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Numerical modelling of bubble growth in microchannel using Level Set Method

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ABSTRACT

Development of more efficient thermal management systems is of prime importance not only in the context of environmental and energy concerns, but also due to ever-increasing demands of computational power. Flow boiling in microchannels holds a lot of promise and is capable of removing high heat fluxes. However, the physics behind the heat transfer and fluid flow during flow boiling at micro scales is not completely understood. Various studies have been performed to classify the flow regimes and identify the dominant mode of heat transfer in two phase flow through microchannels. In the present work, a numerical study is performed to investigate the bubble dynamics in a confined microchannel. A DGLSM (Dual-Grid Level Set Method) based numerical model is used to capture the unsteady bubble interface dynamics. The Navier–Stokes equation is being solved using Finite Volume Method (FVM) based Semi-Explicit Pressure Projection Method. The effect of parameters namely contact angle, surface tension, wall superheat, Reynolds number and system pressure on the bubble dynamics and bubble growth rates is investigated. Three distinct stages of heat transfer corresponding to the rapid reduction, stabilization and enhancement of evaluated Nusselt number are identified from the parametric investigation. The results show that the system pressure plays a vital role in controlling the bubble shape, as compared to remaining parameters.

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1. Introduction

Thermal management is increasingly becoming a bottleneck for a variety of applications such as integrated circuits, solar cells, microprocessors, and energy conversion devices. The reliability of an electronic device is defined as its ability to perform a required function under stated conditions for a given time. An electronic device fails to fulfil its intended function when its application or environmental condition exceeds its tolerable limit. Theoretically, electronic components are said to be reliable, if they are operated for a long duration of time at recommended operating temperatures, known as critical temperature. However, adverse environment and unusual operation reduces the effective operating time. It has been found that a 1 °C decrease in a component temperature may lower its failure rate by as much as 4% and 10–20 °C increase in component temperature can increase its failure rate by 100% [1]. According to a survey by the US Air Force, the percentage of temperature related failures in electronics exceeded 55% [1]. International Technology Roadmap for Semiconductors (ITRS 2005, [2]) ITRS predicted that the chip power and heat flux of the future generation electronic devices would reach 350 W and 200 W/cm^2 in 2018. Hence, there is a tremendous need for innovative cooling technologies. The new cooling technologies should also comply with the major design goals of thermal management *viz.* performance, cost, physical size and reliability. In the recent years, the research on boiling and two-phase flow in microchannel has gained momentum due to its ability to meet the requirement of dissipating high heat fluxes in a relatively small space and volume.

Several studies have reported the experimental observations of the flow boiling phenomena in microchannels [3–9]. Authors captured the liquid–vapour interface during dry-out conditions at the contact line region and observed flow reversal in some cases indicating a high evaporation rate. Kandlikar et al. [8] studied the effect of pressure drop and artificial nucleation sites on the stability of flow boiling and concluded that the application of pressure drop alone decreases the instabilities whereas the application of artificial nucleation sites alone increases them for the same mass flow and heat flux conditions. Kandlikar [9] proposed a possible mechanism of heat transfer during flow boiling in microchannels. It was observed that convective boiling is diminished in the microchannels and the major mode responsible for heat transfer is nucleate boiling. Two non-dimensional groups K_1 and K_2 were identified, where K_1 represents the ratio of evaporative momentum force

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Nomenclature

c_p	specific heat (J/kg K)
d	bubble diameter (mm)
Fr	Froude number
g	gravitational acceleration (m/s^2)
h	heat transfer coefficient (W/m^2 K)
h_{12}	latent heat (J/kg)
$H(\phi)$	Heaviside function
Ja	Jacob number
k	thermal conductivity (W/m K)
l	length of channel (m)
l_c	characteristic length (m)
$\dot{m}$	interfacial mass flux (kg/m^2 s)
$\dot{M}$, $\vec{M}$	non-dimensional interfacial mass flux
$\vec{n}$, $\hat{n}$	normal and unit vector to the interface
Nu	Nusselt number
p	pressure (N/m^2)
P^*	non-dimensional pressure
Pr	Prandtl number
r_c	Radius of bubble (m)
r_c^*	non-dimensional radius of bubble $\left(=\frac{r_c}{l_c}\right)$
Re	Reynolds number based on channel width
t	time (s)
T	temperature (K)
u, $\vec{u}$	velocity and velocity vector (m/s)
u_c	characteristic velocity (m/s)
U, V	non-dimensional velocities in X–Y coordinate
x, L, l	length (m)
X, Y	coordinate axes
X^*	non-dimensional length
Y^*	non-dimensional width
X_c, Y_c	non-dimensional location of bubble in X–Y coordinate
W	width of channel (m)
W^*	non-dimensional width of channel $\left(=\frac{W}{l_c}\right)$
We	Weber number

