Mesoscale simulation of pool boiling on a cylinder heater under controlled wall temperature

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Abstract. In this study, a phase-change LB model was adopted to simulate the pool boiling on a cylinder. The simulation results showed that the phase-change phenomenon occurred firstly at the top of the cylinder and produced the bubble at a low heating temperature on hydrophilic surface. With the increase of heating temperature, new nucleation sites appeared on both sides of the cylinder. And under the action of buoyancy, the bubbles on both sides risen to the top and merged and then departed. When the heating temperature reached a certain level, a bubble appeared at the bottom of the cylinder and grown steadily. Eventually, the bottom bubble would wrap the cylinder completely so the cylinder entered the film boiling. For hydrophilic surface, the temperature and heat flux over the cylinder surface would vary with the formation of bubble which was similar with flat heater. And we conducted the boiling curve (from the natural convection to the film boiling) on the cylinder by the numerical simulation.

1. Introduction

Over the past few decades, many researchers studied the heat transfer process of saturated pool boiling on a flat heater. Bubble dynamic behaviour[1], heat transfer efficiency[2] of the heater and boiling curve had been studied in detail by experiments and numerical simulation. But in actual engineering design, the flat heater could not meet all engineering needs, therefore many non-flat heaters began to obtain more and more attentions. These include convex heaters[3], concave heaters[4], cylindrical heaters and more. Many researches about the bubble dynamic and heat transfer based on these heaters are developing. Recent years, cylindrical heater has attracted widespread attention. Bubble kinetic behaviors including its formation and merging on a thin cylinder was investigated by Saha and Das[5]. The mixed state of film boiling on cylinder surface and the Nusselt number around the cylinder was conducted by numerical simulation[6]. But complete studies of the saturated boiling (from natural convection to nucleate boiling, to transition boiling to film boiling) on cylinder surface are still lacking as far as we are aware.

In this paper, lattice Boltzmann method (LBM)[7] is adopted to investigate the boiling on cylinder surface numerically. Through this method, the separation of vapour-liquid phase can be realized accurately, and the complex boundary can be implemented without any additional computation. We simulated the bubble’s growth, merging and departure on a cylinder heater for different heating temperatures. And the characteristics of the temperature and heat flux distributions on the cylinder were revealed. Besides, the boiling curve on the cylinder was numerically simulated from natural convection to stable film boiling.
2. Numerical simulation method
A phase-change lattice Boltzmann model[7] conducted by Gong–Cheng was adopted. And an introduction of this model is given in this section.

2.1. Isothermal multiphase LB model
In this LB model, the evolution for the density distribution function is obtained by:

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

where \(f_i(x, t)\) is the distribution function, and \(e_i\) is the discrete speed, \(\tau\) is the relaxation time, and \(f_i^{eq}(x, t)\) is the equilibrium distribution function:

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

with \(\omega_i\) is the weighting coefficient, \(c_s\) is the sound speed in LBM. And the body force term \(\Delta f_i(x, t)\) is given by:

\[
\Delta f_i(x, t) = f_i^{eq}(\rho(x, t), u + \Delta u) - f_i^{eq}(\rho(x, t), u)
\]

where \(\Delta u = F \delta t / \rho\), and \(F\) is given by:

\[
F = F_i(x) + F_g(x) + F_{int}(x)
\]

where \(F_i\) is the interaction force between fluid and solid, \(F_g\) is the gravity or buoyancy, \(F_{int}\) is the interaction force for phase separation which is expressed by:

\[
F_{int}(x) = -G \psi(x) \sum_\tau \omega_\tau \psi(x + e_\tau \delta t) e_\tau
\]

where \(\psi(x) = \sqrt{\frac{2(\rho - \rho c_s^2)}{c_o g}}\) is the effective mass, and \(c_o = 6.0\) for D2Q9 lattice structure. And the (R-K) equation of state is adopted, which is given by:

\[
p = \frac{\rho RT}{1 - h \rho} - \frac{a \rho^3}{1 + b \rho}
\]

And the surface wettability is implemented by \(F_i\), which is given by:

\[
F_i(x) = -\left(1 - e^{-\rho s(x)}\right) s(x + e_\tau \delta t) e_\tau
\]

where \(s(x)\) is equal to 1 if \(x\) is in solid, else it is 0.

