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Effects of millimetric geometric features on dropwise condensation under different vapor conditions

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ABSTRACT

In this work, we investigated the effects of millimetric surface structures on dropwise condensation heat transfer under two different environments: pure vapor and an air-vapor mixture. Our experimental results show that, although convex structures enable faster droplet growth in an air-vapor mixture, the same structures impose the opposite effect during pure vapor condensation, hindering droplet growth. We developed a model for each case to predict the heat flux distribution along the structured surface, and the model shows reasonable agreement with experimental results. This work demonstrates that the effects of geometric features on dropwise condensation are not invariable but rather dependent on the scenario of resistances to heat and mass transfer in the system. The fundamental understanding developed in this study provides useful guidelines for condensation applications including power generation, desalination, dew harvesting, and thermal management.

1. Introduction

Condensation is a useful approach for energy transport due to the large amount of latent heat released during the phase change process. Condensation of water vapor has been routinely observed in nature [1–3] and commonly utilized in a wide range of applications such as desalination systems [4,5], steam cycles [6,7], water harvesting [8,9], and nuclear reactors [1–3,10,11]. In these applications, enhancement of the condensation heat and mass transfer performance can significantly contribute to energy efficiency, economic performance, and environmental sustainability of the overall system. Filmwise condensation is standard in industrial applications due to the high surface energy of common condenser materials, but this mode of condensation suffers from its intrinsic barrier to heat transfer created by the condensed liquid film. On the other hand, dropwise condensation, which has been demonstrated to exhibit 5–7 times higher heat transfer coefficients compared to filmwise condensation [12], has attracted much research interest since its discovery in 1930 [13].

The performance enhancement obtained by dropwise condensation is due to the gravity-induced removal of discrete droplets upon growing to a critical size near the capillary length, allowing renucleation and growth of small droplets; therefore, facilitating droplet growth plays a critical role in dropwise condensation. As such, droplet growth has been studied at great length, both theoretically and experimentally. An early dropwise condensation theory combined the heat transfer rate through a single drop with the expression for drop size distribution to obtain the condensation heat flux on the surface [14]. Following this work, more advanced models have been developed by considering precise descriptions for droplet size distribution [15] and the effect of large contact angles [16,17]. Among experimental studies, a variety of micro- and nanoscale surface structures have been used to manipulate droplet growth. High droplet mobility and rapid droplet removal have been demonstrated on nanowires [18], nanocones [19], and hierarchical structures [20]. In addition, spatial control of micro-droplets has been achieved on micro-pillar arrays [21], mesh-screen structures [22], and hybrid surfaces [23]. Furthermore, superhydrophobic nanotextured copper oxide surfaces [24–26] have been developed to enable micrometer-sized droplets to jump off of a surface regardless of gravity, which yields a higher condensation heat transfer coefficient compared with state-of-the-art dropwise condensing surfaces [27–31].

In contrast to micro- or nanoscale structures that require relatively intricate and costly manufacturing processes and are often prone to physical wear and destruction, recent studies have reported that millimeter-sized convex structures can effectively manipulate dropwise condensation. Park et al. [32] designed slippery asymmetric bumps which significantly facilitate droplet growth and departure and thereby show a sixfold-higher droplet

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Nomenclature

c	concentration (mol/m^3)
c_p	specific heat capacity (J/kg K)
D	diffusion coefficient (m^2/s)
h	heat transfer coefficient (W/(m^2 K))
J	molecular diffusion rate (mol/s)
j	diffusion flux (mol/(m^2 s))
k	thermal conductivity (W/(m·K))
P	pressure (Pa)
Q	heat transfer rate (W)
q	heat flux (W/m^2)
R_{th}	thermal resistance (m^2 K/W)
T	temperature (K)
t	time (s)

Greek letters

δ	thickness (m)
ζ	diffusion boundary layer thickness (m)

Subscripts

b	bottom surface of the block
s	top surface of the block
∞	bulk state

growth rate compared to flat surfaces. Keeping track of droplet size distribution on the bumpy surface, they experimentally demonstrated that millimetric bumps alone can enhance condensation on the top of the bumps. Medici et al. [33] also studied the effect of millimeter-sized geometric features (corners, edges, grooves, and scratches) on droplet growth during condensation. They concluded that millimetric surface discontinuities can modify droplet growth rates such that droplets near outer corners and edges grow faster than those near inner corners, in agreement with Park's result. They also mentioned that this geometric effect disappears when condensing on a substrate with poor thermal conductivity. However, they attributed this phenomenon to the low thermal conductivity of the substrate material and did not consider the effects of the material property on the overall thermal resistance network, which is the critical aspect of the condensation profile.

