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# Lattice Boltzmann Simulation of Vapor Bubble Growth from Two Heated Plates with Different Temperatures

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***Abstract*—In this work the pseudo-potential based lattice Boltzmann method is adopted to numerically study the bubble departure from two heated plates with different temperatures. By doing this the temperature for one plate is fixed while that for the other one is varied to examine the effect of the inhomogeneity on the heat transfer in pool boiling. The present method is validated by the benchmark test of a single bubble growth and departure from a heated plate. The liquid-vapor phase transition as well as the resulting heat flux is presented under different conditions. It has been found that the inhomogeneity in the temperature is of great significance for the heat transfer in pool boiling.**

***Keywords*—vapor bubble; phase change; lattice boltzmann method***

## I. INTRODUCTION

Two-phase flows are very common in many natural processes such as the weather as well as in industrial applications such as combustion engines, heat exchangers, boilers, dryers. 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. As a consequence, it is important to pay much attention to the phenomena and mechanism of phase transition between liquid and vapor, which helps to provide a better understanding of the behavior of heat transfer in two-phase flows.

The lattice Boltzmann method (LBM), which is based on the well-known Boltzmann equation, 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, 3] and the free-energy model [4]. The pseudo-potential model which was first proposed by Shan and Chen [2], has become the most popular model due to its conceptual simplicity and computational efficiency. Based on the pseudo-potential scheme [2], Gong and Cheng [3] 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 demonstrated to improve the numerical stability.

Over the past decades the problem of a single bubble departure from a heated wall (also known as micro-heater) is extensively studied [5-7] at the numerical level. However, the situation is quite different and complex when multiple heated plates are involved, which is not well-understood owing to the nonlinear effect in the two-phase flows. In this case the hydrodynamic interaction between bubbles arises and may play a key role in the process of phase change as well as the resulting heat transfer. This motivates the present work. Overall, the purpose of this study is to provide a preliminary understanding of the characteristics of heat transfer at the presence of more than one heated plates having different temperatures.

## II. LATTICE BOLTZMANN METHOD

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

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

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

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

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 $\boldsymbol{F}_{int}$, the gravitational force $\boldsymbol{F}_g$ and the interaction force between solid surface and fluid $\boldsymbol{F}_s$. The fluid density and velocity are obtained through,

$$\rho = \sum_i f_i, \rho \boldsymbol{u} = \sum_i \boldsymbol{e}_i f_i \tag{3}$$

Due to the forcing term, the real fluid velocity of fluid $\boldsymbol{U}$ is modified by,

$$\rho \boldsymbol{U} = \sum_i \boldsymbol{e}_i f_i + \frac{\Delta t}{2} \boldsymbol{F} \tag{4}$$

similarly, the lattice Boltzmann equations are proposed [3] to solve the fluid temperature $T$,

$$g_i(\boldsymbol{x} + \boldsymbol{e}_i \Delta t, t + \Delta t) - g_i(\boldsymbol{x}, t) = -\frac{1}{\tau_g}\left[ g_i(\boldsymbol{x}, t) - g_i^{(eq)}(\boldsymbol{x}, t) \right] + \Delta t w_i \phi \tag{5}$$

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

$$g_i^{(eq)} = w_i T \left[ 1 + \frac{\boldsymbol{e}_i \cdot \boldsymbol{U}}{c_s^2} + \frac{(\boldsymbol{e}_i \cdot \boldsymbol{U})^2}{2c_s^4} - \frac{\boldsymbol{U}^2}{2c_s^2} \right] \tag{6}$$

The source term  is responsible for the phase change, determined by,

$$\phi = T \left[ 1 - \frac{1}{\rho c_v} \left( \frac{\partial p}{\partial T} \right)_\rho \right] \nabla \cdot \boldsymbol{U} \tag{7}$$

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

$$T = \sum_i g_i \tag{8}$$

## III. VALIDATION

The present method is validated through the computations involving a single bubble released from a heated plate. The length of the heated plate is 30 (in lattice unit, the same as below). The computational domain is 330×1200. The saturation temperature of the liquid is fixed at $T_s$=0.9$T_c$ ($T_C$ is the critical temperature) and the temperature of the heated plate is chosen as $T_w$=0.98$T_c$ (unless otherwise specified). The P-R EOS (Peng-Robinson equation of state) is used to determine the fluid pressure.

