Enhancement of nucleate boiling by combining the effects of surface structure and mixed wettability: A lattice Boltzmann study

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Abstract

The combination of microstructures and mixed wettability for enhancing nucleate boiling has attracted much attention in recent years. However, in the existing experimental and numerical studies, the tops of microstructures are entirely subjected to wettability modification. To further disclose the joint effects of surface structure and mixed wettability, in this work we numerically investigate the boiling heat transfer performance on an improved type of pillar-textured surfaces with mixed wettability, in which the tops of square pillars are partially subjected to wettability modification. Numerical simulations are carried out using a three-dimensional thermal multiphase lattice Boltzmann model. Numerical results show that the width of the wettability-modified region plays an important role in the boiling performance of the improved mixed-wettability surface and the best boiling performance is achieved in the situation that the width of the wettability-modified region is sufficiently large but the bubble nucleated on the pillar top still does not interfere with the coalescence-departure mechanism of the bubbles nucleated around the pillar, which optimizes the joint effects of surface structure and mixed wettability for enhancing nucleate boiling heat transfer. The influences of the shape of the wettability-modified region are also studied. Among the investigated shapes, the square is found to perform better than the other two shapes.

Keywords: Nucleate boiling; mixed wettability; boiling enhancement; lattice Boltzmann model
1. Introduction

Nucleate boiling is one of the most effective heat transfer modes [1] and has been widely utilized in various energy conversion and heat exchange systems, such as power generation, propulsion, electronic cooling, chemical processes, etc. [1-3]. In the past decades, many researchers have carried out either experimental or numerical studies to investigate the mechanism of nucleate boiling and explore how to improve the boiling heat transfer performance. Nevertheless, owing to the extreme complexity of the nucleate boiling process, the mechanism of enhancing nucleate boiling heat transfer has not been well understood. In recent years, two methods of surface modification have attracted much attention in the studies of enhancing nucleate boiling heat transfer: one is to regulate and control the wettability of the heating surface [4, 5] and the other is to apply micro/nano-scale structures [6].

At the very dawn of boiling studies, the importance of surface wettability was not recognized since the wettability effect was often included in the effects of surface characteristics such as roughness and material properties [7]. Through numerous experiments, it is now widely recognized that the surface wettability has a significant influence on the boiling curve and the critical heat flux of boiling heat transfer. Generally, a hydrophobic surface can more easily trigger the nucleation of bubbles than a hydrophilic surface because the decrease of wettability can reduce the energy barrier required for liquid-vapor phase change [8, 9]. Accordingly, the onset of boiling on a hydrophobic surface begins at a lower wall superheat. However, the critical heat flux decreases dramatically on a hydrophobic surface, while a hydrophilic surface shows a higher value of critical heat flux [10]. Therefore, a recent trend in surface modification is to make full use of the advantages of hydrophobic and hydrophilic surfaces, which leads to the applications of heterogeneous surfaces combining hydrophilicity and hydrophobicity for enhancing nucleate boiling through experiments [11-15] and numerical simulations [16-20].

Betz et al. [11] manufactured oxidized silicon wafers surfaces with networks combining hydrophilic and hydrophobic regions and experimentally demonstrated that the heterogeneous surfaces perform better than a hydrophilic surface with 7° wetting angle. Jo et al. [12] coated hydrophobic Teflon dots on a
hydrophilic silicon surface in the absence of micro-scale roughness and showed that the heterogeneous surface can provide better nucleate boiling heat transfer than the surfaces with homogeneous wettability. They found that the number of hydrophobic dots and the pitch distance between dots are key parameters for boiling performance. Subsequently, Jo et al. [13] fabricated a heterogeneous wetting surface comprising a wetting pattern located at the head of surface microstructures. They observed that the heterogeneous wetting surface with micro-pillars can interrupt the expansion and coalescence of bubbles and thereby enhance the boiling heat transfer performance.

