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Numerical investigation of condensation on microstructured surface with wettability patterns

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ABSTRACT

A numerical investigation of condensation on microstructured surfaces with wettability patterns is reported in this paper. Detailed droplet dynamics and heat transfer performance of four different wettability patterns are discussed: a hydrophilic case, a superhydrophobic case, a hybrid wettability case, and a dynamic wettability case. Several interesting droplet dynamic phenomena such as droplet coalescence jump, pillar squeezing droplet jump, and droplet dragging up by wettability gradient were observed. Through comparison of droplet distribution on the microstructured surface with the corresponding wall heat flux contour, a previously unknown impact is revealed: the regions where droplets sit have higher heat transfer rate due to the large heat transfer area of the droplet surface. The hybrid wettability case shows the highest heat transfer rate compared to the hydrophilic and superhydrophobic cases, because it not only increases droplet nucleation density but also sustains large liquid–vapor interfacial areas. Dynamic control of wettability is finally suggested to detach large droplets to avoid the flooded state of the hybrid wettability case. The detachment of droplets from the surface decreases the condensation heat transfer rate sharply because of the loss of effective liquid–vapor interfacial area, but it cleans the surface for fast re-nucleation. This paper provides promising insights to improve heat and mass transfer of condensation on microstructured surfaces of heat exchangers.

1. Introduction

The increasing integration density and reliability requirements in microelectronics industries require advanced thermal dissipation technology to remove excess heat fluxes in small areas. Two-phase heat transfer, such as condensation and boiling, provides higher heat transfer coefficients than traditional single-phase heat transfer. During the condensation process, nucleation, growth, and coalescence of droplets have important effects on the consequent heat transfer rate. It is well known that heat transfer rates in dropwise condensation can be much higher than in filmwise condensation. Hence, dropwise condensation is preferred for high heat flux dissipation.

Favorable nucleation sites and rapid removal of droplets are essential to continuous dropwise condensation; thus, wettability control appears to be an intuitive method. This method lies in the fact that hydrophobic surfaces are favored for droplet motion while hydrophilic surfaces are favored for droplet nucleation and growth. In the last two decades, substantial work has been done on this topic. Zhao and Beysens [1] studied condensation on a solid substrate with a wettability gradient experimentally and reported that nucleation rate was affected by the surface heterogeneity and wettability gradient was discrepant from heterogeneous nucleation theory. Chatterjee et al. [2] discussed the effects of steam mass flux when condensation occurred on a flat surface with three surface conditions: hydrophobic, hydrophilic, or a pattern of hydrophilic and hydrophobic regions. The patterned surface outperformed the hydrophilic surface but underperformed the hydrophobic surface. Later on they found that the heat transfer coefficients were either higher or lower than that of the completely hydrophobic surface depending on the type of hybrid pattern (island-patterns or tree-pattern) [3]. Inspired by the vein network of plant leaves, Ghosh et al. [4] examined different wettability patterns to realize sustainable dropwise and filmwise condensation on the hydrophobic and hydrophilic surface respectively and thereby improve the overall condensation rate. Peng et al. [5] adjusted the maximum droplet radius and droplet size distribution with a vertically patterned hydrophobic-hydrophilic hybrid surface. Alwazzan et al. [6,7] conducted a parametric experiment study to determine the influence of ratios between hydrophobic and less-hydrophobic regions on the heat transfer performance and droplet dynamics, and they found that an optimum ratio of 2:1 exists to achieve a drastic enhancement of heat transfer coefficient because of the maximum droplet departure frequency and the minimum

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droplet area coverage rate at this ratio. All the works mentioned above are based on flat surface geometry.

To further enhance the condensation rate and corresponding heat transfer rate, wettability control combined with microstructures have been actively studied in recent years. Chen et al. [8] reported dropwise condensation on a superhydrophobic surface with two-tier roughness. Zheng et al. [9] investigated dynamic suspension of droplet during condensation on a nano-/microstructure with gradient wettability and discussed the driving force to suspend the droplet. Chen et al. [10] designed a hierarchical (multiscale) nanograssed micropyramid architecture that yielded global superhydrophobicity as well as locally wettable nucleation sites. The experimental results demonstrated that this surface increases both the number of droplets and the volume of drop self-removal. Anand et al. [11] applied a lubricant on a hierarchical micro-/nano-scale texture to enhance droplet mobility and thereby enhance the drop-wise condensation. Cheng et al. [12] observed film-wise condensation on a two-tier superhydrophobic surface when the surface was put in a custom-designed vapor chamber. In addition, the flooding phenomenon became more pronounced with the increase of the heat flux and the saturation pressure. Under these conditions, they claimed that active actuation is necessary to facilitate droplet removal. Enright et al. [13] presented a mechanistic framework to explain the complex nature of water condensation on structured surfaces, which defines local energy barriers as keys to understanding the growth process and identifies the role of nucleation density on the emergent droplet morphology. Hou et al. [14] reported the development of a bioinspired hybrid surface with high wetting contrast that allows for seamless integration of filmwise and dropwise condensation modes, and showed that the recurrent condensation modes improve all aspects of heat transfer properties.

