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A three-dimensional lattice Boltzmann model for numerical investigation of bubble growth in pool boiling☆

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ABSTRACT

In this paper, a three-dimensional lattice Boltzmann model is proposed to simulate pool-boiling phenomena at high-density ratios. The present model is able to predict the temperature field inside the bubble. The three-dimensional multiphase model is validated against the analytical solution of evaporation d^2law problem and Laplace's law. In addition, effects of different parameters including, Jacob number, gravitational acceleration (g) and surface tension (σ) on bubble departure diameter are presented for further validation. The bubble departure diameter is found to be proportional to $g^{-0.354}$ and $\sigma^{0.5}$, and has a linear relation with Jacob number. These results are more consistent with previous experimental correlations when compared with available lattice Boltzmann literature. Furthermore, the dynamic behavior of multiple bubble formation sites such as micro convection and vortex ring mechanism are presented to show the capability of presented model for capturing more complex physical phenomena. To sum up, the proposed three-dimensional lattice Boltzmann model is feasible and accurate for numerical simulations of pool boiling.

1. Introduction

Boiling is one of the most important phenomena that occur in various industrial fields. Pool boiling happens when the heating surface is submerged in a large body of stagnant liquid. Although a great number of experimental works have been performed to study boiling during the past century, its theory is rather complex and not yet fully understood. Recently by the advancement of computer technologies and the development of numerical simulations, many techniques have been developed to simulate pool-boiling phenomenon.

Pool boiling is a complicated multiphase process. Multiphase flows occur when two or more fluids are in the vicinity of each other while sharing an interface. To simulate multiphase flows, precise representation of the interface and capturing its topological changes, several macroscopic methods have been developed so far. This includes, but not limited to front-tracking method [1], volume of fluid (VOF) [2,3], level set method [4], and smoothed particle hydrodynamics [5,6], among others. A comprehensive recent review on available techniques and their advantages and disadvantages can be found in [7,8].

In recent years, lattice Boltzmann method (LBM) became a popular tool to simulate physical phenomena [9]. LBM has great potentials in modeling multiphase flows and appears to be an effective tool for simulation of the problems that involve complex boundaries and interfacial dynamics [10]. Compared to traditional computational fluid dynamics (CFD) methods, LBM has many advantages such as easy programming and parallelizing. Besides, in this method, it is not necessary to solve the poison equation for the pressure field. Thus, LBM can be much faster than common CFD methods.

Several LBM models have been developed to simulate multiphase flows. Among others one can mention, color-gradient model [11], Shan-Chan model [12], free-energy model [13], finite difference LBM [14] and HZN interface tracking model [15]. It is noted that all of these pioneering works have limitations in the simulation of interfacial flows with high-density ratios. To overcome such shortcomings several new models have been proposed in the last decade. For instance, Inamaru et al. [16] developed a new free-energy model which can track the interface by applying a diffuse equation which is analogy to the Cahn–Hilliard (C–H) equation. Although they achieved high-density ratios, the computation load of their model was heavy due to

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solving the poison equation. Zheng et al. [17] developed a Galilean-invariant free-energy model which is simpler to the Inamaru's model and does not require pressure correction as before. Lee [18] proposed a new model, based on HCZ interface tracking model [15], to handle the multiphase problems with high-density ratios. In the Lee's model, intermolecular forces are expressed in the potential forms and the parasitic current, which is initiated with truncation errors of interfacial stresses, is eliminated. Safari and Rahimyan [19] developed a model based on phase-field lattice Boltzmann approach of Lee & Lin [20]. They extend the Lee & Lin model by adding a suitable equation to account for the finite divergence of the velocity field within the interface region. Furthermore, the convective Cahn-Hilliard equation is extended to take into account vaporization effects. This model was successfully validated for varies problems including high-density ratio condensations and evaporations (see [21–23]).

Besides above-mentioned works, some researchers studied the simulation of pool boiling by LBM. Yang et al. [24] investigated transition mechanism in boiling regime by using the Shan & Chen [12] multiphase model on vertical and horizontal surfaces. The density ratio reported in this work was limited to low density ratios. Ryu & Ko [25] performed the free energy based multiphase LBM to simulate the pool boiling. Gong & Cheng [26] simulated the bubble growth and departure from a horizontal surface by using modified pseudo-potential model. More recently, Li et al. [27] utilized a thermal pseudopotential LB model for simulating liquid-vapor boiling process. They simulated three boiling stages (nucleate, transition, and film boiling) as well as the boiling curve. Zhiqiang et al. [28] simulated the bubble growth and its departure from a superheated wall with an improved hybrid LBM. Sun & Li [29] investigated three-dimensional pool boiling from a horizontal heated wall using a hybrid LBM. Although, according to the thermal interferometric pattern presented by Beer [30] the temperature inside a growing and rising vapor bubble varies in time, in the models utilized in these works, the temperature field inside the bubble were assumed to be constant in these works. Satari et al. [31] simulated the pool boiling phenomenon by using the combination of three-dimensional isothermal and two-dimensional non-isothermal models. A recent review of the applications of LB methods for thermal flows and thermal multiphase flows with phase change can be found in [32].

