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Water droplet dynamics on bioinspired conical surfaces

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Cacti use the Laplace pressure gradient due to conical geometry as a mechanism for collecting water from fog. Bioinspired surfaces using conical geometry can be developed for water collection from fog for human consumption. A systematic study is presented which investigates the dynamics of water droplets on a bioinspired conical surface. A series of experiments was conducted where a known volume of droplets was deposited on the cone. This was followed by an investigation into droplet dynamics where the droplets are deposited from fog and the volume is unknown. This includes a study on the macroscopic level as well as the microscopic level. The main parameters that were varied for these tests were the tip angle and the cone orientation. The droplet movement observed was compared relatively. Based on captured videos of droplet movement, distance travelled and velocities were measured. The Laplace pressure gradient, gravity and droplet coalescence were found to be the mechanisms of droplet movement on a conical surface. The findings of this study should be of interest in designing bioinspired surfaces with high water collection.

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

1. Introduction

The cactus is one of the studied species which collect water from fog [1]. A cactus possesses small barbs located upon conical spines that assist the interception of water droplets from desert fog. Water droplets grow on the barbs and then move onto a spine, has a curvature gradient that results in a

Laplace pressure gradient. This pressure gradient within the droplet facilitates droplet movement toward the base of the spine where it can be collected by the cactus. There have been numerous attempts to create a water collector inspired by the cactus [2–8]. These studies have found that a cone or a triangular pattern is able to transport water droplets to its base because of a curvature gradient creating a Laplace pressure gradient inside of the droplets.

The Laplace pressure gradient is a force that can drive collected fog droplets against gravity. A droplet sitting upon a constant curvature surface such as a cylinder has a constant Laplace pressure of $\Delta P = 2\gamma/(r + h)$, where γ is the water–air surface tension, r is the radius of curvature and h is the height of the droplet from the centreline [1,9]. When a droplet is placed on a cone, a curvature gradient (variation of r) is introduced in the underlying surface. This results in a Laplace pressure gradient being introduced inside of the droplet. This causes droplets to move toward regions of higher radius as this decreases the average Laplace pressure inside the droplet [6].

It has been found that when collecting water from fog, other factors also play a role in droplet movement. These other factors are gravity and droplet coalescence [5,6]. The roles played by Laplace pressure gradient, gravity and coalescence need to be quantified.

In this study, measurements of distance travelled and velocities of droplets on cones were made. Two cones of 10° and 45° tip angle were chosen. Experiment conditions were varied to characterize the effects of Laplace pressure gradient, gravity and coalescence separately.

2. Experimental method

This droplet dynamics study is based on the distance travelled by the droplets and droplet velocities along the cone length. Cones of two tip angles, 10° and 45° were chosen and their length was kept constant at 15 mm. The length was kept constant to keep the travel distance constant for the droplets.

The measurements were made in two types of conditions—single droplet experiment and fog experiment. In the single droplet experiment, a droplet of known volume was placed at the very tip of the cones, with fog flow off, and measurements were made. In the fog experiment, fog flow was turned on, a single droplet was placed at the tip and measurements were made. The deposited water droplets were dyed for reliable tracking. The reason for two types of experiments was to characterize the effect of coalescence that occurs during fog flow. To characterize the effect of Laplace pressure gradient and gravity, two orientations were chosen for each type of experiment. One was sideline horizontal orientation, which was used to eliminate the effect of gravity. In this orientation, droplets are driven strictly by Laplace pressure gradient. The other orientation was centreline horizontal, which was used to characterize the effect of gravity.

In this section, the fabrication process of the cones is described. This is followed by a description of the set-up of the single droplet experiment, and a description of the set-up for the fog experiment.

(a) Fabrication and design of cone

The cones were fabricated by using a 3D printer (Objet30 Prime, Stratasys, Ltd, Eden Prairie, Minnesota). It has an accuracy of about 0.1 mm. The material used was an acrylic polymer, RGD720 [5,6].

Two tip angles were chosen: 10° and 45°. Cacti conical spines have a tip angle of 10° [2]. For comparison, a larger tip angle of 45° was also chosen. Both cones were designed with a length of 15 mm, measured from the tip of the cone to its base. The 10° tip angle cone had a surface area of about 65 mm² while the 45° tip angle cone had a surface area of around 330 mm². As a result, the larger surface area provided the 45° tip angle cone with more water nucleation sites compared to the 10° tip angle cone when the cones were exposed to fog.

