Experimental Investigation of Condensation Phenomenon on Hydrophilic and Hydrophobic Titanium (Ti) Pillared Glass Surfaces

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Atmospheric condensation is very important for multiple practical applications such as heat transfer, aerospace, and water harvesting etc. Surfaces below the dew point temperature, heterogeneously nucleate water droplets on the surfaces. Gibbs free energy of heterogeneous nucleation barrier for a condensed droplet on a rough surface changes significantly with the change of humidity content. The influence of environmental factors and substrate characteristics (topology, surface chemistry, and substrate temperature) on atmospheric condensation is very important to elucidate the droplet shape and wetting state. Condensation from the humid air has been studied on Titanium (Ti) pillars and Teflon© coated Ti pillared glass surfaces in order to reveal the condensate harvesting and dropwise condensation applications.

1. Introduction

The field of dropwise condensation has been investigated for many years [1]. The condensation phenomenon is significantly affected by the environmental factors [2] and surface morphologies [3-5]. Therefore, early studies clearly indicate the importance of surface engineering on dropwise condensation heat transfer. For heterogeneous nucleation of droplets [6] -

$$\Delta G_{heterogenous} = [\underbrace{-\frac{4}{3}\pi\rho_d R_m T \ln\left(\frac{e}{e_s}\right) R^3}_{(a)} + \underbrace{4\pi\gamma R^2}_{(b)}] s(\theta) \quad (1)$$

$$s(\theta) = \frac{(2+\cos\theta)(1-\cos\theta)^2}{4} \quad (2)$$

Where, e is the partial pressure of water vapor (Pa), e_s is the pressure of water vapor at saturation (Pa), γ is the surface tension of water in air (N/m), ρ_d is the droplet density (Kg/m3) and R_m is the gas constant (J/kg.K). The term $s(\theta)$ in Eq. (2) increases as θ increases for hydrophobic surface. Total free energy change depends on bulk free energy difference between the vapor and the liquid (a), and interfacial free surface energy (b). The bulk energy term (a) of Eq. (1) can be increased by nearly 80% for changing the relative humidity (RH) to 40% from 60% for nucleating a similar sized droplet under same operating condition. Hence, less energy is required to form nuclei at relatively higher RH. In this study, the condensation test from air-vapor mixture (presence of non-condensable gas) running the optical microscopy experiments have been conducted. The images of droplet growth dynamics on plain Ti pillared and Teflon© coated Ti pillared glass surfaces have been reported. The behavior of this nanopillar surface in dropwise heat transfer [7] and condensate harvesting [8] applications has also been revealed.

2. Sample fabrication and coating

The hexagonal array of holes was patterned by microsphere photolithography on the glass substrate as shown in Figure 1. Later, Ti was transferred on to glass by lift-off process to form Ti pillar arrays (2 µm in periodicity, 200 nm tall, and 800 nm in diameter).

