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Numerical study of bubble growth and wall heat transfer during flow boiling in a microchannel

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ABSTRACT

A numerical study has been performed to analyze the wall heat transfer mechanisms during growth of a vapor bubble inside a microchannel. The microchannel is of 200 μm square cross section and a vapor bubble begins to grow at one of the walls, with liquid coming in through the channel inlet. The complete Navier-Stokes equations along with continuity and energy equations are solved using the SIMPLER method. The liquid vapor interface is captured using the level set technique. Experiments have been conducted to validate the numerical model. The bubble growth rate and shapes show good agreement between numerical and experimental results. The numerical results show that the wall heat transfer increases with wall superheat but stays almost unaffected by the liquid flow rate. The liquid vapor surface tension value has little influence on bubble growth and wall heat transfer. However, the bubble with the lowest contact angle resulted in the highest wall heat transfer.

1. Introduction

Flow through microchannels is a subject of extensive study due to wide ranging applications in engineering and biological sciences. Microchannel heat sinks with liquid cooling are extensively used in various applications such as electronic chip cooling. Bubble formation inside microchannels can take place if the fluid is a mixture of a gas and a liquid or the temperature of the wall reaches above the local liquid saturation temperature. During flow boiling, bubbles nucleate on the microchannel walls and may grow big enough to fill up the entire channel cross-section. When the bubbles are of the same size as the microchannel, they regulate the flow characteristics and if applicable the wall heat transfer. The wall heat transfer from the channel wall to the liquid is affected by the bubble nucleation and growth inside the channels.

At microscale the surface tension forces are expected to dominate the gravitational forces and control the bubble dynamics. Water has been the preferred coolant for flow boiling for its excellent thermal properties. Direct application of boiling water on a chip surface may not be desirable due to its poor dielectric properties and high boiling temperature. Fluorochemicals with excellent dielectric properties are also often used for electronics cooling. The heat transfer mechanism in microchannels is affected not only by the thermal properties but also by the contact angle between the bubbles and the microchannel walls. The bubble nucleation temperature is also known to be dependent on the contact angle. Dielectric liquids typically are highly wetting in nature with much lower contact angle and surface tension as compared to water.

2. Literature review

Excellent reviews are available on flow boiling in microchannels, e.g. Bergles et al. [1], Garimella and Sobhan [2] and Thome [3].

Kandlikar [4] carried out a critical literature review on flow boiling through minichannels and microchannels. He identified the effect of surface tension to be significant in microchannels causing the liquid to form small uniformly spaced slugs that fill the channel. He pointed out that one of the main reasons for the boiling instability in microchannels is the explosive growth of a vapor bubble after it nucleates. It is therefore important to understand the dynamic growth characteristics of a bubble upon its nucleation during flow boiling in microchannels.

Yen et al. [5] studied convective flow boiling in a circular pyrex glass microtube and a square pyrex glass microchannel. Higher heat transfer coefficient was observed in the square microchannel as compared to the circular crossectional microtube because of square corners acting as active nucleation sites.

Agostini et al. [6–8] studied high heat flux flow boiling of refrigerants in microchannel heat sinks in a three-part paper. The authors compared the heat transfer results with their own theoretical models. Lee and Pan [9] studied eruptive boiling in silicon based microchannels and argued that it may be caused by the nano-sized cavities present at the channel walls.

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Nomenclature

A	wall area
C_p	specific heat at constant pressure
D	characteristic dimension
D	grid spacing
G	mass flux
G	gravity vector
H	heaviside function
h	heat transfer coefficient
h_{fg}	latent heat of evaporation
k	thermal conductivity
$K1$	Kandlikar number 1 $\left(\frac{q}{Gh_{fg}}\right)^2 \frac{\rho_L}{\rho_G}$
$K2$	Kandlikar number 2 $\left(\frac{q}{h_{fg}}\right)^2 \frac{D}{\sigma\rho_G}$
L	length of bubble
$L1$	upstream bubble cap location
$L2$	downstream bubble cap location
l_0	length scale
m	mass transfer rate at interface
ms	milliseconds
Nu	Nusselt number
p	pressure
q	heat flux
Re	Reynolds number
T	temperature
ΔT	superheat, $T_w - T_{\text{sat}}$
t	time
t_0	time scale
u	x direction velocity
u_0	velocity scale
v	y direction velocity
w	z direction velocity
x	distance in x direction
y	distance in y direction
z	distance in z direction

