Increased Heat Transfer through Dropwise Condensation on a Bio-inspired Superhydrophobic-Hydrophilic Surface

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ABSTRACT

Condensation of water vapor is an essential process in power generation, water collection, and thermal management. Because of the high surface energy of the metal surfaces, filmwise condensation of water vapor occurs, forming a static, thermally insulating film. Numerous efforts have been made to create surfaces that promote dropwise condensation; however these result in thermally insulating layers or degrade over time. Nature provides an alternative approach. The Namib beetle (Stenocara gracilipes) has a carapace that collects water by promoting dropwise condensation on raised hydrophilic regions which then roll off and slide along the hydrophobic surface. We designed and fabricated a hybrid superhydrophobic-hydrophilic surface to mimic, and improve upon, this behavior. Condensation occurs preferentially on the needle surface due to differences in wettability and temperature. As the droplet grows, the liquid on the needle remains in the Cassie state and does not wet the underlying superhydrophobic surface.

Keywords: namib beetle, Cassie state, wettability, surface energy, nucleation.

1 INTRODUCTION

Condensation of water vapor is an essential process in power generation [1], water collection [2], water desalination [3], and thermal management[4]. Efficiency of a power plant is directly related to the condenser heat transfer performance. Accumulation of condensed water on thermal components of the heating, ventilation and air conditioning (HVAC) system, which consumes ~20% of total energy consumption in developed countries, can lead to performance degradation and increased costs.[5] Because of the high surface energy of the metal surfaces used in these industrial systems, filmwise condensation of water vapor occurs, forming a static, thermally insulating film of water. Condensation rates slow as the film of water forms on the condenser surface, increasing the thermal resistance between heat sink and vapor and thus degrading the efficiency of the condensing system. In contrast, when dropwise condensation occurs, the condensing vapor forms discrete droplets on the condenser surface that are removed before coalescing into a film. A surface that exhibits dropwise condensation would lead to increased heat transfer efficiency and water removal ability. Numerous efforts have been made on creating surfaces which can promote dropwise condensation.Typically these approaches involve either polymer layers, which thermally insulate the surface from the metal conductor, or hydrophobic surface monolayers that degrade over time.

Nature provides an alternative approach to forming surface that promotes stable dropwise condensation. The Namib beetle (*Stenocara gracilipes*)[6] has a carapace that collects water from moist air by promoting dropwise condensation on raised hydrophilic regions which then roll off and slide along the hydrophobic surface (see Figure 1). A superhydrophobic surface could improve droplet mobility [7] and collection efficiency; however water vapor can condense uniformly on such a surface, resulting in the formation of low-mobility droplets in the Wenzel state (where the liquid wets into the rough surface). Thus there is a need to prepare a surface which can maintain highly mobile water droplets in the superhydrophobic Cassie-Baxter state (where droplets are formed on top of rough surface features) in a condensing environment.

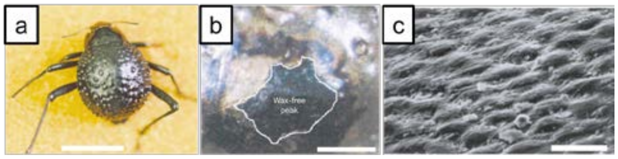

Figure 1. a) *Stenocara* beetle with a bumpy wing case, b) bumps:tops are wax-free hydrophilic and c) sides and trough are wax-coated & hydrophobic.Scale bar: 10 mm, 0.2 mm and 10 µm for images a, b & c respectively.

To meet the need for a heat-transfer or water collection surface that can maintain stable dropwise condensation, we designed and fabricated a hybrid superhydrophobic-hydrophilic surface. Arrays of hydrophilic needles, thermally connected to a heat sink, are forced through a robust superhydrophobic polymer film. Condensation occurs preferentially on the needle surface due to differences in wettability and temperature (see Figure 2).

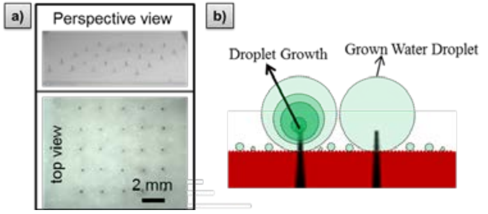

Figure 2. a) Hybrid superhydrophobic-hydrophilic surface, b) a schematic of droplet formation due to preferential nucleation and growth on the hydrophilic needle.

