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Bioinspired triangular patterns for water collection from fog

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Cacti use spines with conical geometry to transport water to its base. A conical shape with curvature gradient generates a Laplace pressure gradient along the droplet, which is responsible for droplet motion. In this study, the triangular shape was used which also generates a Laplace pressure gradient along the droplet. A bioinspired surface, composed of a hydrophilic triangular pattern surrounded by a rim of superhydrophobic region, was used to transport water collected from the fog on the hydrophilic pattern. The growing droplets start to coalesce into bigger ones. Eventually, they are big enough to touch the superhydrophobic borders, which trigger the transport motion. Droplet mobility and water collection measurements were made on triangular patterns with various geometries to determine the most efficient configurations. Results from this study can be used to enhance the performance of water collection systems from fog.

This article is part of the theme issue 'Bioinspired materials and surfaces for green science and technology (part 2)'.

1. Introduction

Climate change and world population growth have led to water scarcity. Global water security requires new approaches to collecting water. Water collection systems from fog in the atmosphere and water condensation from ambient vapour have proven to be promising techniques [1–5]. The surface wettability of the collectors plays a dominant role to collect and transport water droplets from air. A hydrophilic substrate can easily attach an impacting droplet, however, it is hard to remove the attached water. When a droplet makes contact with a superhydrophobic

surface, it can easily roll off the substrate with only a small amount of water being collected [6–8]. To optimize the water collection rate, proper design of the wettability of a surface that can both attach water droplets and provide high water mobility is crucial.

Insects and plants living in arid regions can collect water from fog at a sufficient rate to support their life [9,10]. Before the collected water is evaporated, they have mechanisms to transport it to where it is consumed or stored. Inspired by nature, biomimetic approaches have attracted attention in the area of water collection from fog. The cactus uses conical spines to spontaneously collect droplets and to trigger droplet movement. The conical geometry of the spines generates a curvature gradient along the droplet, which produces a Laplace pressure gradient on the droplet. This pressure gradient can drive the droplet from the tip to the base of a cone to move with a relatively high speed without external energy [8,11,12]. Incidentally, to transport liquids in microfluidic devices, various geometries have been used to transport water droplets [13,14].

In addition to fog collection, the temperature in the desert at night can be lower than the dew point, and can lead to water condensation from ambient. Song & Bhushan [15,16] were the first to use condensed water from ambient as a source for water collection using bioinspired triangular patterns. Triangular patterns also develop Laplace pressure gradient.

In this paper, for the first time, fog is used as a source for water collection using bioinspired triangular patterns. The effect of the included angle on the water droplets' growth and transport was investigated using a single hydrophilic pattern. The water collection rate was increased by integrating an array of triangular patterns and was then measured.

2. Experimental details

A water collection system, fabrication of the bioinspired samples and technique for measuring the amount of collected water are described. Two types of samples were used—a single triangular pattern for the detailed investigation of the water transport process, and a reservoir with multiple triangular patterns to increase the amount of collected water and weigh it.

(a) Experimental system

Figure 1*a* shows a schematic of the system for water collection from fog. A commercial humidifier (Crane, EE-3186) was used to generate a stream of fog which was injected into a box. A rectangular opening at the bottom of the box shaped the fog flow into a rectangular channel about 40 mm × 25 mm. The bioinspired samples were placed on top of a piece of transparent glass (3 mm × 150 mm × 150 mm). A digital microscope CCD camera (Koolertron, 5MP 20-300X) was used to record the water collection process. Experiments were conducted in an ambient with a temperature of $22 \pm 1^\circ\text{C}$ and relative humidity between 35 and 50%.

(b) Fabrication method of the bioinspired triangular patterns

A single triangular pattern and a reservoir with multiple patterns are schematically shown in figure 1*b,c*. Region A is hydrophilic, surrounded by a rim of superhydrophobic region which is labelled as region B. The superhydrophobic region constrained the droplet deposited in the triangular pattern.

To fabricate the patterned sample, the boundaries of the desired pattern B were printed on a paper that was placed under a glass slide with a piece of adhesive tape put on top. Next, region B was cut into the adhesive tape, guided by the pattern on the paper underneath, so that region B was exposed to air and region A was protected by the tape. Then a superhydrophobic coating was spray coated on the glass slide followed by removal of the adhesive tape that covered region A. The superhydrophobic coating consisted of 10 nm hydrophobic SiO₂ nanoparticles (Aerosil RX300) and a binder of methylphenyl silicone resin (SR355S, Momentive Performance Materials),

Figure 1. Schematics of (a) the water collection system from fog, (b) sample with a single triangular pattern and (c) a reservoir with an array of triangular patterns.

