Numerical Simulation of Liquid-vapor Phase Transition Induced by a Heated Surface in a Shear Flow

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Abstract. The influence of the external flow on the liquid-vapor phase transition is numerically studied in this work. The bubble growth and departure from a heated surface in a shear flow is realized through a pseudo-potential based lattice Boltzmann method. The benchmark test of the pool boiling induced by a single heated plate is adopted to validate the present method. The averaged heat flux, the bubble releasing frequency and flow features are presented, along with the effects of the flow intensity on them. It is shown that the external flow significantly enhances the heat transfer of the system in two respects: increasing the averaged heat flux and the bubble releasing frequency.

1. Introduction
Two-phase flows are very common in many natural processes as well as in industrial applications. The phase transition may occur under certain conditions in numerous industrial process involving two-phase flows, which is known as boiling heat transfer. The phase change has a significant influence on the liquid-vapor flows in terms of heat transfer rate as well as flow characteristics. It is important to pay much attention to the phenomena and mechanism of phase transition between liquid and vapor, which may provide a fundamental understanding of the behavior of heat transfer in two-phase flows.

The lattice Boltzmann method (LBM), which is based on the well-known Boltzmann equations, has emerged as a powerful numerical scheme for the simulation of particle suspensions, multiphase flow, microfluidics, and turbulence due to its several remarkable advantages since it was originated. In particular, the LBM is proved to be a promising method for dealing with interfacial flows such as solid-liquid and liquid-vapor flows. So far several lattice Boltzmann models have been proposed to simulate the liquid-vapor flows, including the color-gradient model [1], the pseudo-potential model [2-4] and the free-energy model [5]. Based on the popular pseudo-potential scheme [2], Gong and Cheng [3, 4] proposed an improved lattice Boltzmann model for liquid-vapor phase change. In their model, a new form of the source term in the energy equation was derived, which was shown to improve the numerical stability. Overall, the mechanism of liquid-vapor phase change is not well-understood even though much effort [6-8] has been devoted to it, owing to highly nonlinear effects in a two-phase system.

It is known that the major body of fluid is quiescent for the pool boiling, which, however, is not the general case in the industrial applications. In comparison with the pool boiling, things may become more complex when the major body of fluid is driven to move, such as Poiseuille flow and shear flow. The external flow may have a noticeable influence on the vapor bubble departure and the behavior of heat transfer. However, literature survey shows that the study on the liquid-vapor phase change in the Poiseuille flow or shear flow is rare. Much more attention should be paid to this issue. Therefore, the
objective of this work is to present a preliminary understanding of the bubble departure from a heated-surface in a shear flow. The improved LB model proposed by Gong and Cheng [3, 4] was used here.

2. Lattice Boltzmann Method

The two-phase lattice Boltzmann method [3, 4] is briefly introduced here. The single-relaxation-time lattice Boltzmann equations are expressed as,

\[ f_i(x + e_i \Delta t, t + \Delta t) - f_i(x, t) = -\frac{1}{\tau_f} \left[ f_i(x, t) - f_i^{(eq)}(x, t) \right] + \Delta f_i \]  \hspace{1cm} (1)

where \( f_i(x, t) \) is the density distribution function corresponding to the microscopic velocity \( e_i \), \( \Delta t \) is the time step of the simulation, \( \tau_f \) is the relaxation time. \( f_i^{(eq)}(x, t) \) is the equilibrium distribution function which is given by,

\[ f_i^{(eq)} = w_i \rho \left[ 1 + \frac{e_i \cdot u + (e_i \cdot u)^2}{2c_s^4} - \frac{u^2}{2c_s^2} \right] \]  \hspace{1cm} (2)

where \( c_s \) is the speed of sound, and \( w_i \) are weights related to the lattice model. \( \Delta f_i \) is the discrete form of the body force \( F \), which accounts for the inter-particle interaction force \( F_{int} \), the gravitational force \( F_g \) and the interaction force between solid surface and fluid \( F_s \). The fluid density and velocity are obtained through,

\[ \rho = \sum_i f_i, \rho u = \sum_i e_i f_i \]  \hspace{1cm} (3)

Due to the forcing term, the real fluid velocity of fluid \( U \) is modified by,

\[ \rho U = \sum_i e_i f_i + \frac{\Delta t}{2} F \]  \hspace{1cm} (4)