As it can be seen from these works, most of the available literatures are limited to either low-density ratio models, or the temperature field is either neglected or miscalculated especially for three-dimensional pool boiling case. Therefore, in this paper, the modified Lee model is extended and a three-dimensional LBM is proposed to simulate pool boiling with high-density ratios on horizontal superheated walls. The code is validated by three-dimensional droplet evaporation, Laplace's law and evaporation d^2 law problems. The process of the bubble growth and its topology found to be in good agreement with available literature. Effects of gravitational acceleration, surface tension and Jacob number on the bubble departure diameter in three-dimensional model are also compared with experimental correlations where it is found that the presented model is in better agreement with these correlations when compared with available LBM results. Additionally, the simulations are extended for multi-bubble growth to show the capability of current three-dimensional model in capturing more complex physics.

2. Numerical model

In this section we introduce the extended model of Lee [18] with considering the phase change by incorporating a source term at the three-dimensional phase interface. This model is originally presented by Safari and Rahimian [19] for two-dimensional phase change phenomena and is extended to three-dimension in this work for the first time according to the authors' best knowledge.

2.1. Governing equation

Considering the system of two incompressible and immiscible fluids with different densities and viscosities, the continuity equation of Cahn-Hilliard in the presence of phase change can be written as:

$$\frac{\partial \tilde{\rho}_i}{\partial t} + \nabla . q_i = \pm \dot{m}''', \tag{1}$$

where $\tilde{\rho}_i$ is the local density of the component i (vapor or liquid phase), t is time, q_i and $\dot{m}'''$ denote the mass flow rate per unit volume of component i and the volumetric mass source term for evaporation, respectively ($q_i = \tilde{\rho}_i u$ and u is the volumetric flow averaged velocity). In regions close to the interface, the total mass flow rate of each component is affected by the diffusive mass flow, which is indicated by $\rho_i j_i$. Therefore, the volume diffusive flow rate, j_i, for ith component read as:

$$\rho_i j_i = \tilde{\rho}_i (u_i - u), \tag{2}$$

where u_i and ρ_i are the volumetric flow averaged velocity and density of the phase i (vapor or liquid phase). Thus, at the interface, the total mass flow of component i expresses as:

$$q_i = \tilde{\rho}_i u - \rho_i j_i. \tag{3}$$

The local averaged density (ρ) is a function of local densities (vapor or liquid component):

$$\rho = C\rho_l + (1-C)\rho_v, \tag{4}$$

where $C = \tilde{\rho}_l/\rho_l$ is the liquid phase composition, and ρ_l and ρ_v are the local densities of the liquid and vapor phases, respectively. Note that the subscripts l and v are used for distinguishing between liquid and vapor phases, receptively, in the rest of this manuscript. The Cahn-Hilliard continuity equation (Eq. (1)) is, therefore, separated to two equations for either component:

$$\frac{\partial C}{\partial t} + \nabla \cdot (uC) - \nabla \cdot j_l = -\frac{\dot{m}'''}{\rho_l}, \tag{5}$$

$$\frac{\partial (1-C)}{\partial t} + \nabla \cdot (u(1-C)) - \nabla \cdot j_v = -\frac{\dot{m}'''}{\rho_v}. \tag{6}$$

Since $j_l = -j_v$, the divergence of the velocity field within the interface is obtained by summing Eqs. (5) and (6) as follows:

$$\nabla . u = \dot{m}''' \left(\frac{1}{\rho_v} - \frac{1}{\rho_l} \right). \tag{7}$$

Additionally, the volumetric mass source of evaporation can be obtained by:

$$\dot{m}''' = \frac{K \nabla T}{h_{fg}} \cdot \nabla C. \tag{8}$$

Here h_{fg} is the latent heat of vaporization, K is the thermal conductivity and T indicates the temperature field. Since the mass flux is dependent on ∇C, the gas volume generated by evaporation is increased by increasing the density ratio as a result of Eq. (7). In order to decrease the maximum value of ∇C and provide a balance in estimating the evaporation and boiling speed, the interface thickness should increase as the density ratio increases. Hence, 3, 4 and 5 lattice unit interface thicknesses are set for density ratios of 10, 100 and 1000, respectively. Cahn and Hilliard assumed that the volume

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