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Simultaneous dropwise and filmwise condensation on hydrophilic microstructured surfaces

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ABSTRACT

While wicking or spreading of a liquid through microstructures has been found to be promising for applications such as textiles, microelectronics or heat sinks, the effects of such structured surfaces on condensation phase change has received less attention. On a hydrophilic surface and for a fixed micropillar aspect ratio (height/diameter), the spacing between pillars is found to have a strong impact on the dynamics of condensation and on the final morphology of the condensate. In the case of micropillars with a large spacing between pillars, the condensate grows initially dropwise, and thereafter, as condensation develops, the condensate overcomes the pillars' height flooding the substrate, and condensation continuous in a filmwise condensation (FWC) fashion. In contrast, filmwise condensation and the continuous nucleation, growth, and departure of drops at the pillars' tops in a dropwise condensation (DWC) fashion occurs when the spacing between pillars is decreased. In this configuration, the geometry of the microstructures constrains the condensate between the pillars and rise of the condensate interface above the micropillars' height is not thermodynamically favorable, while the top of the pillars act as nucleation sites. We refer to this latter condensation behavior as simultaneous dropwise/filmwise condensation. These observations were enabled by the excellent spatial and temporal resolution of Environmental Scanning Electron Microscopy. A heat transfer model is proposed to demonstrate the greater heat transfer performance of the simultaneous dropwise/filmwise condensation behavior on these surfaces when compared to solely filmwise condensation. The enhanced heat transfer is realizable due to the ability to maintain a thin film within the microstructures and to the active dropwise condensation at the micropillars' tops. We report for the first time the occurrence of dropwise condensation on a completely hydrophilic wettability configuration without the assistance of a hydrophobic coating. Our findings pave the way to the development of microstructures for enhanced condensation heat transfer.

1. Introduction

The use of microstructures have been found to play an important role in drop bouncing [1,2], on the spontaneous levitation upon freezing or vaporization [3] and on surface self-cleaning [4], amongst others. However, the effects of microstructure on condensation has received less attention. Two phase heterogeneous condensation occurs in many industrial and everyday applications such as water harvesting [5–7], dew drops [8], water desalination [9], air conditioning, solvent evaporation [10] and electricity generation [11]. The two main mechanisms of heterogeneous condensation onto surfaces are dropwise condensation (DWC) and filmwise condensation (FWC), and their occurrence depends on the wettability and topography of the substrate, the nature of the vapor/liquid, and the ambient conditions [12–15]. While current industrial condensation processes rely on FWC as the condensation mode, this mechanism offers low heat transfer coefficients due to the

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Nomenclature

DWC	dropwise condensation
FWC	filmwise condensation
h	height of the micropillar (μm)
d	diameter of the micropillar (μm)
s	spacing between micropillars (μm)
ϕ	roughness factor
θ_f	equilibrium contact angle on a flat substrate (deg)
$\theta_{f,Si}$	equilibrium contact angle on a flat silicon substrate (deg)
t	condensation time (s)
h/d	micropillar aspect ratio
$d/(s+d)$	micropillar density
q''	theoretical heat flux (W/m^2)
A_φ	heat transfer area fraction with micropillars
$A_{1-\varphi}$	heat transfer area fraction without micropillars
R_{DWC}	total thermal resistance due to dropwise condensation (K·m/W)
R_{FWC}	total thermal resistance due to filmwise condensation (K·m/W)
ΔT	surface subcooling temperature (K)
T_{sat}	saturated vapor temperature (K)
T_s	substrate temperature (K)
R_p	thermal resistance across the micropillar (K·m/W)
k_{Si}	thermal conductivity of Si (W/m·K)
R_d	thermal resistance of the condensing drop (K·m/W)
δ_{drop}	thickness of the condensing drop (μm)
k_w	thermal conductivity of water (W/m·K)
$h_{i,DWC}$	interfacial heat transfer coefficient due to drop condensation (W/m·K)
R_w	thermal resistance across the liquid film (K·m/W)
δ	thickness of the condensate (mm)
$h_{i,FWC}$	interfacial convective heat transfer coefficient due to film condensation (W/m·K)
ρ_w	density of water (kg/m^3)
ρ_a	density of air (kg/m^3)
μ	viscosity of water (kg/m·s)
h_{fg}	latent heat of condensation (J/kg)
g	gravity (m/s^2)

thermal resistance imposed by the liquid layer [16–18]. On the other hand, DWC can achieve up to one order of magnitude greater heat transfer coefficients than FWC [17,19,20]. In addition to the two well-known condensation mechanisms, by varying the spacing between the pillars of a micropillar array, we demonstrate for the first time a simultaneous DWC/FWC mechanism that outperforms the heat transfer of FWC surfaces without the assistance of a hydrophobic coating.

Most current research on DWC focuses on the design of superhydrophobic surfaces to induce the detachment of drops by using mixed micro- and nano-structures [14,21–23], oxide nanostructures [24–26], micro and/or nano-structures with patterned or mixed wettability [27–29], nanopillars, nanocones or nanoneedles [24,30,31], or the application of external forces [32,33]. These investigations have led to promising and exciting phenomena such as the self-propulsion of drops [34–36], drop dewetting on micro-/nano-textured surfaces [37], or enhanced condensation heat transfer when applying an external electric field [32,33]. On a micropillared superhydrophobic surface, Boreyko et al. reported the self-propulsion of drops upon coalescence due to the excess of surface energy released [34]. Thereafter, making use of one-tier nanorough superhydrophobic surfaces, Miljkovic et al. reported a 25% increase in the condensation heat transfer coefficient in the case of jumping-drop condensation when compared to solely DWC [25]. In addition, by adding an external electric field Miljkovic et al. demonstrated a 50% increase in the heat transfer coefficient [32]. Since then, other authors have also exploited new fabrication techniques and coatings to induce DWC and jumping-drop condensation. Ölçeroğlu and McCarthy and Hou et al. made use of a hybrid surface that combines hydrophilic spots on a superhydrophobic background for the spatial control of drop nucleation and drop jumping with the consequent enhancement in the heat transfer coefficient [27,28]. In addition, they also reported the delay in surface flooding. Besides the use of randomly oriented oxide nanostructures, by using superhydrophobic nanocones, Zhao et al. reported an 89% increase in the DWC heat transfer when compared to bare copper [30]. And Zhu et al. reported a 125% increase in the heat transfer rate when using structured copper ribbed nanoneedles [31]. Recently, the shift of condensate from the sides of micropillars to their tops was achieved by patterning these surfaces with different wettabilities and without the need to apply external forces [29,38]. Kumagai et al. and Peng et al. achieved the coexistence of DWC and FWC by making use of hydrophobic coating to promote DWC areas [39,40]. The greater heat transfer performance of their proposed configuration when compared to slowly FWC was also demonstrated. However, the need for a hydrophobic coating renders all these surfaces impractical and unreliable for several applications [41–44]. Hence, in this work we only make use of microstructural features to induce a condensation behavior that outperforms that of FWC without the need for a hydrophobic coating.

Although the interactions between liquid drops and micro- and/or nano-structured hydrophilic surfaces has been extensively addressed [45–50], the use of bare hydrophilic surfaces with micro- or nano-structures for condensation has received lesser attention. Rahman and Jacobi recently reported an improved condensate drainage of microgrooved aluminum surfaces when compared to bare aluminum [51,52]. The depth of the grooves was found to have an impact on condensate drainage and on the defrosting time. Their study showed that for deeper grooves, the retention of melted water was found to decrease when compared to the sallow ones. Since micropillar arrays have been reported as surfaces with excellent liquid propagation properties [53–58], we explore different configurations aiming for the design of condensation surfaces on which the condensate can wick between pillars, keeping a thin condensate layer with a height equal to that of the micropillars [53,54,59,60]. In addition, these surfaces should exhibit active DWC on the exposed tops of the micropillars. The presence of a film around the pillars facilitates removal of growing drops, which coalesce with the film when they become sufficiently large, and allows sustained DWC. We henceforth refer to this condensation behavior as simultaneous DWC/FWC. Such simultaneous DWC/FWC behavior is possible due the design of the micropillars, specifically by careful selection of the micropillar density and micropillar aspect ratio that do not allow the surface of the condensate film to rise above (and cover) the tops of the micropillars. For the first time, we have exploited the fundamental interactions between drops and micro-structured surfaces to design such surfaces. We then make use of the thermodynamic criterion and the energy minimization limits for pinning or wicking on regular