International Journal of Heat and Fluid Flow 71 (2018) 1–12

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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

Simulation of impacting process of a saturated droplet upon inclined surfaces by lattice Boltzmann method

Rui Ma[a], Xun Zhou[b], Bo Dong[b,*], Weizhong Li[b], Jing Gong[a]

[a] College of Mechanical and Transportation Engineering, China University of Petroleum, Beijing 102249, China
[b] Key Laboratory of Ocean Energy Utilization and Energy Conservation of MOE, Dalian University of Technology, No. 2 Linggong Road, Ganjingzi District, Dalian, Liaoning 116024, China

ARTICLE INFO

Keywords:
Lattice Boltzmann method
Phase transition
Droplet
Impacting angle
Wettability
Weber number

ABSTRACT

In the current work, the impacting process of a saturated fuel droplet on an inclined blade surface in superheated gas is simulated by the lattice Boltzmann method (LBM). Firstly, wetting boundary condition is derived for the phase transition LBM model, and then it is validated by calculating static contact angle of a droplet on partial wetting solid wall. Next, the dynamic behavior and phase transition of the droplet during its impacting process are analyzed on the basis of impacting angle, surface wettability, and Weber number. The results indicate that both deformation and evaporation of the droplet are enhanced by these three factors. Furthermore, the influence of impacting angle on droplet velocity is more obvious than that of other factors.

1. Introduction

Droplet dripping or jetting to an inclined solid surface widely exists in the fields of energy and chemical industry. For example, in gas turbine combustor, liquid fuel is sprayed through nozzles, and a large number of small fuel droplets are formed (Elperin and Krasovitov, 1995). The saturated fuel droplets move with superheated gas, and then impact upon blades of gas turbine, which can be viewed as inclined solid surfaces. Initially, since the temperature of fuel droplets is lower than that of their surrounding gas, the droplets evaporate as they absorb heat from the superheated gas. However, incomplete evaporation of some droplets with relative large radius accounts for impacting behavior upon the gas turbine blades. As intense mass and heat transfer occurs during this process, it has a negative effect on the performance of gas turbine. Therefore, the mechanism of hydrodynamic and thermodynamic behavior of a droplet during its impacting upon an inclined solid surface deserves special attention, and it plays an important role in the guidance and development of gas turbine (Chandra and Avedisian, 1991; Pasandideh-Fard et al., 1996; Liang et al., 2013; Dou et al., 2017).

Actually, numerous efforts have been made to investigate the process of droplet impacting upon inclined surfaces. In terms of experimental studies, Kang and Lee (2000) focused mainly on the effect of impacting angle on dynamic behavior of a liquid droplet in its impacting upon an inclined heated surfaces. They found out that the droplet merely slips without noticeable contraction when the impacting angle is less than 90°, and they pointed out that the impacting angle is a key factor in impacting dynamics. Šikalo and Ganić (2007) discussed different outcomes of droplet-surface interactions. However, little information about the detail of impacting on wetting inclined surfaces was reported. Experimental observations concerning spreading and splashing processes during a single liquid drop impacting on an inclined wetted surface were performed by Liang et al. (2013). Their results revealed that both surface tension and viscosity can significantly affect spreading and splashing behaviors of droplet. For the numerical analyses, Lunkad et al. (2007) investigated the dynamics of a droplet impacting on horizontal and inclined surfaces by using the volume of fluid (VOF) method. The effects of surface inclination, wetting characteristics, liquid properties, and impacting velocity on spreading dynamics were considered. Yao et al. (2017) simulated the impacting, spreading, and freezing of a water droplet on horizontal and inclined superhydrophobic cooled surfaces by using a three dimensional phase change model on OpenFOAM platform. The effects of Weber number and Ohnersorge number on the oblique impacting and freezing process were investigated. Based on the above-mentioned studies, it can be found out that only few of them specially focused on phase transition of droplet during the impacting process.