The wettability of the cone surfaces was determined by creating a flat acrylic surface and measuring the contact angle. The contact angle was measured using a standard automated

goniometer (Model 290, Ramé-Hart Inc.) using 5 μl of distilled water droplets. The contact angle was averaged over five measurements at different locations and the standard deviation denoted the error bar. The hydrophilic acrylic surface has a contact angle of $61^\circ \pm 2^\circ$.

(b) Single droplet experiment

This experiment was designed to investigate the effect of tip angle and cone orientation on the movement of deposited droplets whose volume is known. Both the 10° and 45° tip angle cones were used for these tests. For the first round of tests, the cones were positioned with the sideline of the cones horizontal. The reason for this was to prevent gravity from affecting the movement of the droplets. For the second round of tests, the cones were positioned with the centreline of the cones horizontal. This was done to examine the effect of gravity on droplet movement, in addition to Laplace pressure gradient.

To start the test, a pipette was used to place a droplet at the tip of the cone. The goal was to start the droplet at the location closest to the tip. The droplet instantaneously moved to a certain distance from the cone tip and then stopped. The droplet moved due to the Laplace pressure gradient inside the droplet resulting from the underlying curvature gradient [6]. As the droplet moved away from the cone tip, the curvature of the cone beneath the droplet decreased. This decrease in curvature was believed to cause a decrease in the local Laplace pressure inside the droplet (Laplace pressure gradient). The droplet stopped after travelling a short distance because the Laplace pressure gradient was lowered enough to be in equilibrium with the adhesion force between the cone surface and the droplet [6].

The pipette was set to deliver droplets with a volume of 5 μl . This volume was chosen because a droplet must have a small enough volume to stick to the narrow tip as opposed to falling off the cone as soon as it is discharged from the pipette. When the first droplet comes to a halt, the pipette is positioned to deliver another 5 μl droplet directly into the existing droplet causing the droplets to merge together. This process is repeated until the merged droplets detach and fall off the cone. The droplets eventually fall because gravity overcomes the capillary forces at higher volumes [6]. On the sideline horizontal cones, the droplets tend to detach when their volume is increased above 40 μl .

The volume versus distance travelled by a droplet on a cone was recorded. The distance was measured from the tip of the cone to the centre of the droplet. The centre of the droplet was determined by taking the midpoint of the distance between the left edge and the right edge of the droplet. This experiment was repeated three times for each test. The average distance travelled and the standard deviations have been reported at every 10 μl increment before droplet detachment.

(c) Fog experiment

This experiment was performed to study the velocity of water droplets on cones. Figure 1 shows a schematic of the experimental set-up. A commercial humidifier was used to deliver a stream of fog onto a conical surface and a deposited droplet is observed as it travels from the tip to the base. A video camera is positioned at the same level as the cone and is orientated perpendicular to the centreline of the cone so that accurate distance measurements can be made.

The humidifier used for these tests was a PJ1011 (Mainstays). The humidifier emits fog at a speed of about 20 cm s^{-1} and was positioned 4 cm away from the tip of the cones. At this distance, the fog stream was in contact with the entire cone surface area at all times. The video camera used was the digital microscope camera (Jiusion-1000 $\times$, Jiusion). Once the camera was calibrated with the cone in focus, the picture sequences taken by the camera were used to determine distance along the cone.

The experiment was started by using a pipette to deposit a 3 μl droplet on the tip of the cone. A 3 μl droplet volume was chosen because it was the smallest possible volume that the pipette could deposit on the cone tip. A small droplet size was desired to mimic the natural water droplet size

Figure 1. Schematic of the experimental apparatus. A commercial humidifier delivers a stream of fog on a bioinspired cone kept at a distance of 4 cm. The cone is orientated with either its sideline horizontal or its centreline horizontal (centreline horizontal pictured). The velocity is determined by running a video camera level with the cone and then measuring droplet distance travelled at specific timestamped screenshots.

that forms at the tip during fog deposition. A deposited droplet is required for these tests because it allows droplet tracking at time of 0 s. Without the deposited droplet, the droplet origin position would require subjectivity to be determined. After this first droplet was deposited, the humidifier was turned on to create the fog stream.

