DROPLET DETACHMENT DURING CONDENSATION PROCESS ON A DOWNWARD-FACING GROOVED SURFACE

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ABSTRACT

A hybrid thermal lattice Boltzmann method is employed to numerically simulate the condensation process on a two-dimensional downward-facing grooved surface. Nucleation, growth, coalescence and detachment process on surfaces with different wettability are reproduced with a focus on the droplet dynamic behavior during the detachment. The droplet detachment during condensation in pendent state is investigated in a wide range of equilibrium contact angle. The numerical simulation identified a single-droplet mode and a coalescence-induced mode for droplet detachment during condensation process on the downward-facing grooved surface. In the single-droplet detachment mode, the critical departure radius is negatively correlated with the equilibrium contact angle with two inflection points. The first inflection point is related to the transition of droplet wetting morphology from Wenzel to Cassie mode, and the second is corresponding to the transition of departure morphology from breakup to non-breakup mode.

1. INTRODUCTION

Organic Rankine cycle (ORC) is an effective technology for low-grade heat recovery (Hung *et al.*, 1997; Tchanche *et al.*, 2011; Sprouse and Depcik, 2013), which could alleviate energy shortage and reduce environmental pollution. An ORC system mainly consists of four parts: evaporator, expander, condenser and pump. The heat transfer performance of condenser significantly affects the cycle efficiency. Between the two modes of condensation, the heat transfer performance of dropwise condensation can be an order of magnitude higher than filmwise condensation. However, as the droplets coalesce and form a liquid film, it difficult to maintain the dropwise condensation for a long time. Micro-scale or nano-scale structures and modification coatings are applied onto the condensation surface to enhance the hydrophobicity and thereby promote the detachment of condensed droplets. To investigate the condensation phase change heat transfer on an inverted groove surface can provide theoretical support for the design of the condenser.

Droplet departure driven by gravity is the most common mode, while another is coalescence-induced jumping, which is first observed in experiment by Boreyko and Chen (2009). Due to the difficulty to accurately control influencing factors to quantify their effects in experiment, theoretical analysis and numerical simulation become ideal research methods. Molecular dynamics (Niu and Tang, 2018), Level Set method (Gibou *et al.*, 2007) and VOF method (Welch and Wilson, 2000) can be used to investigate the condensation process. However, it takes a significant amount of computing resources for molecular dynamics to work in the scale of departure radius. The Level Set method and the VOF method are not well satisfied in tracking the gas-liquid interface during droplet coalescence and breakup; more importantly, both methods require artificially setting of the liquefaction core, which makes the initial morphology of the droplet hard to determine. As a mesoscopic method, lattice Boltzmann method (LBM) can effectively simulate micro-scale flow and heat transfer problems, and possesses the inherent advantages in parallelism and no manual tracing interface. In recent years, Li et al. (2015) propose a model that uses direct differential method to solve the energy equation, therefore both the vaporization core and the condensing core can be generated by energy evolution. Thus LBM becomes a powerful mathematical tool for simulating boiling and condensation phase change heat transfer processes.

A pseudo-potential model of lattice Boltzmann method coupled with finite difference method is used to numerically simulate the condensation process on a two-dimensional downward-facing grooved surface. Nucleation, growth, coalescence and detachment process on surfaces with different wettability are reproduced with a focus on the droplet dynamic behavior during the detachment. In addition, effects of wettability of solid wall on critical departure radius are discussed.

2. THEORETICAL MODEL

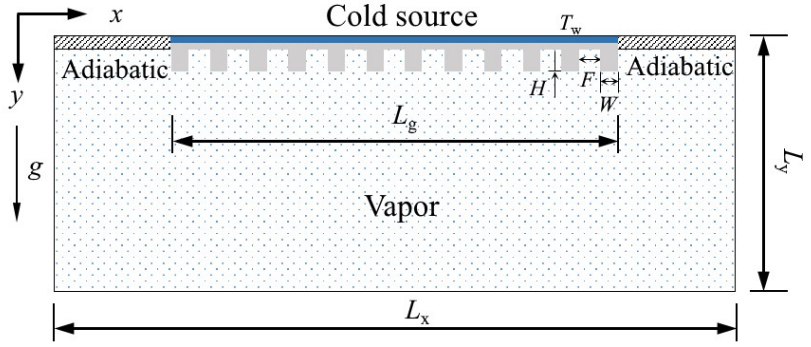

Figure 1: Schematic of a downward-facing grooved surface

As shown in Figure 1, the computational domain is a semi-open area with a width L_x and a height L_y. The center of the substrate has a rough section with a width of L_g. The width and height of the pillar of the roughness is respective W and H. Pillars are uniformly arranged with the space of F. A cold source with a constant temperature T_w is set at bottom of the rough section while the smooth area of the wall is adiabatic. The space outside the wall is filled with vapor at a saturated temperature of T_s. As the vapor near the substrate being cooled down, condensation gradually develops on the rough area.

