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Investigation of coalescence-induced droplet jumping on superhydrophobic surfaces and liquid condensate adhesion on slit and plain fins

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ABSTRACT

The coalescence-induced droplet jumping on superhydrophobic complex textured surface, as well as the liquid condensate adhesion on slit and plain fins with hydrophobic and hydrophilic coatings in the tube-and-fin heat exchanger is studied numerically using the three-dimensional multi-relaxation-time (MRT) pseudopotential lattice Boltzmann model. It is found that the height of the surface conical posts, the spacing between the consecutive conical posts, the number of the droplets, the radius of the droplet, and the wettability property of the complex textured surface have important effect on the spontaneous jumping of the coalesced droplet. For the liquid condensate adhesion on slit and plain fins, it is found that both the hydrophilic coating with small contact angle and the hydrophobic coating with large contact angle are effective on avoiding liquid bridge between fins. Furthermore, the coating is required more strictly for slit fin than for plain fin to avoid liquid bridge.

1. Introduction

Dropwise condensation behavior plays significant role in engineering applications, such as heat exchangers, air conditioners, thermal management, etc. When the droplets coalesce on a superhydrophobic surface (the contact angle between liquid and surface exceeds 150°), the coalesced droplet can jump spontaneously from the surface due to the released excess surface energy [1]. If the shape and the wettability property of the textured surface are designed properly, the coalesced droplet can not only jump from the textured surface easily but also enhance the heat transfer performance, which is widely used in the applications of self-cleaning, microfluidics, and lab-on-chip devices. Recently, more and more studies have been focusing on the spontaneous jumping of coalesced droplet on superhydrophobic surfaces during dropwise condensation [2,3]. Peng et al. [3] experimentally observed the properties of the coalesced droplet induced by the coalescence of two droplets with the same volume and used the two-dimensional free energy lattice Boltzmann model to simulate the droplet coalescence process. Nam et al. [4] found that approximately half of the excess surface energy released during the coalescence is efficiently converted to kinetic energy on the superhydrophobic surface before the detachment process. Liu et al. [5] used two-dimensional lattice Boltzmann method to simulate the droplet self-propelled jumping on superhydrophobic surfaces. Wang et al. [6] established the relation among the coalescence-induced velocity, surface energy, viscous dissipation, and droplet size without consideration of gravity.

The tube-and-fin heat exchanger is commonly applied in refrigeration, air-conditioner, and humidifier system. However, the liquid bridge forms easily between the adjacent fins with small spacing. Liquid condensate adhesion on fins may increase the pressure drop and deteriorate the heat transfer performance. Furthermore, the water condensate may corrode fins, produce corrosion, and cause superfluous noise [7]. Sommers et al. [8] showed that the anisotropic micro-grooved structure of the fin surface in combination with an alkyl silane coating can reduce liquid retention by more than 27%. Guo et al. [9] obtained stable biomimetic superhydrophobic surfaces on aluminum alloy using wet chemical etching followed by modification of the surface with a cross-linked silicone elastomer, perfluorononane (C_9F_{20}) and perfluoropolyether (PFPE). Shin et al. [10] found that the water hold-up in a heat exchanger could be reduced by the enhancement of the surface hydrophilicity and the design with lower number of fins.

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Although researchers have numerically investigated the spontaneous droplet jumping on the textured surface and the different wettability coatings of the tube-and-fin surface, most of them simulated the spontaneous droplet jumping from two-dimensional point of view and the textured surface is simple [3,5,6]. The three-dimensional (3D) numerical simulations about the geometry and the wettability property of the complex textured surface for spontaneous jumping of the coalesced droplet, as well as the different wettability coatings of the tube-and-fin surface for the liquid condensate adhesion are still lacking. In the present work, we aim to investigate the coalescence-induced droplet jumping on superhydrophobic complex textured surfaces and to simulate the liquid condensate adhesion on slit and plain fins with hydrophobic and hydrophilic coatings in tube-and-fin heat exchanger using the 3D MRT pseudopotential lattice Boltzmann method. To the authors' best knowledge, there is no one using the 3D MRT pseudopotential lattice Boltzmann model to study the spontaneous droplet jumping on the complex textured surface, especially for the curved solid boundary, as well as the liquid condensate adhesion on slit and plain fins. The present work fills a gap in the literature by demonstrating that the three-dimensional MRT pseudopotential lattice Boltzmann method is effective to simulate the coalescence-induced droplet jumping on the complex textured surface and investigate the liquid condensate adhesion on slit and plain fins. The results can also be helpful to understand the processes involved with droplet in engineering applications of enhanced heat transfer.

Because the lattice Boltzmann method (LBM) is naturally suitable for massively parallel computation, this method can be used for large-scale simulations of complex fluids in various specific cases and boundary conditions [11–15]. The pseudopotential model, also known as the Shan–Chen (SC) model, is one of the most widely used and successful outgrowths of lattice Boltzmann models for multiphase flows. In this model, a density-dependent interparticle potential is employed to mimic the intermolecular interactions which separate phases in real fluids. Consequently the computational cost is reduced. Moreover, different wetting properties can be easily obtained just by tuning the interaction strength between the fluid and solid wall [16] and different equations of state (EOS) can also be easily incorporated [17]. However, this model also suffers from several drawbacks such as large spurious currents and thermodynamic inconsistency. Such deficiencies lead to numerical instability and put severe limitations on its application. To overcome this problem many researchers improved the pseudopotential model significantly. Shan [18] proposed a method of highly isotropic gradient operators to reduce the spurious currents. Sbragaglia et al. [19] developed the multirange pseudopotential model which moves the spatial range of the pseudopotential interactions to the next-nearest-neighbor lattice site. Li et al. [20] improved the forcing scheme of the two-dimensional pseudopotential lattice Boltzmann model to achieve thermodynamic consistency and large density ratio.

The rest of this paper is organized as follows. Firstly, a brief introduction is given to the three-dimensional MRT pseudopotential lattice Boltzmann model. Secondly, the three-dimensional MRT pseudopotential lattice Boltzmann model is validated with two tests. Thirdly, the coalescence-induced droplet jumping on superhydrophobic complex textured surfaces and the liquid condensate adhesion on slit and plain fins of fin-and-tube heat exchanger for different wettability coatings are investigated. Finally, a brief conclusion is drawn.

2. Three-dimensional MRT pseudopotential lattice Boltzmann model

The multi-relaxation-time method is able to improve numerical stability and reduce the spurious velocity by tuning the adjustable relaxation parameters [21]. In this article, the three-dimensional nineteen-velocity (D3Q19) lattice Boltzmann model with MRT collision operator is considered. The evolution equation of the D3Q19 lattice Boltzmann model with MRT collision operator can be written in a more general form as [22]

$$f_\alpha(\mathbf{x}+\mathbf{e}_\alpha\delta_t, t+\delta_t) = f_\alpha(\mathbf{x},t) - \sum_\beta \mathbf{\Omega}_{\alpha\beta}(f_\beta(\mathbf{x},t) - f_\beta^{eq}(\mathbf{x},t)) + S_\alpha(\mathbf{x},t) - \frac{1}{2}\sum_\beta \mathbf{\Omega}_{\alpha\beta}S_\beta(\mathbf{x},t) \quad (1)$$

where $f_\alpha(\mathbf{x},t)$ is the density distribution function, $\mathbf{x}$ is the spatial position, and $\mathbf{e}_\alpha$ ($\alpha = 0, 1, \ldots 18$) is the discrete velocity along the αth direction given by

$$[\mathbf{e}_0, \mathbf{e}_1, \ldots, \mathbf{e}_{18}] = \begin{bmatrix} 0 & 1 & -1 & 0 & 0 & 0 & 0 & 1 & 1 & -1 & -1 & 1 & -1 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 & 0 & 0 & 1 & -1 & 1 & -1 & 0 & 0 & 0 & 0 & 1 & 1 & -1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 1 & 1 & -1 & -1 & 1 & -1 & 1 & -1 \end{bmatrix} \quad (2)$$

$S_\alpha(\mathbf{x},t)$ is the forcing term in the velocity space written as [23].

$$S_\alpha(\mathbf{x},t) = w_\alpha\left[\frac{\mathbf{e}_\alpha - \mathbf{u}}{c_s^2} + \frac{\mathbf{e}_\alpha\cdot\mathbf{u}}{c_s^4}\mathbf{e}_\alpha\right]\cdot\mathbf{F} \quad (3)$$

where $w_0 = 1/3$, $w_\alpha = 1/18$ for $\alpha = 1-6$ and $w_\alpha = 1/36$ for $\alpha = 7-18$. $\mathbf{F}$ is the total force on each particle, including the fluid–fluid force $\mathbf{F}_f$, the fluid–solid interaction force $\mathbf{F}_s$ and the body force $\mathbf{F}_b$. $\mathbf{\Omega}_{\alpha\beta}$ is the collision matrix in the velocity space. Eq. (1) is projected to moment space by the transformation matrix $\mathbf{M}$. Thus, Eq. (1) can be transformed to the following form

$$f_\alpha(\mathbf{x}+\mathbf{e}_\alpha\delta_t, t+\delta_t) = f_\alpha(\mathbf{x},t) - \mathbf{M}^{-1}\mathbf{\Lambda}(\mathbf{m}(\mathbf{x},t) - \mathbf{m}^{eq}(\mathbf{x},t)) + \mathbf{M}^{-1}(\mathbf{I} - \frac{\mathbf{\Lambda}}{2})\bar{\mathbf{S}}(\mathbf{x},t) \quad (4)$$

where the transformation matrix $\mathbf{M}$ for the D3Q19 lattice model is given by