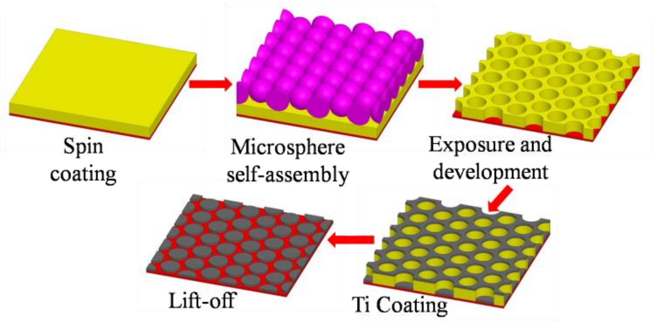

Figure 1. Schematic of Ti nanopillar fabrication process

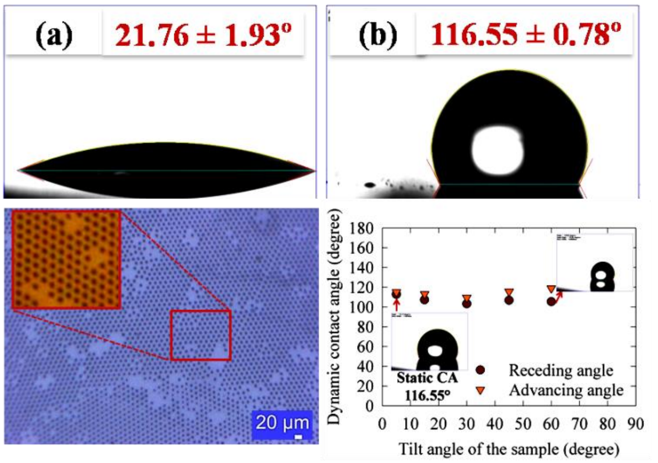

Figure 2. Static and dynamic contact angle measurement on (a) plain Ti pillared (b) Teflon© coated Ti pillared glass surfaces

Hydrophobic Ti pillared surface has been created by an easy recipe of spray coating of the Teflon© and FC - 40 solutions at a ratio of 2:10. Contact angle measurements of injected water droplet was observed in Figure 2 to characterize the wetting behavior. Lower CA hysteresis promotes prolonged dropwise condensation.

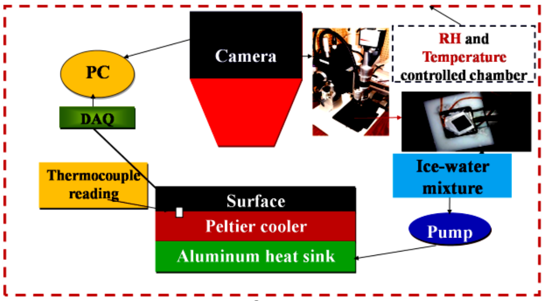

Figure 3. Schematic diagram of the experimental setup in a RH controlled chamber

For condensation test, samples were placed on a Peltier device in a condensation stage. The stage consists of an aluminum heat sink where ice-water mixture was circulated from a pump below a Peltier cooler as shown in Figure 3. The stage was cooled to 274±0.5K-278±0.5K. The RH was 30±5%-60 ±5%. All the images and videos were captured by a Leica DVM2500 microscope.

3. Results and Discussion

At 60% RH, less nucleation energy barrier and higher nucleation rate were observed. Within the first 130 s, droplet density decreases for 60% RH as the higher rate of coalescence events happened. However, irregular shaped droplets were observed for both RHs.

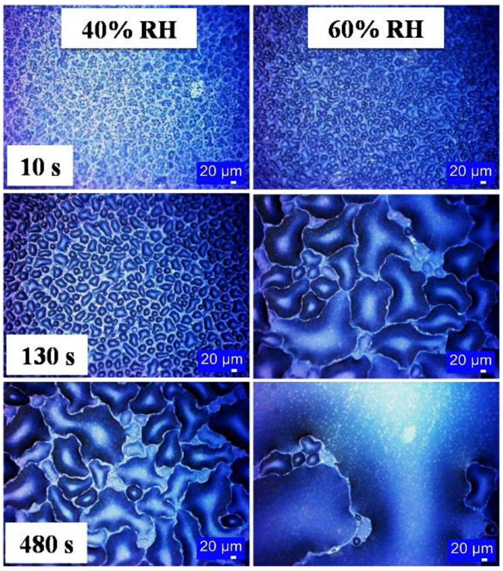

Figure 4. Time-lapsed droplet growth on plain Ti pillared glass surface at 40% RH and 60% RH respectively

At 60% RH, the larger diameter of the condensed droplets was found due to 1) the increased rate of water vapor accumulation from the humid air into the vapor-liquid interface of the droplet and 2) higher coalescence rate. At t = 480 s, lower droplet density and higher area coverage were observed for 60% RH which signifies the application of large scale condensate harvesting [8]. However, droplet dynamics changed significantly for the hydrophobic Ti pillared glass surfaces as shown in Figure 5. At t = 15 s, spherical shaped droplet nucleated. It promotes dropwise condensation which exhibits higher heat transfer coefficient [7] compared to filmwise condensation happened for the plain Ti pillared surface.

