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# Effects of surface chemistry and groove geometry on wetting characteristics and droplet motion of water condensate on surfaces with rectangular microgrooves

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## ABSTRACT

The study of the wetting characteristics and motion of condensed droplets is important in any multiphase flow applications. The present work focuses on condensate morphology and growth on cooled horizontal substrates featuring microgrooves. Microfabrication techniques are employed to produce chemically homogeneous and heterogeneous substrates with microgrooves 20–40 μm in spacing and 20–180 μm in depth. Strong anisotropic wetting behavior was observed on the chemically heterogeneous sample whereas isotropic wetting appeared on the homogeneous samples. Groove geometry is found to have a profound impact on the drainage behavior of condensed droplets but is less important for deposited droplets. Isolated drop growth in microgrooves was simulated numerically to study various wetting modes. The simulation results show that the critical volume for droplets to change morphology decreases with the increase in the contact angle of surface materials in chemically homogeneous grooves. The critical volume for droplets on the chemical heterogeneous sample is much smaller than those on the homogeneous surfaces.

## 1. Introduction

Condensation has a profound impact on the thermo–hydraulic performance of heat and mass transfer systems. Hence, condensate retention and drainage have to be carefully managed. Condensate retention is largely dependent on surface wettability, an intrinsic property of a solid–liquid–gas system and directly characterized by the contact angle of a droplet. It has been shown that water drainage can be enhanced by parallel microgrooves on a surface (see for example [1–4]). Sommers and Jacobi [1,2] created surfaces with microgrooves and reported the droplet volume at incipient sliding was reduced by more than 50% compared to droplets on a surface without microgrooves. Liu et al. [3] found a consistent reduction of the critical sliding angle for water droplets deposited on the embossed aluminum surfaces with microgrooves. Both empirical and theoretical models were developed to explain the droplet shapes on such surfaces [2,4]. Moreover, so-called superhydrophobic surfaces with contact angles of more than 150° for water have recently been developed [5]. These surfaces of a moderately hydrophobic material with surface microstructures are water repellent. That is, deposited droplets roll off the surface at a small tilt angle. Thus, water retention can be managed by modifying surface microstructures and surface materials.

Most research efforts related to condensation on microstructured surfaces has been directed at surface fabrication and the wetting modes of droplets deposited on the surface [5], with only a few studies focusing condensation on such surfaces. Quere et al. [6,7] were the first to report that deposited droplets had a wetting behavior different from that condensed droplets. Their study showed a dramatic increase in contact angle hysteresis and the pinning of condensed droplets as compared to deposited ones. Lau et al. [8] condensed water on PTFE-coated surfaces with nanotubes. They reported that hysteresis becomes smaller as the height of the nanotubes increases. Narhe and Beysens et al. [9–12] experimented on surfaces with various microstructure designs and concluded that the growth rate of condensate on micro-structured surfaces was similar to that on flat surfaces. Wier and McCarthy [13] demonstrated that a superhydrophobic surface covered with condensate lost its water-repellent ability, and they attributed the immobility of droplets to the presence of condensate between the microstructures. Dorrer and Ruhe [14] reported air entrapment underneath nearly circular droplets during the condensation process, and condensed droplets were observed to either completely wet the microstructures or suspend on the top. Only surfaces with two-tier textures at both the micro- and nano-scales were found to remain superhydrophobic for condensed droplets [15,16]. All of

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**Nomenclature**

| | |
|---|---|
| $\alpha$ | critical inclination angle for a droplet to start moving on a tilted surface |
| $\beta$ | aspect ratio of the depth to the spacing of the microgrooves, $\beta = D/L$ |
| $\theta$ | equilibrium contact angle on flat surfaces or apparent contact angle on surfaces with microgrooves |
| $\theta_{\|\|}$ | contact angle viewed in the direction parallel to microgrooves |
| $\theta_{\perp}$ | contact angle viewed in the direction perpendicular to microgrooves |
| $\phi$ | relative humidity of moist air |
| $D$ | depth of the microgrooves |
| $L$ | spacing of the microgrooves |
| $L_z$ | maximum dimensionless distance from a point on the contact line to the edge on the bottom of a groove |
| $L_y$, $L_{edge}$ | dimensionless distance between two points on the contact line on the edge of the bottom surface of a groove |
| $L_{middle}$ | dimensionless distance between two points on the contact line in the middle on the bottom of a groove |
| $L_x$ | maximum dimensionless distance from a point on the condensate-air interface to the side wall of a groove for the side drop mode; or maximum dimensionless distance from a point on the contact line to the edge on the bottom |
| $s$ | area of the air–water interface |
| $S$ | dimensionless area of the water–air interface or dimensionless contact area |
| $S_{xz}$ | dimensionless contact area on the sidewall of a channel |
| $S_{xy}$ | dimensionless contact area on the bottom of a channel |
| $T_s$ | temperature of surface |
| $T_a$ | temperature of moist air |
| $v$ | volume |
| $V$ | dimensionless volume |
| $V_c$ | critical volume for droplets to change from drop mode to bridge mode |
| $W$ | width of the plateau between microgrooves |
| $X,Y,Z$ | coordinates attached to the microgroove surfaces |

