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On the dynamics and heat transfer of bubble train in micro-channel flow boiling

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ABSTRACT

The dynamics and heat transfer characteristics of flow boiling bubble train moving in a micro channel is studied numerically. The coupled level set and volume of fluid (CLSVOF) is utilized to track interface and a non-equilibrium phase change model is applied to calculate the interface temperature as well as heat flux jump. The working fluid is R134a and the wall material is aluminum. The fluid enters the channel with a constant mass flux (335 kg/m^2∗s), and the boundary wall is heated with constant heat flux (14 kW/m^2). The growth of bubbles and the transition of flow regime are compared to an experimental visualization. Moreover, the bubble evaporation rate and wall heat transfer coefficient have been examined, respectively. Local heat transfer is significantly enhanced by evaporation occurring vicinity of interface of the bubbles. The local wall temperature is found to be dependent on the thickness of the liquid film between the bubble train and the wall.

1. Introduction

Flow boiling in micro-channel is a common phenomenon among various industrial applications such as liquid electronic cooling system and fuel cells [18]. Different flow patterns have been observed. Starting from the inlet, there are nucleate boiling, confined bubbles, elongated bubbles, annular flow, and dry-out near the end [7,14].

It is believed that each flow pattern has its own heat transfer characteristics, which makes estimation of the overall or average heat transfer coefficient difficult. Experiment study has contributed in the overall heat transfer coefficient estimation and flow pattern visualization. Xu [22] studied stability of seed bubbles in parallel micro-channels. Tibirica [20] investigated the flow patterns and bubble departure characteristics and developed two methods for estimation of average surface heat flux. Cosolini [3]proposed a model for predicating coalescing bubbles based on collected experiment data. Yang [23] examined heat transfer characteristics of annular flow regime. Ali and colleagues [1,2,12] investigated different refrigerants' performance in micro channel flow boiling. Deng, Fernandino et al. [4] modelled the dry-out of annular and mist flow regime during binary mixtures boiling. Their results suggest a large initial entrainment and a non-negligible nucleation induced entrainment must be included. Based on their model, the local critical heat flux and the dry-out location are almost linearly dependent on the mixture compositions under non-uniform heat flux distributions. Wang, Zhang et al. [21] studied the critical heat flux (CHF) of liquid film by employing a confocal optical sensor system. They measured the dynamics and the integrity of a thin liquid film sheared by a co-current air above and heated from below at a horizontal aluminum channel. Their results indicate that the entrainment governs the liquid film thinning process under adiabatic or lower heat flux conditions, whereas the evaporation becomes more pronounced in a higher heat flux system.

However, experimental tool has encountered difficulties in local heat transfer calculation and flow regime transitions. This is mainly caused by the extremely small scale of the channels and quick process of the transitions.

Thanks to the advancement in computational facilities and algorithms, computational fluid dynamic (CFD) becomes popular in certain aspects of micro-channel boiling study [13]. conducted one of the earliest study in bubble growth in micro channel. They used level set as the interface tracking tool. Magnini [10,11] has studied a single confined bubble grow in micro-channel. Sun [6,17] developed a volume of fluid and level set (VOSET) method. Gong [5] used lattice Boltzmann method to study droplet formation under electric field. The transition processes between nucleate boiling and confined bubbly flow regime has been studied [8,9]. Sato [15] investigated the conjugate heat transfer by including the solid wall.

As far as the author's knowledge is concerning, there is not study on

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Nomenclature

Latin letters

A	area
C	coefficient
c	specific heat
Ca	capillary number
D	diameter
Eo	Eotvos number
F	force
G	mass flux
H	enthalpy
k	thermal conductivity
$\boldsymbol{n}$	normal vector
L	length
Pr	Prandtl number
q	heat flux
R_{int}	thermal resistance
Rg	gas constant
Re	Reynolds number
$\boldsymbol{U}$	velocity vector
Z	vertical distance
We	Weber number

Greek letters

α	volume fraction
β	growth constant
δ	thickness
θ	contact angle
μ	viscosity
ρ	density
σ	surface tension
φ	level set function
Φ	*dissipation heat*

Subscripts

b	bubble
c	condensation
d	diffusion
e	evaporation
f	fluid
g	gas
l	liquid
int	interface
w	wall
sat	saturation

the bubble train in micro channel flow boiling has reported. The objective of this paper is to numerical study this process by a state-of-art CFD method. The dynamics of the bubble train and parameters including bubble generating frequency and wall heat flux are investigated as well.