As the droplet grows, the liquid drop on the needle does not wet the underlying superhydrophobic surface as shown in Figure 2. Once the droplet reaches a critical volume, gravity overcomes the triple contact line (TCL) forces and the droplet is released from the needle if the surface is inclined at an angle from horizontal position. During roll-off, the droplet removes all smaller droplets in its path and thus leaves the needle and superhydrophobic surface available for another cycle of nucleation, growth and release.

2 EXPERIMENTAL

2.1 Preparation of superhydrophobic surface

Superhydrophobic surfaces were prepared by laminating an ultra-high molecular weight polyethylene (Saint Gobain Performance Plastics) film (120 µm thick) against a layer of silica nanoparticles under 70 MPa for 45-60 mins. Excess particles were removed by rinsing the surface with water followed by ultrasonicating the film in water for 10 mins.

2.2 Characterization of Superhydrophobic Surfaces

The surface structures were studied by scanning electron microscopy (FESEM, Amary 1910) and optical microscopy (Nikon-SMZ 1500). The static contact angles (CAs) and roll-off angles were measured with a goniometer (250-F1, ramé-hart Instrument Co) at room temperature and pressure using distilled water. Droplet volume of 2-5 µL and 10 µL were used to measure CA and roll-off/slip angle respectively.

2.3 Fabrication of Hybrid Superhydrophobic-Hydrophilic Surface

Hybrid superhydrophobic-hydrophilic surfaces were prepared by impaling the superhydrophobic film onto an array of steel needles. A detailed image of the needle is shown in the inset to Figure 3. The polymer substrate was pierced by the needles insuring a good seal between needle and surface. To maintain a specific needle height above the superhydrophobic surface, a glass slide with shims of the desired thickness, made from Kapton tape, was used as a spacer. A hybrid surface with 5 x 5 needle arrays at 2 mm pitch was fabricated.

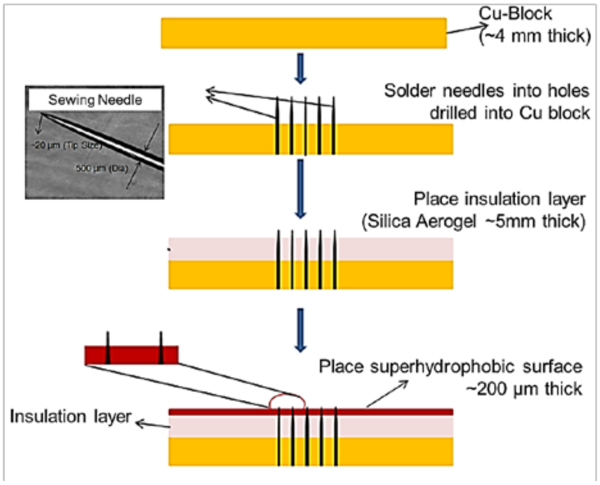

Figure 3. Schematic of the fabrication sequence of the hybrid superhydrophobic-hydrophilic surface.

2.4 Condensation Experiment

Condensation studies were performed in a Delrin® condensation chamber as shown schematically in Figure 4. The temperature of cooling stage was maintained with a chiller (NESLAB RTE-740, Thermo Scientific, USA) using water as the fluid. The substrate to be tested was placed onto the cooling stage using a thin layer of thermal grease.

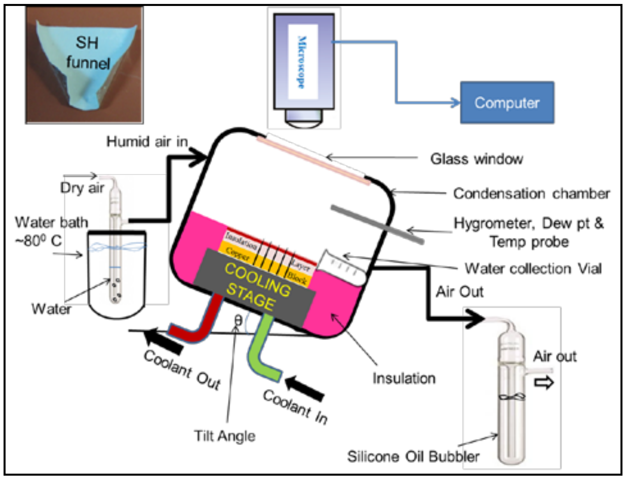

Figure 4: Experimental set-up for condensation study.

