Effects of Wall Wettability on the Interaction between Vapor Bubbles in Pool Boiling

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Abstract. The interaction between vapor bubbles resulting from phase change in pool boiling was simulated through a two-phase lattice Boltzmann method. Two heated plates with constant heat flux were used to serve as the nucleate sites. The effects of wall wettability were examined. In doing so, three types of surface were taken into account, i.e. the hydrophilic surface, neutral surface and hydrophobic surface. It has been shown that the effects of wettability on the interaction between bubbles are significant in terms of the bubble mergence as well as the rate of heat transfer. In addition, the influence of the separation between the heated plates was also checked.

1. Introduction
For pool boiling the liquid-vapor phase transition may take place frequently resulting from heated walls, which gives rise to the departure of a large number of vapor bubbles at high frequency. The vapor bubbles usually carry much heat into the liquid and as a result enhance the heat transfer. So far pool boiling becomes an important technique of heat removal in many industrial and engineering fields, such as power generation, water purification and air separation.

It is well-known that the lattice Boltzmann method (LBM) has become a popular tool for simulating multiphase flows because of its high ability in dealing with the interface between different phases. Several lattice Boltzmann models were developed to simulate the boiling heat transfer involving the phase transition, such as the color gradient model [1], the pseudo-potential model [2] and the free-energy model [3]. Accordingly, much attention has been paid to the numerical study of heat transfer in the pool boiling [4-7]. Based on the pseudo-potential model [2], Gong and Cheng [8] proposed an improved LBM which was shown to have better ability in tracking the liquid-vapor interface. Through the improved LBM Gong and Cheng [9, 10] further investigated the effects of wall wettability as well as vapor phase’s thermal conductivity on the pool boiling heat transfer. In addition, Fang et al. [11] presented a two-dimensional study on the pool boiling with large liquid-vapor density ratio. Recently, the LBM was also used to numerically investigate the enhancement of heat transfer in pool boiling involving a type of hydrophilic-hydrophobic mixed surfaces. According to these studies [12-14], the use of the mixed surface may promote the bubble nucleation and departure, and hence enhance the heat transfer of system under certain conditions.

When there are two or more nucleate sites in the pool boiling, the interaction between vapor bubbles may become significant in the process of liquid-vapor transition. For instance, the bubble merging may occur under certain conditions, which has a noticeable influence on the bubble departure diameter as well as on the bubble release frequency. The situation is more complicated when the effects of wall wettability are taken into account. According to Gong and Cheng [9], the hydrophobic wall and the hydrophilic wall exhibit different boiling heat transfer features. For instance, a hydrophobic wall has a higher heat flux and a lower onset of nucleate boiling temperature than a
hydrophilic wall. It has also been revealed [9] that the three-phase contact line heat transfer is the important heat transfer mechanism for boiling on a hydrophobic wall. By contrast, the microlayer evaporation is the important heat transfer mechanism for boiling on a hydrophilic wall [9]. However, literature survey shows that the effects of wall wettability on the bubble interactions is far from well understood. This motivates the present work.

2. Method

The two-phase lattice Boltzmann method developed by Gong & Cheng [8] was adopted here to solve the flow and temperature fields. The lattice Boltzmann equations for updating the fluid density ($\rho$) and velocity ($\mathbf{u}$) are expressed as,

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

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 given by,

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

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, which accounts for the inter-particle interaction force, the gravitational force and the interaction force between solid surface and fluid. The fluid density and velocity are obtained through,

$$\rho = \sum_i f_i, \rho \mathbf{u} = \sum_i e_i f_i$$

Due to the forcing term ($\mathbf{F}$), the real fluid velocity of fluid ($\mathbf{U}$) is modified by,

$$\rho \mathbf{U} = \rho \mathbf{u} + \frac{\Delta t}{2} \mathbf{F}$$

Similarly, another set of lattice Boltzmann equations were used here to update the fluid temperature ($T$),

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

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

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

The source term $\phi$ is responsible for the liquid-vapor phase change, determined by,

$$\phi = T \left[ 1 - \frac{1}{\rho c_v} \left( \frac{\partial p}{\partial T} \right)_\rho \right] \nabla \cdot \mathbf{U}$$

where $p$ is the pressure and $c_v$ is the heat capacity. Then the temperature is obtained through,

$$T = \sum_i g_i$$

Note that the Peng-Robinson (P-R) equation of state [15] was adopted in this work to account for the pressure involving phase transition.
For both \( f_i \) and \( g_i \), the 9-velocity model in two dimensions (i.e. D2Q9) was used here, which has the following discrete velocity vectors,

\[
e_i = \begin{cases} 
(0,0), & \text{for } i = 0, \\
(\pm 1,0)c, & \text{for } i = 1 \text{ to } 4, \\
(\pm 1,\pm 1)c, & \text{for } i = 5 \text{ to } 8,
\end{cases}
\]

where \( c = \Delta x/\Delta t \) is the lattice speed and \( \Delta x \) is the lattice space. For simplicity, both the lattice space and the time step are set to be 1 in the simulations, i.e. \( \Delta x = \Delta t = 1 \).

