Computers & Fluids 88 (2013) 400–409

Contents lists available at ScienceDirect

Computers & Fluids

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

Three-dimensional numerical simulation of nucleate boiling bubble by lattice Boltzmann method

Tao Sun, Weizhong Li *

Key Laboratory of Ocean Energy Utilization and Energy Conservation of Ministry of Education, Dalian University of Technology, Dalian City, Liaoning 116024, PR China
School of Energy and Power Engineering, Dalian University of Technology, Dalian City, Liaoning 116024, PR China

ARTICLE INFO

Article history:
Received 17 April 2013
Received in revised form 14 August 2013
Accepted 7 October 2013
Available online 15 October 2013

Keywords:
Three-dimension
Lattice Boltzmann method
Nucleate boiling
Phase change
Bubble departure diameter
Twin-bubble coalescence

ABSTRACT

In this paper, a three-dimensional hybrid lattice Boltzmann model is first proposed to simulate nucleate boiling. A single bubble growth on and departure from horizontal heated wall is investigated. The simulation results demonstrate the bubble departure diameter is proportional to $g^{-0.346}$ in three-dimensional condition, where g is the gravitational acceleration. Linear relationship is found between the bubble departure diameter and Jacob number. The velocity field and temperature field are presented and the simulation results support the transient micro-convection model. In addition, the three-dimensional model is also employed to simulate the process of two bubbles growth, coalescence and departure from a horizontal heated wall.

1. Introduction

Nucleate boiling is a complicated physical process, which is not only associated with bubbles growth, deformation and rising, but also involves thermodynamics, kinetics and hydrodynamics. The physical problem has been researched for half a century, because nucleate boiling is an efficient heat transfer way widely used in various industrial fields. In particular, boiling phenomenon is important for the design of the steam generator, and condensation heat exchange of the nuclear reactor. Early stage investigations on the nucleate boiling used experimental methods primarily. Although experimental investigations can account for the physical phenomenon qualitatively, quantitative prediction is still confronted with a challenge.

Due to the fast advancement of computer technology and emergence of numerical methods, numerical simulation has become an available approach for such complicated study. Many techniques have been developed to simulate nucleate boiling in the past several decades. But all these techniques concerned with tracking interface are very complicated because of topological deformation induced by phase change. Generally, the methods of tracking interface can be classified as the singular and the diffuse interface models. For example, Blake et al. [1] used an approximate integral-equation to model the growth and collapse of a vapor cavity in close proximity to an initially plane free surface. Li and Yan proposed two numerical methods [2,3] and they model a vapor bubble growth in uniformly superheated liquid in Ref. [4]. Yoon et al. [5] presented a mesh-free numerical method for direct calculation of bubble dynamics behavior in pool boiling. An arbitrary Lagrangian–Eulerian (ALE) method proposed by Hirt [6] et al. was used to simulate two-phase flow. Above numerical methods are the singular interface models, which are not suitable to track bubble large deformation in topology because of limited grid. Therefore, many numerical methods based on diffuse interface model were proposed to overcome the shortcoming, such as phase field, level set and volume of fluid (VOF) method. Tomiyama et al. [7] simulated bubble motion by VOF method. Zu et al. [8] reported the three-dimensional numerical modeling on bubbly flow in confined mini-/micro-channels using VOF method. In Son's study [9], a complete numerical simulation of a growing and departing bubble on a horizontal surface has been performed. Mukherjee and Kandikar [10] investigated single bubble with dynamic contact angle during nucleate pool boiling by level set method. To the author's knowledge, although a lot of papers are reported about the numerical simulation of vapor bubble with phase change, little information is related to the evolution of temperature field during nucleate boiling.

In the recent 20 years, lattice Boltzmann method (LBM) has attracted a lot of scientific attention as an emerging approach to

* Corresponding author at: School of Energy and Power Engineering, Dalian University of Technology, Dalian City, Liaoning 116024, PR China. Tel.: +86 411 84708774; fax: +86 411 84708460.
E-mail addresses: suntao@mail.dlut.edu.cn (T. Sun), wzhongli@dlut.edu.cn (W. Li).