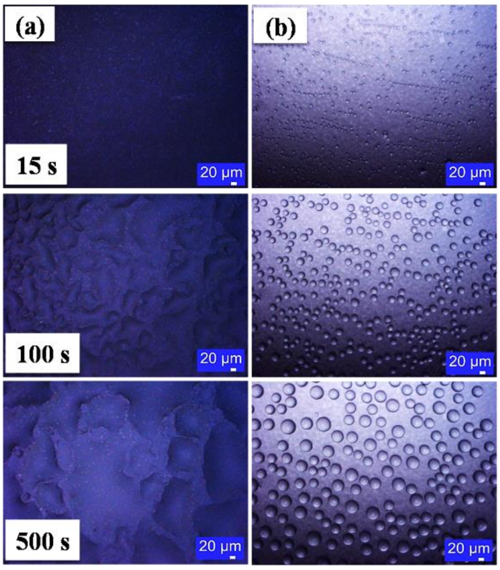

Figure 5. Time-lapsed droplet growth on (a) plain Ti pillared (b) Teflon© coated hydrophobic Ti pillared glass surfaces at 35±5 % RH and 275±0.2K surface temperature.

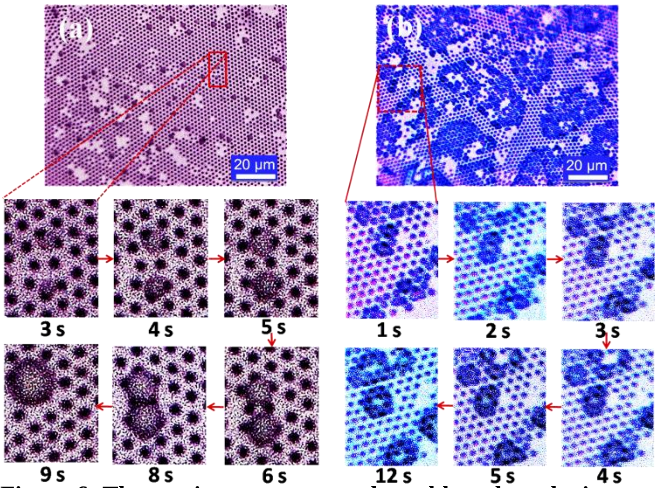

Figure 6. The wetting state was evaluated based on the images recorded for the droplet growth in a unit cell (a) hydrophobic surface, 30 % RH (b) plain Ti pillared surface, 40% RH.

For nearly same time-lapsed, initially droplets nucleated in between the nanopillars, extends towards multiple pillars and regular spherical droplets were observed for hydrophobic surface (Fig. 6 a), while for the plain Ti pillared surface (Fig. 6 b), droplets span towards multiple pillars and eventually irregular spherical droplets results.

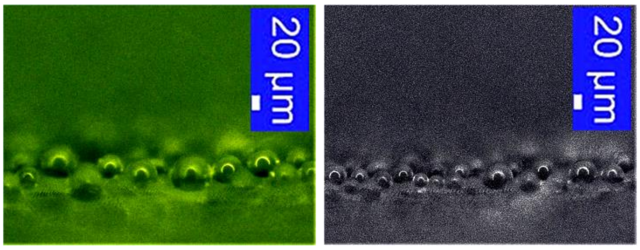

Figure 7. Droplet growth images for Teflon© coated nanopillar surface. Spherical cap shaped condensed droplets with average contact angle greater than 90° have been observed (side-view).

To conclude, the present study demonstrates that, increasing the relative humidity in the atmosphere reduces the nucleation energy barrier significantly and yields higher condensate harvesting. It also stated that, Teflon© coated hydrophobic Ti pillared surfaces would be a viable and easy method to promote dropwise condensation for several heat transfer units (such as condenser unit in steam cycled power plant) in industrial applications.

4. References

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