In order to reproduce the multiphase and multi-scale dynamic behavior during condensation, a hybrid thermal lattice Boltzmann model proposed by Li *et al.* (2015) is adopted to solve flow field and temperature field equations. The evolution process of lattice Boltzmann equation is mainly divided into two steps of collision and streaming, in which the collision step is implemented in the moment space as shown in Equation (1) and the streaming step is implemented in the velocity space with the form of Equation (2)

$$\tilde{\mathbf{m}} = \mathbf{m} - \mathbf{\Lambda}(\mathbf{m} - \mathbf{m}^{eq}) + \delta t(\mathbf{I} - \frac{\mathbf{\Lambda}}{2})\bar{\mathbf{S}} + \mathbf{\Lambda C} \tag{1}$$

$$f_\alpha\left(\mathbf{r} + \mathbf{e}_\alpha \delta t, t + \delta t\right) = \widetilde{f_\alpha}(\mathbf{r}, t) \tag{2}$$

where $\mathbf{m} = \mathbf{M}\mathbf{f}$ and $\tilde{\mathbf{m}} = \mathbf{M}\tilde{\mathbf{f}}$ is the distribution function before and after collision step in moment space, $\mathbf{f}$ and $\tilde{\mathbf{f}}$ are corresponding distribution function in velocity space, $\mathbf{M}$ is the transformation matrix, $\mathbf{m}^{eq}$ is the equilibrium moment, $\mathbf{\Lambda}$ is the diagonal relaxation matrix, δt is the lattice time step, $\bar{\mathbf{S}}$ is the forcing term in moment space, $\mathbf{C}$ is an additional term, $\mathbf{I}$ is the unit tensor, $\mathbf{r}$ is the spatial position, $\mathbf{e}_\alpha$ is the discrete velocity along the αth direction.

3. RESULTS AND DISCUSSION

The condensation process is significantly affected by factors such as thermophysical properties of the working fluid, wettability, roughness and supercooling degree of the solid wall. As the embodiment of the interaction between the working fluid and the solid wall, surface wettability affects the condensation heat transfer process from beginning to end. Therefore, this paper first analyzes the condensation process on the inverted grooved surface of different wettability to clarify the droplet detachment mode, and then studies the influencing factors on critical departure radius, which is the key parameters of the detachment process.

3.1 Condensation On Downward-Facing Walls With Different Wettability

Simulation is carried out in a computational domain of $L_x \times L_y = 600 \times 600$ lattice unit (l.u.) in size and the width of the rough section takes 455 l.u. with $F = 5$ l.u., $W = 4$ l.u., $H = 6$ l.u. Half-way bounce back scheme and constant temperature boundary are imposed on the boundary between the fluid and solid phase. Periodic boundary conditions are implemented on the left and right boundaries of the computation domain. Constant pressure condition is specified on the bottom serving as a stable vapor source. The temperature of cold source is set at a temperature of $0.6T_c$ and the space except the solid wall is filled with vapor at $0.85T_c$.

