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CONTROLLING DROPLET SIZE DENSITY DURING DROPWISE CONDENSATION ON SILICONE OIL GRAFTED SURFACES

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1. ABSTRACT

We present a hydrophobic functionalization method based on silicone oil grafting on a solid substrate to promote dropwise condensation closely related to heat transfer efficiency improvement. While independently of the grafting parameters adopted hydrophobicity of the surface and dropwise condensation is achieved, the different functionalisation procedure, such as oil viscosity, volume and application method, can actually impose different droplet-surface interactions. A high viscosity oil grafted surfaces empower the lowest of the contact angle hysteresis (CAH) and hence very mobile smaller sized droplets can be easily removed from the surface, creating space for new droplets to nucleate, grow, coalesce and shed. Whereas low viscosity oils and low number of layers impose a greater contact angle hysteresis (CAH) with the consequent increase on the size of the shedding droplets. The control of the droplet size distribution during condensation phase-change is then here proposed based on the grafting parameters adopted.

2. INTRODUCTION

Condensation is a critical phenomenon for various industrial applications. Depending on the surface wettability different condensation behaviours can be achieved. On hydrophobic surfaces, dropwise condensation has gained increasing attention due to enhanced heat transfer rates with up to approximately 6-8 times higher heat transfer rates when compared to filmwise condensation [1]. Since then, various surface modification techniques have been explored to promote dropwise condensation. [2, 3]. One of these techniques includes the application of low surface energy coatings, which create low contact angle hysteresis (CAH) surfaces and stimulate smaller sized droplets shedding. In this work silicone oil grafting is exploited, which transforms an intrinsic hydrophilic silicon substrate into a hydrophobic surface. Grafting of silicone oil creates polydimethylsiloxane (PDMS) brushes attached to the original solid surface. While we make use of smooth silicon, other substrates such as copper, aluminium and glass could also be factionalized. The surface wettability and adhesion can then be tuned by various parameters such as viscosity, volume and/or number of layers [4]. By optimizing these grafting parameters functionalized surfaces exhibit favourable results in terms of hydrophobicity with high contact angles (CA $\approx$ 108°) and low CAH (below 1°), which is comparable to Slippery Omniphobic Covalently Attached Liquid (SOCAL) surfaces and/or Slippery Lubricant Infused Porous Surfaces (SLIPS). Further fabrication parameters can empower different CAH ranging between 1° to 20°, which anticipates a different droplet size distribution during dropwise condensation. This study provides an understanding on silicone oil grafted functional surfaces for condensation phase-change ultimately affecting heat transfer rates.

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3. METHDOLOGY

Surfaces are prepared via grafting of various viscosity silicone oils (5 and 100 cSt), varying volumes (from up to 10 µL via the pipette method to 0.2 µL via dip coating), and number of layers [4]. The condensation setup includes a custom-built controlled humidity chamber, a temperature-controlled Peltier stage attached to a cooling bath, a copper block with a thermocouple inserted in it, and insulating block around the copper block. Fabricated samples are then attached to the copper block on the Peltier stage via double-sided copper tape. The ambient conditions inside the chambers are considered as follows: ambient temperature T_{amb} = 20 ± 2 °C, Peltier stage temperature or substrate temperature T_{surf} = 5 ± 1 °C, and relative humidity RH = 70 ± 5%.

4. RESULTS

The two samples reported here are 1 layer 5 cSt (sample 1) and 1 layer 100 cSt (sample 2) silicone oil grafted. Figure 1 shows a typical snapshot before the shedding of droplet (red circle) takes place, where the smaller size and the more mobile of the droplets on Sample 2, which offers the lowest of the CAH below 1° are evident. The shedding droplet diameter on Sample 2 is almost half of the size of droplet on Sample 1.

