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Numerical simulation of droplet evaporation on a hot surface near Leidenfrost regime using multiphase lattice Boltzmann method

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ABSTRACT

In the present article, evaporation of a liquid drop spreading on hot surface, based on the lattice Boltzmann method, is simulated. Liquid and gas phases are considered to be incompressible. The divergence-free condition of the velocity field is no longer satisfied since the phase change occurs at the interface. In order to take into account the vaporization effects, the convective Cahn–Hilliard equation is extended. The phase change process is modeled by employing a proper source term at the interface. The D2Q9 structure is used in the present simulation. Effects of different non-dimensional parameters including the Bond number, liquid Archimedes number, gas Stefan number, density ratio, and the Prandtl number on behavior of liquid drop are investigated. Computational results showed that increasing the Bond number, liquid Archimedes number and density ratio accelerates the evaporation rate. The Leidenfrost regime is observed in high Stefan numbers, while in low Stefan numbers, the drop is attached to the heated wall. Furthermore, decreasing the equilibrium contact angle leads to the lagging of the Leidenfrost regime.

1. Introduction

Impinging of liquid drops into a hot surface is an important phenomenon in industrial applications. It plays significant role in internal combustion engines as well as metallurgical heat treatment and cooling of the electronic devices.

When a drop of liquid is deposited on a hot surface with the temperature around liquid boiling point, the drop boils and quickly vanishes. But if the surface temperature is far greater than the boiling point, the drop is levitated above its own vapor, and not anymore in contact with the surface. In this case, the evaporation rate decreases due to the insulation properties of the vapor film. Furthermore, the absence of contact between the hot surface and the droplet prevents the nucleation of bubbles, so that the droplet doesn't boil but just quietly evaporates. Such floating droplets are called Leidenfrost droplets, the name of the physician who first surveyed the phenomenon [1].

Numerous experimental works are found in the literature for understanding the different aspects of droplet evaporation in the above mentioned flow. David Quere has presented a good review on Leidenfrost regime [2]. Different numerical works can also be found in the literature. Most of them have employed Navier–Stokes equations for solving the flow field and used either level set or volume of fluid (VOF) methods to capture the liquid–gas interface. One of the first investigators, who used the solution of Navier–Stokes equations for vaporizing droplet, was Karl et al. [3]. They used VOF method to simulate an

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evaporating and non-wetting droplet in contact with a hot surface. The effect of the vapor velocity was neglected in the fluid flow. Using VOF method, Harvie and Fletcher [4] developed an axisymmetric code to simulate droplet evaporation in contact with a hot plate. They used a one-dimensional model for heat transfer inside the vapor film between wall and liquid drop. Fan and Ge [5] used level set method to simulate impact of saturated liquid drop on a hot surface. They solved a sub-cooled droplet impact on a hot surface and found that by increasing the sub-cooled degree, the Leidenfrost degree decreases. Chatzikyriakou et al. [6] solved a full Navier–Stokes equations for vapor under the boiling drop. Pournaderi and Pishevar [7] used projection method to solve Navier–Stokes equations for impinging of a drop to a superheated wall. They used level set method for capturing the interface.

All of the aforementioned numerical works used the Navier–Stokes equations for the flow field. Although the research on the preceding flows is growing, the direct simulation of multi-phase flows including dynamic interfaces is still a challenging duty. The dominant difficulties are caused by the coupling of many effects such as latent heat, interfacial mass transfer, and surface tension, likewise the relevant conservation laws include energy, momentum, and mass.