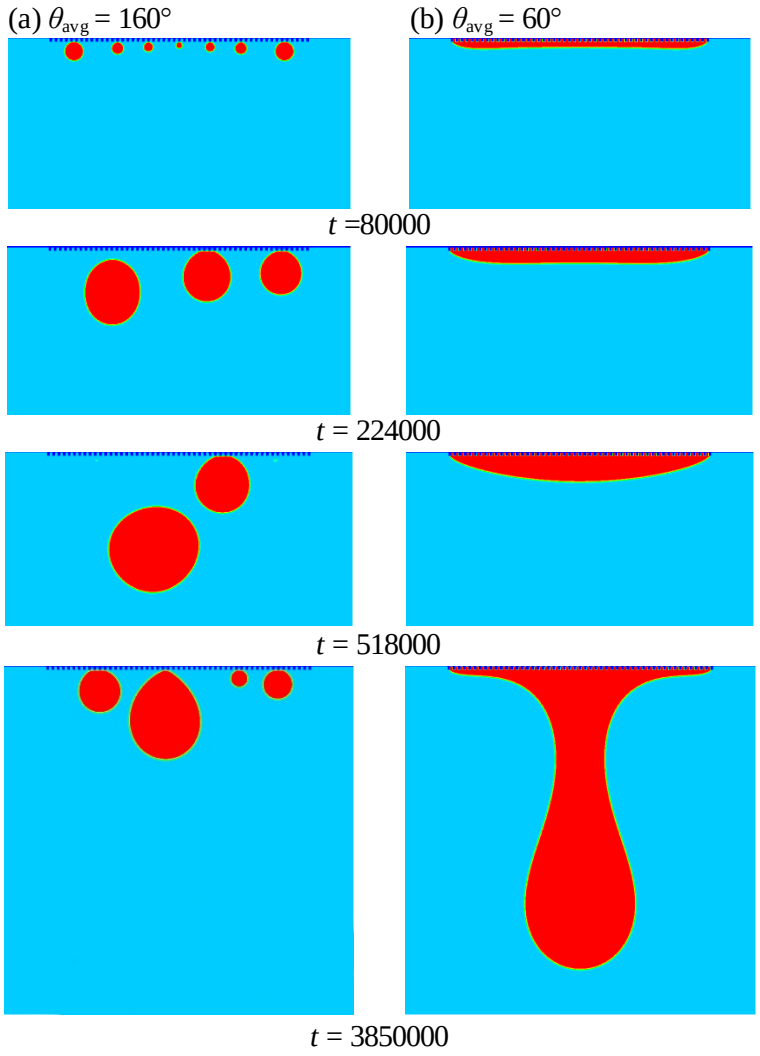

Figure 2: Evolution of vapor–liquid two-phase morphology during condensation process

Varying the contact angle changes the droplet distribution and significantly affects the heat transfer performance. At current stage, the contact angle of water on a surface treated by mechanical and chemical processing can be up to 160°. In Figure 2, the condensation processes on a wall with contact angles of 160° is presented. Another surface with contact angle of 60°, where the condensation process is mainly filmwise condensation instead of dropwise condensation, is taken for comparison.

In Figure 2, the surface of the equilibrium contact angle $\theta_{avg} = 60°$ has been covered by the liquid film growing from the bottom of the groove at $t = 80000$ while several droplets in Cassie morphology grow on the surface of $\theta_{avg} = 160°$. As the equilibrium contact angle increases, the contact area between the droplets and the wall decreases, and the adhesion force decreases correspondingly, which results in an enhancement of droplets mobility with frequently occurring migration and departure behavior. On the

one hand, the droplets migrate on the surface after coalescence, sweeping and merging more droplets; at the same time, the surrounding gas rapidly rushes to the space before the droplet migrates, destroying the temperature boundary layer near the surface, strengthening the heat exchange between the supercooled wall and the gas. Furthermore, droplets departure benefits from the action of the shearing force of the airflow. On the other hand, the airflow disturbance caused by the low pressure when the droplets depart from the wall contributes to the migration of surrounding droplets to the departure place. In addition, a larger area of supercooled wall is exposed to vapor after droplets departure, promotes a new condensation cycle on the surface.

It is noteworthy that there are two different morphologies when condensate leaves the two downward-facing walls, one is breakup mode and the other is non-breakup mode. On the surface of θ_{avg} = 160°, adhesion force is smaller than droplet surface tension and lose balance with the increasing gravity first, which results in the separation point occurring at the attachment point. The droplet surface tension keeps the droplet as a whole without breakup during the detachment process. In contrast, the adhesion between droplets and the surface of θ_{avg} = 60° is relatively large, and the surface tension of the liquid film is the first to get out of balance with gravity, causing the film unstable and form a slender neck at t = 3850000. The surrounding gas is dragged to the neck due to the pressure loss, and two symmetric counter-rotating circulations are formed on both sides, which contributes to breakup in the neck with the remaining liquid retracting back to the wall.

3.2 Critical Departure Radius Under Single-Droplet Detachment Mode

The critical departure radius of droplets is a key parameter to measure the heat transfer characteristics of the dropwise condensation, which affects not only the size distribution of the droplets on the super-cooled surface, but also the update frequency of droplets. The wettability of the solid wall has significant influence on the critical departure radius of the droplet.