Recently, Zhang et al. [14] and Shen et al. [15] have also experimentally studied boiling heat transfer by applying the combination of microstructures and mixed wettability. In the work of Zhang et al. [14], they observed that the combination of microstructures with hydrophobicity contributes to a high heat transfer coefficient at low heat fluxes and small superheat for the onset of boiling since microstructures provide potential bubble nucleation sites and hydrophobicity reduces the energy barrier of liquid-vapor phase change. Shen et al. [15] fabricated hybrid wetting surfaces with square pillars by the chemical deposition approach. They found that the hybrid wetting surfaces are superior to the spatially uniform wetting surfaces and can provide higher values of critical heat flux under the same geometric size and heating power conditions. Among the investigated hybrid modes, they observed that the hybrid mode of which the top surface of square pillars is hydrophobic and the bottom substrate is hydrophilic is the most effective one.

Besides the aforementioned experimental studies, some numerical studies of boiling heat transfer on heterogeneous wetting surfaces have been performed using the lattice Boltzmann (LB) method [16-20], which is a mesoscopic numerical approach built on the kinetic Boltzmann equation [21-24] and has been widely applied to simulate liquid-vapor phase change in recent years [16-20, 25-32]. A distinct advantage of using the LB method to simulate interface phenomena is that the interface between different phases can arise, deform, and migrate naturally without using any techniques to track or capture the interface [23]. Inspired by the work of Betz et al. [11], Gong and Cheng [16] have investigated the boiling heat transfer on flat surfaces with mixed wettability using the LB method. The effects of the size of
hydrophobic spots and the pitch distance between hydrophobic spots on the boiling performance were studied. They numerically demonstrated that adding hydrophobic spots on smooth hydrophilic surfaces can promote bubble nucleation and reduce nucleation time drastically.

Li et al. [17, 18] numerically investigated the boiling heat transfer performance on a type of hydrophilic-hydrophobic mixed surfaces, in which the combination of microstructures and mixed wettability is applied. The mixed surfaces were textured with pillars consisting of hydrophilic side walls and hydrophobic tops. They found that the hydrophobicity of the tops of pillars promotes bubble nucleation and reduces the required wall superheat for the onset of nucleate boiling. They numerically showed that increasing the contact angle of the tops of pillars leads to a leftward shift of the boiling curve and a leftward-upward shift of the heat transfer coefficient curve. Recently, Ma et al. [19] investigated the boiling performances of four types of micro-pillar heat sinks with mixed wettability patterns. They found that the heat sink with hydrophobic pillar tops and hydrophilic base has the best boiling heat transfer performance. Moreover, Ma and Cheng [20] numerically studied the boiling heat transfer on micro-pillar and micro-cavity hydrophilic heaters and showed that the high critical heat flux of the micro-pillar structured hydrophilic heater is mainly attributed to the considerable effect of capillary wicking.

Although significant progress has been achieved in applying the combination of microstructures and mixed wettability for boiling heat transfer, a limitation of current studies should also be pointed out, i.e., in the existing experimental and numerical studies, the tops of microstructures are entirely subjected to surface modification, which means that the effect of mixed wettability is non-independent and is related to the characteristic length of the microstructures (e.g., the width of the microstructures). In order to further disclose the joint effects of surface structure and mixed wettability, in the present study we numerically investigate the boiling heat transfer performance on an improved type of pillar-textured surfaces with mixed wettability, in which the tops of square pillars are partially subjected to wettability modification. Numerical simulations are performed using a three-dimensional (3D) thermal multiphase LB model with liquid-vapor phase change [18]. The rest of the present paper is organized as follows. The
3D thermal multiphase LB model with liquid-vapor phase change is introduced in Section 2. In Section 3, numerical investigations are presented and some discussions of the joint effects of surface structure and mixed wettability are also provided there. Finally, a brief summary is given in Section 4.