these studies demonstrate experimentally that condensed droplets can be in various wetting states, resulting in different drop motion. When condensed droplets on the top of the microstructures are in contact with the condensate inside the microstructures, droplet mobility is significantly reduced. Thus, condensate retention is strongly affected by the microscopic droplets inside the microstructures.

It has been shown that the interaction between micrometer-sized droplets inside the microstructures and the millimeter-sized droplets on the top is critical in condensate retention. However, very little work has been reported on condensate morphology and growth inside the microstructures, with attention on how the contact line geometry changes as condensation ensues. Information on contact lines inside the microstructures is necessary to the wetting state of condensate and how it relates to the Wenzel and Cassie–Baxter wetting modes. Moreover, although both surface chemistry and surface microstructures play an important role in water retention, all the micro-structured surfaces studied previously are chemically homogeneous [1–16], and the wetting behavior of water droplets on chemically heterogeneous surfaces has not been investigated. For chemically homogeneous surfaces, only one study [9] considered surfaces with different materials but no quantitative comparison reported; only three of these studies [8,9,13] included surfaces with different geometries. Nevertheless, the data available is insufficient to completely understand geometric effects on the motion of condensed droplets.

Therefore, the present study has focused on the effects of both chemical and geometric parameters on the wetting characteristics and the motion of condensed droplets. Surfaces with rectangular microgrooves were fabricated to produce both chemically heterogeneous and homogenous samples. For chemical homogenous surfaces, the impact of different surface materials and groove geometries were studied. The surfaces were first characterized by contact angles with deposited droplets. The wetting and drainage behavior of millimeter-sized condensed droplets were reported, and then special attention was directed to the condensate morphology and growth in a microgroove. In order to understand the interaction between the condensate inside a microgroove and droplets on the plateaus, results of condensate contact lines and contact areas in a microgroove were also obtained from a numerical simulation based on surface energy minimization.

## 2. Experiment and numerical simulation

### 2.1. Experimental specimens and apparatus

The sample surfaces with microgrooves were fabricated using standard photolithographic methods [17,18] as described in Fig. 1, in which the vertical coordinate, $z$, has its origin at the edge where the sidewall and the bottom of a microgroove meet, and on the horizontal plane, $y$ is parallel to the microgroove and $x$ perpendicular to the microgroove. An example image of a resulting surface obtained with a Scanning Electron Microscope (SEM) is shown in Fig. 2(a). The specifications of the sample surfaces are provided in Table 1 with the geometric parameters defined in Fig. 2(b). The geometric parameters of grooved surfaces were measured using a scanning confocal microscope (SCM) and compared to the measurement from a contact profilometer. The uncertainty in the geometric measurement was estimated to be ±1 μm [19,20]. These samples were first subjected to experiments to determine the wetting behavior using sessile droplets, i.e. the water droplets deposited usually with a micro-syringe. Condensation experiments were also conducted to study the impact of these microgrooves on the condensate growth and drainage.

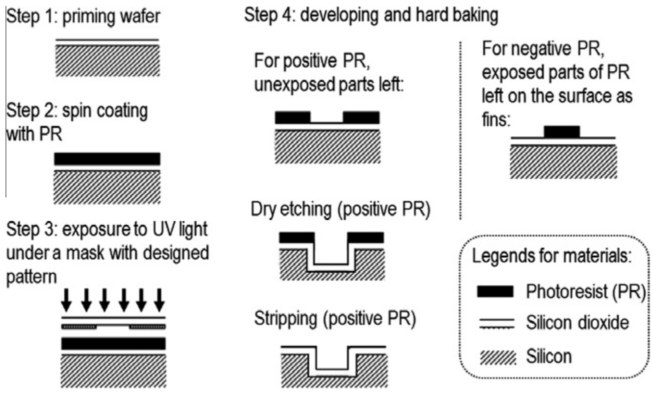

**Fig. 1.** A schematic of the classical photolithographic method used to fabricate micro-finned surfaces.