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Modeling of boiling flow in microchannels for nucleation characteristics and performance optimization

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A B S T R A C T

The implementation of forced convective boiling in microchannels is developed to be very promising, as the attainable heat transfer rate is very favorable when compared to traditional thermal solutions. In this study, numerical simulations are conducted to investigate nucleate boiling in microchannels, with the interface separating liquid and vapor phases tracked by a conservative level set method (LSM). The behavior of bubbles in uniformly superheated liquid, and flow boiling regimes in a microchannel are identified to validate the applicability of the proposed methodology. Boiling mechanisms are found to be strongly dependant on wall surface conditions, simulations are thereby conducted to investigate flow boiling in microchannels with reentrant cavities. Comparisons of the performance of the enhanced and the plain-wall microchannels are performed, and the structured surfaces are demonstrated to facilitate nucleating and enhance critical heat flux (CHF). The identification and quantification of key design parameters of cavities including mouth opening (R), depth (H), diameter (D) and density are conducted, addressing an optimal topology design with R of 9.5 μm, H of 60 μm and D of 120 μm, which nucleates first under a given set of conditions from rather low superheating. To enable a compatible view, two cavity characteristic models are investigated. The stochastic model with randomly sized and located cavities has been proved to hinder the cooling capability by decreasing CHF, as compared to the deterministic model that comprises regular cavities. Nevertheless, it still outperforms the plain-wall microchannel. Finally, heat flux conditions of the cooling target are studied to seek high-performing cooling schemes, considering seven different heating loads.

1. Introduction

As the power density increases, the convergence of increased volume and mass of heat sink makes it inconvenient and impractical to utilize conventional thermal solutions by placing a large element at the backside of a processor. Correspondingly, a sharp increase in heat removal requirements has imposed a need for an alternative cooling method, consequently leading to greater challenges in electronic packaging and microprocessor cooling. Several works have focused on microchannel heat sinks applying forced convective boiling at the package level, which play an important role in thermal management and energy systems. Overcoming the scaling barrier, favorable heat transfer rate, less pumping power, minimal coolant usage, small heat sink mass and volume, and relatively isothermal cooling surface (single-phase cooling creates a downstream temperature rise) are drawing considerable attentions to this promising cooling solution [1]. Extensive literatures [2–6] are available on a systematic view of the microchannel two-phase flow.

As demonstrated previously, the mechanisms controlling two-phase pressure drops, heat transfer coefficients, and critical heat flux (CHF, a point within the microchannel systems where electronic dry-out and possibly critical thermal failure may occur) at the micro-scale, are inherently related to flow regimes. Saisorn and Wongwises [7] performed experiments in a microchannel, and presented a flow pattern map. Megahed and Hassan [8] conducted an experimental investigation of the pressure drop and flow visualization of two-phase flow in a rectangular microchannel heat sink. Bubble growth and flow regimes were observed by high speed visualization, identifying three flow boiling regimes: bubbly, slug, and annular. Huh et al. [9] investigated the characteristics of flow boiling in a microchannel, such as pressure drops and temperature fluctuations in a long time period, which exactly matched the transition of two alternating flow patterns: bubbly/slug flow and elongated slug/semi-annular flow. Bogojevic et al. [10] and Megahed [11] experimentally studied two-phase flow instabilities in micro-channel heat sinks to investigate flow patterns caused by alternating liquid/vapor flows.

In addition to experimental studies, the emergence of powerful computers and robust numerical techniques in the last few decades has made the numerical solution of two-phase conservation

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Nomenclature

x	axial distance along fluid flow axis, m
y	gap-wise direction, m
$\mathbf{u}$	fluid velocity vector, m/s
P	pressure, Pa
T	temperature, K
R	cavity mouth, m
D	cavity diameter, m
H	cavity height, m
C_P	heat capacity, J/(kg K)
k	thermal conductivity, W/(m K)
L	latent heat, (J/kg)
q_{eff}	effective heat flux, (kW/m^2)
G	mass flux, (kg/m^2)
$\mathbf{g}$	gravity vector, m/s^2

Greek symbols

η	kinetic viscosity, m^2/s
ρ	density, kg/m^3
σ	surface tension, N/m
κ	interfacial curvature, m