2. Numerical model

The LB method is a mesoscopic numerical method, in which the fluid flow is simulated by solving the discrete Boltzmann equation with a specific collision operator, such as the Bhatnagar-Gross-Krook (BGK) [33, 34] collision operator and the multiple-relaxation-time (MRT) [35-38] collision operator. The macroscopic average properties are obtained by accumulating a density distribution function. Using the MRT collision operator, the LB equation can be written as follows [18, 23, 37]:

\[
f_\alpha (x + e_\alpha \delta_t, t + \delta_t) = f_\alpha (x, t) - \overline{\Lambda}_{\alpha\beta} (f_\beta - f_\beta^{eq}) \bigg|_{x, t} \delta_t + \delta_t \left( G_\alpha - 0.5 \overline{\Lambda}_{\alpha\beta} G_\beta \right) \bigg|_{x, t}, \tag{1}
\]

where \( f_\alpha \) is the density distribution function, \( f_\alpha^{eq} \) is the equilibrium density distribution function, \( x \) is the spatial position, \( e_\alpha \) is the discrete velocity in the \( \alpha \)th direction, \( t \) is the time, \( \delta_t \) is the time step, \( G_\alpha \) is the forcing term in the discrete velocity space, and \( \overline{\Lambda}_{\alpha\beta} = (M^{-1} \Lambda M)_{\alpha\beta} \) is the collision operator, in which \( M \) is the transformation matrix and \( \Lambda \) is a diagonal matrix.

The D3Q19 lattice model is adopted, which corresponds to the following lattice velocities:

\[
e_\alpha = \begin{bmatrix}
0 & 1 & -1 & 0 & 0 & 0 & 0 & 1 & -1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0
\end{bmatrix}.
\tag{2}
\]

Through the transformation matrix \( M \), the right-hand side of Eq. (1) can be implemented as follows:

\[
m^* = m - \Lambda (m - m^{eq}) + \delta_t \left( I - \frac{\Lambda}{2} \right) S,
\tag{3}
\]

where \( m = Mf \), \( m^{eq} = Mf^{eq} \), \( I \) is the unit matrix, and \( S = MG \) is the forcing term in the moment space. The details of the transformation matrix \( M \), the equilibria \( m^{eq} \), the diagonal matrix \( \Lambda \) for relaxation times, and the forcing term \( S \) can be found in Ref. [18]. The streaming process is given by

\[
f_\alpha (x + e_\alpha \delta_t, t + \delta_t) = f_\alpha^* (x, t),
\tag{4}
\]

where \( f^* = M^{-1}m^* \) and \( M^{-1} \) is the inverse matrix of the transformation matrix. The macroscopic
density and velocity are obtained by the following relationships:

\[ \rho = \sum_{a} f_{a}, \quad \rho u = \sum_{a} e_{a} f_{a} + \frac{\delta}{2} F, \]  

(5)

where \( F \) is the total force exerted on the system.

For single-component multiphase systems, the interaction force in the pseudopotential multiphase LB method is given by [23, 39]

\[ F_{m} = -G \psi(x) \sum_{a} w_{a} \psi(x + e_{a} \delta_{a}) e_{a}, \]  

(6)

where \( G \) is the interaction strength, \( \psi(x) \) is the pseudopotential, and \( w_{a} \) are the weights. For the D3Q19 lattice, the weights \( w_{a} \) in Eq. (6) are given by \( w_{1,6} = 1/6 \) and \( w_{7,8} = 1/12 \). The total force includes the pseudopotential interaction force \( F_{m} \) and the buoyant force given by \( F_{b} = (\rho - \rho_{ave}) g \), where \( \rho_{ave} \) is the average density in the computational domain and \( g = (0, 0, -g) \) is the gravitational acceleration.

The pseudopotential \( \psi(x) \) is taken as \( \psi(x) = \sqrt{2 \left[ (p_{EOS} - \rho c_{v}^{2}) / G c^{2} \right]} \) [36, 40], in which \( p_{EOS} \) is the non-ideal equation of state and \( c = 1 \) is the lattice constant. In the present study, the Peng-Robinson equation of state is utilized [40], i.e.,

\[ p_{EOS} = \frac{\rho RT}{1 - b \rho} - \frac{a \varphi(T) \rho^{2}}{1 + 2 b \rho - b^{2} \rho^{2}}, \]  