Greek symbols

χ	density ratio (ρ_2/ρ_1)
$\delta(\phi)$	Dirac delta function
η	viscosity ratio (μ_2/μ_1)
ϵ	diffused half interface thickness
γ	specific heat ratio ($c_{p,2}/c_{p,1}$)
κ	curvature of the interface
μ	dynamic viscosity (Pa s)
∇	gradient operator
ϕ	level set function
ρ	density (kg/m^3)
σ	coefficient of surface tension
θ	contact angle
τ	non-dimensional time
φ	improved reinitialization parameter
ς	thermal conductivity ratio (k_2/k_1)

Subscripts

1, 2	liquid (fluid 1) and vapour (fluid 2)
DC	downstream cap
cap	bubble cap
eq	equivalent
i	index
in	inlet
int	interface
m	mean
max	maximum
s	pseudo
p	phase
PC	phase change
sat	saturation
UC	upstream cap
w	wall

Superscripts

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

and inertia force and K_2 represents the ratio of evaporative momentum force and surface tension force. The effect of surface tension was found to be significant in microchannels, which leads to slug-annular flow regime, when the vapour bubble fills the entire channel allowing the liquid to flow around the bubble in thin films. Moreover, the primary reason for flow boiling instability was attributed to the explosive growth of bubble after its nucleation, resulting in reversal of flow in parallel microchannels.

Numerical studies have also been performed by various researchers for both pool boiling and flow boiling [10–17]. Tomar et al. [12] performed a study on bubble formation in film boiling using Coupled Level Set and Volume of Fluid (CLSVOF) method on water and a refrigerant, R134a at near and far critical pressures. They concluded that an increase in wall superheat initially reduces instability and later enhances it and results in higher frequency of bubble formation. A similar numerical study of film boiling was performed by Gada and Sharma [13], where Dual Grid Level Set Method (DGLSM) was used to study the ebullition cycle of water vapour bubbles at near critical pressures for both normal and reduced gravity conditions. They reported periodic release of bubbles at nodes and antinodes alternatively. Son et al. [14] simulated nucleate boiling on a horizontal surface using Level Set Method (LSM) and studied the effect of static contact angle and wall superheat on bubble dynamics. They included the effect of microlayer evaporation in their analysis. They reported outwards and inwards motion of the vapour contact line with the wall during the growth and departure of the bubble respectively. Dhir et al. [15] employed LSM to study the effect of wall superheat, liquid subcooling, contact angle, gravity level, noncondensables and conjugate heat transfer on the bubble dynamics of single as well as multiple bubbles during pool boiling. Pan and Chen [16] performed a two-dimensional numerical study of bubble dynamics in a microchannel using a front tracking method based on immersed-boundary method. They obtained a regime map for bubble slug passing through a contraction section using Weber number (*We*) and Reynolds number (*Re*). They also studied the interactions between multiple bubbles rising through a cavity under gravity. Mukherjee et al. [17] performed a three-dimensional numerical study of the bubble growth and heat transfer where-in they studied the effects of static contact angle, Reynolds number, wall superheat and surface tension on bubble dynamics and heat transfer.

However, the mechanisms of bubble growth and heat transfer are not fully understood. Besides, several aspects such as influence of pressure and channel dimensions on the onset of dry out and boiling instabilities are yet to be systematically investigated. Therefore, in this paper, a numerical study is performed on the heat transfer during flow boiling in microchannels using different parameters such as wall superheat, surface tension, contact angle,

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