Similarly, the lattice Boltzmann equations are proposed [3, 4] to solve the fluid temperature \( T \),

\[ g_i(x + e_i \Delta t, t + \Delta t) - g_i(x, t) = -\frac{1}{\tau_g} \left[ g_i(x, t) - g_i^{(eq)}(x, t) \right] + \Delta t w_i \phi \]  \hspace{1cm} (5)

where \( \tau_g \) is the relaxation time for the fluid temperature and \( g_i^{(eq)}(x, t) \) is the corresponding equilibrium distribution function,

\[ g_i^{(eq)} = w_i T \left[ 1 + \frac{e_i \cdot U + (e_i \cdot U)^2}{2c_v^4} - \frac{U^2}{2c_v^2} \right] \]  \hspace{1cm} (6)

The source term \( \phi \) is responsible for the phase change, determined by,

\[ \phi = T \left[ 1 - \frac{1}{\rho c_v} \left( \frac{\partial p}{\partial T} \right)_p \right] \]  \hspace{1cm} (7)

where \( p \) is the pressure and \( c_v \) is the heat capacity. Then the temperature is obtained through,

\[ T = \sum_i g_i \]  \hspace{1cm} (8)

3. Validation

In the case of boiling, the bubble release frequency plays a key role in the process of heat transfer, which has been an everlasting topic from both numerical and theoretical points of view. According to the balance between adhesive force and buoyant force experienced by a vapor bubble, Fritz [9] obtained a formulation for the departure diameter which is related to the magnitude of gravity force \( (|g|) \).
where $\sigma$ is the surface tension, $\rho_l$ and $\rho_v$ is the density of liquid and vapor, respectively. Eq. (9) indicates a power-law relationship between $D_b$ and $g$, i.e. $D_b \sim |g|^{0.5}$. Similarly, Zuber [10] developed a formulation for the release frequency of bubbles,

$$ T = \frac{1}{f} \sim D_b \left[ \frac{\sigma |g| (\rho_l - \rho_v)}{\rho_l} \right]^{0.25} $$

From (9) and (10), it is easy to reach the following relationship: $T \sim |g|^{-0.75}$.

According to the present LBM simulations, Figure 1 shows the bubble releasing period of a single vapor bubble in the case of pool boiling. It can be clearly seen that the dependence of $T$ on the gravity force is realized.

4. Results
This work aims to present a preliminary study on the behavior of heat transfer in a shear flow. Figure 2 shows the schematic diagram of the present problem. The liquid of density $\rho_s$ and temperature $T_s$ is filled with in a two-dimensional domain with dimensions $L \times H$. A heated plate with length $L_h$ and temperature $T_w$ is placed in the middle of the bottom wall. The upper wall is driven to move with a constant speed $U_0$, which eventually results in the shear flow of the domain. The periodic boundary conditions are applied in the horizontal direction. In the simulations, the parameters are fixed as follows: $L = 600$, $H = 400$, $L_h = 10$, $T_w = 0.98T_c$, $T_p = 0.9T_c$, and $\rho_s = \rho_c = \rho_l$. $T_c$ denotes the critical temperature of the liquid, respectively. It should be stated here that the parameters are all in lattice units, which is very common for the lattice Boltzmann computations.
Figure 3 presents the instantaneous density contours at different times, which shows the vapor bubble growth and departure from the heated plate during one period. Three values of shearing velocity are taken into account, i.e. \( U_0 = 0 \) (top), 0.05 (middle) and 0.1 (bottom). Obviously, the case of \( U_0 = 0 \) corresponds to the classical pool boiling. As seen in Figure 3, the symmetry in bubble shape is destroyed when there is external flow (i.e. \( U_0 \neq 0 \)). As a result, there is a difference between the upstream and downstream contact angles of bubble, which becomes more significant at larger values of \( U_0 \). Moreover, it is seen that the existence of the external flow delays the generation of bubble neck, suggesting a different bubble releasing frequency.

![Figure 3](image)

Figure 3. Instantaneous density contours showing the bubble growth and departure from a heated surface under the external flow with different intensities, i.e. \( U_0 = 0 \) (top), \( U_0 = 0.05 \) (middle) and \( U_0 = 0.1 \) (bottom), at different times: (a) \( t = 0 \), (b) \( t = 0.25T \), (c) \( t = 0.5T \) and (d) \( t = 0.75T \).