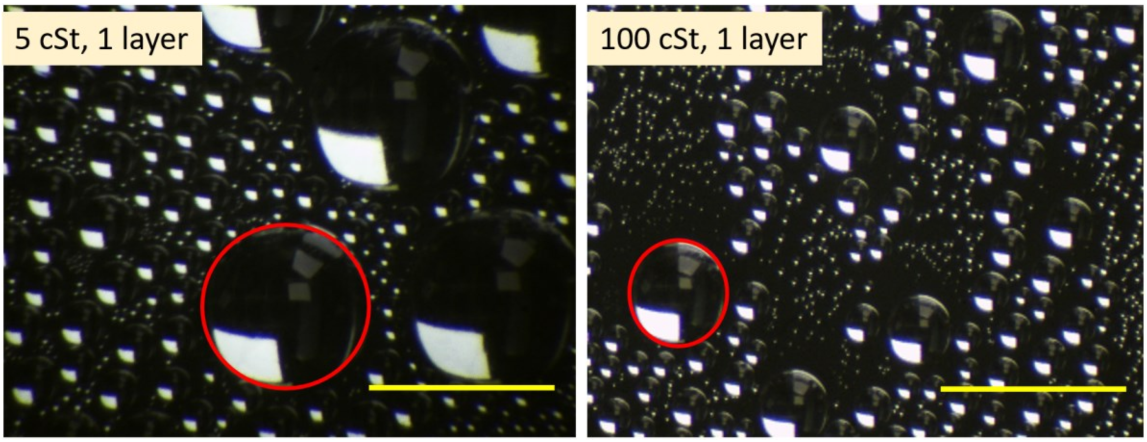

Fig. 1: Characteristic snapshot during condensation on 1 layer of 5 cSt silicone oil grafted (left) and 1 layer of 100 cSt silicone oil grafted (right) samples prior to the shedding of the circled droplets (in red). The scale bar (in yellow) is 1mm.

In order to provide some quantification on the droplet size distribution on the different surfaces at a given time, the droplet number density $N(r)$ is calculated using the formula given below [5]:

$$N(r) = (N_d/A)/r \qquad (1)$$

where, N_d is number of droplets, A is the surface area, and r is the average droplet radius. Figure 2 shows the droplet number density $N(r)$ function of the droplet size/radius r on the above reported samples. On one hand, from Fig. 2 it is evident that the droplets grow quite large in size ($r \sim 475$ µm, indicated by red line in Fig. 2) before they shed from the surface on Sample 1. This is because Sample 1 has higher CAH presumably due to ungrafted localized pinning sites on 1 layer of 5 cSt silicone oil [4]. More specifically, low viscosity 5 cSt silicone oil evaporates rapidly leaving behind regions with no PDMS coating, which causes pinning and hinder droplet mobility during condensation. On the other hand, Sample 2 has been grafted with a high viscosity 100 cSt oil via the dip-coating method [4]. This allows a homogeneous spread of a thin layer of the oil which results in uniform PDMS layer on the sample. Since Sample 2 provide the lowest of the CAH because of reduced pinning sites, the droplets mobility is greatly enhanced. This enhanced mobility reduces the size/radius of the shedding droplets to roughly half of that on Sample 1($r\sim 275$ µm). When smaller sized droplets are removed from the surface, it creates sites for new droplets to grow, coalescence and shed, which can be related to high heat transfer during dropwise condensation.

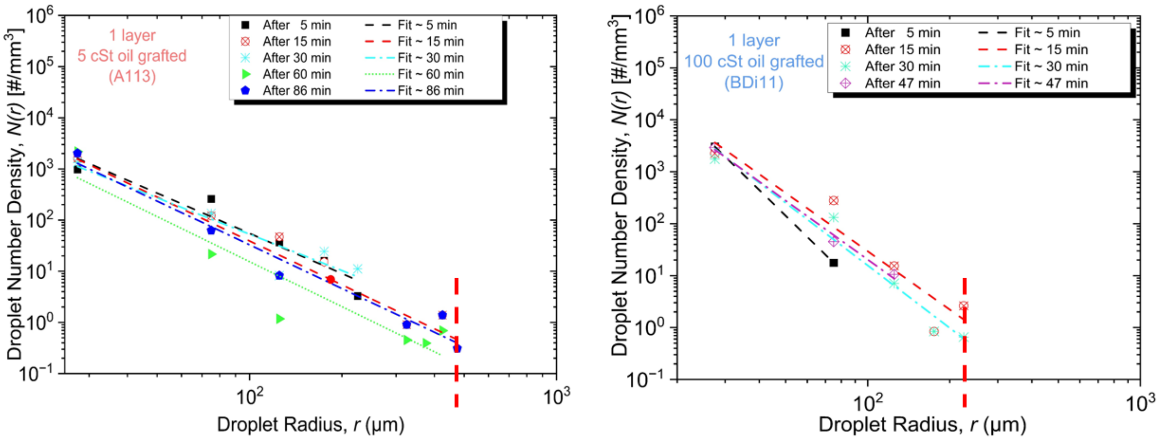

Fig. 2: Droplet size distribution as droplet number density $N(r)$ function of the droplet size/radius r on Sample 1: 1 layer 5 cSt silicone oil (left) and Sample 2: 1 layer 100 cSt silicone oil grafted (right). Vertical red line indicates the cut-off shedding radius.

5. CONCLUSIONS

A simple and easy functionalisation coating method is introduced here to prepare hydrophobic surfaces on which dropwise condensation is promoted opposed to filmwise condensation ensuing otherwise on a hydrophilic surface. The different affinity of droplets to the various coated surfaces anticipates differences on the shedding, which ultimately have an impact on the droplet size density and on the heat transfer rates. This work provides further fundamental insights to select the grafting parameters for preparing surfaces on which dropwise condensation is favourable and/or the droplet size distribution can be controlled.

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