(7)

where \( \varphi(T) = \left[ 1 + (0.37464 + 1.54226 \omega - 0.26992 \omega^{2}) \left( 1 - \sqrt{T/T_{c}} \right) \right]^{2} \), \( a = 0.45724 R^{2} T_{c}^{2} / p_{c} \), and \( b = 0.0778 R T_{c} / p_{c} \). The parameter \( \omega = 0.344 \) is the acentric factor. By neglecting the viscous heat dissipation, the governing equation for the temperature field is given by [27, 41]

\[ \nabla \cdot T = -u \cdot \nabla T + \frac{1}{\rho c_{v}} \nabla \cdot (\lambda \nabla T) - \frac{T}{\rho c_{v}} \left( \frac{\partial p_{EOS}}{\partial T} \right)_{p} \nabla \cdot u, \]  

(8)

where \( \lambda \) is the thermal conductivity and \( c_{v} \) is the specific heat at constant volume. Similar to the previous studies in Refs. [17, 18, 27], the present study also solves the temperature equation (8) with the classical fourth-order Runge-Kutta scheme. The isotropic central schemes are applied for spatial discretization. For a quantity \( \phi \), the spatial gradient of \( \phi \) and the Laplacian of \( \phi \) can be calculated by
the following second-order isotropic difference schemes, respectively

\[
\partial_t \phi(x) \approx \frac{1}{c_s^2 \delta_i^2} \sum_x \omega_x \phi(x + e_a \delta_i) e_{ai},
\]

\[
\nabla^2 \phi(x) \approx \frac{2}{c_s^2 \delta_i^2} \sum_x \omega_x \left[ \phi(x + e_a \delta_i) - \phi(x) \right],
\]

where \( c_s = c / \sqrt{3} \) is the lattice sound speed and \( \omega_x \) are given by \( \omega_{1,s} = 1/18 \) and \( \omega_{2,s} = 1/36 \). The saturation temperature is set to \( T_s = 0.8T_c \) (\( T_c \) is the critical temperature), which corresponds to the liquid density \( \rho_L \approx 7.2 \) and the vapor density \( \rho_v \approx 0.197 \). In the present work all the quantities are taken in the lattice units, i.e., the units in the LB method.

3. Numerical results and discussions

3.1. The simulation setup

The sketch of textured heating surfaces with micro-pillars is shown in Fig. 1 and the domain within the red dotted lines is chosen as our computation domain due to employing the periodic boundary condition in the \( x \) and \( y \) directions. The grid system of the computational domain is taken as \( L_x \times L_y \times L_z = 150 \text{l.u.} \times 150 \text{l.u.} \times 250 \text{l.u.} \), in which l.u. represents lattice units. Figure 2 illustrates three types of pillar-textured surfaces with different wettability, i.e., a homogeneous hydrophilic surface, a mixed-wettability surface whose pillars consist of hydrophilic side walls and hydrophobic tops, and an improved mixed-wettability surface in which the tops of pillars are partially subjected to wettability modification (represented by the light blue region). The square pillar is located at the center of the bottom substrate and the height and width of the square pillar are denoted by \( H \) and \( W \), respectively.

Initially, the computational domain is a liquid phase (\( 0 \leq z \leq 150 \text{l.u.} \)) below its saturated vapor phase (\( 150 \text{l.u.} \leq z \leq L_z \)) and the initial temperature of the computational domain is taken as \( T_s = 0.8T_c \). The surfaces of the square pillar and the bottom of the computational domain are heating surfaces and the temperature is given by \( T_s = T_r + \Delta T \), while the temperature of the top boundary is maintained at \( T_r \). The periodic boundary condition is employed in the \( x \) and \( y \) directions and the Zou-He boundary scheme
[42] is applied to the heating surfaces. In our simulations, the thermal conductivity is given by

\[
\lambda = \lambda_v \frac{\rho_l - \rho_v}{\rho_l - \rho_v} + \lambda_l \frac{\rho - \rho_v}{\rho_l - \rho_v},
\]

where \( \lambda_v \) is defined as \( \lambda_v = \rho_v c_v \chi_v \), in which \( \chi_v \) is taken as 0.03. The ratio \( \lambda_l / \lambda_v \) is chosen as 15 and the gravitational acceleration is set to \( g = 3 \times 10^{-5} \).

