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A study of boiling on surfaces with temperature-dependent wettability by lattice Boltzmann method

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ABSTRACT

Effects of surface wettability have been the focus of boiling heat transfer research in recent years, due to its important role on boiling performance. It is reported that hydrophobic surface has higher boiling heat transfer coefficient while hydrophilic surface has higher critical heat flux. In this study, a surface with temperature-dependent wettability was proposed to take advantages of both hydrophilic and hydrophobic surfaces. A hybrid thermal lattice Boltzmann model with an improved forcing scheme was used to simulate and evaluate the effects of wettability control. First, single bubble dynamics on hydrophilic and hydrophobic surfaces were depicted to analyze the heat transfer features on both surfaces. Second, boiling curves for each condition have been obtained under stepwise heat flux control condition, and the controlled wettability surface shows higher boiling performance than both hydrophobic and hydrophilic surfaces. In addition, we found an optimal relation between temperature and surface wettability for heat transfer rate, and it is evaluated through the parameter test of the temperature-wettability relation. This research may provide a potential way of controlling surface wettability to improve boiling performance and also offer conceptual design of enhanced boiling surface.

1. Introduction

Boiling heat transfer (BHT) is one of the most effective heat transfer modes in energy conversion and cooling system. It has been widely used in electric power generating and thermal management of electric components. Over the past century, many researchers intended to enhance the heat transfer coefficient (HTC) and the critical heat flux (CHF) to improve the performance of BHT. Recently, the effect of wettability has arisen much attention, for that it influences the volume of trapped vapor/air in a cavity, bubble departure diameter, bubble departure frequency, incipience superheat and liquid supply, which play important roles on boiling performance [1,2].

There were many reports about wettability effects on boiling performance. Takata et al. [3] used UV light to change the wettability of TiO_2 coated surface, they found that the CHF doubled compared to non-coated surface but the temperature at the onset of nucleate boiling increased about 100 K. They also reported that there was no nucleate boiling regime on a super water-repellent surface. The stable film boiling occurred in very small superheating [4]. Then, Forrest et al. [5] changed the surface wettability through application of nanoparticle thin-film coatings and found that hydrophobic surface coated with fluorosilane can enhance HTC by about 100%, but gives lower CHF than hydrophilic surface. After this, Bourdon et al. [6] studied the influence of wettability in terms of surface temperature quantitatively and showed that grafted surfaces which has higher contact angle enabled an easier boiling, they also reported that wettability can be of primary importance and can control the position of incipient boiling even with a certain amount of roughness. Hsu et al. [7] investigated the effects of surface wettability on CHF under various wettability from superhydrophilic to superhydrophobic and found that CHF values increased with the decrease of surface contact angle. They also reported that size of growth bubbles increases with increasing contact angle. Most recently, Girard and Kim [8] conducted pool boiling experiments and verified that boiling heat transfer coefficient increase with contact angle increase. Besides, You et al. [9] and Bang et al. [10] reported a big enhancement in CHF with nanofluid and Kim et al. [11], Coursey et al. [12] attributed the CHF enhancement to the nanoparticle deposition which increased wettability of the heating surface.

According to the above literatures, generally, it is showed that hydrophobic surface can promote bubble nucleation and has a higher HTC than hydrophilic surface, while hydrophilic surface can induce liquid supply to the dry area of a heater and delaying

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Nomenclature

a, b	parameter in P-R equation of state
c	lattice speed $(\mathrm{m\cdot s^{-1}})$
$\boldsymbol{e}$	lattice velocity vector $(\mathrm{m\cdot s^{-1}})$
f	distribution function
F	body force vector (N)
$\mathbf{F_b}$	gravitational force (N)
$\mathbf{F_m}$	interaction force (N)
$\mathbf{F_{ads}}$	fluid-solid interaction force (N)
g	gravitational acceleration $(\mathrm{m\cdot s^{-2}})$
h_{fg}	latent heat $(\mathrm{J\cdot kg^{-1}})$
Ja_R	Jacob number calculated by Rohsenow's equation
Ja	Jacob number
L_H	length of heater (m)
l_0	characteristic length (m)
p	pressure (Pa)
q	heat flux $(\mathrm{W\cdot m^{-2}})$
s	entropy $(\mathrm{J\cdot K^{-1}})$
$t*$	dimensionless time
t_0	characteristic time (s)
T	temperature (K)
$\boldsymbol{v}$	velocity vector $(\mathrm{m\cdot s^{-1}})$
w_α	weight coefficient
$\boldsymbol{x}$	co-ordinates (m)