And the \(F_g\) is given by:

\[
F_g(x) = (\rho(x) - \rho_{ave}) g
\]

where \(g\) is the gravitational acceleration and \(\rho_{ave}\) is the average density of the whole domain at every time step.

And the density and velocity are calculated by:

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

It should be noted that \(u\) is not the actual fluid velocity, and the actual fluid velocity \(U\) is given by:

\[
\rho U = \sum_i e_i f_i + 0.5 \delta F
\]

2.2. Energy equation model
The evolution for the temperature distribution function is expressed by:
g_i(x + \varepsilon_i \delta_t, t + \delta_t) - g_i(x, t) = -\frac{1}{T_r} \left[ g_i(x, t) - g_i^{eq}(x, t) \right] + \delta_t \omega_i \phi \tag{11}

where \(T_r\) is the temperature relaxation time, and the temperature equilibrium distribution function \(g_i^{eq}(x, t)\) is given by:

\[ g_i^{eq} = \omega_T \left[ 1 + \frac{\varepsilon_i \cdot U}{c_i^2} + \left( \frac{\varepsilon_i \cdot U}{2c_i^2} \right)^2 - \frac{U \cdot U}{2c_i^2} \right] \tag{12} \]

And the source term \(\phi\) which is responsible for phase change, is expressed by:

\[ \phi = T \left[ 1 - \frac{1}{\rho_c} \left( \frac{\partial \rho}{\partial T} \right)_p \right] \nabla \cdot U \tag{13} \]

The temperature is given by:

\[ T = \sum_i g_i \tag{14} \]

3. Results and discussion

3.1. Computation domain and boundary conditions

In the rest simulations, characteristic length \(l_u\), characteristic velocity \(u_0\), characteristic time \(t_0\) are given by:

\[ l_0 = \sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}; \quad u_0 = \sqrt{\frac{g}{l_l}}; \quad t_0 = l_0 / u_0 \tag{15} \]

where \(\sigma\) is the surface tension, \(\rho_l\) and \(\rho_v\) are saturated liquid density and saturated vapour density.

In this study, the lattice structure was set to be \(300 \times 1000\) \((L_x \times L_y = 18.8 l_0 \times 62.5 l_0)\) as shown in Figure 1. A cylinder with the radius \(R\) is set at the position of \((L, H) = (9.4 l_0, 9.4 l_0)\). And an internal heater with the radius \(r\) is in the cylinder, noted that the heater’s temperature is expressed by \(J_u = c_p(T_u - T_{sat}) / h_{in}\), where \(T_u\) and \(T_{sat}\) are the heater’s temperature and the water’s saturation temperature, respectively, \(c_p\) and \(h_{in}\) are the water’s specific heat and latent heat. The upper boundary of the calculation region is convective boundary and the bottom is an adiabatic wall, left and right
sides are periodic boundary. Initially, the domain is filled with saturated liquid at $T_{sat} = 0.9 T_c$. Noted that $T_c$ is the critical temperature, and $\rho_r = 5.426$, $\rho_v = 0.8113$.

3.2. Bubble growth at different heat temperature

Figure 2 shows the different bubble growth forms (onset of nucleate boiling, multi-bubble nucleate boiling, transition-boiling and film boiling) at different $Ja$ on hydrophilic wall. Noted that the wall’s contact angle is $\theta = 60^\circ$, $R = 1.88 l_h$ and $r = 1.25 l_h$. As shown, the bubble nucleation sites did not appear immediately on the cylinder. At low heating temperature $Ja = 0.08$, a bubble formed at the top of the cylinder firstly. This was because the liquid flowed from the bottom of the cylinder to the top, as a result, the heat from the cylinder surface condensed at the top so the bubble appeared firstly on the top. At $Ja = 0.10$, the nucleation sites appeared on the cylinder, the bubbles merged above the cylinder and formed a larger bubble. This phenomenon was also observed by Saha and Das[5]. And the merging of bubbles accelerated the departure of bubbles from the wall because of the larger buoyancy for larger bubble. At $Ja = 0.14$, the upper surface of the cylinder continuously produced bubbles and departed. It should be noted that a bubble was formed at the bottom of the cylinder which was different from $Ja = 0.08$, 0.10. Due to the bottom bubble was in the force equilibrium state, it grown steadily without any deviation. With the increasing of its volume, the surface of the cylinder was gradually covered by the vapour. When the cylinder was completely wrapped by the vapour, it’s boiling regime changed to the film boiling from the nucleate boiling, and this was the transition-boiling on the cylinder surface. This change of the boiling regime would not occur on the flat heater, because no bubble could grow steadily and continuously on the flat heater during nucleate boiling. At $Ja = 0.20$, the liquid would evaporate over the cylinder totally, therefore the cylinder entered the stable film boiling directly. It should be noted that when the bubble grown to a certain volume, necking occurred at the top of bubble because of the buoyancy as shown in Figure 2. Finally, the necking ruptured and a bubble detached from the cylinder. The phenomenon of the film boiling was similar to the previous work[6].