Indeed, these two studies of millimeter-scale geometric effects on dropwise condensation are of great importance, since the condensation situation that is being considered there, i.e., vapor condensation in air, is ubiquitous in a variety of applications such as desalination [34], water harvesting [9], air cooling [35], and waste heat recovery [36]. However, these previous works did not take into account that the condensation performance is affected not only by geometric features but also by vapor conditions, i.e., the presence of non-condensable gases (air, in this case). Vapor condensation in the presence of non-condensable gases (NCGs) is hindered by the required vapor diffusion across a boundary layer introduced by NCG accumulation near the liquid-vapor interface [37–39]. It has been demonstrated that NCGs introduce additional heat and mass transfer resistance and therefore significantly degrade condensation performance in both the filmwise and dropwise modes [40]. In an early experimental demonstration of the filmwise mode [41], a decrease of nearly 50% in condensation heat transfer coefficient was observed in the presence of 0.5% NCG volume fraction. In accordance with this, a numerical study on laminar filmwise condensation [42] showed that the presence of a few percent of NCGs can substantially reduce condensation heat transfer and furthermore introduce a dramatic change in the temperature profile. The temperature of the liquid-vapor interface was calculated to be as high as the bulk vapor temperature in the absence of NCGs, but decreased to almost the cold wall temperature in the presence of 2% mass fraction of NCGs. A similar temperature profile altered by NCGs was observed in an experimental study where filmwise condensation with and without NCGs inside a vertical tube was investigated [43], and the authors attributed the altered temperature profile to the prominent influence of NCGs on the thermal resistance network. The wall temperature was observed to be close to the bulk vapor temperature in the pure-steam condensation mode because the gas side had negligible thermal resistance; however, it approached the coolant temperature when the NCGs on the gas side dominated the overall thermal resistance network. This viewpoint of a NCG-influenced thermal resistance network was also explored in an experimental study [44] where the dropwise and the filmwise modes resulted in a similar range of heat transfer rates when condensing air-steam mixtures, owing to the governing role of the air-rich diffusion boundary layer in the thermal resistance network dominating that of the condensation modes.

Prior work has compared condensation heat transfer performance with and without NCGs [41–43,45], and recent work has shed light on geometrically enhanced dropwise condensation with NCGs [32,33], but geometric effects on dropwise condensation performance with and without NCGs have not been considered simultaneously. In the present study, we investigated the effects of millimetric geometric features on dropwise condensation under different vapor conditions by examining the heat transfer performance in two cases (air-vapor mixture vs. pure vapor). To provide an improved understanding of the physical phenomenon, we developed numerical models for both case studies based on analysis of the thermal resistance network involved in the heat and mass transfer process. The reasonable agreement between experimental results and modeling predictions demonstrates that the effect of geometric features on dropwise condensation is not absolute, but rather is determined by the specific thermal resistance scenario involved in the given case of heat and mass transfer, which can be completely altered by the presence of NCGs.

2. Materials and methods

2.1. Condensation substrate

A metal block 2.03 cm in width, 1.83 cm in height, and 2.11 cm in length, including a bump 0.38 cm in width, 0.38 cm in height, and 2.11 cm in length on the top surface, was milled to serve as the geometric-featured substrate for the present study (Fig. 1). In order to guarantee that heat would conduct from the top to the bottom surface of the block during condensation and to prevent condensation on the sidewalls, thermal insulation for the block sidewalls was provided with a 0.5 mm-thick polyetherimide (Ultem) frame snugly fit around the sides of the condensation block.

In order to demonstrate opposite condensation scenarios on the same substrate under the two vapor conditions (air-vapor mixture vs. pure vapor), we deliberately designed reverse thermal resistance scenarios under the two conditions by selecting titanium as the block material upon a preliminary thermal resistance analysis. The thermal resistance of the titanium block can be estimated using a simplified 1D conduction model by the following equation:

$$R_{th} = \delta/k \tag{1}$$