International Journal of Heat and Mass Transfer 128 (2019) 185–198

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

3D lattice Boltzmann investigation of nucleation sites and dropwise-to-filmwise transition in the presence of a non-condensable gas on a biomimetic surface

Qing Guo, Ping Cheng *

MOE Key Laboratory of Power Machinery and Engineering, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China

ARTICLE INFO

Article history:
Received 8 June 2018
Received in revised form 23 July 2018
Accepted 24 July 2018

Keywords:
Biomimetic surface
Condensation
Nucleation site
Transition
Non-condensable gas
Lattice Boltzmann method

ABSTRACT

Condensation in the presence of non-condensable gas on a biomimetic pillared subcooled surface with hybrid wettability (with hydrophilic top and hydrophobic side and bottom) is investigated using a newly developed 3D multi-component multiphase lattice Boltzmann model. Three preferred nucleation sites with different surface wettability contrasts are found: (i) at the corner of side and bottom hydrophobic surface; (ii) at the center of the bottom hydrophobic surface, and (iii) on the top hydrophilic surface of the pillar. Influencing factors, such as pillar geometrical parameters, subcooling degree and non-condensable gas concentration, on dropwise-to-filmwise condensation transition are examined. For dropwise condensation on a top hydrophilic pillar surface, the droplet undergoes a two-stage growth pattern from “changing contact line” to “constant contact line”. Non-condensable gas is found to aggregate near the condensing interface in the vapor phase and at corners of pillar side surface and bottom surface. Increasing pillar width or pillar height (with other geometric parameters remained unchanged), as well as decreasing degree of wall subcooling or non-condensable gas concentration, can delay transition from dropwise to filmwise condensation.

1. Introduction

Dropwise condensation (DWC) and filmwise condensation (FWC) are omnipresent in various industrial processes involving heat and mass transfer [1–7]. Although DWC is the preferred condensation mode due to its better thermal performance, it is difficult to maintain this mode of heat transfer because droplets will coalesce and form a film eventually. In recent years, much effort [8–16] has been given to promote DWC through surface wettability modifications. In particular, mixed wettability surfaces have recently been proposed to improve condensation performance. Peng et al. investigated vapor condensation on hydrophilic-hydrophobic hybrid surfaces with strip patterns both in experiments [8] and through heat transfer models [9]. They found obvious improvement of condensation heat transfer coefficient on hybrid surfaces at low wall cooling. Lan et al. [10], Vanga and Kim [11] and Lee et al. [12] also reported enhanced condensation heat transfer on hybrid surfaces with similar patterning but different wettability pairs than on a uniformly hydrophobic surface. Chatterjee et al. [13] carried out condensation experiments on hydrophobic surfaces with island-shaped and tree-shaped hydrophilic patterns, and observed better condensation performance on hybrid surfaces. Bai et al. [14] designed a five-pointed-star-shaped hybrid surface with optimal water collection performance and captured directional movements of condensing droplets near star edges. Mahapatra et al. [15] and Ghosh et al. [16] also found that adding wedge-shaped superhydrophilic veins to a strip patterned hybrid surface helps the drainage of condensing droplets, leading to an efficient and recurrent DWC on the hydrophilic area of the hybrid surface.

After millions of years of evolution, some living creatures have adapted to the natural environment with the finest and optimal morphology [17,18]. It is believed that shell of a desert beetle with hydrophilic protrusions on a hydrophobic surface helps to collect water to survive in extreme environments. This has inspired a novel surface modification with hybrid wettability and nano/micro structures, for improved condensation characteristics [19–22]. Hu et al. [19] experimentally investigated and revealed better condensation performance on hydrophilic-hydrophobic and hydrophilic-superhydrophobic finned tubes than tubes with uniform wettability under high vapor volume fraction. Lee et al. [20] conducted an experiment for water collection, and obtained better water collection performance on a biomimetic surface with

---

* Corresponding author.
E-mail address: pingcheng@sjtu.edu.cn (P. Cheng).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.07.124
0017-9310/