Greek symbols

β_T	coefficient of thermal expansion
κ	interfacial curvature
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
σ	surface tension
τ	time period
ϕ	level set function
φ	contact angle

Subscripts

evp	evaporation
G	gas or vapor
in	inlet
L, l	liquid
sat	saturation
v	vapor
w	wall
x	$\partial/\partial x$
y	$\partial/\partial y$
z	$\partial/\partial z$

Superscripts

$*$	non-dimensional quantity
$\rightarrow$	vector quantity

Bertsch et al. [10] measured local flow boiling heat transfer coefficient in a microchannel-based cold plate evaporator using HFC-134a. The heat transfer coefficient showed a peak value at 0.2 vapor quality in all of the experiments. Lee and Garimella [11] investigated flow boiling of water in a microchannel array and presented new correlations for predicting two-phase pressure drop and local saturated boiling heat transfer coefficient.

Wang and Cheng [12] investigated subcooled flow boiling and microbubble emission boiling (MEB) of water in a microchannel. The occurrence of MEB resulted in removal of high heat flux at moderate rise in wall temperatures. Geisler and Bar-Cohen [13] studied saturated flow boiling CHF (Critical Heat Flux) in narrow vertical microchannels and observed that bubble confinement led to heat transfer enhancement in the low heat flux region of the nucleate boiling curve.

Harirchian and Garimella [14] defined a new transition criterion to qualify microscale two-phase flow. They termed this number as the 'convective confinement number' that incorporated mass flux, fluid properties and channel cross-sectional area.

Yang et al. [15] simulated bubbly two phase flow in a narrow channel using a numerical code FlowLab based on the Lattice-Boltzmann method. Single or multiple two-dimensional Taylor bubbles were placed in a vertical channel and their behavior was studied for different values of surface tension and body forces. No heat transfer or phase change was considered between the two phases. The authors found little effect of surface tension on the movement of the bubbles or the flow regime transition.

Jacobi and Thome [16] developed an analytical model of elongated bubble flows in microchannels and compared the results with experimental data. The central idea to this model was the thin film evaporation around the elongated bubbles. The model correctly predicted the heat transfer coefficient to be dependent on heat flux but insensitive to mass flux. The model did not include the possibility of formation of vapor patches at the walls and thus completely excluded the effect of contact angle. The success of this model depended exclusively on initial guesses of the critical nucleation radius and initial liquid film thickness. The authors argued that the experimental studies that show heat-flux dependence of the convection coefficient along with relative independence from quality and mass flux cannot be ascribed only to the nucleate boiling mechanism. They developed a hypothesis that microchannel evaporation is thin-film dominated.

There are a few studies that have appeared in the literature on the effect of contact angle on vapor bubble growth inside microchannels. Mukherjee and Mudawar [17] studied microchannel electronics cooling using dielectric coolant FC-72 and water which has large differences in surface tension and contact angle. The results showed opposite trends in critical heat flux (CHF) with decrease in channel size for the two liquids. Water produced large diameter bubbles that blocked liquid flow through the channel cross-section and hence CHF decreased with decrease in channel gap below the departure diameter of the bubbles. In the case of the dielectric liquid, the departure bubble diameters were much smaller as compared to water and these bubbles blocked the liquid flow only below a channel gap of 0.13 mm. When the channel gap varied between 3.56 mm and 0.13 mm the CHF increased with a decrease in channel diameter because partial blockage caused by the tiny bubbles increased the two-phase mixture velocity and improved heat transfer.

Thome et al. [18] and Dupont et al. [19] developed a three-zone flow boiling heat transfer model to describe evaporation of elongated bubbles in a microchannel and compared the time-averaged local heat transfer coefficients from several independent experimental studies. Their numerical model consisted of sequential