In the case of pool boiling, the departure diameter ($D_b$) as well as the release frequency ($f$) of bubbles 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 [8] obtained a formulation for the departure diameter which is related to the magnitude of gravity force ($|g|$),

$$D_b \sim \sqrt{\frac{\sigma}{|g|(\rho_L - \rho_G)}} \tag{9}$$

where $\sigma$ is the surface tension, $\rho_L$ and $\rho$G 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 [9] developed a formulation for the release frequency of bubbles,

$$T = \frac{1}{f} \sim D_b \left[ \frac{\sigma |g| (\rho_L - \rho_G)}{\rho_L^{\,2}} \right]^{-0.25} \tag{10}$$

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

According to the present LBM simulations, Fig. 1 shows the departure diameter and release period of a single vapor bubble in the case of pool boiling. It can be clearly seen that the dependence of $D_b$ or $T$ on the gravity force is realized.

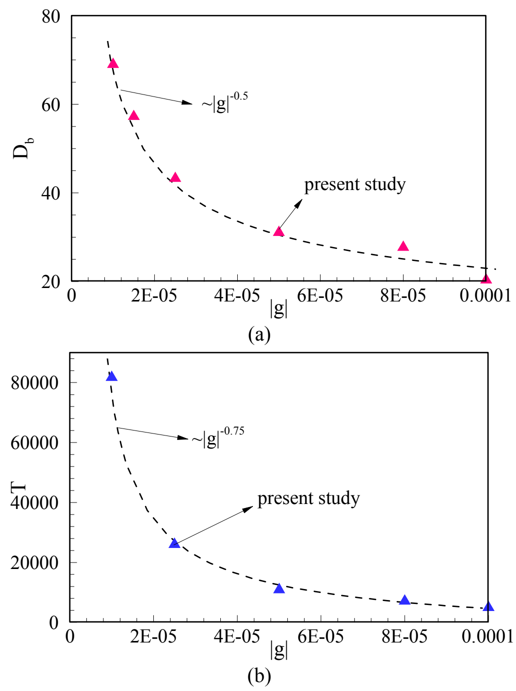


FIGURE I. DEPARTURE DIAMETER ($D_B$) AND RELEASE PERIOD (T) FOR A SINGLE BUBBLE RELEASING FROM THE HEATED WALL AS A FUNCTION OF GRAVITY FORCE (|G|)

## IV. RESULTS AND DISCUSSION

The present problem is illustrated in Fig.2. A computational domain, consisting of a 192×478 lattice structure, is initially filled with the saturated liquid with $T_S$=0.9$T_C$ and $\rho_S$=2.32. Two heated plates, which are referred as to plate1 and plate2, respectively, are symmetrically placed on the bottom wall. The constant temperature $T_{W1}$ as well as $T_{W2}$ is applied on the heated plate, respectively. The value of $T_{W1}$ is fixed at 0.97$T_C$ unless otherwise is specified. The boundary conditions are also shown in Fig. 2. In the following, the value of $T_{W2}$ is varied to study the effect of bubble departure on the heat transfer.