It's worth noting that the lattice Boltzmann method has been established to be a novel and powerful CFD tool for multiphase flow simulation (Li et al., 2014). Several LBM models have been developed, including the chromodynamics model proposed by Rothman and Keller (1988), the pseudo-potential method of Shan and Chen (1993),

* Corresponding author.
E-mail address: bodong@dlut.edu.cn (B. Dong).

https://doi.org/10.1016/j.ijheatfluidflow.2018.03.001
Received 18 October 2017; Received in revised form 2 March 2018; Accepted 3 March 2018
0142-727X/

the free energy method of Swift et al. (1995) and the method of He et al. (1999). The original above-mentioned models are limited to small density ratio. Inamuro et al. (2004) proposed a lattice Boltzmann method for incompressible two-phase flows with large density differences. Then, Zheng et al. (2006) proposed a multiphase model for the two-phase system with large density ratio by using the C−H equation to track and define two-phase interface, which is closer to the Landau mean-field theory than other models. In order to consider phase transition, Dong et al. (2010a) proposed a hybrid LBM model by combining Zheng's multiphase model with thermal LBM model of Inamuro et al. (2002). Later, Luo et al. (2016) developed the model of Dong et al. and applied it to study the falling process of a subcooled droplet in saturated steam. The effect of relative velocity between droplet and steam on the growth and falling processes of droplet was obtained. But, the influence of surface wettability was not considered.

As droplet-surface interaction plays an important role in the hydrodynamics and thermodynamics, wetting boundary condition should be considered. For the free energy based multiphase LBM model, wetting property can be modeled via two ways. One is developed by Briant and Yeomans (2004) and Briant et al. (2002) for a liquid-gas system and binary fluids in two dimensions. In their work, a surface term dependent on imposed wetting properties is added into the free energy equation to define the surface energy which is assumed to have a simple linear relation with the order parameter on the wall. The order parameter derivatives on the wall are appropriately modified through the equilibrium distribution functions. This method was also used by Zu and Yan (2011) and Tang et al. (2015) for modeling droplet dynamics on partial wetting surfaces in three dimensions. It is remarkably noted that additional strategies are required to obtain the order parameter derivatives at the corners and the intersections of orthogonal planes (Huang et al., 2009; Ju et al., 2017). The other wetting boundary condition is proposed by Graaf et al. (2006). They assigned a certain value of the order parameter at solid lattice sites to incorporate the fluid-surface interaction. Specifically, for a binary system with fluids A and B, if the order parameter at solid lattice sites is equal to that of fluid A, it is believed that fluid A totally spreads on the surface while fluid B does not, and vice versa. For partial wetting surface, the order parameter at solid lattice sites lies between those of fluids A and B. For neutral wetting surface, the order parameter at solid lattice sites is zero. Compared with the method of Briant and Yeomans (2004) and Briant et al. (2002), this approach is more easily to be implemented. Thus, in the present work, following the idea of Graaf et al. (2006), a wetting boundary condition is derived for the phase transition model developed by Luo et al. (2016). Then, the processes of a saturated droplet moving with superheated gas and impacting upon an inclined surface are simulated. The effects of impacting angle, surface wettability, and Weber number are analyzed in detail.

The rest of this paper is organized as follows: In Section 2, the phase transition LBM model is briefly introduced, and the wetting boundary condition is specified. In Section 3, model validation is performed by calculating static contact angle of a droplet on partial wetting solid wall and one-dimensional Stefan problem, respectively. In Section 4, numerical simulations and results are presented and discussed. Finally, the conclusion is summarized in Section 5.

