Research

Cite this article: Gurera D, Bhushan B. 2019 Bioinspired conical design for efficient water collection from fog. *Phil. Trans. R. Soc. A* **377**: 20190125.
<http://dx.doi.org/10.1098/rsta.2019.0125>

Accepted: 29 April 2019

One contribution of 15 to a theme issue
'Bioinspired materials and surfaces for green
science and technology (part 2)'.

Subject Areas:

nanotechnology, mechanical engineering

Keywords:

bioinspiration, water collection, fog, cone,
Laplace pressure gradient, nonlinear

Author for correspondence:

Bharat Bhushan

e-mail: bhushan.2@osu.edu

Bioinspired conical design for efficient water collection from fog

Dev Gurera and Bharat Bhushan

Nanoprobe Laboratory for Bio- and Nanotechnology and Biomimetics (NLBB), The Ohio State University, 201 W. 19th Avenue, Columbus, OH 43210-1142, USA

DG, 0000-0002-6790-9986; BB, 0000-0001-7161-6601

Nature is known for using conical shapes to transport the collected water from fog for consumption or storage. The curvature gradient of the conical shape creates a Laplace pressure gradient in the water droplets which drives them towards the region of lower curvature. Linear cones with linearly increasing radii have been studied extensively. A smaller tip angle cone transports water droplets farther because of higher Laplace pressure gradient. Whereas a larger tip angle with a larger surface slope transports water droplets because of higher gravitational forces. In this study, for the first time, a nonlinear cone with a concave profile has been designed with small tip angle and nonlinearly increasing radius to maximize water collection.

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

1. Introduction

Nature uses conical geometries to transport the collected water from fog to the reservoir [1]. The role of conical geometry in driving droplets can be substantial. It can even drive droplets against gravity. A droplet sitting on a constant curvature surface has a constant Laplace pressure of $\Delta P = 2\gamma/(r + h)$, where γ is the surface tension of the liquid, r is the radius of the curvature and h is the height of the droplet from the cone axis [2]. If curvature gradient is introduced in the underlying surface, a Laplace pressure gradient is introduced in the droplets. The resultant Laplace pressure gradient will result in droplets moving towards regions of larger radius, as it will

decrease the average Laplace pressure inside the droplet. This means that a droplet will always move away from the tip on a conical surface.

Various attempts have been made to study the water collection by fog from the conical structures [3–5]. Two tip angles have been largely studied: 10° , inspired from cactus, and 45° . Based on the droplet dynamics study on cones, it was found that there are two driving forces for the droplets on a cone: the Laplace pressure gradient and the gravity [5,6]. The Laplace pressure gradient is higher for smaller tip angle cones, for a short length. The gravitational force is higher for heavier droplets and larger cone slopes. Therefore, a smaller tip angle is desired for transporting liquids over short distances, and a larger tip angle is desired for transporting heavier droplets over longer lengths. Under a fog flow, tiny droplets form on the surface which coalesce into bigger droplets and move. Therefore, a smaller tip angle is desired to move the tiny droplets at the tip, and a larger slope near the base is desired for moving the heavier droplets at the base faster.

In this study, for the first time, a nonlinear cone with a concave profile has been designed with small tip angle and nonlinearly increasing radius, to maximize the water collection. The data are compared with linear-shaped cones of either the same tip angle or the same base diameter. Single droplet experiments were performed to study the movement of the droplets. Water collection rates were measured. The cones were tested parallel to the fog flow, at 0° inclination.

2. Experimental method

The design of various cones and their fabrication technique are described first. Next, the calculation procedure of curvature gradient is presented for the cones, which helps to understand the differences in the Laplace pressure gradient inside the droplets on different cones. This is followed by a description of single droplet experiments and the experimental set-up for water collection from fog.

