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Research Paper

Boiling heat transfer on hydrophilic-hydrophobic mixed surfaces: A 3D lattice Boltzmann study

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HIGHLIGHTS

- The boiling performance on a type of mixed surfaces is studied using a 3D LB model.
- The optimal contact angle of hydrophilic region decreases with increasing the wall superheat.
- The hydrophilic region plays an increasingly important role when the wall superheat increases.
- The orthogonal array tests are performed to identify the most important influential factor.

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ABSTRACT

In this paper, the boiling heat transfer performance on a type of hydrophilic-hydrophobic mixed surfaces is numerically investigated using a three-dimensional (3D) thermal multiphase lattice Boltzmann model with liquid-vapor phase change. The mixed surface is square-pillar textured with the pillar being composed of hydrophilic side walls and a hydrophobic top surface. Numerical simulations are carried out to investigate the influences of the contact angle of the hydrophilic region of the mixed surface, the pillar width, and the pillar height. It is found that an appropriate increase of the contact angle of the hydrophilic region, θ_{phi}, can promote the bubble nucleation on the bottom substrate and hence enhances the nucleate boiling on the hydrophilic-hydrophobic mixed surface, but a larger θ_{phi} may make the boiling enter the transition or film boiling regime. Moreover, it is shown that the heat flux initially increases with the increase of the pillar width and shows a declining trend after reaching its peak value. The optimal θ_{phi} and the optimal pillar width are found to decrease with the increase of the wall superheat, revealing that the hydrophilic region of the mixed surface should play an increasingly important role when the wall superheat increases. The orthogonal array tests are performed and it is found that the contact angle of the hydrophilic region is the most important influential factor among the three investigated factors.

1. Introduction

Boiling is widely utilized in industry and is one of the key technologies in thermal power plants, nuclear reactors, and steel manufacturing [1] as it is the best way to cool a hot body and to retrieve heat from a heat source effectively. Numerous research efforts have been made regarding boiling heat transfer and a lot of enhanced heat transfer techniques have been developed to promote the performance of boiling heat transfer [1–3], among which the surface modification approach such as controlling the surface wettability [4,5] and applying micro/nano-scale structures [6] has attracted significant attention.

At the very dawn of boiling studies, the importance of surface wettability was not recognized since the wettability effect was included in the effects of surface characteristics such as roughness and material properties [1]. Through many experimental and numerical studies, the importance of surface wettability on boiling heat transfer has been revealed. Generally, the advantage of a hydrophobic surface lies in that the onset of boiling on a hydrophobic surface requires a lower wall superheat than that on a hydrophilic surface [7,8]. Conversely, the advantage of a hydrophilic surface is that its critical heat flux is much higher than that of a hydrophobic surface [9].

An ideal heating surface may make use of the hydrophobicity to promote boiling onset and the hydrophilicity to achieve a high critical heat flux. Therefore a recent trend in surface modification is to combine the advantages of hydrophobicity and hydrophilicity to develop a variety of mixed-wettability surfaces for enhancing boiling heat transfer

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[4,10–17]. Betz et al. [10] performed a pioneering study in this field. They prepared two types of flat surfaces with mixed wettability. One is a surface with hydrophobic hexagonal islands on a hydrophilic network and the other is that with hydrophilic hexagonal islands on a hydrophobic network. Both patterns were shown to be capable of enhancing nucleate boiling heat transfer.

Jo et al. [4,13] fabricated a heterogeneous wettability surface composed of a hydrophilic substrate with hydrophobic dots and showed that the surface with heterogeneous wettability can provide better nucleate boiling heat transfer than that with homogeneous wettability. Dai et al. [11] proposed a type of hydrophilic-hydrophobic mixed surfaces, which was synthesized from functionalized multiwall carbon nanotubes by introducing hydrophilic functional groups on the pristine multiwall carbon nanotube surfaces, and demonstrated that the mixed surface is superior in enhancing nucleate boiling. Jo et al. [14] suggested a mixed surface comprising a wetting pattern located at the head of surface microstructures and showed that hydrophilic self-assembled monolayer patterns and spatially fabricated micro-post structures can enhance nucleate boiling heat transfer. Kumar et al. [15] have investigated the effects of mixed wettability on the boiling performance of cylindrical copper surfaces.