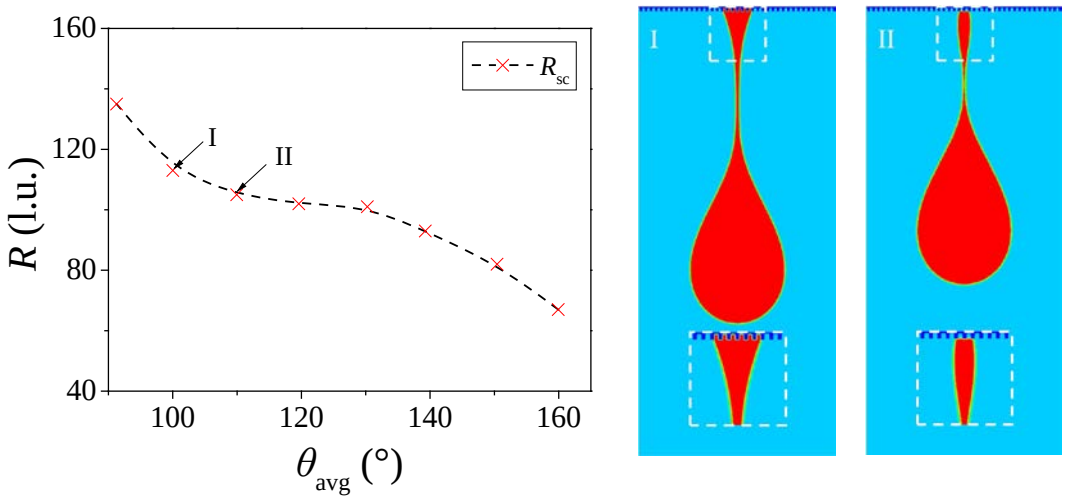

Figure 3: Critical departure radius of single-droplet detachment mode on the grooved surfaces (σ = 0.339)

Figure 3 shows the critical departure radius of single-droplet detachment mode R_{sc} on the grooved surfaces. The result indicates that R_{sc} on hydrophobic grooved surface is negatively correlated with the equilibrium contact angle with two inflection points. With θ_{avg} increases from 90° to 110°, R_{sc} decreases rapidly from 135 l.u. to 105 l.u.; then it goes through a stable stage and maintains around 102 l.u. on the moderately hydrophobic surface (110° < θ_{avg} <140°); a rapid decrease occurs again from 102 l.u. to 70 l.u. when θ_{avg} increases from 140° to 160° afterward. The droplet morphology at I and II points are shown right beside the phase diagram, which indicates that the first inflection point is related to the transition of droplet wetting morphology from Wenzel to Cassie mode. The phase distribution demonstrates that whether the droplet breakup or not is independent of the droplet gravity but depends on the wettability of the wall. For the same volume of droplets, the departure morphology transits from

breakup to non-breakup mode with the solid surface tends to be hydrophobic, which leads to the second inflection point of critical departure radius.

4. CONCLUSION

In this paper, condensation on the two-dimensional downward-facing grooved surface is numerically simulated using a hybrid thermal lattice Boltzmann method. Particular focus is paid on the effects of surface wettability on detachment behaviour. The conclusions can be drawn as follows.

(1) There are two modes of droplet detachment during condensation in pendent state, namely single-droplet mode and coalescence-induced mode. Wettability of solid wall plays a significant role in both modes.
(2) In the single-droplet detachment mode, droplet wetting morphology and departure morphology affect the critical departure radius, which is negatively correlated with the equilibrium contact angle with two inflection points. The transition of droplet wetting morphology from Wenzel to Cassie mode, and the transition of departure morphology from breakup mode to non-breakup mode both contribute to the rapid decrease of the critical departure radius. The departure morphology is independent of the droplet gravity but depends on the wettability of the wall.

The above findings not only provide better understandings on condensation phenomena on a downward-facing grooved surfaces but also shed light on optimal designs of heat exchangers. It suggests special treatment on the heat exchange surface to keep the nucleation site on the top of the roughness or transfer the wetting morphology to Cassie mode. For example, pillars with hydrophilic top and hydrophobic side walls can be textured on the heat exchange surface to drive the droplet to the top without an external force. Thus, the droplets are easier to detach from the surface, improving the heat transfer efficiency in heat exchanger and thereby the organic Rankine cycle efficiency.

NOMENCLATURE

t	time	(s)
L	length	(m)
T	temperature	(K)
$\mathbf{g}$	gravity acceleration	(m s^{-2})
$\mathbf{r}$	spatial position	(m)
$\mathbf{e}_\alpha$	discrete velocity	(m s^{-1})
$\mathbf{f}$	distribution function in velocity space	(-)
$\mathbf{m}$	distribution function in moment space	(-)
θ_{avg}	equilibrium contact angle	(°)
Subscript		
v	vapor	
l	liquid	
c	critical	

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