![Fig. 1. Schematic illustration of pillar-textured surfaces.](image)

![Fig. 2. Schematic illustration of three types of pillar-textured surfaces with different wettability. (a) a homogeneous hydrophilic surface, (b) a mixed-wettability surface whose pillars consist of hydrophilic side walls and hydrophobic tops, and (c) an improved mixed-wettability surface in which the tops of pillars are partially subjected to wettability modification (the light blue region).](image)

3.2. Boiling performances on pillar-textured surfaces with different wettability

In this section, the boiling performances on the aforementioned three types of pillar-textured surfaces are compared. In simulations, the height of the square pillar is taken as \( H = 20 \) l.u. and the contact angles of the hydrophilic and hydrophobic regions are chosen as \( \theta_{\text{phi}} \approx 37^\circ \) and \( \theta_{\text{pho}} \approx 94^\circ \), respectively. Figure 3 displays some snapshots of the boiling processes on the homogeneous hydrophilic
surface and the mixed-wettability surface at $t = 4000\delta$. The wall superheat is $\Delta T = 0.015$ and the pillar width in the figure varies from $W = 40$ l.u. to 140 l.u. From the figure we can see that the main difference between the boiling processes on the two surfaces lies in that, for the homogeneous hydrophilic surface, there is no bubble nucleated on the top of the pillar. Contrarily, for the mixed-wettability surface, a bubble would be formed on the top of the pillar owing to the hydrophobicity of the top surface. Then the bubble will interact with the four bubbles nucleated around the square pillar, leading to a larger bubble, which can be seen in the left and middle panels of Fig. 3(b).

![Snapshots of boiling](image)

**Fig. 3.** Snapshots of boiling on the homogeneous hydrophilic surface and the mixed-wettability surface at $\Delta T = 0.015$ and $t = 4000\delta$. From left to right, the pillar width is $W = 40$ l.u., 80 l.u., and 140 l.u., respectively.

For the boiling processes on the mixed-wettability surface, Fig. 4 depicts the variations of the heat flux with the pillar width in the cases of $\Delta T = 0.014$ and 0.015. The heat flux is the time average of the transient heat flux during $2 \times 10^4$ time steps. The figure shows that in the case of $\Delta T = 0.015$ the heat
flux initially increases with the increase of the pillar width and reaches its peak at $W = 80$ l.u. After that, the heat flux gradually decreases. A similar trend can also be observed in the case of $\Delta T = 0.014$. Such a trend is attributed to the fact that increasing the pillar width can promote bubble nucleation on the four edges formed by the bottom substrate and the square pillar. However, when the pillar width further increases, the boiling process may enter into the transition or film boiling, which would result in a sharp decrease of the heat flux, as can be seen in Fig. 4 for $W = 140$ l.u.

![Graph showing heat flux vs. pillar width for different $\Delta T$.](image)

**Fig. 4.** Simulations of boiling on the mixed-wettability surface. Variations of the heat flux with the pillar width in the cases of $\Delta T = 0.014$ and 0.015.

Now we turn our attention to the boiling performance on the improved mixed-wettability surface, in which the top of the pillar is partially subjected to wettability modification. According to Fig. 4, the best boiling performance on the mixed-wettability surface is achieved around $W = 80$ l.u. in the cases of $\Delta T = 0.014$ and 0.015. For comparison, the pillar width of the improved mixed-wettability surface is also chosen as $W = 80$ l.u. The wettability-modified region is a square located at the center of the pillar top (see Fig. 2(c)). The width of the wettability-modified region is denoted by $W_{\text{mod}}$, which is smaller than $W$. Obviously, the improved mixed-wettability surface reduces to the homogeneous hydrophilic surface and the mixed-wettability surface when $W_{\text{mod}} = 0$ and $W_{\text{mod}} = W$, respectively. Figure 5 displays the variations of the heat flux with the width of the wettability-modified region in the cases of $\Delta T = 0.014$, 0.015, and 0.016. From the figure we can observe the same trend for the three cases, namely
the heat flux initially increases with the increase of the width of the wettability-modified region, and then gradually decreases after reaching its peak value. More specifically, the peak of the heat flux is achieved at $W_{\text{mod}} = 60$ l.u., 50 l.u., and 40 l.u. for the cases of $\Delta T = 0.014$, 0.015, and 0.016, respectively, which implies that a relatively smaller $W_{\text{mod}}$ is required when the wall superheat increases. Moreover, Fig. 5 also shows that in each case the peak value of the heat flux is much higher than the heat flux achieved at $W_{\text{mod}} = 80$ l.u., indicating that the improved mixed-wettability surface performs better than the mixed-wettability surface (i.e., $W_{\text{mod}} = W = 80$ l.u.). For example, in the case of $\Delta T = 0.015$ the heat flux is increased by 31% when $W_{\text{mod}}$ varies from 80 l.u. to 50 l.u.