Recently, Li et al. [16] numerically investigated the boiling heat transfer performance on a type of hydrophilic-hydrophobic mixed surfaces, which was textured with pillars consisting of hydrophilic side walls and hydrophobic tops. They showed that the hydrophobicity of the tops of pillars promotes bubble nucleation and reduces the required wall superheat for boiling onset. Moreover, it was found that increasing the contact angle of the tops of pillars leads to a leftward shift of the boiling curve and a leftward and upward shift of the heat transfer coefficient curve. Meanwhile, Shen et al. [17] studied the boiling performance on mixed surfaces with square-pillars in millimeters at low heat fluxes. They showed that, under the same geometric size and heating power conditions, the heat transfer coefficients of mixed surfaces are higher than those of spatially uniform wetting surfaces, regardless of mixed modes.

In recent years, the rapid development of computer technology has brought a drastic advancement in numerical simulations of boiling phenomena for the understanding of boiling fundamentals [3]. The molecular dynamics (MD) method is a promising way to grasp an understanding of the fundamental physics of boiling phenomena. However, the MD method is usually limited to systems of very small size [1]. The lattice Boltzmann (LB) method, which is a popular mesoscopic numerical approach for simulating fluid flow and heat transfer [18–22], has been applied to investigate phase-change heat transfer in the past decade [16,23–29]. The LB method can be viewed as a special discrete solver for mimicking the kinetic Boltzmann equation. An important advantage of the LB method for modeling interfacial phenomena is that the interface between different phases can arise, deform, and migrate naturally without using any technique to track or capture the interface [20].

Following a recent study of Li et al. [16], in the present work we aim to investigate the boiling performance on a type of hydrophilic-hydrophobic mixed surfaces using a three-dimensional (3D) thermal multiphase LB model with liquid-vapor phase change. The mixed surface is square-pillar textured with the pillar being composed of hydrophilic side walls and a hydrophobic top surface. The rest of the present paper is organized as follows. A 3D thermal multiphase LB model with liquid-vapor phase change is introduced in Section 2. In Section 3, numerical simulations of boiling heat transfer on the hydrophilic-hydrophobic mixed surface are carried out to investigate the effects of the contact angle of the hydrophilic region of the mixed surface, the pillar width, and the pillar height. Some discussions of the related physical mechanisms are also provided there. A brief summary is given in Section 4.

2. Numerical model

In the LB method, the fluid flow is simulated by tracking the evolution of the density distribution function and then the macroscopic averaged properties are obtained by accumulating the density distribution function. The viscous effect is modeled through a linearized collision operator such as the Bhatnagar-Gross-Krook (BGK) collision operator [30,31] and the multiple-relaxation-time (MRT) collision operator [16,26,32–36]. Using the MRT collision operator, the LB equation, which governs the evolution of the density distribution function, can be written as follows:

$$f_\alpha(\mathbf{x}+\mathbf{e}_\alpha\delta_t,\, t+\delta_t) = f_\alpha(\mathbf{x},\, t) - \bar{\Lambda}_{\alpha\beta}(f_\beta - f_\beta^{eq})|_{(x,t)} + \delta_t(G_\alpha - 0.5\bar{\Lambda}_{\alpha\beta}G_\beta)|_{(x,t)}, \tag{1}$$

where f_α is the density distribution function, f_α^{eq} is the equilibrium density distribution function, $\mathbf{x}$ is the spatial position, $\mathbf{e}_\alpha$ is the discrete velocity in the α th direction, t is the time, δ_t is the time step, G_α is the forcing term in the discrete velocity space, and $\bar{\Lambda}_{\alpha\beta} = (\mathbf{M}^{-1}\Lambda\mathbf{M})_{\alpha\beta}$ is the collision operator, in which $\mathbf{M}$ is the transformation matrix and Λ is a diagonal matrix.

With the aid of the transformation matrix $\mathbf{M}$, the right-hand side of Eq. (1), i.e., the collision process, can be implemented in the moment space:

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

where $\mathbf{I}$ is the unit matrix, $\mathbf{m} = \mathbf{Mf}$, $\mathbf{m}^{eq} = \mathbf{Mf}^{eq}$, and $\mathbf{S} = \mathbf{MG}$ is the forcing term in the moment space. The streaming process is then implemented as follows:

$$f_\alpha(\mathbf{x}+\mathbf{e}_\alpha\delta_t,\, t+\delta_t) = f_\alpha^*(\mathbf{x},\, t), \tag{3}$$

where $\mathbf{f}^* = \mathbf{M}^{-1}\mathbf{m}^*$ and $\mathbf{M}^{-1}$ is the inverse matrix of the transformation matrix. The macroscopic density and velocity are calculated through the following relationships:

$$\rho = \sum_\alpha f_\alpha, \quad \rho\mathbf{u} = \sum_\alpha \mathbf{e}_\alpha f_\alpha + \frac{\delta_t}{2}\mathbf{F}, \tag{4}$$

where $\mathbf{F}$ is the total force exerted on the system.

In the classical MRT-LB method, the transformation matrix $\mathbf{M}$ is an orthogonal matrix. Recently, some studies [37–40] have shown that the transformation matrix of an MRT-LB model is not necessary to be an orthogonal one. In the present study, a non-orthogonal 3D MRT-LB model proposed in Ref. [40] is employed, which is constructed based on the D3Q19 lattice model. In comparison with the usual orthogonal 3D MRT-LB model, the non-orthogonal MRT-LB model can retain the numerical accuracy while considerably simplifying the transformation matrix $\mathbf{M}$ and its inverse matrix $\mathbf{M}^{-1}$ [40].

The lattice velocities $\{\mathbf{e}_\alpha\}$ of the D3Q19 lattice are given by

$$\mathbf{e}_\alpha = \begin{bmatrix} 0 & 1 & -1 & 0 & 0 & 0 & 0 & 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 & 0 & 0 & 1 & -1 & -1 & 1 & 0 & 0 & 0 & 0 & 1 & -1 & 1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \end{bmatrix}. \tag{5}$$

The equilibria $\mathbf{m}^{eq} = \mathbf{Mf}^{eq}$ in Eq. (2) are given by

$$\begin{gathered} m_0^{eq} = \rho,\ m_1^{eq} = \rho u_x,\ m_2^{eq} = \rho u_y,\ m_3^{eq} = \rho u_z,\ m_4^{eq} = \rho + \rho\,|u|^2, \\ m_5^{eq} = \rho(2u_x^2 - u_y^2 - u_z^2),\ m_6^{eq} = \rho(u_y^2 - u_z^2),\ m_7^{eq} = \rho u_x u_y,\ m_8^{eq} = \rho u_x u_z, \\ m_9^{eq} = \rho u_y u_z, \\ m_{10}^{eq} = \rho c_s^2 u_y,\ m_{11}^{eq} = \rho c_s^2 u_x,\ m_{12}^{eq} = \rho c_s^2 u_z,\ m_{13}^{eq} = \rho c_s^2 u_x,\ m_{14}^{eq} = \rho c_s^2 u_z, \\ m_{15}^{eq} = \rho c_s^2 u_y, \\ m_{16}^{eq} = \varphi + \rho c_s^2(u_x^2 + u_y^2),\ m_{17}^{eq} = \varphi + \rho c_s^2(u_x^2 + u_z^2), \\ m_{18}^{eq} = \varphi + \rho c_s^2(u_y^2 + u_z^2), \end{gathered} \tag{6}$$

where $c_s^2 = 1/3$ and $\varphi = \rho c_s^4(1 - 1.5\,|\mathbf{u}|^2)$. The relaxation matrix Λ (the