International Journal of Heat and Fluid Flow 000 (2016) 1–13

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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

A three-dimensional numerical study on dynamics behavior of a rising vapor bubble in uniformly superheated liquid by lattice Boltzmann method

Tao Sun[a,*], Jiangang Sun[a], Xueye Ang[a], Shanshan Li[a], Xin Su[b]

[a] College of Civil Engineering, Dalian Nationalities University, Dalian 116024 PR China
[b] Simulation and Design Center, Beijing Institute of Collaborative Innovation, Beijing 100094 PR China

ARTICLE INFO

Article history:
Available online xxx

Keywords:
Rising vapor bubble
Growth and deformation
Phase change
Lattice Boltzmann method
Three-dimensional simulation

ABSTRACT

In this paper, dynamics behaviors of a rising vapor bubble in uniformly superheated liquid are firstly studied by a hybrid three-dimensional lattice Boltzmann model. In order to validate this model, two test cases regarding bubble rising in an isothermal system and vapor bubble growth in a superheated liquid are performed, respectively. The test results are consistent with existing results and indicate the feasibility of the hybrid model. The hybrid model is further applied to simulate growth and deformation of a rising vapor bubble in different physical conditions. Some physical parameters of vapor bubble such as equivalent diameter and growth rate are evaluated accurately by three-dimensional simulations. It is found that the growth rate of vapor bubble changes with time and temperature gradient. It reaches a maximum value at the initial stage and then decrease until a certain value. The growth and deformation of vapor bubble at different ratios of *Re*/*Eo* are discussed. The numerical results show the vapor bubble will take place a larger deformation at high ratio of *Re*/*Eo* at the middle and final stages. In addition, the hybrid model is also applied to predict the evolution of flow and temperature fields. The bubble wake has a great influence on the motion and deformation of vapor bubble during rising process. As far as the temperature field is concerned, a ratio of *Re*/*Eo* has an important influence on heat transfer and evolution of temperature field.

1. Introduction

The behavior of a vapor bubble in uniformly superheated liquid is a complicated physical process, which is associated with bubble growth, deformation and rising. Study on the vapor bubble is of fundamental importance in many engineering applications, such as power, refrigeration and chemical and process industries (Dong et al., 2009). In the process of bubble rising, if the temperature of bulk liquid exceeds saturation temperature, the vapor bubble will grow in the liquid; the opposite process is bubble collapse. The dynamics behavior of bubble is often influenced by temperature and velocity gradients and the balance of surface tension forces at vapor–liquid interface. Thus, it is difficult to quantitatively predict the interaction mechanisms by using traditional experiment methods. Fortunately, due to the fast development of computer technology and emergence of advanced numerical method, numerical simulation provide a powerful tool to study the behavior of vapor bubble in a superheated liquid.

In numerical simulation, one of the major issues is to deal with the motion and deformation of vapor–liquid interface and the topology change (Cheng et al., 2010). The vapor–liquid interface is often extraordinarily complicated because of its non-linearity variety and time-dependence behavior induced by phase-change accompanying heat and mass transfer. Generally, the vapor–liquid interface is identified by a marker function that is advected by the flow. Several numerical methods have been developed for that purpose. For example, Blake and Gibson (Blake and Gibson, 1981) used an approximate integral-equation to simulate growth and collapse of a vapor cavity near a free surface. Li and Yan proposed two numerical methods in Li and Yan (2002a, b) and they model a vapor bubble growth in uniformly superheated liquid (Yan and Li, 2006). Yoon et al. (Yoon et al., 2001) presented a mesh-free numerical method for the analysis of gas–liquid two-phase flows, which show a good agreement with experimental observations. The numerical methods mentioned above are the singular interface models, which are not suitable to track bubble large deformation in topology because of limited grid. For this reason, several numerical

* Corresponding author.
E-mail addresses: suntao@dlnu.edu.cn, dutjustao@gmail.com (T. Sun), sjg@dlnu.edu.cn (J. Sun), Yxa60@dlnu.edu.cn (X. Ang), lishanshan@dlnu.edu.cn (S. Li), suxin2015@bimba.pku.edu.cn (X. Su).

http://dx.doi.org/10.1016/j.ijheatfluidflow.2016.09.012
0142-727X/

Nomenclature

d_e	equivalent diameter
e	velocity vector of LBM
Eo	Eötvös number
$\mathbf{F}_b$	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	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
σ	surface tension coefficient
υ	kinematic viscosity

