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Numerical investigation the effects of working parameters on nucleate pool boiling☆

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ABSTRACT

In the present paper the combination of three-dimensional isothermal and two-dimensional non-isothermal Lattice Boltzmann Method (LBM) are employed to simulate the nucleate pool boiling phenomenon. In order to validate the proposed model, rising bubble phenomenon is simulated afterward the boiling process is investigated by employing a function for heat transfer. The investigation is compared with other numerical works and is found to be in very good agreement. The effects of the parameters including contact angle, heat flux and heater length on departure dimensionless time and departure diameter of bubble are studied. The results show that departure diameter of bubble increases due to the increase of contact angle and decrease of gravity force. Formation, motion and breakup of the bubbles are also investigated as results of gravity force and heat flux. Furthermore, it is worthwhile pointing that out departure diameter of bubble increases as the heat flux increases and increasing of the heater length has more effect in comparison to heat flux on bubble growth. Transient regime is shown by increasing the contact angle and the small bubbles vanishing while rising upward at high gravity force.

1. Introduction

In recent years due to the efficiency of heat transfer in two phase flow which is much higher than in single phase flow, much attention is devoted to the application of the two-phase fluid flows in industry. Boiling plays highly significant and effective parts in various industrial and engineering applications such as core-steam generator, and condensation heat exchanger.

The physical mechanism of two-phase flow is very complicated. Thus, clear understanding of two-phase flow mechanisms is still unavailable. The numerical study in two-phase flows is important due to inability of experimental studies to access to the physical parameters in the bubble and droplet. Therefore, it is preferable to derive this numerically from simulations.

The Lattice Boltzmann method is an almost new numerical method based on kinetic theory which is used for simulation of fluid flows. In comparison with the conventional CFD, LBM has some advantages such as simple process, simple and efficient implementation for parallel computation, and easy and robust handling of complex geometries. There are different models which proposed for two-phase flows using Lattice Boltzmann method. Gunstensen et al. [1] introduced a multi-component method based on two dimensional lattice-gas hydrodynamics. In their model of two particle distribution functions, red and blue, were presented for simulating two different fluids. Shan and Chen [2] proposed a model for multicomponent and multiphase flows considering microscopic interaction. Swift et al. [3] propounded a method for multiphase and multicomponent flows using free energy approach. The major advantage of this method is the ability to include multi component and non-ideal thermodynamics of fluid in isothermal. It should be noted that, in the all mentioned LBM two-phase methods, the density ratio is considered less than 10, while in reality density ratio is more than 10 at most of the liquid–gas systems. Numerical instability in interface is the major problem in numerical solution of two phase flow with large density ratio. Inamuro et al. [4] proposed a new method based on free energy approach for two-phase flow with large density ratio and studied motion of a bubble and many bubbles under buoyancy force in three dimension (3D) simulation. Inamuro et al. [5] used their model to simulate the rising of two bubbles and their coalescence in a vertical and horizontal rectangular channel. In another study, Inamuro et al. [6] employed this method to simulate coalescence of two droplets with the same diameter with initial velocity in 3D and also of two droplet with unequal diameter in 3D [7]. Inamuro [8] carried out simulation of a set of bubbles in a branch channel, the employed geometry was utilized as a cooling system in air conditioning system, and managed to simulate two phase fluid flow.

Yoshino and Mizutani [9] investigated contact angle adding wettability condition to Inamuro [4–8] model. Yan and Zu [10–12] simulated static and dynamic contact angles in a different condition of surface wettability in 3D.

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Later on, making some changes on the original method was employed by Tanaka [13,14] for two dimensional and reactive flows. Tanaka et al. [13] studied different contact angles along with terminal shape of bubble in impedimental flows. In addition, they investigated dynamic behavior of droplet on solid surface and used this method for simulating of boiling process [14].

In 2010, Dong et al. [15] simulated the growing of a bubble while departing from superheated wall using LBM. They reported departure diameter of the bubble as output and used Fritz correlation to validate their method. Rio and Ko [16] carried out simulation of nucleate pool boiling in 2012, using free energy approach based on multiphase LBM. In their study, growing of a bubble in a superheat liquid was simulated and compared to the analytical results. According to their results, bubble departure diameter depends on gravity force, surface tension, contact angle and wall temperature. Another significant point of their work is studying of bubble growing in single and multiple nucleation sites. In their work departure diameter of bubble has been reported as output parameter and Fritz correlation have been employed to validate their method. Gong and Cheng [17] studied heat transfer in liquid–gas phases using LBM. Two distribution functions for density and temperature in their models have been used. They also reported that the departure diameter of bubble was reported as output and Fritz correlation was used to validate their method. Gong and Cheng [17] performed another simulation [18] they simulated available heater condition at surface with constant wall temperature and constant heat flux and educed results in both modes. They studied the effects of surface temperature difference with surrounding liquid in constant temperature heater.

To the best of our knowledge, formation of the bubbles in boiling phenomenon has been poorly investigated. Most of the previous studies focused on growing and detaching the bubbles from the surface [15–18] or using nozzle instead of heater [20,21]. In the present study, the LBM coupling the density, velocity, pressure and the temperature distribution functions is used to simulate forming, growing and finally detaching the bubbles from the surface in nucleate pool boiling phenomenon. For this mean, the combination of Inamuro [4–8] and Tanaka model [13,14] are used. The effects of the parameters including contact angle, heat flux and heater length on departure dimensionless time and departure diameter of bubble are studied. It should be noted that by exhibiting the preceding and subsequent nucleate boiling regimes for the first time, this study would provide a better insight on the boiling phenomenon with LBM for further study.