To create a flow of humid air through the chamber, a stream of dry air (at a 10 psi delivery pressure, flow rate of 50 cc/min) was introduced to a heated water bubbler maintained at 80 ^{0}C to saturate the air stream before entering the condensation chamber. The relative humidity

(RH) and air temperature of the chamber was monitored using a Traceable® Hygrometer, Thermometer, Dew point probe (model 4085 Control Company, USA).

The entire condensation chamber was tilted at an angle of 33^o relative to the horizontal. Images of the condensation process were acquired with a Nikon-SMZ 1500 (1x objective) stereo microscope equipped with a Infinity-2 digital camera at pre-set time intervals (1 to 5 min) and then analyzed using ImagePro7 software.

Water that condensed and rolled-off the surface was quantified to determine condensation rate by weighing the collected water. A superhydrophobic funnel was fabricated, as shown in top left of the Figure 4, put under the condensing surface such that water rolling off the hybrid surface was directed into a vial.

3 RESULTS AND DISCUSSION

3.1 Characterization of the Superhydrophobic (SH) Surfaces

The superhydrophobic surface is composed of silica nanoparticles partially embedded into the polyethylene substrate forming a surface with hierarchical roughness. The static contact angle and slip angle of the superhydrophobic background surface were measured to be 168 ± 2^o and 2^o respectively (Figure 5b insert). The hybrid surface exhibited a similar static contact angle when a drop was formed on the needle. The slip angle of a droplet pinned on the tip of the needle, however, was 21^o when the height of the needle was 300 µm above the superhydrophobic surface.

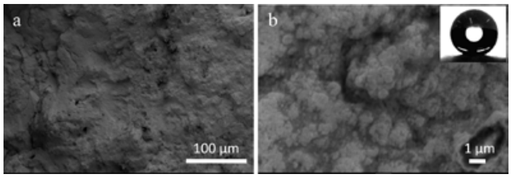

Figure 5. SEM Image of the superhydrophobic surface at low magnification (a) and higher magnification (b), an image of a 3µL water droplet on the superhydrophobic surface used for contact angle measurements (CA ~ 168^o) (Inset).

3.2 Sustained Dropwise Condensation on the Hybrid Superhydrophobic-Hydrophilic Surface

Dropwise condensation on the hybrid superhydrophobic surface was observed with the condensing droplet forming an almost spherical droplet that remained in the Cassie-Baxter state throughout the experiment as shown in Figure 6b-d. Images from one experiment, conducted with a needle temperature of 10^o C and a superhydrophobic surface temperature, measured between adjacent needles, of 12^oC are shown in Figure 6. Once humid air was introduced into the chamber, condensation was observed to selectively occur on the cooler, hydrophilic needle surfaces as shown in Figure 6a. This selective condensation is consistent with predictions based on the effect of surface energy on droplet nucleation rates. The high nucleation rate on the needle surface and relatively sparse nucleation of droplets on the SH surfaces is apparent in Figure 6.

The growth of droplets on the needle tips proceeds not only by condensation of vapor, but also through the merging of the satellite droplets formed on the background surface which have either rolled into the pinned droplet, or have been imbibed by the growing droplet. Figure 6 shows a series of optical images at 0.03, 2.03, 5.28 and 5.53 h of a condensation experiment which covers one full cycle of water nucleation, droplet growth and roll-off. Initially (2 min after onset of the condensation experiment) water condensed onto the needle tips is visible (see Figure 6a).

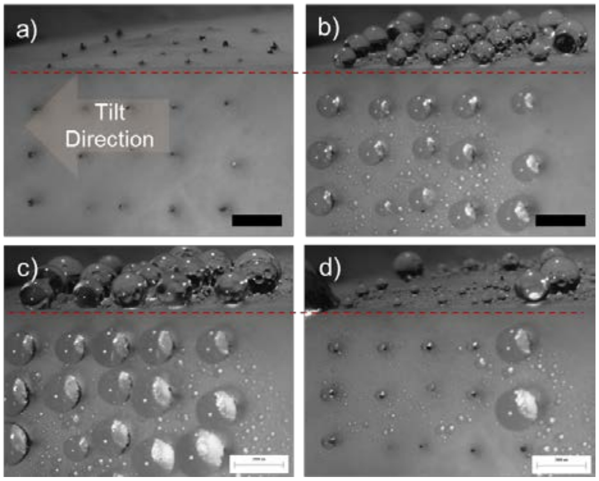

Figure 6. Dropwise condensation on the hybrid surface: a) surface at 0.03 h (~2 min) of the condensation experiment. Preferential nucleation and droplet growth occurred on the hydrophilic needles, b) droplet grown at 2.03 h c) droplet almost reach to critical mass at 5.28 h, d) In between 5.28 and 5.53 h droplets roll-off and another cycle of nucleation and droplet growth occurs. Dotted red line separates side view (above) and from top view (below) of images from optical microscope. Surface tilt at 20^o. Scale bar 2 mm.