Subscripts/superscripts

i	discrete number
eq	equilibrium
G(*g*)	gas
L(*l*)	liquid

methods based on the sharp interface schemes were proposed to overcome the shortcoming, such as level set and volume of fluid (VOF) method etc. (Prosperetti and Tryggvason, 2009). Typically, Tomiyama et al. (Tomiyama et al., 1993) used VOF method to study a two-dimensional single bubble in a stagnant liquid and in a linear shear flow. It was clarified that the VOF method gives qualitative predictions for the effects of some dimensionless parameters on fluctuating bubble motion in a stagnant liquid. Zu et al. (Zu et al., 2011) reported the three-dimensional numerical modeling on bubbly flow in confined mini-/micro-channels using VOF method. In Son's study (Son et al., 1999), a complete numerical simulation of a growing and departing bubble on a horizontal surface has been performed. The vapor–liquid interface is captured by a level set method which is modified to include the influence of phase change at the interface. Though VOF and level set method are applied extensively, it is well known that they may encounter some issues in dealing with the topological deformation of interface (Huang et al., 2010). Moreover, VOF is very complicated to extend to three-dimensional simulation. Because in this method, the interface is given implicitly by a color function, defined to be the fraction of volume within each cell of one of the fluids. For the color function, a reconstruction of interface is made and the interface is then propagated implicitly by updating the color function (Zu et al., 2011). It will cost a lot of computation time and memory requirements, especially for simulations in three-dimension. For the level set method, which requires a re-initialization procedure to keep the distance property when large topological change occurs around the vapor–liquid interface may violate the mass conservation. A conservative method of level set type for moving interfaces in divergence free velocity fields is presented by Olsson and Kreiss (Olsson and Kreiss, 2005).

Recently, lattice Boltzmann method (LBM) has attracted a lot of scientific attention as a popular tool to simulate incompressible viscous flow. Unlike the traditional computational fluid dynamics (CFD) methods, LBM is based on the molecular kinetic theory and it solves partial differential equation based on a special kind of discretization. The original convection–diffusion equation, such as the Navier–Stokes equation, is replaced by a kinetic LB equation. Several lattice Boltzmann (LB) models have been proposed to model multi-phase and multi-component flows since its birth, mainly including Shan and Chen' pseudo-potential model (Shan and Chen, 1993), He et al.' model (He et al., 1999), color model (Rothman and Keller, 1988), and Swift et al.' free energy model (Swift et al., 1995). Succi et al. also contribute very important and seminal work in the lattice Boltzmann field (Benzi et al., 1992; Sbragaglia et al., 2007; Succi, 2001). Based on these LB models, researchers have performed many studies on two-phase flow with phase change. For example, the pseudo-potential model is recognized as an efficient and simple approach to deal with multi-phase flows. An extended pseudo-potential method (Sbragaglia et al., 2007) was developed by Sbragaglia et al. Surface tension can be tuned independently of the equation state, by formulating a two-parameter version of the Shan–Chan model with mid-range interactions. Falcucci et al. (Falcucci et al., 2010) performed lattice Boltzmann simulations of phase-separating flow at large density ratios: the case of doubly-attractive pseudo-potentials. Colosqui et al. (Colosqui et al., 2012) presented a dynamic optimization strategy to generate customized equations of state for the numerical simulation of non-ideal fluids at high density ratio. Besides that, Hazi and Markus (Hazi and Markus, 2009) presented the numerical simulation of heterogeneous boiling on a horizontal plate in stagnant and slowly flowing fluid using LBM, which included the phase change model with an isothermal two-phase LBM. Gong and Cheng (Gong and Cheng, 2012, 2013) 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. Dong proposed a hybrid two-dimensional LB model (Dong et al., 2009), which consisted of a developed free energy model and a LB thermal model (Inamuro et al., 2002). This hybrid LB model was applied to simulate the motion and growth of a rising vapor bubble through a uniformly superheated liquid. The prediction of temperature field in two-dimensional condition was presented. In Ryu and Ko' literature (Ryu and Ko, 2012), 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. Sun used a similar model to simulate bubble growth and departure during flow boiling period (Sun et al., 2013) and a three-dimensional LB phase-change model is first proposed to simulate nucleate boiling in reference (Sun and Li, 2013). All in all, previous studies on the behavior of a rising vapor bubble in uniformly superheated liquid were performed only in two-dimensional condition. Moreover, some studies are focused primarily on the process of bubble growth and departure, rather than the behavior of a rising vapor bubble through a uniformly superheated liquid. So far, to the best of the author's knowledge, there are few literatures related to simulation of dynamics behavior of a vapor bubble in three-dimensional condition by LBM.

In this paper, the three-dimensional LB phase-change model proposed by Sun (Sun and Li, 2013) is firstly used to predict two-phase flow in the non-isothermal system with phase change. The present work aims to extend this model to study different flow regimes. More specifically, the LB model is used to simulate the growth and deformation of a rising vapor bubble through

Please cite this article as: T. Sun et al., A three-dimensional numerical study on dynamics behavior of a rising vapor bubble in uniformly superheated liquid by lattice Boltzmann method, International Journal of Heat and Fluid Flow (2016), http://dx.doi.org/10.1016/j.ijheatfluidflow.2016.09.012