2. Methodology

For all cases studied in the present paper, the continuum assumption still holds, thus the Navier-Stocks equations are solved by finite volume method. The governing equations are listed as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = \dot{\rho} \tag{1}$$

$$\rho\left(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u}\right) = -\nabla P + \nabla(\mu(\nabla \cdot \boldsymbol{u} + \nabla \cdot \boldsymbol{u}^{\boldsymbol{T}})) + \rho g + \boldsymbol{F}_{\sigma} \tag{2}$$

$$\rho C_p\left(\frac{\partial T}{\partial t} + \boldsymbol{u} \cdot \nabla T\right) = \boldsymbol{\Phi} + \nabla \cdot (\lambda \nabla \mathbf{T}) + S_e \tag{3}$$

$$\frac{\partial \alpha}{\partial t} + \boldsymbol{u} \nabla \alpha = -\frac{\dot{\rho}}{\rho_v} \tag{4}$$

$$\frac{\partial \phi}{\partial t} + \boldsymbol{u} \nabla \phi = 0 \tag{5}$$

These are the continuity Eq. (1), the momentum Eq. (2), the energy Eq. (3), the volume fraction Eq. (4), and the level-set Eq. (5). All physical properties including density, viscosity, thermal conductivity, are defined by Eq. (6)

$$\Phi = \sum_{1}^{n} \Phi_i \alpha_i \ \forall\ \alpha(x,t) = \begin{cases} 1 & \text{if } x \in \text{primary phase} \\ (0,1) & \text{if } x \in \text{interface } \Gamma \\ 0 & \text{if } x \in \text{secondary phase} \end{cases} \tag{6}$$

where α is the volume fraction of the primary phase (gas in the present paper) in each computational cell.

The level-set function ϕ is a signed distance to the interface. Accordingly, the interface level function is defined as below.

$$\phi(x,t) = \begin{cases} + & \text{if } x \in \text{primary phase} \\ 0 & \text{if } x \in \text{interface } \Gamma \\ - & \text{if } x \in \text{secondary phase} \end{cases} \tag{7}$$

The temperature of the interface is not fixed but iterated during calculation. And the heat flux jump at the interface is

$$q_{e0} = \frac{T_{int} - T_{sat}}{h_{lg} R_{int}} \tag{8}$$

The details of the numerical model as well as validations cases can be found in our previous published papers [8].

3. Set up

3.1. Boundary and initial parameters

Two cases with different channel diameter and boundary conditions are studied herein. With the first case focusing on the bubble dynamics,

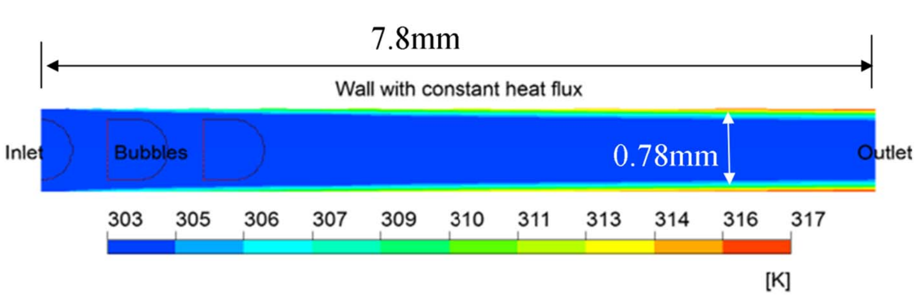

Fig. 1. Sketch of micro channel with three bubbles initialized.