![Graph showing heat flux vs. width of wettability-modified region](image)

**Fig. 5.** Simulations of boiling on the improved mixed-wettability surface, in which the top of the pillar is partially subjected to wettability modification (denoted by the light blue region in Fig. 2(c)). Variations of the heat flux with the width of the wettability-modified region (i.e., $W_{\text{mod}}$) in the cases of $\Delta T = 0.014$, 0.015, and 0.016.

In order to reveal the joint effects of the mixed wettability and the square pillar (surface structure), the bubble dynamics is analyzed by taking the case of $\Delta T = 0.015$ as an example. Figure 6 displays some snapshots of the boiling process on the improved mixed-wettability surface with $W_{\text{mod}} = 50$ l.u. To illustrate the bubble dynamics more clearly, we have plotted two more square pillars in Fig. 6. Firstly, we can observe that the bubbles are nucleated at two regions, namely the four edges formed by the pillar and the bottom substrate, which is caused by the surface structure, and the wettability-modified region on the
top of the pillar, which is yielded by the wettability modification. As time goes on, the bubbles gradually grow up. Particularly, for the bubbles nucleated around the square pillar, each of the bubbles will coalesce with another bubble generated from an adjacent pillar (see Fig. 6(b)), and then grows up and departs from the heating surface, as shown in Fig. 6(c). On the contrary, the bubble nucleated on the top of the pillar does not coalesce with the bubbles on the bottom substrate.

Fig. 6. Snapshots of boiling on the improved mixed-wettability surface in the case of $\Delta T = 0.015$. The pillar width is $W = 80$ l.u., while the width of wettability-modified region is $W_{\text{mod}} = 50$ l.u. Two more pillars are plotted in this figure so as to illustrate the bubble dynamics more clearly.
Actually, for the bubble on the pillar top, the three-phase contact lines are pinned at the hydrophilic-hydrophobic boundary, which can be seen clearly in Fig. 6. The size of the bubble on the pillar top is limited by the width of the wettability-modified region and the vapor expansion is interrupted by the hydrophilic-hydrophobic boundary. As shown in Fig. 6 ($W_{\text{mod}} = 50 \text{ l.u.}$), the bubble on the pillar top does not interfere with the coalescence-departure mechanism of the bubbles nucleated around the square pillar. However, when the width of the wettability-modified region is further increased, the size of the bubble on the pillar top would increase. Correspondingly, the bubble on the pillar top may coalesce with the bubbles nucleated around the pillar, and then the coalescence-departure mechanism of the bubbles on the bottom substrate may be changed.

To illustrate the aforementioned point, some snapshots of boiling process on the mixed-wettability surface ($W_{\text{mod}} = W = 80 \text{ l.u.}$) are shown in Fig. 7. By comparing the bubble dynamics in Fig. 7 with that in Fig. 6, we can find that each of the bubbles nucleated around the square pillar is no longer coalesce with another bubble generated from an adjacent pillar. As a result, the multiple bubble-departure mode in Fig. 6 has been changed to the single bubble-departure mode in Fig. 7, which definitely affects the heat transfer. Figure 8 illustrates the variations of the transient heat flux with time during the boiling processes on the mixed-wettability surface and the improved mixed-wettability surface ($W_{\text{mod}} = 50 \text{ l.u.}$) in the case of $\Delta T = 0.015$. As seen in the figure, the heat flux obtained by the improved mixed-wettability surface is much higher than that of the mixed-wettability surface during the entire boiling process.

