dominance of surface tension at L–V interface of growing bubble which resulted higher heat transfer contact area, lower thermal resistance and higher thin film evaporation. Whereas, inertia force is dominant at L–V interface of fully grown bubble and it helps in bubble removal process and rewetting before flow reversal. Significant differences between SiNW and plainwall microchannels have been observed in bubble growth mechanism, heat transfer mode and forces acting on L–V interface.

1. Introduction

A novel boiling surface with submicron pores formed by silicon nanowire (SiNW) bundles and nanoscale pores created by individual nanowires was developed by our team [1]. Significant enhancement of heat transfer and critical heat flux (CHF) in flow boiling SiNW microchannels have been achieved owing to SiNW-induced single annular flow regime and liquid renewal enabled by superhydrophilic SiNWs. SiNWs can reduce the transitional flow boiling regimes (slug, plug, churn, etc.) in two-phase microchannels to a single annular flow regime starting from onset of boiling (ONB) to CHF condition 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 [1–3]. This is a unique flow boiling behavior and the underlying physical phenomena of this observed behavior are needed to be investigated. Forces acting on liquid–vapor (L–V) interface play a significant role to establish different flow boiling regimes in microchannels. Therefore, the roles and relative effects of these forces during bubble growth and flow regime establishment in microchannels are necessary to understand the underlying mechanisms and also to design high performance heat transfer systems.

A number of research efforts on flow boiling in microchannels were focused on understanding the underlying mechanisms [4–13]. Zhang et al. [4] investigated the bubble nucleation, flow patterns, heat transfer and pressure performances in silicon microchannels by varying surface roughness. They reported that the phase change mechanism was closely associated with wall surface conditions, and in order to induce and maintain a steady annular flow for microchannel heat sink applications, the channel wall must have enough gas-trapping cavities to ensure typical nucleation. Peles et al. [5] developed a one-dimensional model of evaporating two phase flow in a triangular microchannel, during steady-state operation to determine the dry-out length of a self sustained flow. They simplified the momentum equation as the contribution of gravity; wall-liquid friction forces and L–V friction forces were very small and were of order O (10^{-3}). It was shown that the dry-out length increased as the hydraulic diameter increased, and decreased as the heat flux increased. A three-zone flow boiling model was proposed by Thome et al. [6] and validated

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Nomenclature

A_b	bubble surface area, m^2
A_c	channel cross-sectional area, m^2
A_i	bubble interface area, m^2
A_{pl}	shear plane area, m^2
D	bubble diameter, m
D_s	Sauter diameter
D_h	channel hydraulic 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
t	time, s
U	fluid mean velocity, m/s
V_b	volume of bubble, m^3
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

by Dupont et al. [7] to describe the evaporation of elongated bubbles in microchannels. This model illustrated the transient variation in local heat transfer coefficient during the flow boiling cyclic from liquid slug to evaporating elongated bubble to vapor slug in microchannels. They also reported that heat transfer in the thin film evaporation region was typically on the order of several times that of the liquid slug while that for the vapor slug was nearly negligible. Numerical simulation of bubble dynamics and heat transfer during pool and flow boiling had been carried out by Dhir et al. [8]. Effects of different parameters on bubble dynamics had been quantified by numerical simulation and validated with experimental data. Mukherjee et al. [9] also performed a numerical study of bubble growth mechanism and heat transfer performance in flow boiling microchannels. They concluded that surface tension at L–V interface had little influence on bubble growth and heat transfer. Moreover, the bubble with the lowest contact angle resulted in the highest wall heat transfer. Studies have been performed to understand the bubble dynamics in flow boiling microchannels, however, the underlying mechanisms of this boiling cycle (formation and impact on heat transfer and pressure drop) have not been discussed yet.

Kandlikar [10] proposed a new method by considering interfacial phenomena to address flow boiling characteristics in microchannels. He proposed two new non-dimensional group K_1 (ratio of evaporation momentum force to inertia force) and K_2 (ratio of evaporation momentum force to surface tension force) and generated a correlation using these two parameters to predict CHF. He also suggested further investigating the interfacial phenomena for better understandings and validations. Recently, Kandlikar [11] provided excellent discussion on the effects of different forces acting on the L–V interface and based on his scaling analysis, he evaluated the flow pattern transitions and stability for flow boiling of water and FC-77. He concluded that surface tension and evaporation momentum forces played a dominant role at microscale. Miner et al. [12] experimentally investigated the pressure drop in an expanding microchannels array. They discussed the results in light of a comparative force analysis and linked the observed behaviors of the pressure drop and heat flux relationship with the balance of these forces. Liaofei et al. [13] theoretically and numerically investigated the evaporating momentum force and the shear force acting on the meniscus of an evaporating and elongating bubble in flow boiling in a microchannels. They reported that the evaporating momentum force was relatively small and can always be neglected in analyzing the bubble elongation process in microchannels flow boiling, but whether the shear force should be considered or not was determined by its relative order of magnitude and the particular conditions such as channel dimension and the operating conditions. Literature review shows that the relative effects of major forces acting on the L–V interface are still not well understood and contradict with each others. Therefore, more studies are needed to advance the understanding of underlying physical phenomena of flow boiling in microchannels.

Although numerous researches have been focused on the force analysis of bubble and L–V interface during flow boiling in microchannels, the investigation on force analysis during transient bubble growth and flow regime establishment in SiNW microchannels are still deficient to the best of the authors' knowledge. The objectives of this paper are to understand the bubble dynamics, significance of forces acting on the growing vapor bubble and L–V interface during flow boiling in SiNW microchannels based on theoretical, experimental and visual studies.

2. Experimental study

Experiments have been performed in SiNW and Plainwall micro devices to investigate the bubble dynamics in flow boiling microchannels. These micro devices consist of five parallel straight microchannels and each channel dimension is W: 220 μm X H: 250 μm X L: 10 mm. SiNWs formed by nanowire bundles and surrounded by nanoscale gaps were created over the boiling surface to fabricate SiNW microchannels. SiNWs are approximately 20 nm in diameter and 5 μm in length. The design and fabrication of the microchannel devices were detailed in our previous studies [2]. The difference between the dynamic contact angle and the static contact angle is small as shown by Kandlikar and Steinke [14]. Hence, due to the difficulty in measuring dynamic contact angle in flow boiling microchannels, static contact angles were measured and used in force analysis. Static contact angle over flat silicon is 45.13 ± 0.67° and SiNW is 10.21 ± 2.74° as described in our earlier study [18]. Experiments were conducted in a forced convection loop with deionized (DI) water over a range of mass fluxes, 100–600 kg/m^2s and heat fluxes, up to 400 W/cm^2. The experimental apparatus including the test module, flow loop, experimental procedure, and the data reduction method established in our previous studies are adopted in this study. High speed visualization at a frame rate 5000 frames per second (fps) has been performed along with experimental investigations and theoretical analysis to reveal