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Simulation of Two-Phase Flow and Heat Transfer in a Channel and around a Tube by Lattice-Boltzmann Method

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ABSTRACT: Determination of multiphase flow dynamics and thermal behavior of two-phase flow in a channel are of importance. The small-scale surface tension effect and related simulation efficiency, precision, and stability, have caused mesoscopic Lattice Boltzmann method broadening application. In the current study, the thermal-hydraulic behavior of subcooled falling flow in a vertical channel and around a single horizontal tube is simulated by using the Lee method and phase-filed model, and thermal passive scalar model. The modified curved boundary conditions and two different boundary conditions for side boundaries are investigated. The density ratio is 20 and other property's ratios of water are applied, and the outside diameter of the tube is 28.9mm. The flow, temperature, and pressure fields are presented and a detailed understanding of the movement of the three-phase contact line, circulating flow and local and average Nusselt numbers are determined. The film thickness, thermal boundary layer variation by the film thickness, Reynold number effect on Nusselt number and mass conservation are investigated as verification. The results have shown good consistency and high effectiveness in the simulation of multiphase gas-liquid flows in the presence of a circular obstacle, and for viscosity and thermal diffusivity ratios of water.

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1. INTRODUCTION

Falling Film Flow and heat transfer around a horizontal heated tube have significant applications in several industries. There are several interdependent mechanisms that have not been recognized yet. Narvaez and Simões [1] reviewed experimental studies and noted that the available empirical correlations are strongly dependent on operating conditions under which they had been developed.

Moreover, the dynamic behavior of microscopic phenomena at the interface is the main problem of numerical methods. Also, deficiency in the calculation of small-scale surface tension and gradients cause the formation of parasitic currents and instabilities. Mirjalali et al. [2] reviewed and evaluated the most common classic methods. They concluded that phase-filed and Volume of Fluid (VOF) are the most reliable methods. Meanwhile, there is not any comprehensive theoretical solution to this problem. Rogres [3] investigated the falling film on a single tube and applied several significant simplifications. Their results are applicable for limited ranges of non-dimensional numbers.

Mirjalali et al. [4] have done another study and showed the superiority of the phase-filed model in comparison to the volume of fluid, in terms of accuracy and stability. They concluded that the biggest remaining challenge is the development of a stable more cost-effective model. Therefore, it could be concluded that because of the application of the phase-field model in most of Lattice Boltzmann Methods (LBM), and because of the molecular kinetic nature of LBM, it is the most effective method for simulation of two-phase flows. In this regard, several studies have compared LBM with classic numerical methods [5-7]. Their results have approved the precision, stability, time-efficiency, simplicity and applicability of LBM.

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Due to the kinetic instinct of LBM, instability increases with the increase of differences in properties of phases. Lee [8] in 2009 introduced a model which is stable up to a density ratio of 1000. In this paper, the thermal and flow behavior of a jet of water at 100°C that flows around a horizontal tube at 110°C under the gravity force is simulated by multiphase Lee's method and passive scalar method. The modified curved boundary treatments are used. Finally, the flow and temperature fields are presented and investigated.

2. METHODOLOGY

In Lee's method, two distribution functions h and g are used to simulate the flow behavior of two immiscible and incompressible phases. The final Discrete Boltzmann equation for the evolution of the hydrodynamic pressure and momentum, g, is

$$\bar{g}_\alpha(\boldsymbol{x}+\boldsymbol{e}_\alpha\delta t, t+\delta t)-\bar{g}_\alpha(\boldsymbol{x},t) = -\frac{1}{\tau+0.5}\left(\bar{g}_\alpha-\bar{g}_\alpha^{eq}\right)\Big|_{(\boldsymbol{x},t)} + \delta t\,(\boldsymbol{e}_\alpha-\boldsymbol{u}).\left[\nabla\rho c_s^2\left(\Gamma_\alpha-\Gamma_\alpha(0)\right)+(-C\nabla\mu+F_{ext})\Gamma_\alpha\right]_{(\boldsymbol{x},t)} \tag{1}$$

where $\bar{g}_\alpha$ and $\bar{g}_\alpha^{eq}$ are particle and equilibrium distribution functions respectively:

$$\bar{g}_\alpha = g_\alpha + \frac{\left(g_\alpha - g_\alpha^{eq}\right)}{2\tau} - \frac{\delta t}{2}\left(e_\alpha - u\right).\left[\nabla\rho c_s^2\left(\Gamma_\alpha - \Gamma_\alpha(0)\right) + \left(-C\nabla\mu + F_{ext}\right)\Gamma_\alpha\right] \tag{2}$$

$$\bar{g}_\alpha^{eq} = g_\alpha^{eq} - \frac{\delta t}{2}\left(e_\alpha - u\right).\left[\nabla\rho c_s^2\left(\tilde{A}_\alpha - \tilde{A}_\alpha(0)\right) + \left(-C\nabla\mu\tilde{A}_\alpha + F_{ext}\right)\right] \tag{3}$$