As the droplets continue to grow, the spherical droplet shape and CA of 168 ± 2^o is maintained through 5.53 h (Figure 6b-d). The growth rate of the droplets pinned on the needles is 0.25 mg/h or 4.2×10^{-3} mg/min as determined by the increase in droplet volume over time. Typically, once the droplet grows above a critical volume through condensation and other mechanisms (e.g. small, satellite droplets colliding or merging with the pinned drop, or two neighboring pinned droplets merge together) it detaches from the needle and rolls downwards. As the droplet rolls, all droplets in its path, both those droplets pinned on needle tips as well as smaller droplets nucleated on the SH surface, merge with the moving droplet and are carried away leaving a swath free of condensate (Figure 7b). Thus droplet roll-off leaves the needles relatively dry and free for another cycle of droplet growth.

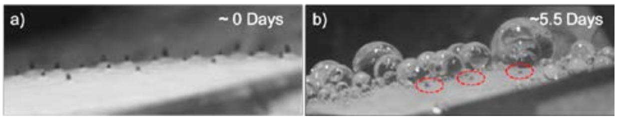

Figure 7. Optical images: a) a hybrid surface before the condensation experiment, b) droplets form high CA (>162^{o}) and roll-off the surface after 5.5 days of continuous operation. (Relative humidity (RH), 68 ± 2 %; cooling stage temp, 5^{o}C **;** surface temp, 10-12 ^{o} C; surface tilt angle, 33 ^{o}).

This cycling process (nucleation-growth-roll off) is repeated numerous times throughout the condensation experiment with no evidence of water wetting the superhydrophobic surface. The CA between droplets and the SH surface was maintained above 160^{o} up to 28h. This is true for both the large droplets pinned by the needles, as well as smaller droplets that randomly nucleate on the SH surface. Condensation experiments have been studied for more than 5 days without any indication of water wetting the superhydrophobic surface or a reduction in contact angle.

3.2 Condensation on different control surfaces

To determine the relative effectiveness of the hybrid superhydrophobic-hydrophilic surface on heat transfer and water collection, condensation experiments were performed on a series of control surfaces with different surface chemistries and textures. Flat, smooth surfaces of copper, polyethylene and silicon (treated with dichlorodimethylsilane) were used to compare flat surfaces that are hydrophilic, hydrophobic with high CA hysteresis (CAH ~ 25^{o}) and hydrophobic with low CA hysteresis (CAH < 1^{o}) respectively. Water collection rates, which are directly proportional to the condensation rates, are compared in Table 1.

Table 1. Comparison of condensation rate of various surfaces.

Substrate	**Water Collection Rate (mg/mm^{2}-min) × 10^{-4}**
Clean Copper	8.1 ± 1.1
Polyethylene	13.2 ± 1.4
Flat hydrophobic silicon	16.7 ± 1.0
Superhydrophobic PE	15.8 ± 1.7
Hybrid	34.4 ± 0.5

The hybrid superhydrophobic surface (with needles) showed as much as four times higher condensation rate than clean copper surface which usually gives filmwise condensation. This water collection results indicate enhanced heat transfer and water collection abilty of this hybrid surface.

4 CONCLUSION

A hybrid superhydrophobic-hydrophilic surface was fabricated by impaling an array of thermally conductive needles (soldered to a copper heat sink) through a polyethylene nanocomposite superhydrophobic surface. This hybrid surface showed sustained dropwise condensation for more than 5.5 days in a condensing environment. Contact angle measurements of the growing droplets confirm a stable Cassie state (CA > 160^{o}) throughout the condensation process. Water droplets roll off easily due to gravity above a critical tilt angle and can be collected. Rolling droplets imbibe smaller drops as well as pinned droplets, accelerating droplet growth and increasing water collection effeciency. This hybrid superhydrophobic-hydrophilic surface showed the highest water collection rate among various control surfaces, including bare copper. Because of the stable properties and low cost, this type of hybrid superhydrophobic-hydrophilic surface should prove beneficial for applications including two-phase heat transfer and water collection.

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