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Numerical simulation of pool boiling heat transfer on smooth surfaces with mixed wettability by lattice Boltzmann method

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ABSTRACT

In this paper, pool boiling heat transfer from smooth surfaces with mixed wettability is investigated based on a recently developed phase-change lattice Boltzmann method, which is capable of simulating the entire ebullition cycle beginning from the bubble nucleation process. It is demonstrated that addition of hydrophobic spots on smooth hydrophilic surfaces promotes bubble nucleation, enhancing boiling heat transfer and reducing nucleation time drastically. The mixed wettability surface is also expected to enhance critical heat flux (CHF) by regulating vapor spreading behaviors over the heater surface. Temperature variations beneath the growing vapor bubble and total boiling heat flux variations during bubble growth process are also investigated. The ebullition cycle is found to have a dominant effect on temporal variations of temperature and total boiling heat flux. Local heat flux distributions on the hydrophobic and the hydrophilic regions are analyzed, and the three-phase contact line (TCL) region is found to have the highest local heat flux. Effects of the size of the hydrophobic spots and pitch distance between these hydrophobic spots on boiling heat transfer are illustrated.

1. Introduction

During the past century, a great deal of experimental work has been devoted to the study of boiling heat transfer for applications in cooling and energy conversion systems due to its high heat transfer rate [1]. It has been recognized that wettability plays an important role on boiling heat transfer performance [1–4], and therefore a great deal of experimental work [5–15] on effects of wettability on pool boiling has been conducted since 1980s. Experimental results of wettability effects on bubble nucleation [5–12], boiling heat transfer (BHT) [8,10,11], critical heat flux (CHF) [13,14] and bubble departure diameter [8,9,15] have been extensively reported in the past. It is generally believed that hydrophilic surfaces exhibit higher CHF [13,16] while hydrophobic surfaces promote bubble nucleation and have higher BHT [10,11].

Most recently, Betz et al. [17] micro-manufactured surfaces combining hydrophobic and hydrophilic zones on oxidized silicon wafers and demonstrated that ultra-smooth surfaces (nanoscale roughness) with networks combining hydrophilic and hydrophobic regions could significantly enhance both the heat transfer coefficient (HTC) and CHF in pool boiling. Suroto et al. [18] investigated experimentally effects of subcooling and length of hydrophobic-spot periphery on pool boiling heat transfer from a mixed wettability copper surface. Their results suggested that heat transfer performance of mixed wettability surfaces (TiO_2 coated copper surfaces with PTFE hydrophobic circle spot) is better than that of superhydrophilic surfaces (TiO_2 coated copper surfaces without PTFE spot). Similarly, Jo et al. [19] demonstrated that a mixed wettability smooth surface (with nanoscale roughness), composing hydrophobic dots on a hydrophilic surface, provided higher HTC than a uniform hydrophilic surface, and the CHF of the mixed wettability smooth surface remained as high as a uniform hydrophilic surface.

In spite of these experimental efforts [17–19], mechanisms of heat transfer enhancement on mixed wettability surfaces remain unclear. In Suroto et al.'s [18] experiments, the mixed wettability surfaces have micro-scale cavities at the edge of the hydrophobic spot, thus it is not possible to distinguish microstructure effects (or roughness effects) from wettability effects in pool boiling heat transfer. The coupling effects of wettability and roughness on pool boiling are very complicated and roughness itself can influence wettability [20,21]. In order to exclude microstructure effects, Jo et al. [19] adopted microstructure-free ultra-smooth surfaces in their experiments to study the pure wettability effects on pool

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Nomenclature

$c_{p,l}$	specific heat of the liquid (J kg^{-1} K^{-1})
c_s	lattice sound speed (m/s)
d	pitch distance (m)
d^*	dimensionless pitch distance
$\mathbf{e}$	lattice velocity vector (m/s)
$\mathbf{F}$	force (N)
f, g	distribution function
h_{fg}	latent heat (J/kg)
H	height of the heated plate (m)
Ja	Jacob number
l_0	capillary length (m)
L_h	length of the heated plate (m)
L_s	hydrophobic spot size (m)
L_s^*	dimensionless hydrophobic spot size
L_x	length of the computation domain (m)
L_y	width of the computation domain (m)
p	pressure (pa)
q'	dimensionless local heat flux
Q'_{ave}	time averaged dimensionless total heat flux
Q'	dimensionless total heat flux
t	time (s)
t^*	dimensionless time
t_0	characteristic time (s)
T	temperature (K)
T'	dimensionless temperature
$\mathbf{u}, \mathbf{U}$	velocity vector (m/s)
u_0	characteristic velocity (m/s)
x	co-ordinates (m)
y	co-ordinates (m)