The lattice Boltzmann method which is based on mesoscopic kinetic equations sounds to be a promising approach for dealing with multiphase and interfacial flows. The mesoscopic nature of the lattice Boltzmann method uses only a minimum amount of microscopic details to reproduce interfacial physics and macroscopic flow hydrodynamics in a consistent manner. Therefore, it can address length scales between micro- and macro-scale and simulate interfacial flows from a more fundamental basis. The lattice Boltzmann method has privileged aspects like simple coding, capture of complicated geometries, parallelism of computation. Shan and Chen [8] proposed a facile method for simulation of multi-phase flows which is executable in complex geometries. He et al. [9] developed two phase modeling based on LBM by introducing two specific distribution functions for the evaluation of mass, momentum and pressure, but they did not distinguish between thermodynamic and dynamic pressures. In their simulation parasitic velocities at the interface region have been decreased, but did not perish completely. Mukherjee et al. [10] introduced an external force which exerts on a wall in order to simulate the contact angle in previous method, and this force strength controls the wettability of the surface. Recently, Lee [11] proposed a two distribution function LBE method in the pressure evolution equation enforced the incompressibility. As long as the intermolecular force is indicated in the potential mode, the incompressible LBE method for interfacial flows could eliminate parasitic currents. His method is capable of simulation of multi-phase flows with density and viscosity ratios up to 1:1000. To model the interface dynamics on partially wetting surfaces, Lee et al. [12] extend Lee's method for incompressible binary fluids.

Safari et al. [13] extended the multi-phase model of Lee to simulate thermal phase-change phenomena by incorporating a proper source term at the phase interface. They modified Chan–Hilliard equation in the existence of phase change, which was employed in Lee's LB model. Begmohammadi et al. [14] evaluated the capability of the model to simulate two-dimensional pool boiling with different density ratios up to 1:1000 and shown the consistency of the model with experimental correlations.

In the current work, Safari's model is used to simulate droplet evaporation on a horizontal hot surface. It's the first time that the evaporation and deformation of the drop in Leidenfrost regime is simulated by the Lattice Boltzmann method. First, the extension of the Chan–Hilliard equation in the presence of phase-change phenomena is presented. Then the LB model of Lee based on the classical convective Chan–Hilliard is given. In the following, the effects of variation of flow and surface characteristics have been explained thoroughly.

2. Mathematical modeling

Considering a binary flow including two incompressible fluids of different bulk density, the continuity equation for each phase without phase change could be written as:

$$\frac{\partial \tilde{\rho}_i}{\partial t} + \nabla \cdot \mathbf{n}_i = 0 \ \ (i = L, G) \tag{1}$$

where $\tilde{\rho}_i$ and n_i are local density and the mass flow rate (per unit volume) of the component i, and ρ_L and ρ_G denote liquid and gas phase density, respectively. In the bulk region, the mass flow is only attribute to advection, thus $\mathbf{n}_i = \tilde{\rho}_i \mathbf{u}$ where $\mathbf{u}$ is the volume averaged velocity of the flow. When phase change occurs, $\dot{m}'''$, the volumetric source due to phase change, should be added to the continuity equation for each phase as:

$$\frac{\partial \tilde{\rho}_i}{\partial t} + \nabla \cdot \mathbf{n}_i = \pm \dot{m}'''(i = L, g) \tag{2}$$

The two phases can be distinguished by their composition (C) in a volume element of the computational domain. By definition of $C = \tilde{\rho}_L / \rho_L$, the composition takes a value of 1 in the liquid phase and a value between 0 and 1 in the gas phase. So $(\tilde{\rho}_i)$ is related to ρ_i by $\tilde{\rho}_L = C\rho_L, \tilde{\rho}_G = (1 - C)\rho_G$. In the interfacial region, a diffusive flow may exist as a result of mild transition of the interface. This diffusive mass flow is expressed by $-\rho_i \mathbf{j}_i$, where $\mathbf{j}_i$ is the volume diffusive flow rate. Thus the component *i*'s total mass flow rate can be denoted as $\mathbf{n}_i = \tilde{\rho}_i \mathbf{u} - \rho_i \mathbf{j}_i$. The continuity equation can be written in the form of C as:

$$\frac{\partial C}{\partial t} + \nabla \cdot (\mathbf{u}C) - \nabla \cdot \mathbf{j}_L = -\frac{\dot{m}'''}{\rho_L} \tag{3}$$