2. Methodology

2.1. LBM model for multiphase flow

In the multiphase model proposed by Zheng et al. (2006) (ZSC model), order parameter ϕ related to density difference is applied to capture the interface, while the fluid dynamics is evolved by mean density n,

$$\phi = \frac{\rho_1 - \rho_2}{2},\ n = \frac{\rho_1 + \rho_2}{2}, \tag{1}$$

where ρ_1 and ρ_2 are densities of two different fluids, respectively. In the ZSC model, the interface evolution is governed by the C−H equation, and it can be solved and expressed in the frame of the LBM as

$$g_i(x + e_i\delta t,\ t + \delta t) - g_i(x,\ t) = -\frac{1}{\tau_g}[g_i(x,\ t) - g_i^{eq}(x,\ t)] \tag{2}$$

where x is lattice position, i is the direction of discrete particle velocity e_i, t and δt are the time and time step. g_i and g_i^{eq} are the particle distribution function and the corresponding equilibrium distribution function related to ϕ, respectively. τ_g is the relaxation time of g_i.

The LBE implementation of continuity and momentum equations can be described as

$$f_i(x + e_i\delta t,\ t + \delta t) - f_i(x,\ t) = -\frac{1}{\tau_f}[f_i(x,\ t) - f_i^{eq}(x,\ t)] + \Omega_i \tag{3}$$

with

$$\Omega_i = \left(1 - \frac{1}{2\tau_f}\right)\frac{3\omega_i}{c^2}\left[(e_i - u) + \frac{3(e_i{\cdot}u)}{c^2}e_i\right](\mu_\phi \nabla\phi + F)\delta t \tag{4}$$

where f_i and f_i^{eq} are the particle distribution function and the corresponding equilibrium distribution function related to n, respectively. F is body force, τ_f is the relaxation time of f_i. ω_i is the weighting coefficient, c is the lattice speed, u is the macroscopic velocity. μ_ϕ is the chemical potential with the form of

$$\mu_\phi = A(4\phi^3 - 4\phi^{*2}\phi) - \kappa\nabla^2\phi \tag{5}$$

where ϕ^* is the equilibrium state of order parameter ϕ, and it is determined by initial fluid densities. A and κ are coefficients related to the surface tension coefficient σ and the interface layer thickness W, which are given as

$$\kappa = \frac{3\sigma W}{8\phi^{*2}} \tag{6}$$

$$A = \frac{3\sigma}{4\phi^{*4}W} \tag{7}$$

For the two-dimensional nine-velocity (D2Q9) LBM model, the discrete velocities e_i and weighting coefficients ω_i are given as

$$e_i = \begin{bmatrix} 0 & 1 & 0 & -1 & 0 & 1 & -1 & -1 & 1 \\ 0 & 0 & 1 & 0 & -1 & 1 & 1 & -1 & -1 \end{bmatrix} \tag{8}$$

$$\omega_i = \begin{bmatrix} \frac{4}{9} & \frac{1}{9} & \frac{1}{9} & \frac{1}{9} & \frac{1}{9} & \frac{1}{36} & \frac{1}{36} & \frac{1}{36} & \frac{1}{36} \end{bmatrix} \tag{9}$$

Then, the corresponding equilibrium distribution function g_i^{eq} and f_i^{eq} can be calculated by

$$g_i^{eq} = \omega_i\left(B_i + \phi\frac{3e_i{\cdot}u}{c^2}\right) \tag{10a}$$

$$B_i = \begin{cases} 3M\mu_\phi/c^2, & i > 0 \\ [\phi - (1 - \omega_0)B]/\omega_0, & i = 0 \end{cases} \tag{10b}$$

$$f_i^{eq} = \omega_i A_i + \omega_i n\left[3e_i{\cdot}u - \frac{3}{2}u^2 + \frac{9}{2}(e_i{\cdot}u)^2\right] \tag{11a}$$

$$A_i = \begin{cases} 3(\phi\mu_\phi + n/3), & i > 0 \\ 9n/4 - 15(\phi\mu_\phi + n/3)/4, & i = 0 \end{cases} \tag{11b}$$

where the parameter M is defined by the mobility coefficient Γ and τ_g as $M = \Gamma/(\tau_g - 0.5)$ (Xie et al., 2016).

The macroscopic variables such as order parameter ϕ, mean density n, and velocity u are evaluated by

$$\phi \tag{12a}$$