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Lattice Boltzmann simulation of co-existing boiling and condensation phase changes in a confined micro-space

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Based on the multiphase lattice Boltzmann method combining the finite difference scheme, a theoretical model of vapor–liquid phase change is developed and numerically analyzed to investigate the two-phase flow and thermodynamic behaviors of co-existing boiling and condensation heat transfer in a confined micro-space. The effects of surface wettability on bubble/droplet hydrodynamic behaviors involving nucleation, growth, coalescence and rupture/dripping as well as the thermal response are examined and analyzed. Besides, the effect of confined scale on the wall temperature and heat transfer coefficient of the heating surface is presented and discussed. The results indicate that the interaction of boiling and condensation in a confined micro-space mainly consists in the dripping of condensate droplets which directly contact the growing bubble, accelerating the bubble collapse, and induce the liquid motion in boiling pool, contributing to bubble movement or detachment. When compared with the hydrophobic surface, a shorter thermal response of boiling phase change is induced and a lower steady-state temperature is maintained on the hydrophilic surface. In addition, the boiling heat transfer coefficient on the hydrophilic surface is higher than that on the hydrophobic surface. Particularly, the heat transfer performance is suppressed with the decrease of confined scale, and this suppression effect is more obvious for the hydrophilic surface.

1. Introduction

With the rapid development of microelectronics, the high heat flux microelectronic devices have been extensively used in the fields of deep space exploration and information communication [1–3]. Faced with the challenge of high heat fluxes, it is crucial to maintaining these devices at a reasonable temperature to ensure their efficient and reliable work. Transferring these heat fluxes through coupling boiling and condensation phase changes in a confined micro-space (such as the micro thermal spreader [4] etc.) is a highly efficient way to avoid the emergence of hotspots [4,5]. Once boiling and condensation occur simultaneously in the confined space, complex two-phase flow dynamics including bubble/droplet nucleation, growth, and departure, vapor–liquid phase change heat transfer as well as phase interface evolution are all involved. Besides, the coupled phase change processes, although often not properly known, could significantly affect the two-phase flow dynamics and thermal performance. In this context, it is of particular interest and significance to fundamentally understand the coexisting boiling-condensation heat transfer and the bubble/droplet dynamic behaviors in the confined micro-space.

Differing from the boiling phase change heat transfer in a large space, when boiling occurs in a confined micro-space, the size of the generated bubble is of the same order to space dimension, and the growth of bubble may even lead to heat transfer enhancement. The available study of phase change heat transfer in a confined space mainly focused on the single boiling heat transfer, with special attention on the role of space confinement (space height, slit size, space constraint) [6,7] to nucleate boiling behaviors and boiling heat transfer coefficient. However, once the boiling occurs on the heating surface in a confined space, the evaporated vapor would inevitably condense on the upper condensing surface. Besides, the condensed droplets would drip into the liquid pool above the heating surface due to gravity. As a result, the boiling and condensation phase changes exist simultaneously and are coupled. This intense interaction also has an important effect on the heat transfer behavior of vapor–liquid phase change in the

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confined micro-space. In regard to this specific co-existing boiling and condensation phase change phenomenon in a confined space, Zhang et al. [8,9] carried out a series of experimental studies and obtained the vapor–liquid two-phase flow regimes. Xia et al. [10] studied the effect of heat flux and liquid-filling ratio on the vapor–liquid interaction. However, these efforts on the co-existing boiling and condensation in a confined space are all based on the experiment, which is difficult to intuitively describe the evolution of temperature and fluid fields inside the confined space. The two-phase flow hydrodynamics (such as nucleation, growth, and merging of bubbles and droplets during boiling and condensation), the phase interface evolution, and the boiling-condensation coupled heat transfer performance are less understood. Besides, wettability, the ability of a liquid to spread on a surface, which is now a center of attention in nanotechnology and nanoscience studies [11–13], has a significant influence on two-phase flow dynamic behaviors, and its effect on the boiling-condensation coupled phase change in a confined space has not been uncovered. Especially, the interaction mechanism of boiling and condensation phase change in a confined space is still waiting to be explored.

Thanks to the rapid development of computer technology, numerical simulation is gradually applied to research the phase change heat transfer owing to the advantages of high efficiency and low cost. Besides, the numerical method is capable to track the evolution of phase interface and obtain the spatial distribution of temperature as well as velocity visually. The difficulty of directly simulating the boiling and condensing phase change progresses lie in how to accurately capture the rapid evolutionary phase interface accompanied by the merging and rupturing processes. Although the VOF method [14] and the Level Set method [15] have been widely used to investigate the boiling and condensation phase change process, these methods are not well satisfied in tracking the phase interface with bubble and droplet growth and departure, particularly the key processes of coalescence and break-up [16,17]. Besides, in these numerical methods, it is too arbitrary to set the vaporization/liquefaction core artificially in the simulation of phase change. All these imply that it is still a challenge to simulate the heat transfer process of boiling and condensing coupled phase change in a confined space with the conventional computational fluid dynamics methods. Recently, lattice Boltzmann method, which possesses the inherent advantages in parallelism and no manual tracing interface, has emerged as a powerful mathematical tool to probe phase change behaviors including evaporation [18], boiling [19–22] and condensation [23–25].