Figure 4 shows the time history of the heat flux which is averaged over the heated surface for three values of \( U_0 \). It is clearly seen that the presence of external flow significantly increases the averaged heat flux, reflecting the fact that the external flow greatly enhances the heat transfer. However, as the flow intensity (\( U_0 \)) increases, the averaged heat flux does not monotonously increase. More importantly, Figure 4 also indicates that the bubble departure is accelerated when the value of \( U_0 \) is nonzero. In other word, the bubble releasing frequency is higher for \( U_0 \neq 0 \) than that for \( U_0 = 0 \). This, of course, increases the speed at which the heat is brought from the heated plate.
Figure 4. Time history of the averaged heat flux of the heated surface for different values of $U_0$.

Finally, Figure 5 summarizes the dependence of the bubble releasing period ($T$) on the flow intensity. It is expected that the time period for $U_0 > 0$ is smaller than that for $U_0 = 0$, which is in accord with the Figure 4. Furthermore, it is seen that the value of $T$ decreases as $U_0$ increases for $U_0 \leq 0.05$. However, a sudden jump can be observed as $U_0$ increases from 0.05 to 0.06, as shown in Figure 5. To be more specific, the value of $T$ is about 21000 for $U_0 = 0.05$, which becomes almost 30600 for $U_0 = 0.06$. This sudden increase indicates a significant change in the behavior of heat transfer for the system, which is expected to owing to the change in the flow features. So far the reason is unclear. It is worth additional simulations and further investigation.

Figure 5. Bubble releasing period as a function of the value of $U_0$.

5. Conclusion

In this work a two-phase lattice Boltzmann method is used to numerically study the influence of the external flow on the phase transition resulted from a heated surface in a cold liquid. The method is validated by simulating the pool boiling involving a single heated plate and comparing the bubble releasing frequency with the theoretical prediction. Numerical tests indicate that the external flow noticeably enhances the heat transfer of the system in two respects, i.e. increasing the averaged heat flux of the heated plate and increasing the bubble releasing frequency. Moreover, in comparison with the case of quiescent fluid, the period is seen to be always smaller in the presence of the external flow. However, it is strange that a sudden increase is seen in the time period of bubble departure at a certain flow intensity. The reason behind this is unclear.

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Reference

[1] A.K. Gunstensen, D.H. Rothman, S. Zaleski, G. Zanetti. Lattice Boltzmann model of immiscible fluids, Phys. Rev. A 43 (1991) 4320–4327.
[2] X. Shan, H. Chen, Lattice Boltzmann model for simulating flows with multiple phases and components, Phys. Rev. E 47 (1993) 1815–1820.
[3] S. Gong, P. Cheng, A lattice Boltzmann method for simulation of liquid-vapor phase-change heat transfer, Int. J. Heat Mass Trans. 55 (2012) 4923–4927.
[4] S. Gong, P. Cheng. Numerical investigation of droplet motion and coalescence by an improved lattice Boltzmann model for phase transitions and multiphase flows, Comput. Fluids 53 (2012) 93–104.
[5] M.R. Swift, E. Orlandini E, W.R. Osborn, J.M. Yeomans, Lattice Boltzmann simulations of
liquid-gas and binary fluid systems, Phys. Rev. E 54 (1996) 5041–5052.

[6] G. Hazi, A. Markus. On the bubble departure diameter and release frequency based on numerical simulation results, Int. J. Heat Mass Trans. 52 (2009) 1472–1480.

[7] S. Ryu, S. Ko. Direct numerical simulation of nucleate pool boiling using a two-dimensional lattice Boltzmann method. Nucl. Eng. Des. 248 (2012) 248–262.

[8] T. Sun, W. Li. Three-dimensional numerical simulation of nucleate boiling bubble by lattice Boltzmann method, Comput. Fluids 88 (2013) 400–409.

[9] W. Fritz. Maximum volume of vapour bubbles, Physik Zeitschr 36 (1935) 379–384.

[10] N. Zuber. Nucleate boiling. The region of isolated bubbles and the similarity with natural convection. Int. J Heat Mass Tran. 64 (1963) 122–132.