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http://dx.doi.org/10.1016/j.compfluid.2013.10.009

Nomenclature

C_{pl}	specific heat at constant presssure
d_e	equivalent diameter
$\mathbf{e}$	velocity vector of LBM
Eo	Eötvös number
F	body force
f	distribution function
g	distribution function
h_{fg}	latent heat of evaporation
Ja	Jacob number
Mo	Morton number
n	total number density
Pe	Peclet number
t	time
T	temperature in fluid field
U_T	bubble terminal rising velocity
$\mathbf{u}$	macroscopic velocity of the fluid
δ	discrete size
Γ	mobility coefficient
λ	thermal conductivity
μ_ϕ	chemical potential
θ_M	the mobility
ρ	density of fluid
τ	relaxation parameter
ϕ	density difference (order parameter)
ω	weight coefficient
Subscripts/superscripts	
b	bubble
i	discrete number
eq	equilibrium
$G(g)$	gas
$L(l)$	liquid

simulate the fluid flows. Unlike the traditional computational fluid dynamics (CFD) methods, LBM is based on the molecular kinetic theory; and it does not solve differential equations. Several lattice Boltzmann (LB) models have been proposed to model multi-phase and multi-component flows since its birth, mainly including Shan and Chen' potential model [11], He et al.' model [12], color model [13], and Swift et al.' free energy model [14]. Among them, the color model and potential model do not explicitly describe the evolution of the interface. The region with non-zero gradient of density difference is regarded as the interface in their models. In He et al.'s model, the mobility is related to the density and cannot be flexibly chosen. Besides, the physics of the interface capturing equation is not clear. In contrast, the free energy model captures the interface based on convection–diffusion equation and has wide application. In the last few years, three improved LB models [15–17] based on free energy model have been proposed. In these models, Inamuro's required solving a pressure Poisson equation at each collision step, which spent an amount of calculation time. Lee and Lin developed a stabilized scheme for multiphase flow. They used a new pressure update scheme to stabilize the LBM computation instead of solving the pressure Possion equation. However, the implementation was quite complex because the process involved discretization of many first and second order derivatives. Besides, these models did not completely recover the LB equation of interface to the Cahn–Hilliard (C–H) equation. Unlike the former two models, Zheng proposed a multiphase model; which utilized a more approximate convective C–H equation to define and track interface and the interface equation can be recovered to C–H equation without any additional terms. The model can be extended further into non-isothermal system with heat and mass transfer. On that basis, Dong proposed a hybrid two-dimensional LB model [9], which consisted of Zheng's multiphase model and a LB thermal model [18]. In Dong's hybrid model, the source terms were added to corresponding C–H equation and the LB thermal equation to define phase-change and latent heat, respectively. Such treatment can track the vapor–liquid interface automatically.

Besides above mentioned work, the lattice Boltzmann studies for nucleate boiling have been performed by many researchers. For example, Hazi and Markus [19] simulated heterogeneous boiling on a horizontal plate in stagnant and slowly flowing fluid by LBM, which included the phase change model with an isothermal two-phase LBM. Gong and Cheng [20,21] used a similar method to simulate liquid–vapor phase-change heat transfer. A new form of the source term in the energy equation was derived and the modified pseudo-potential model was used in the proposed model to improve its numerical stability. However, they did not present the temperature field during nucleate boiling in their papers, although the energy equation was introduced in their methods. In Ryu and Ko' literature [22], nucleate pool boiling is directly simulated by the free energy model based multiphase LBM, which is similar to Dong's method. The heat transfer rates of simulations were calculated and compared to the empirical correlations. Yan [23] researched the hydrophobic characteristics of object surface based on LBM, which is useful for boundary treatment in nucleate boiling. All in all, previous studies on vapor bubble dynamics behavior during nucleate boiling were performed only in two-dimensional condition. So far, there are few literatures related to simulation of nucleate boiling in three-dimensional condition by LBM.

Benefited from the interface processing method, a developed three-dimensional LB model is first proposed to simulate nucleate boiling with phase change process in this paper. The propagations of flow field and temperature field around a vapor bubble are presented and the bubble departure diameter is researched. In addition, the three-dimensional model is also employed to simulate the process of two bubbles growth, coalescence and departure from a horizontal heated wall. The aim of the present studies is to test the feasibility of the three-dimensional LB model for numerical simulation of nucleate boiling. The present simulation results can be regarded as a basic research for applying LBM to two-phase flow and nucleate boiling.

2. Numerical method

2.1. Basic interface capturing equation and continuity and momentum equations

In our study, a three-dimensional LB model is used to solve the Cahn–Hilliard (C–H) equation and Navier–Stokes equations. The interface capturing is modeled by a convective C–H equation and the corresponding three-dimensional LB equation follows as

$$g_i(\mathbf{r}+\mathbf{e_i}\Delta t, t+\Delta t) - g_i(\mathbf{r}, t) = (1-q)[g_i(\mathbf{r}+\mathbf{e_i}\Delta t, t) - g_i(\mathbf{r}, t)] - \frac{1}{\tau_\varphi}[g_i(\mathbf{r}, t) - g_i^{eq}(\mathbf{r}, t)] \quad (1)$$

The three-dimensional LB implementation of continuity and momentum equations can be described as