2. Methodology

In the present paper, the method introduced by Inamuro [4] is employed. f_i is to calculate order parameter which distinguish two phases and g_i is to calculate a predicted velocity of the two-phase fluid without a pressure gradient. The particle distribution functions $f_i(x, t)$ and $g_i(x, t)$ with velocity c_i and at point x and time t is calculated by following equations [4]:

$$f_i(x + c_i\Delta x, t + \Delta t) = f_i^c(x, t) \tag{1}$$

$$g_i(x + c_i\Delta x, t + \Delta t) = g_i^c(x, t) \tag{2}$$

f_i^c and g_i^c are equilibrium distribution functions, Δx is spacing of square lattice, Δt is time step in the scale of LBM during which particles move in lattice spacing. Order parameter ϕ distinguishes two phases and the predicted velocity u^* of the multicomponent fluid is defined according to two particle velocity distribution function as:

$$u^* = \sum_{i=0}^{8} g_i c_i \tag{3}$$

$$\phi = \sum_{i=0}^{8} f_i. \tag{4}$$

Equilibrium distribution functions in Eqs. (1) and (2) are described as:

$$\begin{aligned} f_i^c = {} & H_i\phi + F_i\left[p_0 - k_f\phi\frac{\partial^2\phi}{\partial x_\alpha}\right] + 3E_i\phi c_{i\alpha}u_\alpha \\ & + E_i k_f G_{\alpha\beta}(\phi)c_{i\alpha}c_{i\beta} \end{aligned} \tag{5}$$

$$\begin{aligned} g_i^c = {} & E_i\left[1 + 3c_{i\alpha}u_\alpha - \frac{3}{2}u_\alpha u_\alpha + \frac{9}{2}c_{i\alpha}c_{i\beta}u_\alpha u_\beta\right] \\ & + E_i + \frac{3}{4}\Delta x\left(\frac{\partial u_\beta}{\partial x_\alpha} + \frac{\partial u_\alpha}{\partial u_\beta}\right)c_{i\alpha}c_{i\beta} - 3E_i c_{iy}\left(1 - \frac{\rho_G}{\rho}\right)g\Delta x \\ & + E_i\left[3c_{i\alpha}\frac{\Delta x}{\rho}\frac{\partial}{\partial x_\beta}\left\{\frac{\partial u_\beta}{\partial x_\alpha} + \frac{\partial u_\alpha}{\partial x_\beta}\right\}\right] \\ & + E_i\frac{k_g}{\rho}G_{\alpha\beta}(\rho)c_{i\alpha}c_{i\beta} - \frac{1}{2}F_i\frac{k_g}{\rho}\left(\frac{\partial\rho}{\partial x_\alpha}\right)^2 \end{aligned} \tag{6}$$

where g is the gravitational acceleration, and ρ, ρ_L and μ are density, density of liquid and viscosity of liquid respectively which are determined regarding the density ratio (e.g. if $\rho_L/\rho_G = 50$ then $\rho_L = 50$, $\rho_G = 1$ and $\mu_L/\mu_G = 50$). E is the weighting factor, and c is the particle velocity. H and F are the constant parameters which are defined as follows:

$$\begin{aligned} & E_0 = \frac{4}{9}, \quad E_1 = \ldots = E_4 = \frac{1}{9}, \quad E_5 = \ldots = E_8 = \frac{1}{36} \\ & H_0 = 1, \quad H_1 = \ldots = H_8 = 0, \quad F_0 = -\frac{5}{3} \\ & F_i = 3E_i \quad (i = 1, 2, 3, \ldots, 8), \end{aligned} \tag{7}$$

and

$$G_{\alpha\beta}(\phi) = \frac{9}{2}\frac{\partial\phi}{\partial x_\alpha}\frac{\partial\phi}{\partial x_\beta} - \frac{9}{4}\frac{\partial\phi}{\partial x_\gamma}\frac{\partial\phi}{\partial x_\gamma}\delta_{\alpha\beta} \tag{8}$$

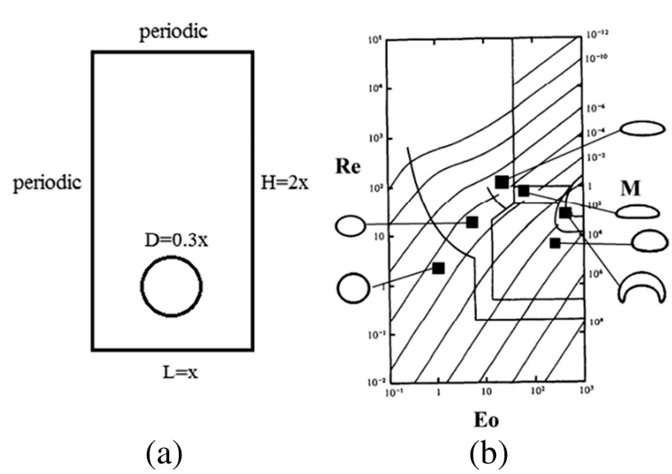

Fig. 1. (a). Computational domain. (b). Comparison of result of this study, and Inamaru's three dimensional study [4].