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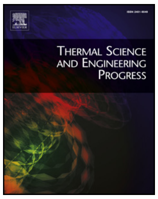

Understanding of bubble growth at nucleation site using energy based non-dimensional numbers and their impact on critical heat flux condition in microchannel

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ABSTRACT

Two phase flow initiates at Onset of Nucleate Boiling, where the first bubble emerges in the downstream flow direction. Bubble nucleation and growth in microchannel heat sinks is very conspicuous phase as the growing bubble can completely block the flow cross-section area at high heat flux. Hence, microchannels are more susceptible to flow boiling instability. In this paper effort has been put to study the bubble dynamics during bubble growth at nucleation site for microchannel in terms of non-dimensional energy ratio numbers and their variation from bubble inception until departure. New non-dimensional energy ratio is also proposed, which helps in differentiating inertia controlled and thermal diffusion controlled region during bubble growth at nucleation site. Further, possible impacts of these non-dimensional energy terms on critical heat flux are discussed.

1. Introduction

Microchannels are finding extensive range of applications due to superior heat transfer characteristics such as in microelectronics [1,2], advanced military avionics [3], laser mirror [4], turbine blades, refrigeration cooling, thermal control in microgravity and capillary pump loops [5]. Combined effect of high surface area to volume ratio and very low thermal resistance facilitate better heat transfer performance of microchannels in comparison to conventional size channels. First time, Tuckerman and Pease [6] had developed microchannel heat sink for cooling purpose of high speed Very-large-scale integration (VLSI) circuit. He showed that microchannels based heat sink can successfully remove heat flux up to the rate of 790 W/cm^2. Further, Kandlikar [7] postulated that enhanced microchannel geometry can successfully dissipate heat rate up to 1000 W/cm^2. Due to superior heat transfer characteristics of the two phase flow, it was extensively explored even in microchannels by many researchers [2,3,5,8–11]. With increase in the range of applications of microchannel heat sink, more efforts are required for comprehensive understanding of the flow boiling mechanism in microchannels. Bubble dynamics during two phase flow in microchannels governs the heat transfer, pressure drop characteristics and associated instabilities. Hence, accurate prediction of heat transfer, pressure drop and associated instabilities rely on how accurately we can predict regarding formation of bubble at nucleation sites, growth, departure and its motion along the fluid.

In conventional channel as explained by Thome [12], the sequence of flow is bubbly, slug, churn, wispy-annular and annular flow in vertical channel flow and in the horizontal channel, bubbly, slug, plug, annular, stratified, annular with mist and wave flow exists. However, in case of the microchannels flow pattern and associated heat transfer characteristics are quite different than conventional channels. Thus, only some of the available macroscale knowledge can be applied to the microscale [13,14]. Flow boiling in microchannels is governed by the nucleate boiling mechanism and the forced convection boiling mechanism [15]. In the nucleate boiling mechanism, heat transfer is controlled by the formation of the vapor bubble at nucleation site, which further depends on density of nucleation sites, and frequency of bubble formation [16]. Hence, bubbles inception, growth and departure are important aspects from the nucleate boiling prospects. Bubble growth at nucleation site is divided between two regions; inertia controlled region and diffusion controlled region [17,18]. In early stage during inertia controlled region as shown in Fig. 1, bubble is surrounded by the liquid with higher degree of superheat near heated wall of the channel. Hence, in the inertia controlled region, bubble growth is governed by the reaction force of the surrounding liquid on bubble interface. In later stage, bubble becomes large and its growth requires extensive evaporation of the liquid at the interface. Thus, bubble growth in later stage is governed by the thermal diffusion process

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Nomenclature

A	area (m^2)
a	bubble centroid (m)
E_{bubble}	energy required for bubble growth (W)
Er	energy required to overcome resistive effect (W)
g	acceleration due to gravity (m^2/s)
G	mass flux (= $\rho_l v$) (kg/m^2s)
h_{fg}	latent heat (J/kg)
r	bubble radius (m)
q''	effective heat supplied to channel (W/m^2)
t	time (s)
V	bubble volume (m^3)

