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Modeling and optimization of condensation heat transfer at biphilic interface

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ABSTRACT

Biphilic surfaces with heterogeneous wettability and hierarchical topography can significantly enhance the condensation heat transfer performance due to the mutual benefits of the hydrophilic patterns and global superhydrophobicity, which facilitate fast nucleation and frequent droplet departure. To investigate the underlying physics of the condensation process on a biphilic surface and further explore the optimal design to achieve preferable heat transfer performance, we develop a comprehensive model that can capture the recurrent transition of filmwise-to-dropwise condensation on biphilic topographies by considering the dynamics of droplet morphology for individual droplet growth and droplet departure, and the associated droplet size distribution. The numerical results indicate that the varying droplet contact angle and the stepwise increase of the droplet contact base area substantially influence the droplet growth and the coalescence-induced droplet departure during the condensation process, and therefore contribute directly to the overall heat transfer enhancement. The model is validated by comparing the results with the heat flux measured in a custom-designed environment chamber. The developed model not only reveals the physics of condensation on biphilic surfaces but also provides important guidelines for the design and optimization of biphilic topographies for high heat flux applications.

1. Introduction

Condensation of water vapor is ubiquitous in nature [1–3] and of significant importance in various applications involved with phase change heat transfer, such as power generation [4], indoor environmental control [5,6], water harvesting and desalination [7]. Improving the condensation heat transfer performance, therefore, can affect significantly on the energy and water industry. Dropwise condensation, by shedding of condensed droplets from a nonwettable surface, is often preferred to filmwise condensation as it offers a much higher heat transfer coefficient [8]. In recent years, nanostructured superhydrophobic surfaces have attracted widespread attention due to their potential for further improvement in the droplet mobility and associated condensation heat transfer [9–12]. Droplets with a typical radius of ~10 to 100 μm condensed on properly designed superhydrophobic nanostructures can spontaneously jump off the surface upon coalescence because of the extremely low adhesion energy at the interface [13]. Such droplet jumping propelled by the released surface energy activates continuous renewal of droplets and thus increases the number density of small droplets on the superhydrophobic surfaces. Therefore, jumping-droplet condensation has led to ~30% enhancement in the heat transfer coefficient compared to the conventional dropwise condensation on a hydrophobic surface [14]. Inspired by nature, several research groups have demonstrated that condensing surfaces with the implementation of heterogeneous wettability and hierarchical structures, which is termed as the biphilic surfaces, facilitate a more rapid droplet nucleation and growth than the homogeneous nanostructured superhydrophobic surfaces [15–18]. By harnessing the combinatorial advantages of contrasting wettability, the biphilic surfaces not only reduce the energy barrier for vapor condensation, but also effectively prevent the condensed water flooding of the nanostructures at higher supersaturations [19]. The development of surface engineering has made feasible the making of micro- and nanoscale features on surfaces as well as altering surface chemistry. Condensation performance has been characterized on various metallic and silicon-based surfaces. The experimental investigations have greatly assisted the understanding of the underlying science [20,21].

In a parallel effort, theoretical and computational models of vapor-liquid phase-change phenomena and heat transfer have been established based on various methodologies. Nusselt, in 1916, first provided a simple model for evaluating the heat transfer coefficient of filmwise condensation by assuming a laminar flow of

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Nomenclature

d	micropillar diameter
d_{np}	nanopillar diameter
E_{adh}	interfacial adhesion work
E_k	kinetic energy
E_{vis}	viscous dissipation
G	droplet growth rate
h	micro/nano-pillar height
H	droplet height
H_c	critical transition size of *Stage I* and *Stage II*
$H_{e,1}$	droplet coalescence length scale at *Stage I*
$H_{e,2}$	droplet coalescence length scale at *Stage II*
h_{fg}	latent heat of vaporization
h_i	interfacial heat transfer coefficient
H_{min}	droplet nucleation size
k_{hb}	thermal conductivity of hydrophobic coating
k_{hl}	thermal conductivity of hydrophilic top
k_{mp}	thermal conductivity of nanopillar
k_{np}	thermal conductivity of micropillar
k_{sub}	thermal conductivity of substrate
k_w	thermal conductivity of liquid water
l	center-to-center space between neighboring micropillars
l_{np}	center-to-center space between neighboring nanopillars
M	droplet mass
n/N	droplet size distribution
N_s	nucleation density
q_{ind}	heat transfer rate of individual droplet
q''	overall heat flux
R_g	specific gas constant
T_{sat}	vapor saturation temperature
T_{sub}	substrate temperature
v	droplet jumping velocity
v_g	water vapor specific volume
δ_{hb}	thickness of hydrophobic coating
δ_{hl}	thickness of hydrophilic top
δ_{mp}	thickness of nanopillar
δ_{np}	thickness of micropillar
δ_{sub}	thickness of substrate
ΔE_s	released surface energy
φ_m	area fraction of hydrophilic micropillar
φ_n	area fraction of hydrophobic nanopillar
Ω	droplet volume
γ_{lv}	water liquid-vapor surface tension
μ_w	liquid water dynamic viscosity
θ_A	apparent contact angle
$\theta_{Y,hb}$	Young's contact angle of the hydrophobic coating
$\theta_{Y,hl}$	Young's contact angle of the hydrophilic top
ρ_w	liquid water density

