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Investigation of vapor condensation on a flat plate and horizontal cryogenic tube using lattice Boltzmann method☆

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ABSTRACT

In this paper simulation of vapor condensation, liquid film formation, and dew drop sprinkling from cryogenic horizontal tube base on two-dimensional lattice Boltzmann method is presented. Lee's multiphase model is used which is applicable to high density and viscosity ratios. The passive scalar thermal lattice Boltzmann framework and proper source term due to phase change are combined with the multiphase model to simulate the film condensation. Lee's model is based on convective Cahn-Hilliard equation and the divergence-free condition of the velocity field. However, as the phase change occurs at the interface, the divergence-free condition is no longer satisfied. The simple passive scalar approach is employed for the evolution of the temperature field in the computational domain and the flow field is affected by temperature under the hypothesis of Boussinesq. The D2Q9 lattice structure is used for the case of density ratio of 25), and the effects of gravitational superheating, contact angle and the temperature of sub-cooled tube on vapor condensation are illustrated. Finally flow fields and three-phase contact line movement of film condensation are analyzed.

1. Introduction

One of the most effective heat transfer modes is condensation. The physical mechanism of film-wise condensation on a horizontal tube is very complicated, as the process includes liquid generation, growth and dew drop sprinkling. In the past century, a great deal of experimental and analytical research has been done in this field. One of the first attempts in investigating of condensation can be found in Nusselt [1]. Date to 1916, laminar film condensation on flat vertical surfaces and horizontal cylinders placed in quiescent saturated vapors were analytically predicted by Nusselt. Since inherent assumptions limit Nusselt's model, many researchers attempted to develop more accurate model which overcomes most of the limitations, Nusselt's model faced. Shekriladze and Gomelauri [2] investigated the flowing vapor condensation considering the interfacial shear by considering momentum transfer across the interface due to the condensation process and found that the phase conversion dominated the interface shear. Fujii et al. [3] proposed an approximate method to solve the two-phase boundary layer equation to investigate the laminar film condensation of flowing vapor on a vertical surface [3] and a horizontal cylinder [4]. Their formulation neglected inertia, convection and pressure gradient effects in the condensate film. Their model was validated against the experimental results.

Gaddis [5] solved the two-phase boundary equations of liquid and vapor flowing perpendicular to a tube for laminar film condensation using series expansions. He neglected surface tension in the momentum equation as well as viscous dissipation and pressure in the energy equation of the condensate film. Rose [6] examined the effects of pressure gradient on the forced-convection film condensation on a horizontal tube. In this model, the pressure gradient on the condensate film is due to the pressure gradient of the vapor, as determined by potential theory, which is impressed on the condensate film. He simplified the analysis by using the Shekriladze–Gomelauri model [2] which ignores inertia and convection in the condensate film and uses the asymptotic expression for the interfacial shear.

Afterward, in order to design the engineering systems, e.g. powerplants, heat exchangers and refrigeration, many effects on the film condensation have been addressed, including surface temperature [7–9], turbulent flow [10,11], wall suction [12–14] and others [15–19].

In the past, most of the researchers in this field focused on saturated vapor while few attentions were paid to superheated vapors. Minkowycz and Sparrow [20,21] and Shang and Wang [22] studied the laminar film condensation of a superheated vapor on isothermal vertical surfaces and proposed a correlation to predict the dimensionless temperature gradient. Yang [23] and Hsu [24] developed a one-phase boundary-layer model without considering the effect of buoyancy especially for the natural convection film condensation.

Recently, the lattice Boltzmann method has attracted considerable attention as an alternative approach for computational fluid dynamics, and has shown great potentials in modeling complex fluid systems. Lee [25] proposed a lattice Boltzmann multiphase scheme based on the Cahn–Hilliard diffuse interface theory, which overcomes most of the limitations which previous lattice Boltzmann models faced. Due to

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the use of potential form of the intermolecular force for non-ideal fluids and compact isotropic discretization of this forcing term, spurious currents could be reduced to round-off and stable solutions are obtained for density ratios up to 1:1000 for low Mach numbers.