Self-propelled droplets were reported by Boreyko and Chen [15] when they directed enhanced dropwise condensation on a flat superhydrophobic surface. After their work, Enright et al. [16] investigated dropwise condensation on superhydrophobic copper oxide nanostructures. The coalescence-induced jumping mechanism was interpreted with $L/2r_p$ nucleation densities. Here, L is the coalescence length and r_p is droplet pinning radius. The analysis was consistent with the experimental measurement through ESEM. Enright et al. [17] continued to investigate the coalescence-induced jump of droplets numerically and experimentally and found that a small fraction of the available excess surface energy ($\sim$6%) is convertible into translational kinetic energy during this process. Miljkovic et al. [18] simultaneously reported a 25% higher overall heat flux and 30% higher condensation heat transfer coefficient in jumping-droplet-enhanced condensation on scalable superhydrophobic nanostructured surfaces. Zamuruyev et al. [19] combined a capillary pressure gradient and wettability gradient mechanisms to fabricate a surface with specific microscopic topography. They managed to directionally move the droplets along the designed wettability gradient created with micropatterns and achieve higher condensation efficiency. Qu et al. [20] proposed a substrate design with regularly spaced micropillars, which leads the coalescing droplets on the sidewalls of the micropillars to jump in a direction parallel to the substrate, producing sweeping removal of multiple neighboring drops.

Substantial numerical studies have been carried out to study droplet nucleation, growth, coalescence and departure. Zhang et al. [21], Da Riva and Del Col [22] used the volume of fluid (VOF) method to model forced convective film-condensation in a channel. In their works, the effect of wettability was not studied. Leach et al. [23] established a computer model to simulate liquid droplet growth incorporating the growth mechanism, in which the simulated predictions matched well with the experimental results. A similar work focusing on the growth mechanism of dropwise condensation was reported by Mei et al. [24], Sikarwar et al. [25]. These works provided a good understanding of the droplet distribution during nucleation and coalescence. However, the effects of microstructures and wettability could not be simulated by these models. Due to the complex geometry and governing laws and large time scales, few studies have been published on dropwise condensation over a microstructure with wettability control.

In this paper, our research is to numerically investigate dropwise condensation over a micro-pillar structure with different wettability patterns. A transient three-dimensional volume of fluid (VOF) model has been used, which has the capability to track the liquid–vapor interface and droplet trajectories continuously for visualizing multi-droplet dynamics. The impact of surface wettability was modeled by specifying the wall adhesion angle in conjunction with the surface tension model. Condensation is modeled by using the Hertz-Knudsen equation derived from kinetic theory. Further investigation on the variation of wettability was conducted to explore the effects of the dynamic control of wettability.

2. Model description

Fig. 1 exhibits the computational domain for condensation on a microstructural surface, which is composed by solid and gas parts. The solid material and working fluid are aluminum and water respectively. The thickness of the aluminum layer is 25 μm. The pillar structure has a height of 125 μm, cross-section of 75 × 75 μm^2, and pitch (center to center) distance of 150 μm. An open boundary condition is applied on the top surface where water vapor is saturated steam. The four surrounding surfaces are considered as periodic boundaries, which enables the limited computational domain to be considered as an extensive domain. Constant temperatures are defined at the solid bottom and gaseous top boundaries, which are 300 K and 400 K respectively. The solid/gas interfaces near the bottom, the vertical surfaces of the pillars and the pillar top surfaces are defined as either superhydrophobic (150°) or hydrophilic (30°), depending on the studied cases, and subgrid contact angle hysteresis is assumed to be zero in this study.

2.1. Governing equations

In volume of fluid (VOF) models, a scalar field represents the portion of phase volume occupation in a certain computational cell. The sum of liquid and gas phase volume fractions (α_l and α_v) is constrained to 1,

$$\alpha_l + \alpha_v = 1$$

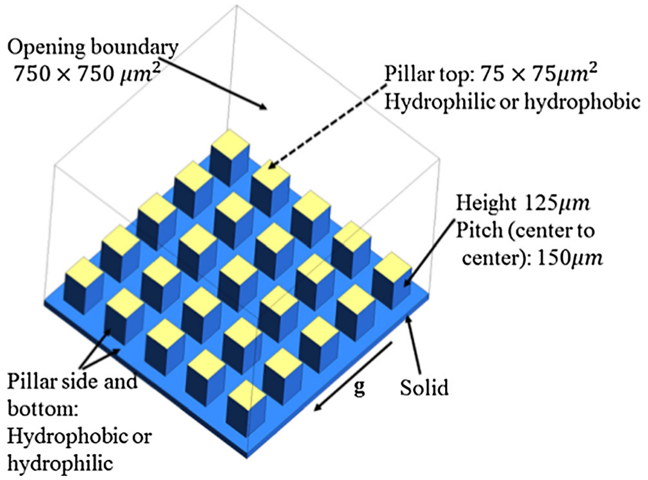

Fig. 1. Computational domain.