the liquid film [22]. With the development of Lattice Boltzmann Method (LBM) [23–25], computational fluid dynamics (CFD) [26,27] and molecular dynamics (MD) [28,29], the numerical studies of initial nucleation, individual droplet behavior, and multi-droplet interactions on textured surfaces revealed in detail the underlying physics during the dropwise condensation process. In particular, these numerical simulations have achieved thorough analysis of the physical processes that usually occur on the nanometer length scale and nanosecond time scale. For overall condensation heat transfer of a condensing surface, the integrated effect of numerous droplets is estimated through a combination of the individual droplet heat transfer and the droplet size distribution theory, which was first proposed by Rose and Le Fever [30,31]. To precisely evaluate the size distribution of condensed droplets, the population balance theory was introduced by Tanaka [32] to calculate the distribution of non-coalescing droplets during condensation. These modeling frameworks have been widely accepted by scientists and further refined to specific surface designs and properties. Kim's [33] investigation of the condensation heat transfer of a droplet with a large contact angle ($\theta > 90°$) discussed the effect of contact angle on the condensation heat transfer on a flat hydrophobic surface. Liu et al. [34] proposed an improved model for dropwise condensation heat flux on a subcooled surface with coatings, where embryo droplet nucleation radius and droplet nucleation density were evaluated. Enright et al. [10] provided a more accurate expression of droplet growth on nanostructured surfaces, which indicated the importance of the droplet wetting morphology on the individual droplet heat transfer. By further taking into account the coalescence-induced droplet self-jumping and associated fluid dynamics [35–37], Miljkovic et al. [38] developed the jumping droplet condensation heat transfer model and demonstrated that homogeneous nanostructured superhydrophobic surfaces were able to enhance the overall surface heat transfer by 190% as compared to flat hydrophobic surfaces.

Despite much effort having been made to capture sequential phenomena in the condensation process, a systematic theoretical model for predicting the condensation heat transfer and exploring the optimal design of condensing surfaces with structural topography and wetting heterogeneity is still lacking. We found that the current condensation models for hydrophobic and superhydrophobic surfaces were inadequate for analyzing the dynamic condensation on a biphilic surface due to the following discrepancies. First, the dynamically varying contact angle was not considered in the established models. The droplet growth process was treated as the swell of droplet volume with constant contact angle [33]. However, on a biphilic surface, the sequential variations in contact angle, especially at the initial growing period, influence the droplet growth and departure significantly and shall be treated carefully. Second, in the previous models, the droplet departure size was determined by the capillary length (sliding) or droplet coalescence length (self-jumping) [38]. However, on a biphilic surface, the droplet departure dynamics involve more complicated interfacial energy calculation due to the heterogeneous patterns. Hence a condensation model need to be further tailored to accommodate the unique droplet growing features and the surface-topography-dependent departure size.

In this work, we establish a comprehensive computational model to study the condensation heat transfer on biphilic surfaces with heterogeneous structural topography and wettability. By considering individual droplet heat transfer on the biphilic structural topography, our model captures the combined filmwise and dropwise condensation modes and the dynamics of droplet morphology of the condensed droplets. The criteria for droplet jumping and resulting size distribution are obtained through energy conservation analysis. Applying the developed model to a typical biphilic surface with hydrophilic arrays surrounded by superhydrophobic nanostructures, we demonstrate the effect of the hydrophilic micropillar size and spacing on the overall condensation heat flux, and optimization of those parameters for the biphilic surface design. The modeling results have been verified by our experimental measurements, suggesting the reliability of the established theory. The outcomes of this study demonstrate the efficacy of biphilic surfaces in condensation heat transfer enhancement, and provide