![Fig. 7. Snapshots of boiling process on the mixed-wettability surface ($W_{\text{mod}} = W = 80 \text{ l.u.}$) in the case of $\Delta T = 0.015$. From left to right: $t = 3000\delta$, $5000\delta$, and $8000\delta$.](image)
Fig. 8. Variations of the transient heat flux with time during the boiling processes on the mixed-wettability surface ($W_{\text{mod}} = W = 80$ l.u.) and the improved mixed-wettability surface ($W_{\text{mod}} = 50$ l.u.) in the case of $\Delta T = 0.015$.

3.3. Influences of the shape of the wettability-modified region

In this subsection, we numerically study the influences of the shape of the wettability-modified region on the boiling performance of the improved mixed-wettability surface. Three different shapes are investigated: square, circle, and 45°-rotating square, which are illustrated in Fig. 9(a), 9(b), and 9(c), respectively. The definition of the width of the wettability-modified region is also shown in Fig. 9. For the three shapes, the area of the wettability-modified region is given by, respectively

![Fig. 9. Three different shapes of the wettability-modified region. (a) square, (b) circle, and (c) 45°-rotating square.](image-url)
\[ S_{\text{square}} = W_{\text{mod}}^2, \quad S_{\text{circle}} = \frac{\pi}{4} W_{\text{mod}}^2, \quad S_{\text{square, 45^\circ}} = \frac{1}{2} W_{\text{mod}}^2. \]  

(12)

For a given value of \( W_{\text{mod}} \), it is obvious that \( S_{\text{square}} > S_{\text{circle}} > S_{\text{square, 45^\circ}} \).

The simulation parameters are the same as those used in the previous subsection and the contact angle of the wettability-modified region is still chosen as \( \theta_{\text{pho}} \approx 94^\circ \). Figure 10 shows the variations of the heat flux with the width of the wettability-modified region (i.e., \( W_{\text{mod}} \)) when different shapes are applied. The wall superheat is \( \Delta T = 0.015 \). From Fig. 10 the following phenomena can be observed.

Firstly, we can see that the heat fluxes of the cases of circle and 45\(^\circ\)-rotating square show the same trend as the case of square, i.e., the heat flux initially increases with the increase of \( W_{\text{mod}} \), and then gradually declines after reaching its peak value. The reason for this trend has been previously discussed.

Furthermore, it can be found that the peak value of the heat flux is achieved at \( W_{\text{mod}} = 50 \) l.u., \( 50 \) l.u., and \( 60 \) l.u. for the cases of square, circle, and 45\(^\circ\)-rotating square, respectively. When \( W_{\text{mod}} \leq 50 \) l.u., the heat flux of the case of square is higher than that of the case of circle, which is in turn higher than the heat flux of the case of 45\(^\circ\)-rotating square. Such a phenomenon is attributed to the fact that the area of the wettability-modified region satisfies the relationship \( S_{\text{square}} > S_{\text{circle}} > S_{\text{square, 45^\circ}} \) for a given \( W_{\text{mod}} \). As long as the bubble nucleated on the pillar top does not coalesce with the bubbles on the bottom substrate, the

![Graph showing heat flux variations with width of wettability-modified region](image)

**Fig. 10.** Simulations of boiling on the improved mixed-wettability surface with different shapes (square, circle, and 45\(^\circ\)-rotating square) of the wettability-modified region. Variations of the heat flux with the width of the wettability-modified region \( W_{\text{mod}} \). The wall superheat is \( \Delta T = 0.015 \).
heat flux would increase with increasing the area of the wettability-modified region. Contrarily, after reaching the peak value, the heat flux would decrease with the increase of the area of the wettability-modified region because the bubble on the pillar top will affect the coalescence-departure mechanism of the bubbles on the bottom substrate. Hence, an inverse phenomenon is observed in Fig. 10 for the heat fluxes of the three cases when $W_{\text{mod}} > 60 \text{ l.u.}$

![Snapshots of boiling on the improved mixed-wettability surface with different shapes of the wettability-modified region.](image)

**Fig. 11.** Snapshots of boiling on the improved mixed-wettability surface with different shapes of the wettability-modified region. The width of wettability-modified region is $W_{\text{mod}} = 50 \text{ l.u.}$ and the wall superheat is $\Delta T = 0.015$. From left to right: $t = 2000\delta$, $4000\delta$, and $6000\delta$. 
Fig. 12. Snapshots of boiling on the improved mixed-wettability surface with different shapes of the wettability-modified region. The width of wettability-modified region is $W_{\text{mod}} = 60$ l.u. and the wall superheat is $\Delta T = 0.015$. From left to right: $t = 2000\delta$, $4000\delta$, and $6000\delta$.