Greek

ε	void fraction.
ρ_l	liquid density (kg/m^3).
ρ_v	vapor density (kg/m^3).
μ	viscosity ($N\ s/m^2$)
θ	contact angle (°)
σ	surface tension (N/m)

Subscript

c	minimum visible cavity
ch	channel cross section
c/s	bubble cross section
g	gravity
i	inertia, instantaneous value when used with volumes and areas
$incep$	inception
min	minimum visible
s	bubble surface
sf	surface tension
sh	shear
m	evaporation momentum

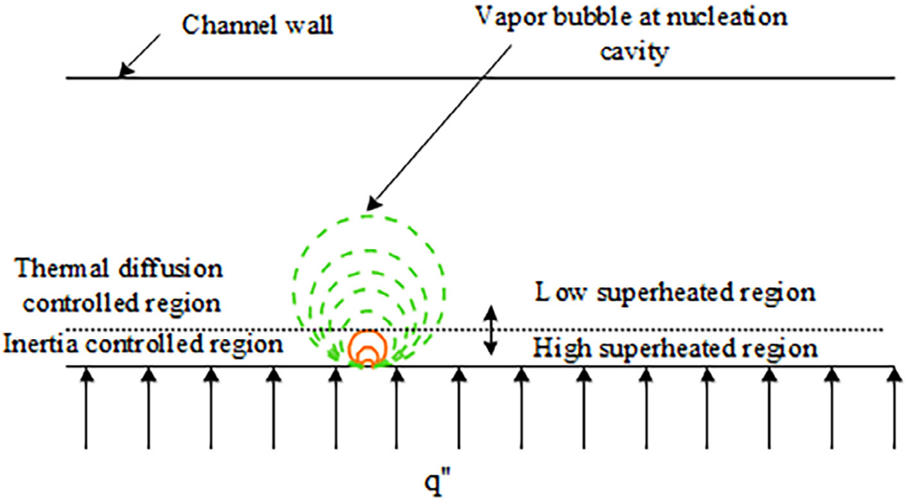

Fig. 1. Inertia controlled and thermal diffusion controlled regions.

between growing bubble and neighboring low temperature surrounding liquid.

Various non-dimensional numbers (such as Martenelli parameter, Convection number, Boiling number, Bond number, Eotvos number, Capillary number, Ohnesorge number, Weber number and Jacob number) are used effectively in flow boiling. Significance of these numbers from two phase boiling prospects is explained by Kandlikar [19]. However, not all these numbers govern the performance of microchannel heat sink. Commonly useful non-dimensional numbers in case of microchannel are K_1, K_2, capillary number (Ca), Weber number

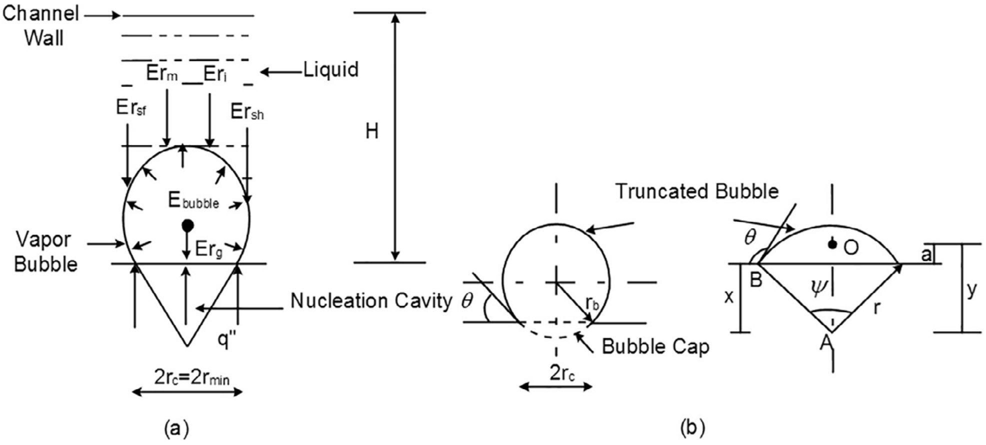

Fig. 2. (a) Energy distribution at nucleation site; (b) truncated bubble and centroid of the bubble (Kadam et al. [20]).