Influence of the external flow on the departure of vapor bubbles

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Abstract. The two-dimensional lattice Boltzmann method (LBM) is used here to numerically study the behaviors of phase change and vapor bubble departure in the presence of external flow. The external flow is induced by the action of shearing applied on the top boundary in this work. The bubble departure pattern is preliminarily revealed under different intensities of shearing. Furthermore, the influence of external flow on the heat transfer is examined. It has been found that the vapor bubbles are likely to depart from the heated plates in an alternative way. The external flow is shown to greatly enhance the heat transfer between the heated plates and the cold liquid. The velocity fields are also presented.

1. Introduction

Boiling is known as one of the best ways to cool a heated body effectively in a short time though the frequent occurrence of liquid-vapor transition, which has a wide range of engineering applications in combustion engines, heat exchangers, boilers, dryers, etc. As is known, the phase change has a significant influence on the vapor-liquid flows in terms of the heat transfer rate as well as the flow features. Therefore, much effort should be devoted to the study on the mechanisms of the growth and departure of vapor bubbles, which helps to improve our understanding of the behaviours of heat transfer in vapor-liquid flows.

The lattice Boltzmann method, 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 vapor-liquid 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]. Recently, a number of articles [6-8] reported the issue of pool boiling enhancement by surface modification. For example, Li et al. [6] and Ma et al. [7] numerically investigated the heat transfer of vapor-liquid flows on a type of hydrophilic-hydrophobic mixed surface. According to their work [6, 7], the heat transfer performance can be greatly improved. Wang [8] also presented a numerical work of the pool boiling on a modified surface with 36 hemispheres in different orientations.

For the classical pool boiling which has been studied extensively, the major body of fluid is at rest, which, however, is not the general case in the industrial applications. In comparison with the pool boiling, the situation is more complex when the major body of fluid is driven to move because the fluid inertia
(as well as the nonlinear effect) becomes significant. On the other hand, little effort was devoted to this subject in the past, which deserves much more attention. Therefore, the motivation of this work is to present a preliminary understanding of the bubble departure from the heated plates in a shear flow. The improved lattice Boltzmann model proposed by Gong and Cheng [3, 4] is used here.

2. Method
The two-phase lattice Boltzmann method [3, 4] is briefly introduced here, which is adopted to simulate the fluid flow. The single-relaxation-time lattice Boltzmann equations are expressed as,

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

(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,

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

(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 \( F_i \), 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,

\[ \rho = \sum_i f_i, \rho \cdot u = \sum_i e_i f_i \]  

(3)

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

\[ \rho U = \sum_i e_i f_i + \frac{\Delta t}{2} F \]  

(4)

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

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

(5)

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

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

(6)

The source term \( \phi \) is responsible for the phase change, determined by,
\[ \phi = T \left[ 1 - \frac{1}{\rho_c} \left( \frac{\partial p}{\partial T} \right)_p \right] \nabla \cdot \mathbf{U} \]  
\( \text{(7)} \)

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

\[ T = \sum_i g_i \]  
\( \text{(8)} \)

3. Results

This work aims to present a numerical study on the departure of vapor bubbles in the presence of external flow, which is depicted in Fig. 1. As shown in the figure, initially the two-dimensional domain with dimensions of \( L \times H \) is filled with saturated liquid of density \( \rho_s \) and temperature \( T_s \). There are two identical heated plates of length \( L_h \) and temperature \( T_w \) which are symmetrically placed on the bottom wall. The separation between them is fixed at \( 6L_h \) in this work. The liquid is subjected to shear as a result of the top wall moving at a constant speed \( U_0 \). Periodic boundary conditions are applied on the lateral direction. In the simulations, some parameters are fixed as follows: \( L = 1000, H = 800, L_h = 10, T_w = 0.98T_c, \rho_s = 2.32\rho_c \) and \( T_s = 0.9T_c \). Note that \( \rho_c \) and \( T_c \) are the critical density and temperature of the liquid, respectively.

Figure 1. Schematic diagram of the present problem.