Once the fog is on, droplets begin to form all across the entire conical surface area since the whole cone is intercepted by fog flow. The deposited droplet starts to move toward the base as it merges with other droplets deposited on the cone from the fog. When the first deposited droplet reaches the base of the cone or when it detaches from the cone, a second $3\text{ }\mu\text{l}$ droplet is immediately deposited at the tip via the pipette. This was done in an effort to keep the amount of fog formed droplets present on the cone surface similar for each test. The deposited droplets were dyed red so that they could be easily tracked as they moved along the cone and merged with other droplets. This second droplet was tracked and used for data collection. The reason for using the second droplet was to examine droplet velocity when the conical surface was already covered with droplets deposited by the fog. The second droplet data is more representative of a real-world water collection from fog scenario where droplets are continuously forming at the tip as well as on the whole surface area of a cone. This droplet test was performed eight times for each tip angle at each cone orientation to account for variation brought on by fog deposition.

The distances between the centres of the droplets from the tip of the cone were measured against time. The centre of the droplet was located by taking the midpoint of the distance between the left edge and the right edge of the droplet. Measurements were performed by using the video camera to record a video that started when the second droplet was deposited and ended when the second droplet reached the cone base or detached from the cone. This video was then reviewed, and screenshots were taken with timestamps to document droplet movement. These screenshots were then analysed by software included with the video camera to accurately determine droplet distance on the cone at certain periods of time. These time/distance data points were plotted and a second-order polynomial equation trend line was fitted to the data. The derivative of this distance equation was then calculated to determine the velocity equation. The droplet velocity at any length on the cone could be found by entering the time associated with a distance measurement into the velocity equation.

3. Results and discussion

This section presents droplet dynamics when a droplet of known volume is deposited on the cone tip. Next, the results of the fog experiment are presented and discussed. Finally, there is

Figure 2. Images showing the effect of evaporation on a 5 µl droplet placed on the tip of a 10° tip angle cone. The droplet completely evaporates after a finite amount of time.

a summary of the results of all experiments conducted. The effect of tip angle on cones of the same length and cone orientation are discussed throughout. The following experiments were conducted at about 22°C and relative humidity (RH) of 40%.

(a) Single droplet experiment

A droplet was first deposited at the cone tip and droplet increments of 5 µl were added directly to this droplet. The combined droplet moved some distance and then came to a stop. If a droplet does not move, it will evaporate in a finite time as shown in figure 2. A droplet with a volume of 5 µl completely evaporated after about 45 min. It is expected that the evaporation rate in real-world scenarios will be higher due to higher ambient temperatures, lower humidity and the presence of wind. As such, it is critical to move droplets from the tip to the base as quickly as possible so that water lost to evaporation is minimized.

(i) Sideline horizontal

Figure 3 (top left) shows the relationship between droplet volume and distance travelled by the droplet. Figure 3 (bottom left) shows images of a 10 µl, 20 µl and 40 µl droplet after they had come to a stop on the cones. The result of the sideline horizontal orientation was that droplets were driven strictly by the Laplace pressure gradient. It was found that a smaller tip angle was better for transporting a droplet further on a cone. During this test, the droplets had a velocity of zero after initial movement. It is evident from the graphs and the images that a droplet of known volume travelled further on the 10° tip angle cone compared to the 45° tip angle cone. The reason for this is that a lower tip angle cone experiences a slower rate of curvature change with length. The cone radius, r , with a tip angle, θ , at a length, l is given by the equation: $r = l \tan(\theta/2)$. Plugging this into the Laplace pressure gradient equation yields $\Delta P = 2\gamma/(r + h) = 2\gamma/(l \tan(\theta/2) + h)$, which implies that the lower rate of curvature change of a smaller tip angle cone should result in higher droplet velocity due to higher local Laplace pressure gradients over the length of the cone.

Figure 3. A controlled droplet volume experiment was conducted to evaluate the effect of Laplace pressure gradient and gravity on a single droplet over the two tip angle cones. Droplets of 5 µl were deposited at the cone tips via a pipette and the pipette was then used to deliver increments of 5 µl to the existing droplet. Distance travelled was measured at 10 µl increments. Increasing the droplet volume beyond 40 µl causes the droplet to fall due to gravity dominating the capillary forces. In the left graph, the cone is positioned with sideline horizontal, which removes the effect of gravity on droplet movement. The graphs and corresponding images show that a droplet travels further on the 10° tip angle cone due to a lower rate of curvature change. In the right graph, the cone is positioned with centreline horizontal so both gravity and Laplace pressure gradient drive the droplets. The graphs and corresponding images show that a droplet travels further on the 45° tip angle cone due to more assistance from gravity. (Online version in colour.)

(ii) Centreline horizontal

Figure 3 (top right) shows the relationship between droplet volume and distance travelled by the droplet. Figure 3 (bottom right) shows images of a 10 µl, 20 µl and 40 µl droplet after they had come to a stop on the cones. It is clear from the graphs and the images that a droplet of known volume travelled further on the 45° tip angle cone compared to the 10° tip angle cone. This is due to the 45° tip angle cone's sideline slant being 17.5° greater than the 10° tip angle cone. The result of the centreline horizontal orientation was that both the gravitational force and the force

Figure 4. The fog experiment was conducted to evaluate droplet velocity over the length of a cone. A stream of fog was directed onto the two tip angle cones positioned with sideline horizontal. Droplets of $3\ \mu\text{l}$ were deposited at the cone tips via a pipette, the fog was turned on and a video camera was used to record observations. Once the first droplet reaches the base or detaches, a second $3\ \mu\text{l}$ droplet is immediately deposited at the tip and tracked. The top graphs show the distance travelled by the droplets plotted against time for both cones. The bottom graphs show the droplet velocity plotted against distance from the tip for both cones.

due to the Laplace pressure gradient were driving droplet movement. It was found that the 45° tip angle cone was able to better leverage the gravitational assist. A droplet on the 45° tip angle cone achieved a velocity of about $0.035\ \text{mm s}^{-1}$ once its volume reached around $40\ \mu\text{l}$.

(b) Fog experiment

The fog tests were also run using two cone orientations to isolate the causes of droplet movement. The cone set-up of these experiments was identical so that all results can be properly compared later. A first droplet was deposited on the cone tip and the fog was turned on to drive droplet movement. As soon as the first droplet reached the cone base, a second droplet was deposited on the tip that was tracked for data collection.

(i) Sideline horizontal

Figure 4 (top) shows the relationship between time and distance travelled by the deposited droplet for the cones. Droplets on both cones were able to travel the full length and reach the base. It is obvious from the graphs that it takes less time to travel the same distance for a droplet on the

Figure 5. The fog experiment was conducted to evaluate droplet velocity over the length of a cone. A stream of fog was directed onto the two tip angle cones positioned with sideline horizontal. Droplets of 3 μl were deposited at the cone tips via a pipette, the fog was turned on and a video camera was used to record observations. Once the first droplet reaches the base or detaches, a second 3 μl droplet is immediately deposited at the tip and is tracked. The images show droplet position at certain time intervals for the second deposited droplet.

10° tip angle cone than a droplet on the 45° tip angle cone. This is because the Laplace gradient is lower on the 45° tip angle cone due to a higher rate of curvature increase. When comparing the two velocity graphs in figure 4 (bottom), it was observed that the 10° tip angle cone initial and final velocities were higher than that of the 45° tip angle cone. Velocity decreases with length for both cones because Laplace pressure gradient decreases with length. Figure 5 shows images of the second deposited droplet at times 0 s and 120 s. It is apparent from the images that the droplets moved faster on the 10° tip angle cone than the 45° tip angle cone by comparing the distance travelled at the 120 s mark.

(ii) Centreline horizontal

Figure 6 (top) shows the relationship between time and distance travelled by the deposited droplet for the cones. Droplets on both cones were able to travel the full length and reach the base. It appeared that droplets took similar time to travel the full distance on both cones. This was because the higher force due to Laplace pressure gradient present on the 10° tip angle cone was balanced out by the greater role of gravity present on the 45° tip angle cone. Figure 6 (bottom) displays the velocity graphs for the two cones. Again, the initial velocity of the 10° tip angle cone was higher than that of the 45° tip angle cone because of larger Laplace pressure gradient. For the 10° tip angle cone, the velocity decreases with distance because of the decreasing curvature gradient responsible the Laplace pressure gradient. However, for the 45° tip angle cone, velocity does not decrease with distance because gravity playing a larger role. This cone also benefits from larger surface area because of the additional water droplets formed on its whole surface. Figure 7 shows images of the second deposited droplet at times 0 s and 120 s. A study of the images suggested that the 10° and 45° tip angle cones had similar average droplet velocity.

Figure 6. The fog experiment was conducted to evaluate droplet velocity over the length of a cone. A stream of fog was directed onto the two tip angle cones positioned with centreline horizontal. Droplets of $3\ \mu\text{l}$ were deposited at the cone tips via a pipette, the fog was turned on and a video camera was used to record observations. Once the first droplet reaches the base or detaches, a second $3\ \mu\text{l}$ droplet is immediately deposited at the tip and tracked. The top graphs show the distance travelled by the droplets plotted against time for both cones. The bottom graphs show the droplet velocity plotted against distance from the tip for both cones.

