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Three dimensional numerical simulation on bubble growth and merger in microchannel boiling flow

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ABSTRACT

This paper presents a three dimensional direct simulation on boiling flow in a rectangular microchannel. A coupled volume-of-fluid and level-set method was adopted to track the liquid–vapor interface. An immersed boundary method was used to deal with the temperature around the interface. The numerical result was compared with a previous experimental result, and the outcomes matched. Growth and merger of the bubbles were simulated and the impact of the bubbles' merger on the heat transfer was analyzed. The results show that the merger can produce a temporal growth in heat flux, while the thin liquid film between the bubble and the wall holds the main reason for the high heat flux in microchannel boiling flow.

1. Introduction

Boiling flow in microchannels is one of the most effective ways in providing high heat transfer coefficient. It is widely used in cooling systems on compact equipments such as electronic chips. The heat transfer characteristic of boiling in microchannels is much different from that in pool boiling owing to the fact that the bubbles are confined by the surrounding walls. Recently, large amounts of studies were carried out on the boiling flow in microchannels. However, the mechanisms have not been completely understood until now.

Literature reviews on microchannel boiling flow were made by Kandlikar [1] and Thome [2]. The primary flow patterns were summarized as isolated bubby flow, elongated bubby/slug flow and annular flow.

Kandlikar [3] defined two non-dimensional numbers to evaluate the relations between evaporation momentum force, inertial force and surface tension. He pointed out that the effect of convection is diminished in microchannels.

Thome et al. [4] proposed a three-zone model to predict the heat transfer in a microchannel. The three zones in this model are liquid slug, evaporating elongated bubble and vapor slug. They demonstrated that the high heat flux during boiling in a microchannel lies in the thin liquid film around the elongated bubble.

Balasubramanian and Kandlikar [5] performed experimental studies on boiling flow in microchannels and minichannels. The process of a bubble's growth and its transition into slug were observed. In addition, they provided some photos displaying the thin liquid film between the bubble and the wall.

Lee et al. [6] explored experimental studies on boiling flow in a single trapezoid microchannel. A high-speed digital camera was used in their study. The bubble was found to grow at a nearly constant speed. However, the measured growth rate varies largely from the values predicted by the Rayleigh equation. Furthermore, in their provided photos, all the bubble seeds were generated on the wall.

Based on a large number of experimental results, Harirchian and Garimella [7] developed a flow region map for boiling flow in channels. A transition criterion was defined to decide whether the bubbles in a channel are confined. They suggested that in a confined flow, a different mechanism lies in the thin liquid films between the bubbles and the walls.

An experimental study was conducted by Edel and Mukherjee [8]. They found that at the early stage of a bubble's growth, the growth rate is nearly constant. However, as the bubble reached the size of the channel diameter and began to elongate, the evaporation speed was observed to increase significantly.

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Experimental studies on boiling flow in microchannel have some limitations due to the difficulties in micro-scale measurements. With the fast development of numerical methods and computer's speed in the past decades, numerical simulation is becoming an effective supplementary way to study micro-scale problems. Through direct numerical simulations, more details can be obtained which can provide better understanding of the heat transfer mechanisms. Various numerical methods were developed for simulations on liquid–gas multiphase flow as well as phase change, and some numerical studies on boiling flow were performed.

Son et al. [9] developed a microlayer model that estimates heat transfer in the liquid film around the three-phase contact line. They carried out a simulation on the growth of a single bubble during a nucleate pool boiling, and the obtained interface positions closely match those by their experiment. On this basis, Lee and Son [10] developed a simplified microlayer model and numerically studied the boiling flow in a rectangular microchannel. They found that the heat transfer rate can be significantly increased if the channel's size is smaller than the bubble's departure diameter. Furthermore, their results show that the contact angle has an important impact on the heat transfer rate.

Mukherjee and Dhir [11] performed a three dimensional simulation on the growth, merger and departure of bubbles in a nucleate pool boiling. The interface was tracked by level-set method and the microlayer evaporation was taken into account using the model proposed by Son et al. [9]. It was found that the merger of the bubbles would produce higher values in the average Nusselt number.