In the same way, the Discrete Boltzmann equation for the transport of composition (h) can be written in the following form:

$$\bar{h}_\alpha\left(x + e_\alpha\delta t, t + \delta t\right) - \bar{h}_\alpha\left(x, t\right) = -\frac{1}{\tau + 0.5}\left(\bar{h}_\alpha - \bar{h}_\alpha^{eq}\right)\Big|_{(x,t)} + \delta t\left(e_\alpha - u\right).\left[\nabla C - \frac{C}{\rho c_s^2}\left(\nabla p_h + C\nabla\mu - F_{ext}\right)\right]\Gamma_\alpha\Big|_{(x,t)} \tag{4}$$

where the modified distribution functions $\bar{h}_\alpha$ and $\bar{h}_\alpha^{eq}$ are written as follows:

$$\bar{h}_\alpha = h_\alpha + \frac{\left(h_\alpha - h_\alpha^{eq}\right)}{2\tau} - \frac{\delta t}{2}\left(e_\alpha - u\right).\left[\nabla C - \frac{C}{\rho c_s^2}\left(\nabla p_h + C\nabla\mu - F_{ext}\right)\right]\Gamma_\alpha \tag{5}$$

$$\bar{h}_\alpha^{eq} = h_\alpha^{eq} - \frac{\delta t}{2}\left(e_\alpha - u\right).\left[\nabla C - \frac{\bar{C}}{\rho c_s^2}\left(\nabla p_h + C\nabla\mu - F_{ext}\right)\right]\Gamma_\alpha \tag{6}$$

where $C = \rho_{local} / \rho_l$ and $h_\alpha = (C/\rho) f_\alpha$. The Lattice Boltzmann equation for the distribution function of temperature is:

$$\bar{s}_\alpha\left(x + e_\alpha\delta t, t + \delta t\right) - \bar{s}_\alpha\left(x, t\right) = -\frac{1}{\tau_T + 0.5}\left(\bar{s}_\alpha - \bar{s}_\alpha^{eq}\right)\Big|_{x,t} \tag{7}$$

where Equilibrium distribution is presented as the following form

$$s_\alpha^{eq} = \omega_\alpha T\left(1 + \frac{e_\alpha u}{c_s^2}\right) \tag{8}$$

When a boundary is located in the middle of the fluid node f and solid node b, the post-collision unknown distribution functions are determined based on the distance from f to the curved boundary (Δ) as below:

$$\Delta = \frac{\left|x_f - x_w\right|}{\left|x_f - x_b\right|} \qquad 0 \le \Delta \le 1 \tag{9}$$

$$f_i\left(x_b + c_i\Delta t, t + \Delta t\right) = \left(1 - \chi\right) f_i\left(x_f + c_i\Delta t, t + \Delta t\right) + \chi f^*\left(x_b, t\right) \tag{10}$$

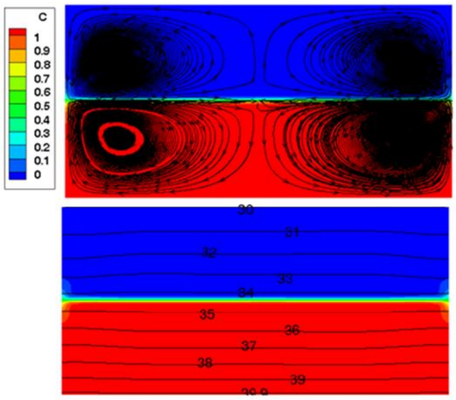

Fig. 1. Flow and temperature lines of two-phase gas-liquid Rayleigh-Benard convection for Ra=2.9×10^3

$$f^*\left(x_b, t\right) = f_i^{eq}\left(x_f, t\right) + \omega_i\rho\left(x_f, t\right)\frac{3}{c^2}e_i\left(u_{bf} - u_f\right) \tag{11}$$

$$u_{bf} = u\left(x_{ff}, t\right), \qquad \chi = \frac{2\Delta - 1}{\tau - 2}, \Delta < \frac{1}{2} \tag{12}$$

$$u_{bf} = \frac{1}{2\Delta}\left(2\Delta - 3\right)u_f + \frac{3}{2\Delta}u_w, \quad \chi = \frac{2\Delta - 1}{\tau + \frac{1}{2}}, \Delta \ge \frac{1}{2} \tag{13}$$

Also, post-collision temperature curved boundary conditions of Guo et al. [9] are employed.