(a) Fabrication of cones

Figure 1 presents various designs of the bioinspired linear and nonlinear cones. A linear-shaped cone with 45° tip angle, 15 mm length and base diameter 13 mm was selected [5]. To design a nonlinear cone, the same length and the same base diameter, but a lower tip angle of 10° , were selected. A cubic polynomial was fitted with selected slopes at the tip and at the base. For comparison, a linear-shaped cone with 10° tip angle and same length was also selected.

The technique used for fabrication was additive manufacturing (three-dimensional printing), because it allows flexibility in design and scalability. The machine used was Objet30 Prime, Stratasys, Ltd., Eden Prairie, Minnesota. It has an accuracy of about 0.1 mm. The material used was an acrylic polymer, RGD720.

(b) Curvature gradient

The curvature gradient was mathematically calculated for the three cones. A droplet of 0.5 mm length was assumed to move along the cone due to the Laplace pressure gradient, where the droplet length is measured along the sideline of the cone. The underlying curvature gradient is calculated by $((1/r_1) - (1/r_2))$, where r_1 and r_2 are two local radii of the cone at two ends of the droplet. As the droplet moves, r_1 and r_2 change accordingly. The curvature gradient was plotted with the distance, which is measured from tip of the cone to centre of the droplet, along the cone axis. The measurements were made at 0.1 mm distance intervals.

(c) Single droplet experiments

Single droplet experiments were carried out to study the movement of water droplets on cones to get a fundamental insight into their motion. A droplet of known volume was initially placed

Figure 1. Design of 3D printed bioinspired water collectors with two linear and a nonlinear conical profiles. A linear cone of 45° tip angle, length 15 mm and base diameter 13 mm was chosen. A nonlinear cone with same length and same base diameter, but a smaller tip angle of 10° was designed with a concave shape. Another linear cone of the same length, but 10° tip angle was also fabricated for comparison.

at the tip using a pipette and its motion was studied. A droplet was placed at the very tip of the cone because the aim was to start with the smallest radius possible. This was done in order to characterize the effect of the known volume. Thereafter, the droplets were fed in increments of $5\ \mu\text{l}$ because they had a small enough volume to stick to the surface, rather than fall off when ejected from the pipette. The subsequent volumes were fed to the moved droplet at its current location and not the tip of the cone. The increments were added until the droplets detached and fell off the cone surface. Droplets fall because, at higher volumes, gravitational forces dominate the capillary forces. A droplet detaches at about $40\ \mu\text{l}$. Droplet volume as a function of distance travelled on the cones was recorded. The distance was measured from the tip of the cone to the centre of the droplet. The experiment was repeated three times for each cone. The average distance along with the standard deviation was reported at every $10\ \mu\text{l}$ increment.

(d) Experimental set-up for water collection

A commercial humidifier was used to produce a stream of fog onto the cones. The cones were placed horizontally. The water collected from the cones was measured using an analytical balance underneath, with time [4,5]. The humidifier used was EE-3186, Crane, Itasca, Illinois. It emits fog at about $10\ \text{cm s}^{-1}$ and was kept about 20 cm away from the surface. The flow speed was calculated by measuring the volume of water lost over time, and by knowing the diameter of the pipe through which the fog was blown out. The analytical balance used in the study was B044038, Denver Instrument Company, Bohemia, New York. The minimum weight it can measure is 1 mg. In the experiments, the lowest weight of collected water measured was about 10 mg. The typical weight range of each collected drop was about 30–60 mg.

Water collected by a cone was measured as a function of time. A straight line was fitted through the points, and the slope of the line was referred to as the water collection rate (mg h^{-1}). This parameter was used throughout the study to estimate the water collection ability of different

Curvature gradient of the nonlinear cone is similar to the 10° tip angle linear cone near the tip.
Curvature gradient of the nonlinear cone converges to the 45° tip angle linear cone near the base.

Figure 2. (a) Effect of the nonlinearity on the curvature gradient of the cones, using a droplet length of 0.5 mm. The top graph shows the curvature gradient variation near the tip and the bottom graph shows the variation near the base with magnified vertical axis. On the linear cones, the curvature gradient increases with shorter tip angle near the tip. The curvature gradient of the nonlinear cones starts out overlapping with the 10° tip angle linear cone, because of the same tip angle (top graph). Later, the curvature gradient converges towards the 45° tip angle linear cone (bottom graph). (b) Overlapped cones' profile for the linear and the nonlinear cones. (Online version in colour.)

surfaces. A minimum of five droplets were allowed to fall before a straight line was fitted and its slope was calculated. The parameter is believed to be a more accurate representation of the water collection rate, when compared with the reported studies which calculate the rate from the beginning of the measurements. The slopes were calculated for three different trials. The average and the standard deviation calculated from a minimum of 15 data points are reported in this study.

Figure 3. Effect of tip angle and the nonlinearity on the droplet movement along the cones in single droplet experiments. The cones are placed with the centreline in the horizontal direction, as shown in the schematic. Droplets were placed at the very tip of the cone using a pipette, the droplet moved instantaneously until reaching equilibrium, and the distance was measured from the tip of the cone to the centre of the droplet. Droplets were fed in an increment of $5\text{ }\mu\text{l}$, and the distance was measured in increments of $10\text{ }\mu\text{l}$. Among the linear cones, the smaller tip angle transports the droplets farther. This is because smaller tip angles provide higher Laplace pressure gradient. The nonlinear cone transports the water droplets farthest among the three cones. This is because of the high Laplace pressure gradient in the beginning and increasing gravitational forces later. (Online version in colour.)

Figure 4. Effect of nonlinearity on water collection for the linear and the nonlinear cones. (a) Water collection rates (mg h^{-1}), and (b) droplet weight (mg) and the frequency (droplets h^{-1}). The water collection rate and frequency of the nonlinear cone was found to be highest, because of high Laplace pressure gradient in the beginning and increasing gravitational forces later. Droplet weight remained similar regardless of the cone.

There are two other parameters by which the collected data can be characterized. First is the frequency of the droplets falling (droplets h^{-1}), which is the sum of the inverse of the wait-time for every droplet except the first. This parameter gives an idea of how fast the surface is collecting water. The second parameter is the average weight of the collected droplet (milligram). It is the

Figure 5. Optical images showing water droplets travelling from tip to base on 10° tip angle linear cone. The first droplet takes the longer time to fall when compared with the subsequent droplets. (Online version in colour.)

average of every droplet dropped in the beaker. This could be measured since a balance reading was recorded before and after the falling of every droplet. This allows one to observe the mass of the droplets being collected by the surface. Ideally, high frequency and high average droplet weight are desired.

3. Results and discussion

(a) Curvature gradient

Figure 2 shows variation of curvature gradient on various cones. Figure 2*a* shows variation of curvature gradient on linear cones of tip angle, 10° and 45° , and the nonlinear cone for a droplet length of 0.5 mm. The top graph shows the curvature gradient variation near the tip, and the bottom graph shows the variation near the base with magnified vertical axis. Figure 2*b* shows overlapped profiles of the three cones for reference. Based on the graphs, the following observations can be made. The curvature gradient decreases with length because of the decreasing curvature of the cones. The curvature gradient of the 10° tip angle cone is higher than the 45° tip angle cone. This is because the radius of the cone increases at a slower rate in 10° tip angle, which will increase the curvature gradient. Curvature gradient of the nonlinear cone was similar to the

Figure 6. Optical images showing water droplets travelling from tip to base for the linear and the nonlinear cones. Only the second droplet has been shown, to present a representative time taken by each cone to form a droplet big enough to fall. The linear cones take a similar time and have a similar hanging droplet size. The nonlinear cones take less time and are of a similar size to the hanging droplet. (Online version in colour.)

linear, 10° tip angle cone for the initial cone length. For the latter part of the cone, the curvature gradient of the nonlinear cone converges towards the linear, 45° tip angle cone with the same base diameter. It is expected that because of the increasing slope of the cone, the gradient should be converging towards the higher tip angle cone.

(b) Single droplet experiments

Figure 3 shows the relationship between droplet volume and distance travelled by the droplet for the linear and the nonlinear cones. It is clear from the graph that, among the linear cones, a smaller droplet volume is transported farther by the 10° tip angle cone [5]. The nonlinear cone transports the liquid farther than the linear cones. This is because of the high Laplace pressure gradient in the beginning and increasing gravitational effect later.

(c) Water collection from fog

Figure 4 shows the water collection data for linear and nonlinear cones. Figure 4*a* shows the water collection rate (mg h^{-1}) and figure 4*b* shows average droplet weight (milligram) and frequency

(droplet h^{-1}) for the cones. The water collection rates for the linear cones were similar [5]; however, the water collection rate of the nonlinear cone was found to be higher. It is believed that because of high Laplace pressure gradient in the beginning and increasing gravitational effects later, the droplets were transported faster, which was observed in the higher frequency of the falling droplets. The weight of the falling droplets remained similar.

Figure 5 shows a sequence of optical images of water droplets travelling from tip to base for the linear 10° tip angle cone. A sequence for the first and the second droplet is presented. The first droplet takes longer time to fall when compared with the subsequent droplets.

Figure 6 shows a sequence of optical images of water droplets travelling from tip to base for the linear and the nonlinear cones. Only the second droplet has been shown in the figure, to present a representative time taken by each cone to form a droplet big enough to fall. The linear cones take a similar time and have a similar hanging droplet size. The nonlinear cone takes less time and has similar size of the hanging droplet. These observations are in agreement with the droplet weight and frequency measurements, discussed earlier.

4. Conclusion and outlook

A nonlinear cone has been designed for maximum water collection from fog. The nonlinear cone was designed with small tip angle of 10° to increase the Laplace pressure gradient near the tip and nonlinearly increasing radius to have higher gravitational effects from the higher slopes. Calculated curvature gradient data show that for the initial part of the cone, the curvature gradient of the nonlinear cones matches that of the linear cone of 10° tip angle, due to the same tip angle. For the latter part of the cone, the curvature gradient approaches the curvature gradient of the linear cone of 45° tip angle, with the same base diameter. A single droplet of known volume is transported farther on a horizontal nonlinear cone due to high Laplace pressure gradient in the beginning and increasing gravitational effect later. A higher water collection rate is also observed for the nonlinear cone. Therefore, for a high water collection rate, a smaller tip angle and broader base diameter with higher surface slope is desired.

Data accessibility. This article has no additional data.

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

Competing interests. We declare we have no competing interests.

Funding. The financial support for this research was provided by a seed grant GOGCAP from the Center for Applied Plant Sciences (CAPS) of The Ohio State University.

References

1. Bhushan B. 2018 *Biomimetics: bioinspired hierarchical-structured surfaces for green science and technology*, 3rd edn. Cham, Switzerland: Springer International.
2. Lorenceau É, Quéré D. 2004 Drops on a conical wire. *J. Fluid Mech.* **510**, 29–45. (doi:10.1017/S0022112004009152)
3. Ju J, Xiao K, Yao X, Bai H, Jiang L. 2013 Bioinspired conical copper wire with gradient wettability for continuous and efficient fog collection. *Adv. Mater.* **25**, 5937–5942. (doi:10.1002/adma.201301876)
4. Gurera D, Bhushan B. 2019 Designing bioinspired surfaces for water collection from fog. *Phil. Trans. R. Soc. A* **377**, 20180269. (doi:10.1098/rsta.2018.0269)
5. Gurera D, Bhushan B. 2019 Optimization of bioinspired conical surfaces for water collection from fog. *J. Colloid Interface Sci.* **551**, 26–38. (doi:10.1016/j.jcis.2019.05.015)
6. Schriener CT, Bhushan B. 2019 Water droplet dynamics on bioinspired conical surfaces. *Phil. Trans. R. Soc. A* **377**, 20190118. (doi:10.1098/rsta.2019.0118)