Safari et al. [26] extended the model of Lee to simulate thermal phase-change phenomena in two-phase fluid flows. Both liquid and gas phases were considered to be incompressible. However, the phase-change process was modeled by incorporating a proper source term at the phase interface. The classical convective Cahn–Hilliard equation in the presence of phase change modified evolution equation, which was employed in the multiphase LB framework of Lee. The developed model was successfully validated for a one-dimensional Stephan problem with different density ratio up to 1:1000, and the ability of the model to simulate two-dimensional droplet evaporation was tested. Begmohammadi et al. [27] employed the phase-change model of Safari et al. [26] to simulate nucleate pool boiling. Bubble growth on and departure from superheated surface was simulated. Also, effects of density, gravity, surface tension, contact angle and the temperature of superheated wall on bubble departure were investigated. Their results were in good agreement with experimental correlations.

In this article, the phase-change model of Safari et al. [26] is extended to investigate the vapor condensation, liquid film formation, and dew drop sprinkling from cryogenic horizontal tube. In the present simulation, the modified curved boundary treatment of Filippova and Hanel (FH) is used, which enable curved solid walls to be treated with second order accuracy. The results are successfully validated with previous correlations.

2. Mathematical model

Consider classical convective Chan–Hilliard equation in the presence of phase change and the system of two incompressible and immiscible fluids of different bulk density (ρ_1 as liquid phase density and ρ_g as gas phase density). The liquid phase composition denoted by $C = \frac{\tilde{\rho}_l}{\rho_l}$ is considered as the order parameter, where $\tilde{\rho}_l$ and ρ_l are local and bulk densities of the liquid phase. The local averaged density (ρ) as a function of the local densities ($\tilde{\rho}_i$) is expressed as

$$\rho = \tilde{\rho}_l + \tilde{\rho}_g = C\rho_l + (1-C)\rho_g. \tag{1}$$

The continuity equation for component i may be written as

$$\frac{\partial \tilde{\rho}_i}{\partial t} + \nabla.\boldsymbol{n}_i = \pm \dot{m}''' \quad (i = l, g). \tag{2}$$

In this equation, $\boldsymbol{n}_i$ is the mass flow rate of the component i and $\dot{m}'''$ expressed the volumetric source due to phase change. In the bulk region, the mass flow is only function of the volume averaged velocity of the flow ($\boldsymbol{n}_i = \tilde{\rho}_i \boldsymbol{u}$). But in interfacial region, the mass flow is effected by the volume diffusive flow rate besides the volume averaged velocity of the flow ($\boldsymbol{n}_i = \tilde{\rho}_i \boldsymbol{u} - \rho_i \boldsymbol{j}_i$) [28]. Thus Eq. (2) can be written in terms of C for liquid phase as

$$\rho_l \frac{\partial C}{\partial t} + \rho_l \nabla.(\boldsymbol{u}C) - \rho_l \nabla.\boldsymbol{j}_l = -\dot{m}'''. \tag{3}$$

And for the gas phase as

$$\rho_g \frac{\partial (1-C)}{\partial t} + \rho_g \nabla.[\boldsymbol{u}(1-C)] - \rho_g \nabla.\boldsymbol{j}_g = \dot{m}'''. \tag{4}$$

Since $\boldsymbol{j}_l = -\boldsymbol{j}_g = \boldsymbol{j}$, summation of Eqs. (3) and (4) result in

$$\nabla.\boldsymbol{u} = \dot{m}''' \left(\frac{1}{\rho_g} - \frac{1}{\rho_l}\right). \tag{5}$$

Cahn and Hilliard assumed that the diffusive flow rate is proportional to the gradient of chemical potential [25] and mobility ($\boldsymbol{j} = M\nabla\mu$). Continuity equation can be written as

$$\frac{\partial C}{\partial t} + \nabla.(\boldsymbol{u}C) = \nabla.(M\nabla\mu) - \frac{\dot{m}'''}{\rho_l}. \tag{6}$$

So the total derivative of C can be written as follows:

$$\frac{DC}{Dt} = (\boldsymbol{e}_\alpha - \boldsymbol{u}) \cdot \nabla C - C\nabla.u + \nabla.(M\nabla\mu) - \frac{\dot{m}'''}{\rho_l}. \tag{7}$$

They related the mixing energy density of an isothermal system to composition by $E_{mix}(C, \nabla C) = E_0(C) + k|\nabla C|^2/2$, where $E_0 = \beta C^2(1-C)^2$ is the bulk energy(β is a constant). The equilibrium profile between two phases may be obtained by minimizing the mixing energy. This will lead to the following equation for the chemical potential μ:

$$\mu = \mu_0 - k\nabla^2 C \tag{8}$$

where k is the gradient parameter, and μ_0 is the classical part of the chemical potential and is obtained by $\mu_0 = \partial E_0/\partial C$. The Boltzmann equation in discrete form for the mass transfer and momentum equations for a system consisting of two non-compressible fluids can be written as follows:

$$\frac{Df_\alpha}{Dt} = \left(\frac{\partial}{\partial t} + \boldsymbol{e}_\alpha \cdot \nabla\right) f_\alpha = -\frac{1}{\lambda}(f_\alpha - f_\alpha^{eq}) + \frac{1}{c_s^2}(\boldsymbol{e}_\alpha - \boldsymbol{u}).\boldsymbol{F}\Gamma_\alpha. \tag{9}$$

In the above equation f_α is the partial distribution function, $\boldsymbol{e}_\alpha$ is the α-direction microscopic particle velocity, ρ is the mixture density, $\boldsymbol{u}$ is the volume averaged velocity, c_s is the speed of sound, λ is the relaxation time, $\Gamma_\alpha = \Gamma_\alpha(\boldsymbol{u}) = f_\alpha^{eq}/\rho$ and f_α^{eq} is the equilibrium distribution function as follows:

$$f_\alpha^{eq} = t_\alpha \rho \left[1 + \frac{\boldsymbol{e}_\alpha \cdot \boldsymbol{u}}{c_s^2} + \frac{(\boldsymbol{e}_\alpha \cdot \boldsymbol{u})^2}{2c_s^4} - \frac{(\boldsymbol{u} \cdot \boldsymbol{u})}{2c_s^2}\right] \tag{10}$$

with t_α being the weight factor determined from lattice structure. Intermolecular forces are calculated according to the following equation

$$\boldsymbol{F} = \nabla\rho c_s^2 - \nabla P + C\nabla\mu \tag{11}$$

where ρc_s^2 is the ideal gas contribution to the pressure and p is the dynamic pressure that enforces the incompressibility. The total pressure is a sum of the dynamic pressure p, the thermodynamic pressure $C\mu_0 - E_0$, and the pressure due to the inclusion of curvature $-kC\nabla^2 C + \frac{k}{2}|\nabla C|^2$.

One can impose body force on to Eq. (11) to consider its effects as follows:

$$\boldsymbol{F_{ext}} = \begin{cases} g(\rho_l - \rho_g) & \rho_l \neq 0 \\ 0 & \rho_l = 0 \end{cases}. \tag{12}$$

In the above equations g indicates the gravitational acceleration. Eq. (9) is the discrete Boltzmann equation for the mass and momentum equations and is to be transformed into the discrete Boltzmann equation for the pressure and momentum as

$$g_{\boldsymbol{\alpha}} = f_\alpha c_s^2 + (p - \rho c_s^2)\Gamma_\alpha(0) \tag{13}$$

and the new equilibrium distribution for $g_{\boldsymbol{\alpha}}$ function as

$$\begin{aligned} g_\alpha^{eq} &= f_\alpha^{eq} c_s^2 + (p - \rho c_s^2)\Gamma_\alpha(0) \\ &= t_\alpha \left[p + \rho c_s^2 \left(\frac{e_\alpha \cdot u}{c_s^2} + \frac{(e_\alpha \cdot u)^2}{2c_s^4} - \frac{(u \cdot u)}{2c_s^2}\right)\right] \end{aligned} \tag{14}$$