3. DISCUSSION AND RESULTS

The efficiency of the method in calculation of the surface tension which plays a major role in multiphase problems is verified by Laplace law. The result shows less than 5% error at initial time steps.

Also, the verification of temperature-flow simulation is done by simulation of Rayleigh-Benard convection. Fig. 1 shows expected mechanical and thermal dependencies, based on rotating flows and temperature profiles.

Moreover, the effect of the side boundaries' conditions on flow and temperature behavior of falling liquid flow in a channel of gas are investigated. The order of falling flow velocity and the variation of pressure and temperature distribution are in line with expectations. Pressure changes in accordance with depth and the temperature of liquid increases as it contacts the heated wall.

The simulation of falling flow around the cylinder is done successfully and the details of flow behavior including the time evolution and location of circulating flow regarding pressure distribution and location of the three-phase interface are determined. These results show the accuracy of curved boundary conditions.

Finally, by restricting the inlet size, the falling film is simulated. The time evolution of film entrance to the domain, formation of the film around the tube, and separation of drops from the tube are presented in Fig. 2. The diameter of the separated drop is validated by the Yung equation [10].

This simulation is done by considering the Prandtl number of two phases and solving the temperature equation for both phases, without any simplification. As Fig. 3. Shows that the

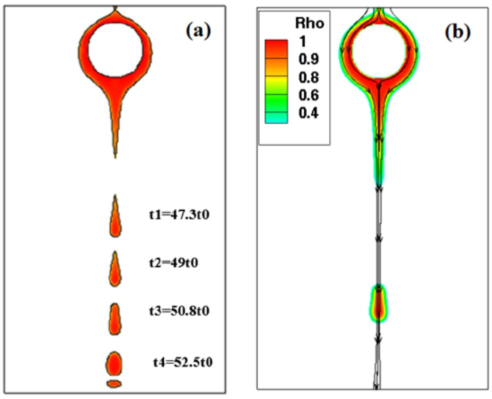

Fig. 2. (a)Time evolution of falling film formation, separation and leaving the domain, (b) Falling film streamlines at t3

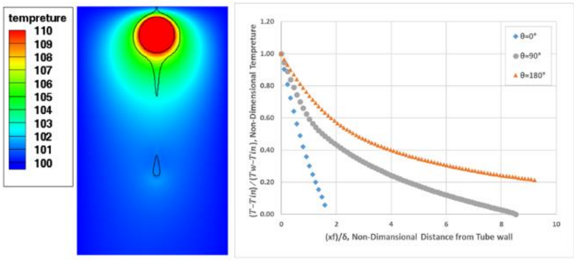

Fig. 3. Temperature distribution around the tube for the steady film at different circumferential angles.

thermal boundary layer thickness increase with increment of circumferential angles in accordance with theoretical results [11, 12].

Local Nusselt number is calculated by $Nu = \frac{h_l D}{\kappa_l} = \frac{\partial T / \partial r|_{r=0} D}{T_w - T_{in}}$ and the average Nusselt number is equal to $\overline{Nu} = \frac{1}{\pi}\sum_0^{\pi} \mathrm{Nu} = 2.18$. This value is equal to 3.66 for single-phase flow in constant temperature tubes and 4.36 for constant heat flux. Also, based on Peclet and Prandtl number of simulations, the comparison of results with the similarity solution of the natural convention is considerable. This value is $\overline{Nu_D} = \left\{0.6 + \frac{0.387 Ra_D^{1/6}}{\left[1+(0.559/\mathrm{Pr})^{9/16}\right]^{8/27}}\right\}^2 = 4.1$ for flooded cylinder in the pool of liquid [13]. The main reason for deviations could be the application limitations of correlations.

4. CONCLUSIONS

In this study, the flow and temperature behavior of two-phase falling flow around a horizontal tube has been simulated by the state-of-the-art Lattice Boltzmann method. The performance of boundary conditions and stability of models for determined geometrical and physical parameters have been concluded. The verifications including Laplace law, Rayleigh-Benard convection, and falling flow in the vertical channel have shown the accuracy of the method. By presenting the flow and temperature field of falling film, the formation and separation of film, and the local and average heat transfers are captured correctly. In Conclusion, despite the limitation of stability due to property ratios and gradients, this method presents reliable results.

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