Subscripts

i	interface
sat	saturation
l	liquid
v	vapor
in	inlet
W	wall
avg	average

equations possible. Homogeneous Mixture Model (HEM) was developed on two-phase forced convection in microchannels by Sarangi et al. [12], consisting of continuous and differentiable correlations and one momentum equation for the entire flow. It assumes that the dispersed and the continuous phase are combined together and modeled as a new, continuous phase. However, no-slip conditions between the liquid and the vapor phase may cause the inaccurate fluid fractions and pressure drop prediction. Two Fluid Model (TFM) is taken to be one of the most widely used two phase flow models: each phase is represented by its own specific momentum, mass and energy equations. The discontinuity in flow pattern transitions becomes a primary limitation of this model. Drift Flux Model (DFX) [13] is a model with intermediate complexity, which is smooth and differentiable, yet still accounts for the slip between the fluids. But, it requires a large number of empirical parameters, and is only valuable when the drift velocity is significantly larger than the volumetric flux. In our previous study [14], HEM and TFM were established to analyze 1D microchannel flow boiling and captured the point of the boiling onset. For interface propagation in two-phase flow problems, there are many choices, e.g. front tracking, phase field, volume-of-fluid (VOF), and level set method (LSM). The VOF multiphase flow model was proposed by Zhuan and Wang [15] to study nucleate boiling in microchannels and had good agreements with experimental data. Mukherjee et al. [16] performed numerical studies to analyze wall heat transfer mechanisms during growth of a vapor bubble inside a microchannel, using LSM to capture the liquid/vapor interfaces.

Moreover, boiling enhancement technique becomes a topic of great interest and many efforts have been put on strengthening nucleate boiling by modifying wall surfaces with micro-machined structures. Kuo and Peles [17] experimentally investigated flow boiling in parallel microchannels with reentrant cavities to obtain and study flow morphologies, heat transfer coefficients, and CHF for various mass velocities and heat fluxes. Chai et al. [18] conducted investigations of fluid flow and heat transfer characteristics in a microchannel heat sink with offset fan-shaped reentrant cavities on both sidewalls. In addition, numerical simulations were also performed on boiling enhancement by structured surfaces [19]. A three-dimensional laminar flow model was proposed to investigate the effect of geometric parameters on flow and heat transfer characteristics in a microchannel heat sink with triangular reentrant cavities. The presence of nucleation sites was demonstrated to significantly reduce the wall superheat and enhance the boiling heat transfer performance [20,21].

A numerical investigation assisted with a description and analysis of forced convective boiling through microchannels is established in this study. The information allows the determination of flow configurations and a better understanding of heat transfer mechanisms. 2D flow boiling in microchannels is simulated with the liquid/vapor interface tracked by a conservative LSM. Experimental and analytical results from open sources are compared with model predictions by mapping flow morphologies that determine boiling heat transfer mechanism governing the flow. The comparison helps prove the applicability of the proposed model tailored for the microchannel flow boiling. Boiling mechanisms are found to be strongly dependant on wall surface conditions. After the applicability of the proposed two-phase flow model being testified, there is a strong need to perform in-depth researches on flow boiling in microchannels fabricated with structured cavities. Comparisons of the performance of the enhanced and the plain-wall microchannels indicate that reentrant cavities can facilitate boiling nucleation and improve CHF. The key design parameters of the cavities consisting of mouth opening (R), depth (H), diameter (D) and density are examined to address an optimal topology design with R of 9.5 μm, H of 60 μm and D of 120 μm, which nucleates first under a given set of conditions from rather low superheating. In addition, two cavity characteristic models are investigated. The stochastic model with randomly sized and located cavities hinders the cooling capability by decreasing CHF, as compared to the deterministic model comprising regular cavities. Nevertheless, it still outperforms the plain-wall microchannel. Finally, heat flux conditions of the cooling target are studied to seek high-performing cooling schemes, considering seven different heating loads.

This work is dedicated to extending the current knowledge on the flow boiling in microscale channels. The results of bubble dynamics, boiling instability, and CHF can significantly contribute to the heat transfer-fluid community with fundamental knowledge in microscale flow boiling as well as the designing understanding of micro fluidic systems.

2. Computational model

The interface separating the two-fluid phases is tracked by the LSM, which is commonly used for computing multiphase flow problems. The method based on the methodology proposed by Olsson and Kreiss [22] is accomplished by the Level Set Two-Phase Flow Mode available in the Chemical Engineering Module in the commercial FEA package COMSOL™ [23,24].