Therefore, a lattice Boltzmann model of vapor–liquid phase change and two-phase flow inside a confined micro-space is developed and numerically analyzed to investigate the boiling-condensation coupled phase change heat transfer, with a particular focus on the effects of the surface wettability and confined scale on the boiling and condensing phase changes and heat transfer behaviors. The phase interface evolution (including the droplets/bubbles nucleation, growth, coalescence, and rupture), the temperature and velocity distributions and the thermal performance during the boiling-condensing coupled phase change are analyzed and discussed.

2. Theoretical model

In order to analyze the boiling-condensation coupled phase-change heat transfer behaviors, a two-dimensional model of two-phase flow and phase change heat transfer in a confined space is developed. As shown in Fig. 1, the confined space is constructed of the upper and lower solid wall, in which the thickness of the lower wall is H_w while the thickness of the upper wall is negligible. The dimensions of the confined space are of the length, L_x, and the height, L_y. The saturated working fluid is filled inside the confined space with a height of H_s. The local heat source with a constant heat flux (q) is placed in the middle of the lower solid substrate with width, L_q.

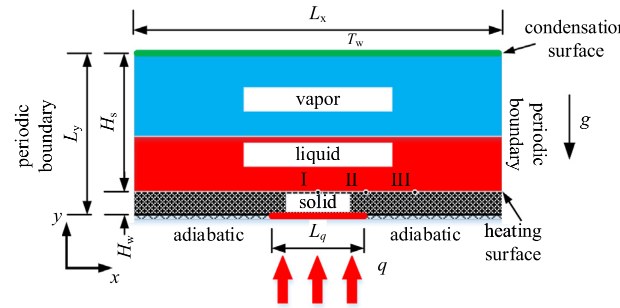

Fig. 1. Schematic diagram of a confined micro-space.

2.1. Hybrid thermal lattice Boltzmann (HTLB) model

The lattice Boltzmann method combined with the finite difference method (FDM) is used to simulate the evolution of the fluid flow and dynamic temperature variation in the confined space. The pseudo-potential model proposed by Shan and Chen [16,26] is adopted to describe the evolution of the liquid–gas two-phase flow field during the process of the boiling-condensing coupled phase change. The corresponding evaluation function with the Bhatnagar-Gross-Krook (BGK) collision operator is expressed as

$$f_i(\boldsymbol{x}+\boldsymbol{e}_i\delta t, t+\delta t) - f_i(\boldsymbol{x}, t) = -\frac{1}{\tau}(f_i(\boldsymbol{x}, t) - f_i^{eq}(\boldsymbol{x}, t)) + \Delta f_i(\boldsymbol{x}, t), \tag{1}$$

where $f_i(\boldsymbol{x}, t)$ is the density distribution function, $\boldsymbol{x}$ represents the location in space, t is the lattice time, τ is a dimensionless relaxation time that is related to the fluid viscosity v. $f_i^{eq}(\boldsymbol{x}, t)$ is the equilibrium distribution, which is a function of the density, ρ and velocity, $\boldsymbol{u}$, and it is expressed as

$$f_i^{eq}(\boldsymbol{x}, t) = \omega_i \rho \left(1 + \frac{\boldsymbol{e}_i \cdot \boldsymbol{u}}{c_s^2} + \frac{(\boldsymbol{e}_i \cdot \boldsymbol{u})^2}{2c_s^4} - \frac{\boldsymbol{u}^2}{2c_s^2}\right), \tag{2}$$

where ω_i is the weight coefficient, c_s is the lattice velocity and $c_s^2 = c^2/3$. Here $c = \delta x/\delta t$, δx and δt are the spatial step and time step respectively and are usually given the value of 1.0. $\boldsymbol{e}_i$ is the discrete velocity and the D2Q9 discrete velocity model is employed to solve the boiling and condensing co-existence problem. The term $\Delta f_i(\boldsymbol{x}, t)$ in Eq. (1) is related to the forces applied on fluid and the expression form of EDM (Exact-Difference-Method) [27] is employed here,

$$\Delta f_i = f_i^{eq}(\rho, \boldsymbol{u} + \Delta \boldsymbol{u}) - f_i^{eq}(\rho, \boldsymbol{u}), \tag{3}$$

where $\Delta \boldsymbol{u} = \boldsymbol{F}\delta t/\rho$ is the change value in velocity, $\boldsymbol{u}$, caused by the force, $\boldsymbol{F}$, in the time step, δt.

$$\boldsymbol{F} = \boldsymbol{F}_{\text{int}} + \boldsymbol{F}_{ads} + \boldsymbol{F}_g. \tag{4}$$

$\boldsymbol{F}$ is the resultant force of $\boldsymbol{F}_{\text{int}}$, $\boldsymbol{F}_{\text{ads}}$, $\boldsymbol{F}_{\text{g}}$ applied on fluid. $\boldsymbol{F}_{\text{int}}$ is the interaction force between particles, and the interaction force form proposed by Gong and Cheng [19] is adopted as follows,

$$\boldsymbol{F}_{\text{int}} = -\beta\psi(\boldsymbol{x})\sum_{x'} G(\boldsymbol{x}, \boldsymbol{x}')\psi(\boldsymbol{x}')(\boldsymbol{x}' - \boldsymbol{x}) - \frac{1-\beta}{2}\sum_{x'} G(\boldsymbol{x}, \boldsymbol{x}')\psi^2(\boldsymbol{x}')(\boldsymbol{x}' - \boldsymbol{x}). \tag{5}$$

β is a weight factor related to the equation of state (EOS), which is used to enhance the numerical stability of the simulation. The variable $\Psi(\boldsymbol{x})$, a so-called parameter of "effective mass", is a func-