Fig. 2 shows the time history of the heat flux at the center of each plate for \( U_0 = 0 \), i.e. the case of classical pool boiling. As expected, the heat flux is the same when there is no external flow, indicating that the liquid-vapor phase transition takes place synchronously on the two plates. In order to better illustrate the process of phase change, Fig. 3 presents a series of snapshots of instantaneous density distribution. Each snapshot is indicated with a circle in Fig. 2. It is clearly seen from Fig. 3(a) ~ (c) that two symmetrical vapor bubbles are generated on the two plates due to the phase change. Note that the heat flux reaches its maximum when the bubbles are going to depart from the bottom wall, as shown in Fig. 3(c). Then the two bubbles are merged into a bigger one at the time when they leave the bottom wall [Fig. 3(d)]. Due to the gravity effect, a crescent-moon like shaped bubble is seen, as shown in Fig. 3(e).
Figure 2. Time history of the heat flux at the center of each plate for $U_0 = 0$.

![Figure 2](image)

Figure 3. Instantaneous flow fields (density contours) at different times for $U_0 = 0$. Each instance is indicated with a circle in Fig. 2 (the same as below).

![Figure 3](image)

However, things become different in the presence of external flow. Fig. 4 shows the time history of heat flux at the center of each plate for $U_0 = 0.05$. It is observed that for the left plate the phase change occurs in a different way from the right plate due to the shear flow. Totally speaking, the heat flux is seen to be larger for the left plate because it is located upstream. Furthermore, it seems that the vapor bubbles depart from the two plates alternatively for a time (note the peak values of heat flux). This trend becomes more significant when increasing $U_0$, as shown in Fig. 5.
Figure 4. Time history of the heat flux at the centers of two plates for $U_0 = 0.05$.

Fig. 5 shows the time history of heat flux at the center of each plate for $U_0 = 0.1$. It is seen that the heat fluxes may be in-phase or out-of-phase, which suggests that the vapor bubbles depart from the two plates synchronously or alternatively. Obviously, the latter occurs more frequently. Figs. 4 and 5 indicate that the effects of external flow on the phase change and heat transfer during the process of boiling are significant. To present a better illustration, Fig. 6 shows a series of instantaneous density contours (each instance is indicated in Fig. 5) for $U_0 = 0.1$.

Figure 5. Time history of the heat flux at the centers of two plates for $U_0 = 0.1$.

It is seen from Figs. 6(a) and (d) that the vapor bubbles depart alternatively, in accord with the peak values of heat flux as shown in Fig 5. As one can see that in Fig. 6(f) the bubbles are generated at almost the same time, which suggests that they may depart simultaneously. After that, the phase change is again seen to take place in an alternative way, as shown in Fig. 5. Moreover, in comparison with the case of $U_0 = 0$ (Fig. 3), no bubble merging is seen when the liquid is subjected to shear. This may be considered as another significant influence of the external flow on the departure of vapor bubbles.
Finally, Figs. 7 and 8 show the instantaneous velocity fields for $U_0 = 0$ and $U_0 = 0.1$, respectively, which may provide a better understanding of the behaviors of heat transfer when there is external flow. As shown in Fig. 7, during the process of the vapor bubbles' generation flow circulations are observed on both sides of the bubbles. These flow circulations transfer some cold liquid into the nucleation sites, which eventually goes into the bulk liquid with a number of heat. This is the forced-convection heat transfer, which is repeated as the occurrence of the departure of bubbles. However, significant changes can be observed when there is external flow (Fig. 8). The cold liquid comes from the upstream due to the action of shearing, which greatly enhances the forced-convection heat transfer in terms of the increasing flow velocity.

**Figure 6.** Instantaneous flow fields (density contours) at different times for $U_0 = 0.1$.

**Figure 7.** Instantaneous velocity fields at different times for $U_0 = 0$.

**Figure 8.** Instantaneous velocity fields at different times for $U_0 = 0.1$.

### 4. Conclusion

This work presents a numerical study on the vapor bubble departure from two heated plates in the presence of external flow. It is shown that the influence of the shear flow on the liquid-vapor change
and heat transfer is significant. The vapor bubbles are seen to depart simultaneously from the two plates when there is no external flow, which, however, is not true for the shearing case. Instead, the vapor bubbles are likely to depart in an alternatively way, which greatly enhances the heat transfer between the heated plates and the cold liquid.

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