3. Problem Description and Validation

This work aims to present a two-dimensional numerical analysis on the interaction between vapor bubbles which depart from walls due to the liquid-vapor transition. The present problem is depicted in Figure 1. Two heated plates of length \( L_h \) and heat flux \( q_h \) are placed on the bottom wall. For simplicity, the thickness of the plates is assumed to be zero. The separation between the plates is denoted as \( L_d \). For all computations, the saturated liquid of density \( \rho_s \) and temperature \( T_s \) is filled with in a computational domain with dimensions \( L \times H \). The periodic boundary conditions are applied in the horizontal directions. For the upper boundary, a constant pressure is always maintained. Except for the heated plates, the bottom wall is assumed to be adiabatic. In the simulations some parameters are fixed as follows (in lattice units): \( L = 400, H = 600, L_h = 5, q_h = 0.001 \) and \( T_s = 0.9T_c \) (\( T_c \) is the critical temperature of the liquid). Note that the choice of \( T_s = 0.9T_c \) results in a liquid/vapor density ratio of \( \rho_v/\rho_l \approx 10 \).

![Figure 1. Schematic diagram of the present problem and notations used in this work.](image)

For the fluid-solid interaction, the following adhesive force model proposed by Li et al. [16] was considered,

\[
F_i = -G_s \psi^2(x) \sum_i w_i s(x + e_i)e_i
\]

where \( G_s \) is the interaction strength and \( s(x) \) is the indicator function which is equal to 0 or 1 for a fluid phase or a solid phase, respectively. \( \psi(x) \) is the so-called “effective mass” [8] and is a function of the local fluid density and temperature. Note that negative values of \( G_s \) refer to hydrophilic surfaces while positive values of \( G_s \) represent hydrophobic surfaces.

In order to validate our computational code, the benchmark test of pool boiling with a single nucleate site was considered. In doing so, the physical model shown in Figure 1 was adopted except that only one heated plate was placed on the bottom wall. The parameters are chosen the same as the ones described above. Figure 2 shows the bubble release period \( \tau_b \) with increasing gravitational force \( g \), along with the least-square fitting curve. Obviously, the simulation results agree well with the
theoretical prediction, i.e. \( t_p \sim g^{0.75} \), which indicates that our computational code is able to accurately resolve the phase change in pool boiling.

\[ \text{Figure 2. Bubble release period (} t_p \text{) as a function of gravitational force (} g \text{) for } G_s = 0.3. \text{ Triangles: simulation results, dashed line: fitting curve.} \]

4. Results
In order to study the effects of wall wettability on the phase change, three values of \( G_s \) were taken into account, i.e. \( G_s = -0.3, 0 \) and 0.3, which are corresponding to the hydrophilic surface, the neutral surface and the hydrophobic surface. As is known, the bubble mergence may occur when the bubbles are close enough to each other, which has a significant influence on the performance of heat transfer in pool boiling. In view of this fact, for a fixed \( G_s \), the separation of the plates (\( L_d \)) was varied from \( 10L_h \) to \( 20L_h \).

Figure 3 shows the instantaneous density contours during one period for \( L_d = 10L_h \) at \( G_s = -0.3 \) (corresponding to the hydrophilic surface), illustrating the departure and interaction of bubbles induced by the two heated plates. It is clear that two bubbles appear symmetrically on the bottom wall due to the liquid-vapor phase change, as shown in Figure 3(a, b). Because of small separation, the two bubbles eventually merge into a larger one before departure [Figure 3(c, d)]. For the neutral surface (i.e. \( G_s = 0 \)), a little difference in the interaction between bubbles can be seen. As shown in Figure 4, the general features are very similar to those shown in Figure 3. However, Figure 4(a) indicates the bubbles do not merge during the next half cycle. Therefore, the bubble mergence takes place in an alternative manner at \( G_s = 0 \).

\[ \text{Figure 3. Instantaneous density fields showing the process of vapor bubble departing from the wall during one period for } L_d = 10L_h \text{ at } G_s = -0.3 \text{ (hydrophilic surface).} \]
Figure 4. Instantaneous density fields showing the process of vapor bubble departing from the wall during one-half period for \( L_d = 10L_h \) at \( G_s = 0 \) (neutral surface).