Nomenclature

a_1, a_2	parameters in P-R equation of state
b^*	pillar width ($b^* = b/B$)
c	lattice speed (m s^{-1})
c_s	lattice sound speed (m s^{-1})
c_p	specific heat at constant pressure (kJ kg^{-1} K^{-1})
c_v	specific heat at constant volume (kJ kg^{-1} K^{-1})
D	diameter (m)
$\boldsymbol{e}$	lattice velocity vector (m s^{-1})
$\boldsymbol{F}$	force vector (N)
f	distribution function of density field
g	distribution function of temperature field
h^*	pillar height ($h^* = h/H$)
h_{gf}	latent heat of condensation (kJ kg^{-1})
i	discrete direction
k	thermal conductivity (W m^{-1} K^{-1})
n	fluid property
p	pressure (Pa)
P	pitch distance
q''	heat flux (W m^{-2})
q	heat transfer rate (W)
R	gas constant (J kg^{-1} K^{-1})
Ja	Jakob number
t	time (s)
T	temperature (K)
T^*	surface subcooling degree ($T^* = T_s/T_b$)
$\boldsymbol{U}$, $\boldsymbol{u}$	velocity vector (m s^{-1})
V	volume
W_g	NCG weight fraction
$\boldsymbol{x}$	lattice position
x, y, z	coordinates (m)

Greek symbol

α	thermal diffusivity (m^2 s^{-1})
β	weighting factor
γ	accommodation coefficient
δ_t	time spacing (s)
θ	contact angle
θ_h	contact angle at top surface of the pillar
θ_u	contact angle at side and bottom surface
φ	source term
λ	thermal conductivity (W m^{-1} K^{-1})
ν	kinetic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})
σ	surface tension
τ	relaxation time
Ψ	availability
ψ	pseudopotential function
ω	acentric factor
ω_i	weight coefficient

Subscripts or superscripts

ads	adhesion
b	bottom
c	curvature
cr	critical parameter
eq	equilibrium
g	NCG component
i	interface
l	liquid phase
max	maximum
s	solid
sat	saturation
t	pillar top surface
u	bottom surface and pillar side surface
v	vapor phase
w	water component
σ, σ'	component

hybrid wettability and micro-ridges than that on a hydrophobic surface. Hou et al. observed filmwise-to-dropwise transition enabled by microstructured surfaces with patterned wettability [21], and experimentally examined condensation on a surface with hydrophilic micropillars and hydrophobic nanograss, and presented enhanced heat transfer coefficient compared to a smooth hydrophobic surface [22].

The mechanism of condensation on biomimetic surfaces (see Fig. 1), however, is very complicated due to coupling effects of hybrid wettability and nano/micro structures, which is not well understood at the present time. Under mutual interactions of nano/micro structure and surface wettability, the preferred nucleation site is yet to be revealed. Furthermore, few parametric studies have been carried out to study effects of geometry of nano/micro structure and surface wettability on dropwise and filmwise condensation. On the other hand, experimental studies on such a complex surface face many difficulties. For instance, most superhydrophobic surfaces prepared in experiments through coating or solvent etching are accompanied by structure modification such as grass-like nanostructures [19] or random nanopores. So, the real cause for heat transfer enhancements or deteriorations remains unknown.

In recent years, the lattice Boltzmann method (LBM) has been gaining popularity as a numerical method to investigate complex phase-change heat transfer problems. In particular, Gong and Cheng used a liquid-vapor phase-change method [23–25] to study pool boiling heat transfer above smooth and rough [26–28] superheated surfaces while Liu and Cheng used the same method to study filmwise and dropwise condensation [29,30] on smooth subcooled plates. Li and Cheng [31] numerically simulated condensation curve and DWC-FWC transition on a hydrophobic surface with hydrophilic spots. Most recently, Zhang et al. [32] proposed a novel multi-component/multi-phase (MCMP) LBM, which enables direct numerical investigation of condensation heat transfer in the influence of non-condensable gas (NCG).

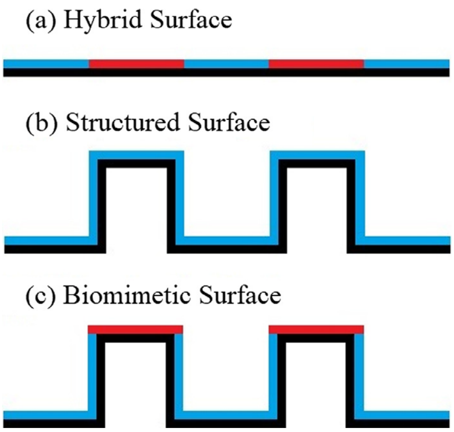

Fig. 1. Three surfaces with different wettabilities and roughness: (a) a smooth surface with different wettabilities; (b) a microstructured uniform wettability surface; (c) a biomimetic surface with hydrophilic tops and hydrophobic sides and bottom.