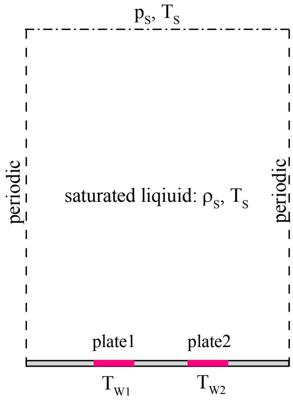


FIGURE II. SCHEMATIC DIAGRAM OF THE PRESENT PROBLEM

For the case of $T_{W2}$=0.97$T_C$ (i.e. $T_{W1}$=$T_{W2}$), two vapor bubbles are symmetrically generated from both heated plates, as shown in Fig. 3(a) and (b). Due to the effect of buoyant force the bubbles are gradually growing and expanding, which leads to the occurrence of bubble merging, as seen in Fig. 3(c). Then, a larger bubble appears and departs from the bottom wall [Fig. 3(d) and (e)]. However, when the temperatures of heated plate are not identical the situation becomes different, as shown in Fig. 4 and Fig. 5.

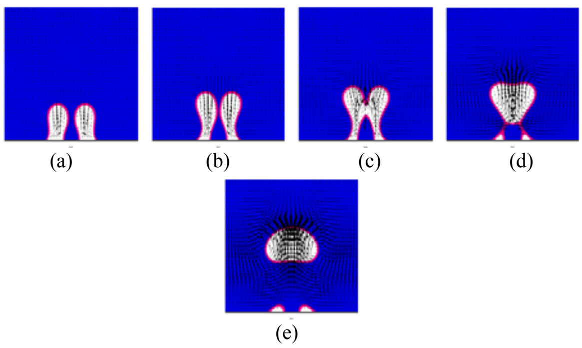


FIGURE III. INSTANTANEOUS FLOW FIELD (FLUID DENSITY AND VELOCITY, THE SAME AS BELOW) AT DIFFERENT TIMES FOR $T_{W1}$=0.97$T_C$ AND $T_{W2}$=0.97$T_C$

Fig. 4 presents the instantaneous flow field at different times for $T_{W2}$=0.96$T_C$, which shows the process of a vapor bubble growing and departing from the left plate (plate1). The bubble neck is clearly seen in Fig. 4(c) before its departure due to the significant buoyant effect. However, no vapor bubble is generated from the right plate (plate2) owing to the absence of a nucleus on the plate, as shown in Fig. 4. For the case of $T_{W2}$>$T_{W1}$, however, a nucleus is clearly seen on each heated plate [Fig. 5(a)]. In comparison with the case of $T_{W2}$=0.97$T_C$ (Fig. 3), the bubble is departing from the plate in an alternative manner. As a result, no bubble merging is observed this time.