Figure 2. Bubble growth forms at $Ja = 0.08, 0.10, 0.14, 0.20$ on hydrophilic wall.

Figure 3. Temperature distribution on the right surface of the cylinder $Ja = 0.08$.

Figure 4. Heat flux distribution on the right surface of the cylinder $Ja = 0.08$. 
Figure 3 and Figure 4 shows the temperature and heat flux distribution on right surface of the cylinder (deviation angle $\alpha$ from $-90^\circ$ to $90^\circ$). It could be seen that the local temperature was lower but the local heat flux was higher at the place where the bubble existed. Therefore, the bubbles could improve the local heat transfer efficiency. This was consistent with the flat heater[8]. Noted that for hydrophilic flat wall, a microlayer existed underneath the bubble[8][9] because of the low temperature and the high heat flux. This microlayer played an important role in boiling heat transfer on the hydrophilic wall. And our LBM simulation results showed that the microlayer also existed on the cylinder surface.

3.3. Boiling curve on cylinder surface

Similar to previous work[4], we calculated the time-averaged value of the average heat flux on the cylinder surface. And we obtained the boiling curve on the hydrophilic wall by changing the heating temperature.

As shown in Figure 5, the nucleate boiling and transition-boiling are indicated. Before the nucleate boiling, it was the natural convection regime at $Ja = 0.06$. And when the onset of nucleate boiling occurred at $Ja = 0.08$, the boiling curve had no significant change which was different from the boiling curve on flat heater[8]. With the increasing of heating temperature at $Ja = 0.10$, bubbles appeared on the top of the cylinder, but no bubble appeared on the bottom. And the boiling curve kept rising steadily until $Ja = 0.11$. When $Ja = 0.12$, the bubble began to appear at the bottom of the cylinder. And eventually the cylinder would be completely wrapped by the bubble, as a result, the boiling regime changed to the film boiling from the nucleate boiling. And the curve jumped a little at $Ja = 0.12$ because the film boiling had a higher heat transfer efficiency than the nucleate boiling. And it could be found that the transition-boiling accounted for a larger part (from $Ja = 0.12$ to $Ja = 0.18$) on the curve than the nucleate boiling, which was different from the boiling curve on flat heater[4]. When the cylinder entered the film boiling completely at $Ja = 0.19$, the curve had a rise evidently. And then the curve kept rising steadily with the increasing of heating temperature. Therefore, the film boiling regime had a stable heat transfer efficiency. Noted that the boiling curve of the cylinder had no obvious critical heat flux, which was different from the flat heater[8][10].

4. Conclusions

This study explored the pool boiling on a cylinder by LBM. Compared to the pool boiling on a flat surface, bubbles exhibited different movement patterns. At a low heating temperature, the top of the cylinder evaporated the bubble firstly. With the increasing of heating temperature, bubbles appeared
on both sides of the cylinder, and then a steadily growing bubble appeared at the bottom. And the nucleate boiling could change to the film boiling because of the bottom bubble. If the temperature was high enough, the cylinder entered the film boiling directly. On the other hand, where the bubbles were attached to the cylinder surface, the temperature was lower and the heat flux was higher. And we obtained the boiling curve on the cylinder by numerical simulation. The results showed that the appearance of bottom bubble and the stable film boiling would increase the heat flux significantly.

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