To illustrate the phenomenon that the heat flux peaks at $W_{\text{mod}} = 50$ l.u. in the cases of square and circle, but peaks at $W_{\text{mod}} = 60$ l.u. in the case of 45°-rotating square, we display some snapshots of boiling processes on the improved mixed-wettability surface with different shapes of the wettability-modified region in Figs. 11 and 12 for $W_{\text{mod}} = 50$ l.u. and 60 l.u., respectively. The left, middle, and right panels of the figures show the results at $t = 2000\delta$, $4000\delta$, and $6000\delta$, respectively. The left panels of these
two figures clearly show that the size of the bubble nucleated on the pillar top increases with increasing the area of the wettability-modified region. Since $S_{\text{square, 45°}} < S_{\text{circle}} < S_{\text{square}}$, the bubble on the pillar top is smallest in the case of 45°-rotating square.

Particularly, from Figs. 11(c) and 12(c) we can see that in the case of 45°-rotating square the bubble on the pillar top does not interfere with the coalescence-departure mechanism of the bubbles on the bottom substrate during the entire boiling process. However, by comparing the right panel of Fig. 12 and with that of Fig. 11, it can be found that in the right panels of Figs. 12(a) and 12(b) (namely the cases of square and circle, respectively) the bubble on the pillar top has coalesced with the bubbles on the bottom substrate and a large portion of the pillar top has been covered by vapor. This is the reason why the heat fluxes of these two cases decrease in Fig. 10 when the width of the wettability-modified region is increased from 50 l.u. to 60 l.u., but the heat flux of the case of 45°-rotating square increases in the meantime. Generally, it can be found that the square performs best among the three investigated shapes since it can provide the highest value of heat flux (see Fig. 10), but its heat flux is relatively sensitive to the width of the wettability-modified region in comparison with the other two shapes. To sum up, the aforementioned numerical results clearly demonstrate that the shape of the wettability-modified region has an important influence on the boiling performance of the improved mixed-wettability surface and further confirm the analysis presented in the previous subsection regarding the joint effects of surface structure and mixed wettability.

4. Conclusions

The combination of microstructures and mixed wettability has been applied to enhance nucleate boiling heat transfer in some recent experimental and numerical studies. However, in the existing studies, the tops of microstructures were entirely subjected to wettability modification, which actually makes the effect of mixed wettability dependant on the characteristic length of the microstructures. In order to further disclose the joint effects of surface structure and mixed wettability, in this paper we have
numerically investigated the boiling heat transfer performance on an improved type of pillar-textured surfaces with mixed wettability, in which the tops of square pillars are partially subjected to wettability modification. Numerical simulations have been performed using a 3D thermal multiphase LB model with liquid-vapor phase change. The main findings and conclusions are summarized as follows.

(i) For the improved mixed-wettability surface, bubbles are nucleated at two regions: one is the four edges formed by the square pillar and the bottom substrate, which is caused by the surface structure, and the other is the wettability-modified region on the top of the pillar, which is yielded by the wettability modification.

(ii) It is found that the width of the wettability-modified region plays an important role in the boiling performance of the improved mixed-wettability surface and the best boiling performance is achieved in the situation that the width of the wettability-modified region is sufficiently large but the bubble nucleated on the pillar top still does not interfere with the coalescence-departure mechanism of the bubbles nucleated around the pillar, which fully takes the advantage of the multiple bubble-departure mode and optimizes the joint effects of surface structure and mixed wettability for enhancing nucleate boiling heat transfer.

(iii) The influences of the shape of the wettability-modified region have also been studied. Three different shapes have been considered: square, circle, and 45°-rotating square. Numerical results show that the square performs best among the investigated shapes as it gives the highest value of heat flux, but its heat flux is relatively sensitive to the width of the wettability-modified region in comparison with the other two shapes.

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