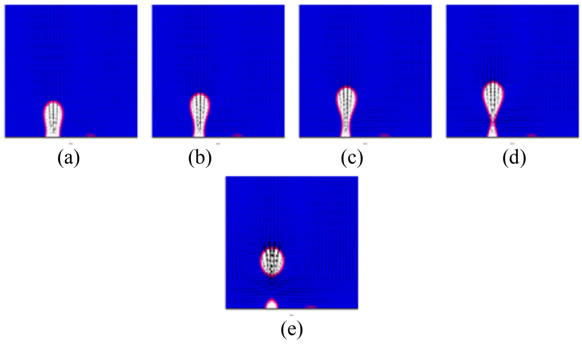


FIGURE IV. INSTANTANEOUS FLOW FIELD AT DIFFERENT TIMES FOR $T_{W1}$=0.97$T_C$ AND $T_{W2}$=0.96$T_C$

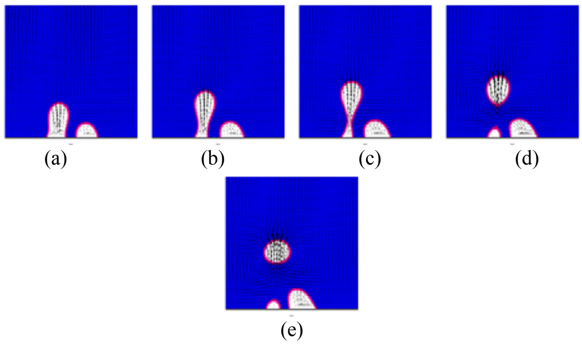


FIGURE V. INSTANTANEOUS FLOW FIELD AT DIFFERENT TIMES FOR $T_{W1}$=0.97$T_C$ AND $T_{W2}$=0.98$T_C$

The effect of the inhomogeneous temperatures of heated plate on the heat flux of plates is illustrated in Fig. 6 and Fig. 7. As expected, for the case of $T_{W2}$<$T_{W1}$, the heat flux of plate2 is much smaller than that of plate1 because there is only natural convection heat transfer from plate1 instead of forced convection, as seen in Fig. 6. When $T_{W2}$ is greater than $T_{W1}$, the heat flux is seen to be larger for plate2 than for plate1, which shows a nearly anti-phase relationship. This is consistent with the observation of an alternative way of bubble departure.

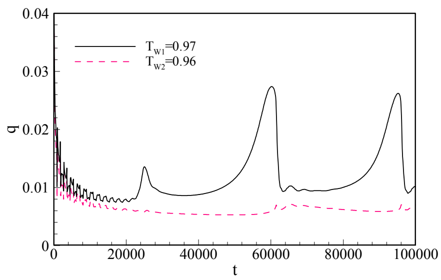


FIGURE VI. TIME HISTORY OF AVERAGED HEAT FLUX OF EACH PLATE FOR $T_{W2}$=0.96$T_C$

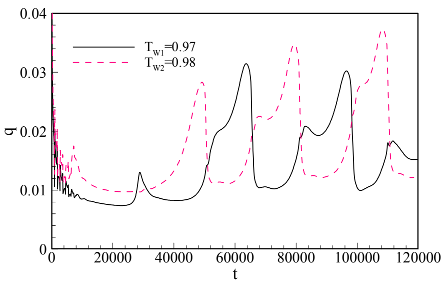


FIGURE VII. TIME HISTORY OF AVERAGED HEAT FLUX OF EACH PLATE FOR $T_{W2}$=0.98$T_C$

The comparison of the heat flux of plate1 is made for three sets of $T_{W2}$, i.e. $T_{W2}$=0.96$T_C$, 0.97$T_C$ and 0.98$T_C$, which is shown in Fig. 8. The influence of $T_{W2}$ on the heat transfer of plate1 is significant. When $T_{W2}$ is not identical to $T_{W1}$, the occurrence of bubble departure from plate1 is always delayed. The reason behind this may be the hydrodynamic interaction resulted from the heated plates with different temperatures, which will be further studied in the next future.

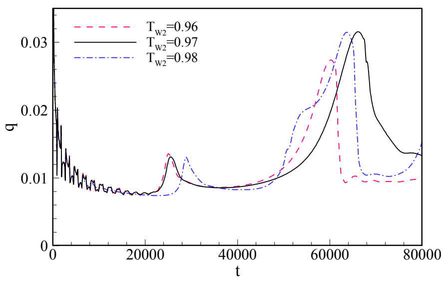


FIGURE VIII. COMPARISON OF THE AVERAGED HEAT FLUX OF PLATE1 FOR THREE SETS OF $T_{W2}$, I.E. $T_{W2}$=0.96$T_C$, 0.97 $T_C$ AND 0.98 $T_C$

## V. CONCLUSION

In this wok a pseudo-potential scheme based lattice Boltzmann method is adopted to numerically study the bubble departure from two heated plates with different temperatures in pool boiling. The problem of a single vapor bubble released from a heated plate is simulated to validate the present work. The computed bubble release frequency as well as the departure diameter, showing a power-law relation with the gravity force, agrees well with the corresponding theoretical prediction. The bubble merging is observed when the temperatures of two plates are identical, which, however, does not occur for the other cases. In addition, the bubble departure is seen to be delayed when the temperatures of plates are not identical. In particular, the phase change may not take place if the temperature for one of the plates is low enough.

## ACKNOWLEDGEMENT

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