Figure 2. Optical images of water droplets on the hydrophilic glass and the superhydrophobic coating and the static contact angles (θ) and contact angle hysteresis (θ_{hyst}). Reproducibility was $\pm 2^\circ$.

both of which were pre-mixed in acetone before spraying [9]. Region B became superhydrophobic after the coating and region A remained hydrophilic.

The water droplet images and contact angles of the hydrophilic and superhydrophobic regions are shown in figure 2. The contact angle/contact angle hysteresis of the superhydrophobic and hydrophilic region are $167^\circ/4^\circ$ and $61^\circ/20^\circ$, respectively.

Two types of samples were fabricated. The first sample contained a single triangular pattern, which was used to investigate the droplet transport process (figure 1b). The single triangular

pattern with a 20 mm length was surrounded by a superhydrophobic border region (0.5 mm wide). Three angles (α) of 5°, 9° and 17° were selected to investigate the effect of α on the droplet transport process. The other sample contained an array of triangular patterns that were located on both sides of a rectangular reservoir, to increase the amount of collected water (figure 1c). Arrays with a total number of 16 patterns with an included angle of 9° and length of 10 mm were used. To study the effect of included angle, arrays with a length of 10 mm and with four included angles of 9°, 17°, 22° and 30°, and numbers of patterns of 16, 10, 8 and 6, respectively, were used. To study the effect of length, arrays with an included angle of 9° and with four lengths of 5, 10, 20 and 30 mm and number of patterns of 26, 16, 5 and 4, respectively, were used. In the case of 20 and 30 mm long patterns, all patterns were placed on one side. The experiments were performed for 60–90 min, until the reservoir was filled.

(c) Water collection measurements

To measure the mass of the collected water for both types of samples, after the test, a piece of tissue paper was used to absorb the collected water. The paper was weighed before and after soaking by a microbalance (Denver Instrument Company No. B044038). The microbalance could measure a minimum mass of 1 mg. The mass of the piece of tissue paper ranged from about 100 to 150 mg. The mass of the collected water was about 100–200 mg. Therefore, the mass of collected water could be measured with an accuracy of about $\pm 5\%$.

3. Results and discussion

The sample with a single triangular pattern was first investigated to study the water transport process along the pattern. Experiments were also conducted on a rectangular pattern to provide a comparison and to demonstrate the role of triangular geometry on droplet mobility. For measurement of water collection rates, a reservoir surrounded by an array of triangular patterns was used to collect a larger amount of water. To study the effect of the geometry of triangular patterns, the water collection rates were measured for various included angles and length of patterns.

(a) Droplet deposition, growth and motion on hydrophilic rectangular and triangular patterns

Figure 3 shows the droplet accumulation process when two surfaces were placed under the fog flow. The hydrophilic patterns were surrounded by superhydrophobic regions. When the surfaces were exposed to the fog flow, the deposition rates of the water from fog on the superhydrophobic and hydrophilic regions were different. More water was collected on the hydrophilic regions than the superhydrophobic ones. This can be attributed to the non-wettability of the superhydrophobic surface, where a normal impacting droplet can bounce and roll off the surface. When a droplet impacts on a hydrophilic surface, the high adhesion force of water will attach the droplets. As a result, the small droplets in fog preferentially deposit on the hydrophilic patterns, which causes more water to be collected on the hydrophilic region compared with that on the superhydrophobic region.

Droplets on the patterns grow and coalesce. In the case of a rectangular hydrophilic pattern, before the droplets (numbered 1–5) grow big enough to touch the superhydrophobic borders around the pattern, they sit at the original position and do not move. As the droplets continue to grow, they come into contact with the neighbouring droplets, and coalescence occurs. The coalesced droplets (1 + 2 + 3 and 4 + 5) still do not move.

On the triangular hydrophilic patterns, the deposited droplets do not move until they grow big enough to touch the superhydrophobic borders (droplets numbered 1–4). However, the water transport occurs when droplets 1, 2 and 3 coalesce into one bigger droplet (1 + 2 + 3) and touch the borders. The droplet moves toward the wider width until reaching the reservoir.

Figure 3. Droplet growth, coalescence and transport on rectangular and triangular patterns. Arrows shown below some droplets correspond to droplet movement observed in videos.

The driving force of the droplet transport along the triangular pattern comes from the Laplace pressure gradient on the wedge-shaped droplet [16]. The Laplace pressure generated by the local curvature can be expressed as $\Delta P \sim \gamma/R(x)$, where γ is the surface tension of water in the air, $R(x)$ is the local radius of the curvature of the droplet and x is the position measured from the tip of the triangle [17]. When a droplet is big enough to touch both superhydrophobic borders, it is wedge shaped. Within the wedge, the droplet, $R(x)$, decreases when moving away from the tip. As a result, the pressure decreases and a pressure gradient is developed. This driving force within the droplet moves it away from the tip.

As long as the droplet can touch both boundaries of the triangular pattern, the Laplace pressure gradient exists. However, its magnitude decreases as the droplets moves farther from the tip. Eventually, the droplet will stop when the driving force of the Laplace pressure is less than the adhesion force.

(b) Effect of included angle on the water transport process

Figure 4a shows the water transport process on triangular patterns with different included angles. The included angle affects the water transport process. The time taken to transport the water droplets across the triangular pattern decreases with the included angle. For example, to transport the collected water to reach the reservoir, $x_r = 20$ mm, it takes about 78, 57 and 42 min on the patterns with included angles of 17° , 9° and 5° , respectively. The size of droplet that triggers the transport of the deposited droplet increases with included angle.

Due to adhesion of the hydrophilic pattern to the droplet, the collected droplet was elongated before it could start to move. The length of the elongated droplet (l) right after the droplet stopped moving as a function of the travel distance, x_r , is shown in figure 4b. Length increased linearly with x_r , and the included angle had no effect. These results agree with observations made in a water condensation study by Song & Bhushan [16].

Figure 4c shows the droplet mass and time needed for the droplet to reach the reservoir through the whole triangular pattern as a function of included angles (α). As α increases, the mass of the droplet that reached the reservoir increased, while it took more time for the droplets to reach the reservoir. These results also agree with observations made in the water condensation study by Song & Bhushan [16].

(c) Water collection rate on array of triangular patterns

To increase the water collection rate, samples containing a reservoir with arrays of patterns were used. Figure 5a shows a photograph of the reservoir with 10 mm long triangular patterns after being exposed to fog for one hour. The collection rate of water was about $0.86 \text{ mg mm}^{-2} \text{ h}^{-1}$.

Figure 4. Droplet growth, coalescence and transport on triangular patterns with various included angles. (a) Selected photographs of the droplet transport at different times. Arrows shown below some droplets correspond to droplet movement observed in videos. (b) Length of the coalesced droplet (I) right after the droplet stopped moving as a function of the travel distance (x_r). (c) Effect of included angle (α) on the mass of the first droplet at the reservoir and time taken for the droplet travelling through the pattern.

For optimization of the water collector design, the effect of the included angle, α , and the length of the triangular patterns, L_a , were studied. Figure 5b shows that the included angle did not affect the water collection rate. Even though the droplet traveled slowly on a triangle with a larger included angle, the size of the droplet was larger which may provide the similar collection

(a) effect of included angle and length of patterns on water collection rate

reservoir with 16 triangular patterns

$\alpha = 9^\circ$, $L_a = 10$ mm, 60 min

(b) effect of included angle on water collection rate

$L_a = 10$ mm

effect of length on water collection rate

$\alpha = 9^\circ$

Figure 5. Water collection in the reservoir surrounded by an array of triangular patterns. (a) Photograph of water collected in the reservoir surrounded by an array of triangular patterns and (b) water collection rate as a function of included angle and length of the triangular patterns.

rates. Figure 5b also shows the water collection rate as a function of the length of the triangular patterns. The water collection rate decreased when the length increased. Since a shorter distance requires less time to transport the droplets and although the droplets being removed are small, the removal rate increases the collection rate.

4. Conclusion

The water collection rates and transportability of the bioinspired triangular patterns from fog were investigated. Hydrophilic triangular patterns were surrounded by a rim of superhydrophobic regions. When exposed to fog, droplets accumulate on hydrophilic patterns. Droplets grow and start to coalesce into bigger ones. Eventually, they are big enough to touch the superhydrophobic borders, which trigger the transport motion. A wedge-shaped droplet generates a Laplace pressure gradient that is able to spontaneously drive the droplet. The collected water moves slower on a triangular pattern with a larger included angle; however, larger water droplets are transported to the reservoir. In experiments with multiple triangular patterns surrounding a reservoir, the water collection rates were measured. The collection rate increased with a decrease in the length of the pattern.

The results of this study can be used to design efficient water collection systems from fog.

Data accessibility. This article has no additional data.

Authors' contribution. D.S. performed the experiments and analysed the data. D.S. and B.B. wrote the main text and participated equally in planning, execution and review of the manuscript.

Competing interests. We declare we have no competing interests.

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