Greek symbols

ρ	density (kg/m^3)
θ	static contact angle (°)
ω_i	weight coefficient
λ	thermal conductivity of the heated plate (W m^{-1} K^{-1})
ϕ	source term
τ	relaxation time
τ^*_{ncl}	dimensionless nucleation time
υ	kinematic viscosity (m^2/s)
σ	surface tension (N/m)

Subscripts or Superscripts

c	critical
eq	equilibrium
int	interparticle
l	liquid
s	saturation
v	vapor
w	wall

boiling. However, they were unable to explain the low superheat for onset of heterogeneous boiling on nanoscale smooth surfaces in their experiments, which is contrary to classic trapped vapor theory [22,23]. Witharana et al. [24] argued that the low superheats for bubble nucleation on these nanoscale smooth heating surfaces suggest the presence of microscale cavities or microscale contaminants. As a matter of fact, Betz et al. [17] observed that bubble nucleation usually occurred at the interface between areas of different wettability, which could support the existence of microscale defects at the interface region between hydrophilic and hydrophobic areas. So, all these experimental studies were unable to get rid of roughness effects in their experiments, and enhanced mechanisms in pool boiling from mixed wettability surfaces need further investigation.

In this paper, we have carried out a 2D phase-change lattice Boltzmann simulation [25,26] on pool boiling heat transfer from smooth surfaces with mixed wettability for a better understanding of its enhanced boiling heat transfer mechanisms. In particular, bubble dynamics, temperature field, flow field, temporal/spatial heat flux are obtained and analyzed. Effects of size of each hydrophobic spot and pitch distance between these hydrophobic spots on boiling heat transfer are discussed. It is relevant to point out that this LB phase-change model is a direct simulation of liquid/vapor phase change heat transfer, which is determined by the thermodynamic relation given by the equation of state, without any empirical correlations or assumptions. Compared with conventional numerical methods for boiling heat transfer such as level-set [27] or VOF [28], this lattice Boltzmann phase-change method is able to simulate the entire ebullition cycle including bubble nucleation process, which is the key of this study. Also, it is not necessary to assume the waiting period between two ebullition cycles in the simulation. Because there is no need to track the interface explicitly, computation cost of this LB phase-change method is much lower than interface tracking methods.

2. Model description

In this section, we shall briefly review the Gong-Cheng phase-change lattice Boltzmann model, which consists of a modified pseudo-potential LBM multiphase flow model [29] and an energy equation model containing a new source term [25,26].

2.1. The modified pseudo-potential LBM model for multiphase flows

In LBM, the fluid is described by the evolution of particle distribution functions. The evolution equation of the density distribution function with the BGK collision operator is governed by [29]

$$f_i(\mathbf{x}+\mathbf{e}_i\delta_t, t+\delta_t) - f_i(\mathbf{x},t) = -\frac{1}{\tau}\left(f_i(\mathbf{x},t) - f_i^{(eq)}(\mathbf{x},t)\right) + \Delta f_i(\mathbf{x},t) \quad (1)$$

where $f_i(\mathbf{x}, t)$ is the particle distribution function with velocity $\mathbf{e}_i$ at position $\mathbf{x}$ and time t, τ is the relaxation time. $f_i^{(eq)}(\mathbf{x}, t)$ is the corresponding equilibrium distribution function given by

$$f_i^{(eq)} = \omega_i\rho\left[1 + \frac{\mathbf{e}_i\cdot\mathbf{u}}{c_s^2} + \frac{(\mathbf{e}_i\cdot\mathbf{u})^2}{2c_s^4} - \frac{\mathbf{u}^2}{2c_s^2}\right] \quad (2)$$

with ω_i being the weighting coefficients and c_s the lattice sound speed. The exact difference method [30] was adopted to implement the body force term $\Delta f_i(\mathbf{x}, t)$ which is given by

$$\Delta f_i(\mathbf{x},t) = f_i^{eq}(\rho(\mathbf{x},t), \mathbf{u}+\Delta\mathbf{u}) - f_i^{eq}(\rho(\mathbf{x},t), \mathbf{u}) \quad (3)$$

where $\Delta\mathbf{u} = \mathbf{F}\cdot\delta t/\rho$ is the velocity change under the action of body force during time step δ_t, with $\mathbf{F}$ given by

$$\mathbf{F} = \mathbf{F}_{\text{int}}(\mathbf{x}) + \mathbf{F}_s(\mathbf{x}) + \mathbf{F}_g(\mathbf{x}) \quad (4)$$

where $\mathbf{F}_{\text{int}}$ is the interparticle interaction force which is responsible for phase separation, $\mathbf{F}_g$ is the gravitational force, and $\mathbf{F}_s$ is the interaction force between solid surface and fluid. $\mathbf{F}_{\text{int}}$ is given by [29,30]