Greek symbol

ω	acentric factor
Ψ	effective mass
λ	thermal conductivity $(\mathrm{W\cdot m^{-1}\cdot K^{-1}})$
σ	surface tension $(\mathrm{N\cdot m^{-1}})$
υ	kinematic viscosity $(\mathrm{m^2\cdot s^{-1}})$
τ	relaxation time
ρ	density $(\mathrm{kg\cdot m^{-3}})$
θ	contact angle (°)
μ	dynamic viscosity $(\mathrm{Pa\cdot s})$

Subscripts or superscripts

ave	average
c	critical
eq	equilibrium
l	liquid
t	time
v	vapor
sat	saturation

CHF. Based on those features, researchers considered taking advantages of both hydrophilic and hydrophobic surfaces. One method is using surface with mixed wettability, such as the work done by Betz et al. [13] and Jo et al. [14], they both found an increase of boiling heat transfer but their conclusions on CHF were not consistent. Different from their ideas, Bertossi et al. [15] considered changing the wettability during the process of boiling. They designed specific surfaces called "switchable surfaces" with polymer coating. The polymer showed wetting transition from hydrophilic to hydrophobic when temperature exceed a specific value. Since hydrophobic surface promotes bubble nucleation and hydrophilic surface enhances bubble detachment, the switchable surface increased boiling heat transfer in the nucleate boiling regime. Recently, Kim et al. [16] found that the wettability of TiO2-coated surface (TCS) could change with temperature under high pressure conditions. They reported this kind of surface had a higher HTC in low-wall-superheat region due to its hydrophobicity and higher CHF because its better wettability in high-wall-superheat.

In this study, we proposed surface whose wettability can be changed with temperature, it has large contact angle at low superheat which can promote bubble nucleation and turns to hydrophilic at higher superheat to increase CHF. Four relations between temperature and wettability were designed and their boiling performance were obtained to investigate whether there is an optimal one. Numerical method is chosen to investigate various cases and get more details to provide guidance on controlling surface wettability to improve boiling performance.

Recently, the lattice Boltzmann method has received great attention and shows promising future in phase change field, models like phase field lattice Boltzmann model [17–19] and pseudopotential model [20–22] were used to study boiling phenomena from nucleate boiling to film boiling. There are several advantages of phase change pseudopotential model. First, the state of vapor or liquid at each lattice is determined by the equation of state, so there is no need to track the interface between liquid and vapor explicitly. Secondly, the nucleation process could be simulated automatically, there is no need to initialize a small bubble at the beginning, so we can get the entire ebullition cycle. Moreover, the effects of surface wettability can be easily implemented [2]. Until now, there are plenty of researches done with LBM in pool boiling field, especially in studying the effects of wettability [2] or designing the patterns of mixed wettability [23–26]. Different with previous models, Li et al. [21] introduced a hybrid thermal lattice Boltzmann model to reduce the spurious term caused by the forcing-term. All terms in the energy equation instead of only the source term are calculated with finite-difference methods in hybrid thermal scheme. In this study, this hybrid thermal lattice Boltzmann method was adopted to investigate the wettability effects on boiling performance.

2. Model description

A brief introduction of hybrid thermal lattice Boltzmann method will be described in this part. As same as Double-Distribution-Function (DDF) approach, the flow field is solved by density distribution function, but instead of LB approach, the temperature field in hybrid model is solved with conventional numerical methods, such as the finite-difference or finite-volume method [27]. For the density distribution function, a multiple-relaxation-time (MRT) collision operator is adopted here, for it has a better numerical stability and lower spurious velocity.

2.1. MRT pseudopotential lattice Boltzmann method for flow field

The standard LB equation with a MRT collision operator can be expressed as follows:

$$f_\alpha(\boldsymbol{x}+e_\alpha\delta_t, t+\delta_t) = f_\alpha(x,t) - (M^{-1}\Lambda M)_{\alpha\beta}(f_\beta - f_\beta^{eq}) + \delta_t F'_\alpha \tag{1}$$

where $f_\alpha(x,t)$ is the density distribution function in α th lattice direction, $\boldsymbol{e}_\alpha$ is the discrete velocity, δ_t is the time step, f_β^{eq} is the equilibrium density distribution function in β th lattice direction, F'_α is the forcing term, M is an orthogonal transformation matrix and can be found in [28], Λ is a diagonal matrix given by (D2Q9 lattice)

$$\Lambda = diag(\tau_\rho^{-1}, \tau_e^{-1}, \tau_\zeta^{-1}, \tau_j^{-1}, \tau_q^{-1}, \tau_j^{-1}, \tau_q^{-1}, \tau_v^{-1}, \tau_v^{-1}) \tag{2}$$

Using transformation matrix M, the right side of Eq. (1) can be rewritten as: