International Communications in Heat and Mass Transfer 81 (2017) 116–123

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Numerical study of the interactions and merge of multiple bubbles during convective boiling in micro channels

Qingming Liu *, Wujun Wang, Björn Palm

Department of Energy Technology, Royal Institute of Technology (KTH), 10044 Stockholm, Sweden

ARTICLE INFO

Available online 18 December 2016

Keywords:
CFD
Flow boiling
Bubbles
Micro-channels

ABSTRACT

Multi bubbles interaction and merger in a micro-channel flow boiling has been numerically studied. Effects of mass flux (56, 112, 200, and 335 $kg/m^2 * s$), wall heat flux (5, 10, a[illegible]5 kW/m^2) and saturated temperature (300.15 and 303.15 K) are investigated. The coupled level set and volume of fluid (CLSVOF) method and non-equilibrium phase model are implemented [illegible] two-phase interface, and the lateral merger process. It is found that the whole transition process can be divided into [illegible] sub-stages: sliding, merger, and post-merger. The evaporation rate is much higher in the first [illegible] stage due to the boundary layer effects in. Both the mass flux and heat flux affect bubble growth. Specifically, the bubble growth rate increase with the increase of heat flux, or the decrease of mass flux.

1. Introduction

As the miniaturization of electronic devices, cooling has become an urging challenge for the information, communication and technology industry. The latest super computers can dissipate heat as high as a few hundred watts per centimeter, which makes traditional [illegible] cooling not capable. Liquid cooling has therefore become a promising [illegible] [1].

There are two thermal management methods available nowadays: single phase and two phase flow micro-channel cooling. The single phase micro-channel cooling method has been studied extensively and already been used in certain applications. Its heat transfer mechanism has been found similar to that of macro scale channels. On the contrary, the mechanism of two phase flow boiling in micro channels remains as an unsolved problem. Some researchers have argued that nucleate boiling is the dominant heat transfer mechanism in micro-channels due to the heat transfer coefficient's dependency on heat flux [2]. Others, on the contrary, have argued that the evaporation of the thin film between the bubbles and the wall plays a more important role [3]. As new experimental phenomena emerge, many methods have been proposed for the e[illegible]tion, pressure drop and heat transfer coefficient. Among these are [illegible] major groups: empirical correlations [4–6], superposition model [7], and mechanistic modeling based on flow regimes [8,9].

It has been found that all these methods, especially the last one, depend on a deep understanding of flow patterns. Experimental studies [illegible]n that there are six major flow patterns in microchannel flow boiling. In addition to the four common flow patterns in macro channels -bubbly flow, slug flow, annular flow and mist flow, there are two new patterns in micro channels [10–13]: confined bubbly flow and elongated bubbly flow. These new flow patterns may play an important role to play in the heat transfer process.

Advancements in multiphase algorithms and computing capacity have facilitated numerical investigations in micro-channel flows. Mukherjee and Kandlikar [14] simulated the growth of a confined bubble in a rectangular micro channel. Kunkelmann and Stephan [15] numerically studied the transient heat transfer during nucleate boiling and effect of contact line speed [16]. Li and Dhir [17] investigated a single bubble during flow boiling by means of the level set method. Gong and Cheng [18] examined periodic bubble nucleation, growth and departure from heated surface by using the lattice Boltzmann method. Agostini et al. [19] studied the velocity of an elongated bubble in an adiabatic micro-channel and proposed a predictive model based on these experiments. Furthermore, the collision process of elongated bubbles in micro channels without heat transfer was studied [20]. More recently, Consolini and Thome [21] proposed an one dimension model to predict the heat transfer coefficient of confined (or elongated) bubbles. Sun and Xu [22] developed a new model based on VOF method for FLUENT. Magnini et al. [23] developed a height function algorithm and investigated the effects of the leading elongated bubble. Liu et al. [24,25] examined the dynamics and heat transfer of the transition from nucleate to confined bubbles in a micro channel. They also studied the effect of contact angle and have found its importance on the bubble's shape.

Most of the micro channel researches only focus on one individual flow regime. Interactions or transitions between flow regimes, however, have not been found in literatures that much. The aim of the present

* Corresponding author.
E-mail address: qingming@kth.se (Q. Liu).

http://dx.doi.org/10.1016/j.icheatmasstransfer.2016.12.011

Nomenclature

Latin letters

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

Greek letters

α	volume fraction
β	growth constant
δ	thickness
θ	contact angle
λ	thermal conductivity
μ	viscosity
ρ	density
σ	surface tension
Φ	level set function

Subscripts

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

paper is to study one of the processes: the transition from isolated bubbly flow to confined bubbly flow, thus enhance the understanding of heat transfer mechanism of micro channel flow boiling.

2. Numerical model

2.1. Interface reconstruction

Interface reconstruction is one of the major challenges in two phase flow simulation. The interface is either "captured" or "tracked" by different numerical means. Tracking method is usually more time consuming and harder to implementation. Among capturing methods, volume of fluid (VOF) and level set (LS) method are two of the most widely used numerical tools. VOF [26] is a one-fluid algorithm deriving from continuum equations which enables it to have a mass-conservation nature. However, this causes relatively poor interface reconstruction due to a less accurate estimation of interface curvatures. The level set method has a better estimation of interface curvature because it is a smooth function, but a poorer mass conservation, specifically when the interface experiences severe stretching or tearing. The complementary features of these two methods lead to a new method, developed by Sussman and Puckett [27] and called coupled level set and VOF method (CLSVOF). With this new tool, both level set function and volume fraction equations are solved, the interface is linearly reconstructed every time step from the volume fraction and surface tension is calculated by the level set function. This new algorithm significantly enhances mass conservation and curvature estimation, albeit with the price of complication.

The governing equations of CLSVOF method are summarized as follows:

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho \boldsymbol{u}) = 0 \tag{1}$$

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

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

$$\frac{\partial \alpha}{\partial t} + \boldsymbol{u}\nabla\alpha = 0 \tag{4}$$

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

These are the continuity Eq. (1), the momentum Eq. (2), the energy Eq. (3), the volume fraction (4), and the level-set Eq. (5). Physical properties, such as density, viscosity, and thermal conductivity are the volume averaged value of all the phases in the cell 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.

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

Solve the level set equation to get the curvature and normal to interface

$$\boldsymbol{n} = \frac{\nabla\phi}{|\nabla\phi|} \quad \boldsymbol{k} = \nabla\cdot\frac{\nabla\phi}{|\nabla\phi|} \tag{8}$$

Then get the surface tension force by the following equation

$$\boldsymbol{F_\sigma} = -\sigma \boldsymbol{k}\delta(\phi)\nabla\phi \tag{9}$$

where

$$\delta(\phi) = \begin{cases} \dfrac{1-\cos(3\pi\phi/2L_{gr})}{3L_{gr}} & \text{if } |\phi|<1.5\,L_{gr} \\ 0 & \text{otherwise} \end{cases} \tag{10}$$

where L_{gr} is the minimum grid spacing.