The situation becomes completely different for the hydrophobic surface, i.e. \( G_s = 0.3 \), as shown in Figure 5. It seems like that there is only one nucleate site on the bottom wall all the time because there is no sign of bubble mergence. Figure 5 also shows that the contact angle between the interface liquid/solid and the tangent to the liquid/gaseous is clearly larger than 90 degree, which is caused by the wettability of the hydrophobic plates. In comparison with Figures 3 and 4, another significant difference is that the residual bubble on the hydrophobic surface is much larger right after the departure of bubble(s) due to the low wettability. The residual bubble may accelerate the departure of bubbles and has a positive effect on the heat transfer in pool boiling.

Figure 5. Instantaneous density fields showing the process of vapor bubble departing from the wall during one period for \( L_d = 10L_h \) at \( G_s = 0.3 \) (hydrophobic surface).

On the other hand, the bubble mergence cannot be seen for all values of \( G_s \) considered when the separation between the heated plates is large enough (e.g. \( L_d = 20L_h \)). Figure 6 shows the density contours at different times during one period for \( L_d = 20L_h \) at \( G_s = -0.3 \), illustrating a different pattern of bubble departure in comparison with Figure 3. Two vapor bubbles are generated from the heated plates due to the phase change, which depart from the wall simultaneously and do not merge all the time.

Figure 6. Instantaneous density fields showing the process of vapor bubble departing from the wall during one period for \( L_d = 20L_h \) at \( G_s = -0.3 \) (hydrophilic surface).

Similar behaviour is also seen for \( G_s = 0 \) and 0.3, as shown in Figure 7 and Figure 8, respectively. In particular, the separation between bubbles is seen to be very small at \( G_s = 0.3 \) when the bubbles are
about to depart from the wall [Figure 8(d)]. However, the bubble mergence is still absent. Moreover, in comparison with Figure 6, one significant difference is seen at \( G_s = 0 \) and 0.3. After the departure of bubbles, noticeable residual bubble is seen in both Figures 7 and 8. As mentioned above, the residual bubble has a significant influence on the rate of heat transfer, which may be better illustrated by the temperature at the centers of the heated plates (\( T_h' \)) shown in Figure 9.

![Figure 7](image1.png)

**Figure 7.** Instantaneous density fields showing the process of vapor bubble departing from the wall during one period for \( L_d = 20L_h \) at \( G_s = 0 \) (neutral surface).

![Figure 8](image2.png)

**Figure 8.** Instantaneous density fields showing the process of vapor bubble departing from the wall during one period for \( L_d = 20L_h \) at \( G_s = -0.3 \) (hydrophobic surface).

As shown in Figure 9, the time history of \( T_h' \) reveals a periodic pattern of bubble departure for the present problem. For \( G_s = 0 \) and 0.3, the results are very similar in terms of both amplitude and frequency of the value of \( T_h' \). This is consistent with the observation made in Figures 7 and 8. By contrast, the hydrophilic surface (i.e. \( G_s = -0.3 \)) results in a different pattern of bubble departure. As shown in Figure 9, the value of \( T_h' \) remains at its maximum for a longer time during one period at \( G_s = -0.3 \), which indicates that the rate of heat transfer is higher at \( G_s = 0 \) and 0.3. The primary reason behind this phenomenon is that there is little residual bubble on the wall right after the departure of bubbles for the hydrophilic surface, as shown in Figure 6.

![Figure 9](image3.png)

**Figure 9.** Time history of the temperature (\( T_h' \)) at the centers of the heated plates for \( L_d = 20L_h \) at different \( G_s \). Note that the value of \( T_h' \) is dimensionless which is normalized through \( T_h' = T_h/T_c \).
5. Conclusion
A two-phase lattice Boltzmann method was used to study the interaction between vapor bubbles resulting from liquid-vapor phase change in pool boiling. Two heated plates with constant heat flux were employed to serve as the nucleate sites. Results show that the surface wettability has a noticeable effect on the bubble interaction as well as the heat transfer of pool boiling. When the separation between the heated plates is small, the bubble mergence is seen for both hydrophilic and neutral surfaces. However, the pattern of bubble departure for the neutral surface is very similar to that for the hydrophobic surface when no bubble mergence happens. In particular, there is little residual bubble on the hydrophilic surface right after the bubble departure, leading to the fact that the temperature of the heated plates remains at its maximum value for a long time during one period.

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7. Reference
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