Mukherjee and Kandlikar [12] conducted a numerical simulation on the growth of a vapor bubble in a microchannel by level-set method. Their result show that the bubble grows at a nearly constant speed in the early stage and the growth rate increases evidently when the bubble fills the channel. This characteristic is consistent with the experiment by Edel and Mukherjee [8]. The rapid growth in the evaporation rate was explained by the thin liquid film around the contact lines. The gravity was found to have little effect on the boiling flow. Using the same numerical methods, Mukherjee et al. [13] analyzed the influences of several parameters. They found the heat transfer as well as the evaporation rate were nearly not affected by the flow rate and surface tension, but they could be obviously increased as the contact angle decreases.

Zu et al. [14] simulated a confined bubble growth in a three-dimension channel using the commercial code FLUENT. The fields of velocity, temperature and pressure during the evaporation were obtained. The evaporation rate in their simulation, however, was artificially given to make it in accordance with experimental results.

Lee et al. [15] performed a numerical simulation on a boiling flow in a finned microchannel using a modified level-set method. The solid region was included in the computational domain so that the thermal response in it could be taken into account. Their numerical results demonstrated the enhancement on the heat transfer by the fins.

Lattice Boltzmann Method is becoming widely used in liquid–gas multiphase flow simulations [16]. Dong et al. [17] carried out a 2D simulation on growths, departures and motions of several bubbles in a microchannel by Lattice Boltzmann Method. Based on the numerical results, they suggested the bubbles growing inside a microchannel would not only enhance the heat transfer but also produce higher flow resistance.

Magnini et al. [18,19] conducted some numerical simulations on a boiling flow in a cylindrical microchannel using an evaporation model. They studied the growth of a single bubble as well as the interaction between two successive bubbles. According to the numerical results, some modifications were made on the three-zone model proposed by Thome et al. [4].

According to the observations in previous experiments [5,6], there are sometimes many bubbles growing simultaneously inside a microchannel. The bubbles will possibly get in touch and merge into larger ones as they grow to enough sizes, which may have an impact on the heat transfer performance. However, few studies have been reported on the mergers of bubbles in microchannels. Therefore, we performed some numerical studies on boiling flow in a microchannel including mergers of bubbles, so that the impact on the heat transfer can be evaluated.

The rest of this article is organized as follows. In Section 2 we present the numerical methods used in our study. The problem studied here will be described in Section 3. The results are displayed and analyzed in Section 4. Based on the results, some mechanisms of boiling flow in microchannels are discussed in Section 5. Finally some conclusions are made in Section 6.

2. Numerical methods

2.1. General description

The Finite Volume Method [20] was used for solving the problem in the present study. Projection method [21] was employed for solving the velocity and pressure fields. The liquid–vapor interface was captured by VOSET, a coupled VOF and Level set method proposed by Sun and Tao [22] and extended to three dimensions by Ling et al. [23]. In one time step of the VOSET method, a level-set function, which is actually represented by the signed distance function, is computed from the volume fraction function using an iterative geometrical method. As a part of the geometrical method, the interface reconstruction is conducted by Piecewise Linear Interface Calculation (PLIC). Due to the use of both the volume fraction function and the level-set function, VOSET can not only keep the mass conservation well, but also calculate the surface tension accurately. The linear equations, generated from the discretisized pressure as well as temperature equations, were solved by BI-CGSTAB method [24]. In the present study, we assumed that the properties including density, viscosity, conductivity and heat capacity of the liquid and vapor phases are constant. The liquid–vapor interface temperature was deemed to hold the equilibrium saturation temperature corresponding to the system pressure. The hysteresis of the contact angle was not taken into consideration, so the advancing and receding contact angles were given as the same value. The microlayer, however, was not considered as well, because its effect in a microchannel is still not well known. A previous numerical study [13] on microchannel boiling flow, where no microlayer model was applied, shows a satisfactory agreement in the evaporation rate with experiments. We also tried incorporating the microlayer model proposed by Lee et al. [10] in the numerical simulation, but finally finding a severe overprediction in the evaporation rate.

2.2. Governing equations

The momentum equation in the present study can be written as:

$$\rho\frac{\partial \mathbf{u}}{\partial t}+\rho\mathbf{u}\cdot\nabla\mathbf{u}=-\nabla p+\nabla\cdot\left(\mu\nabla\mathbf{u}+\mu\nabla\mathbf{u}^{\mathrm{T}}\right)+\sigma\kappa\nabla H. \tag{1}$$

Here H is the smoothed Heaviside function, which is computed from the level-set function with a given smoothing thickness: