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Self-propelled dropwise condensation on a gradient surface

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ABSTRACT

A model of vapor condensation on a solid surface is developed and numerically analyzed using the free-energy lattice Boltzmann method. Based on the model, the condensation phase change on hydrophobic, hydrophilic and gradient surfaces are simulated with a particular focus on the condensation on a gradient surface. The droplet nucleation, growth, deformation, coalescence and motion during the condensation on a gradient surface are investigated. The present simulation reproduces the self-propelled dropwise condensation on a gradient surface, the film condensation on a hydrophilic surface and the conventional dropwise condensation on a hydrophobic surface. The results indicate that the condensed droplets on a gradient surface can be swept in time to provide a favorable condition for the subsequent condensation. On a smooth gradient surface, owing to the unbalanced wetting force, the vapor condenses into a thin film firstly and then fractures into droplet nucleation as the condensation process goes on. The larger wettability gradient results in a larger amplitude oscillation of condensation rate and a slighter variation of surface coverage.

1. Introduction

Vapor condensation, a classical physical phenomenon, is of particular interest in a broad range of technical application [1–3], including condenser, air conditioning, power generation, thermal management, etc. Motivated by the urgent demand for the miniaturization of heat transfer device, dropwise condensation has been actively revisited over the past decades owing to its superior heat transfer performance over film condensation [4–6]. In the real applications, one of the most important challenge consists in how to control and maintain the continuous dropwise condensation [4]. Self-propelled dropwise condensation on a substrate surface with a surface tension gradient (i.e. gradient surface) provides an attractive and promising way to meet this challenge [7–9]. Resulting from the surface tension gradient, the vapor condensation on a gradient surface undergoes a complex gas-liquid phase change process, involving the gas-liquid-solid interactions, droplet dynamics (nucleation, growth, deformation, and coalescence), flow instability, interface evolution and interfacial mass transport [10,11]. Up to now, the mechanism and inherent law of vapor condensation on gradient surface are not properly known. In order to guide the pragmatic construction of solid surface for self-propelled dropwise condensation, it is of great significance to understand the vapor condensation and subsequent droplet dynamic behavior on gradient surface.

The dropwise condensation generally occurs on the hydrophobic surface of the vertical wall where the condensate droplet is eliminated by the gravity. In other words, this method is valid when the gravity is in action for the vapor condensation. However, it is difficult to achieve continuous condensation in some special condition, such as condensation on horizontal surface or external surface of small tube size. The obstacle to achieving dropwise condensation on a horizontal surface is that the generated condensate droplets cannot be spontaneously removed in a timely manner. Fortunately, a surface tension gradient on a substrate surface is capable of inducing the autonomous droplet motion. After the pioneering theoretical work for the motion of a small droplet that wets a surface by Greenspan [12], the droplet motion on a gradient surface was experimentally confirmed by Chaudhury and Whitesides [13–15] as well as other researchers [16,17]. It is demonstrated that the droplet motion on a gradient surface is typically dependent on the gradient degree, droplet size, and viscosity.

Inspired by self-propelled droplet motion on a gradient surface, several efforts have been devoted to investigating continuous

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Nomenclature

A_i	a coefficient in f_i
a	a constant related to surface energy
B_i	a coefficient in g_i
c_s	lattice sound velocity (m s^{-1})
$\boldsymbol{e}_i$	discrete velocity (m s^{-1})
F	Landau free energy expression
f_i	evaluation equation of velocity
g_i	evaluation equation of order parameter
L	length (m)
M	mobility
p	pressure (Pa)
t	time (s)
w_i	weight coefficient
$\boldsymbol{u}$	velocity (m s^{-1})
$\boldsymbol{x}$	spatial position (m)

Greek symbols

Γ	a coefficient related to mobility
θ	contact angle (°)
κ	a constant related to interface thickness
μ	chemical potential
ξ	interface thickness (m)
ρ	density (kg m^{-3})
υ	kinematic viscosity (m^2 s^{-1})
σ	surface tension (N m^{-1})
τ	relaxation time
ϕ	order parameter
Ψ	free energy density

Subscripts or superscripts

i	the direction in a lattice
eq	equilibrium

dropwise condensation via the preparation of functional surface and subsequent experimental observation. Zhao [11] experimentally studied the influence of contact angle for the gradient surface on the droplet motion under the condition of condensation heat transfer. Subsequently, Daniel [15,18] successfully captured the fast droplet movement induced by the vapor condensation on a silicon wafer possessing a radial gradient of surface energy via a visualization system. Recently, he conducted another experiment with similar surface properties to compare the drop size distribution on gradient and uniform surface [19]. The results indicate that the condensation heat transfer coefficient on the gradient surface is significantly improved as compared with the condensation heat transfer on the homogeneous surface. For one reason, the condensed liquid swept away in time, thus avoiding the emergence of the liquid film. For another, the refreshed surface assured the small size drops nucleation and growth. Note that, the available research of vapor condensation on a gradient surface are mainly to take use of experiments and focus on the condensation macroscopic behaviors and their influence factors. However, the theoretical understanding of the underlying physics of vapor condensation on the gradient surface from a microscopic perspective is still waiting to be explored.

Thanks to the rapid development of the modern computational science, the numerical simulation has been emerging as powerful tools for the investigation of vapor condensation and droplet motion. In the simulation, the volume-of-fluid (VOF) method and level set method are generally applied to capture the temporal evolution of gas-liquid interface. Yu et al. [20] adopted the random fractal model to simulate the droplet size and spatial distribution during vapor condensation process. Sikarwar et al. [6] investigated the dropwise condensation on multiple scales. The drop size distributions and spatial patterns of condensation were presented. Park et al. [21] carried out a numerical analysis of the diffusion flux during condensation on biomimetic slippery asymmetric bumps by using the finite element method. Particularly, the recently developed mesoscopic simulation method, lattice Boltzmann method (LBM), possesses the inherent advantages of high computing efficiency, and that there is no need to artificially construct another function to capture the interface. Because of this, lattice Boltzmann method nowadays has been examined and applied to simulate several interface wetting phenomenon and multiphase flow problems [22]. The typical cases include droplet coalescence [23], droplet formation in microfluidics [24], condensation and boiling phase change [25–28], etc. So far as the vapor condensation by using LBM, there have been some successful attempts in the simulation of laminar film condensation on the vertical wall [25], dropwise condensation on the horizontal wall [26]. Specifically, Ashrafi [29] took a complete study of condensation cycle on chemically homogeneous and heterogeneous surfaces with LB model. He provided deep insights into the mechanism of condensation process on heterogeneous surfaces with the effect of contact angle differences including continuous wettability gradient variation. The results provided a convincing evidence for the condensation model proposed by Jakob [30] and indicated that surface heterogeneity like the wettability gradient plays a significant role in dropwise condensation process. Nevertheless, lattice Boltzmann simulations of vapor condensation on a gradient surface have so far remained challenging. Due to complex gas-liquid-solid interactions and interfacial mass transfer, the droplet nucleation and growth on the gradient surface is less understood. In addition, the dynamic behaviors of droplet motion, deformation, and coalescence, as well as the interfacial evolution during the condensation process, are still unclear.

Therefore, simulation with lattice Boltzmann method is conducted to investigate the vapor condensation on a solid surface. Based on the model, the condensation phase change on the hydrophobic, hydrophilic and gradient surfaces are reproduced with special attention paid to gradient surface. The phase change and subsequent droplet dynamic behaviors for the condensation on a gradient surface are considered and presented in the study.

2. Mathematical model

In this paper, a two-dimensional (2D) lattice Boltzmann model of vapor condensation process on the gradient surface is applied to investigate the role of gradient surface on the vapor condensation and the droplet dynamic behaviors. As shown in Fig. 1, the solid surface possesses the property of a surface tension gradient in a liquid droplet, so it is capable of causing the motion of liquid droplet. On this gradient surface, the surface wettability changes uniformly from hydrophobicity to hydrophilicity along the x-axis, i.e. the surface energy of bottom solid wall increases linearly along the x-direction. The contact angle of liquid droplet at the substrate surface is assumed to be $\theta|_{x=0} = \theta_0$ and $\theta|_{x=Lx} = \theta_L$. At the initial time, the computational area is filled with the uniform mixture of gas and liquid at the saturated situation with the order parameter ϕ