(c) Summary

Figure 8 presents a comparison of all experiments performed to summarize the effects of all the droplet driving factors. The distance values on the charts represent the maximum distance travelled by the droplets. The velocity values represent the maximum velocity achieved by the droplets. The Laplace pressure gradient was present in all experiments. Gravity and coalescence were varied to qualitatively examine their effects on droplet movement.

In the single droplet experiment, the addition of gravity (centreline horizontal) caused further droplet travel on both cones. Without gravity (sideline horizontal), both cones experienced no droplet velocity, but with gravity, a droplet on the 45° tip achieved self-propulsion at higher droplet volumes. In the fog experiment, droplet coalescence is present for each orientation. For this experiment, the addition of gravity resulted in the same distance travelled (to base) and

distance travelled by droplet collected from fog
(initially 3 μl volume deposited)
centreline horizontal

Figure 7. The fog experiment was conducted to evaluate droplet velocity over the length of a cone. A stream of fog was directed onto the two tip angle cones positioned with centreline horizontal. Droplets of 3 μl were deposited at the cone tips via a pipette, the fog was turned on and a video camera was used to record observations. Once the first droplet reaches the base or detaches, a second 3 μl droplet is immediately deposited at the tip and tracked. The images show droplet position at certain time intervals for the second deposited droplet.

higher velocities for both cones. Comparing the fog experiment sideline tests to that of the single droplet experiment, it was found that the addition of coalescence resulted in further distance travelled (to base) and positive velocity values for both cones. Comparing the fog experiment centreline tests to that of the single droplet experiment, it was found that the addition of coalescence resulted in further distance travelled (to base) for the 10° tip angle cone. The distance travelled (to base) remained the same for the 45° tip angle cone. The velocity values for both cones were significantly increased with the addition of coalescence.

Examination of all the charts showed that all three driving factors were needed to maximize distance travelled and droplet velocity. Coalescence and gravity complement each other in the sense that coalescence causes the formation of larger droplets that in turn are affected more by gravity, resulting in higher droplet velocity.

4. Conclusion and outlook

A comprehensive study was conducted on the dynamics of water droplets on bioinspired cones. It was shown that adequate droplet velocity is needed for water collection purposes to minimize the water lost to evaporation. Upon studying droplet dynamics, the following observations were noted: cones with centreline horizontal had greater velocity over the entire length of the cone when compared to cones with sideline horizontal due to assistance from gravity. It was found that the initial droplet velocity of lower tip angle cones was always higher than that of higher tip angle cones. This is because the lower tip angle cones experience a greater Laplace pressure gradient whose magnitude appears to decrease with cone length. It was also found that droplet

Figure 8. Summary of data for all the experiments in bar chart format to examine the effect that each droplet driving factor had on the maximum distance travelled and the maximum droplet velocity. The top left charts show the results of the single droplet sideline horizontal experiment in which Laplace pressure gradient was the only force. The top right charts show the results of the single droplet centreline horizontal experiment in which Laplace pressure gradient and gravity both play a role in droplet movement. The bottom left charts show the results of the fog sideline horizontal experiment where both Laplace pressure gradient and droplet coalescence drive movement. The bottom right charts show the results of the fog centreline horizontal experiment where all three driving factors were present.

coalescence is an important mechanism for droplet movement as it was necessary for droplets to reach the cone base in certain configurations.

The information provided here is useful for developing the most efficient bioinspired water collectors. For the best results, it is important to maximize the effects of gravity and coalescence in addition to the Laplace pressure gradient inherent to the cone geometry. This can be done by using large tip angle cones orientated in a position where droplet movement is closely aligned with the direction of gravity. If a collector has a short length requirement (less than 6 mm), in which surface area difference would be smaller, it would be best to use a small tip angle cone as the experiments found that droplet velocity was dominated by Laplace pressure gradient at the tips of the cones. As before, orientating the cone to make the most use of gravity is critical for maximizing droplet velocity.

Based on the velocity graphs, it was theorized that a cone fabricated with an exponentially increasing radius (cones used here have linearly increasing radius) might be able to benefit from a high Laplace pressure gradient at its tip in addition to a high surface area for fog coalescence towards the base. This theoretical cone would ideally achieve maximum average velocity by using

the high initial velocity seen by the small tip angle cone in the experiments and the high final velocity seen by the large tip angle cone in the experiments.

Data accessibility. This article has no additional data.

Authors' contributions. C.T.S. performed the experiments and analysed the data. C.T.S. wrote the main text and C.T.S. and B.B. participated equally in planning, execution and review of the manuscript.

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