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Reducing the Contact Time of Bouncing Droplets using Macro-Textured Surfaces

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Abstract

This study was designed to investigate the possibility of using visible surface features to decrease the amount of time a droplet remains in contact with a hydrophobic surface. Hydrophobic and superhydrophobic surfaces have long been a focus for scientists studying fluids. However, a majority of studies have focused on surfaces with hydrophobic properties rooted in their chemical makeup or other features invisible to the naked eye. In this study, the contact reduction induced by a simple needle protruding from a hydrophobic surface is investigated.

Background

Figure 1 shows micro-textured surfaces, which exhibit hydrophobic, or even superhydrophobic properties. Clavijo et al described this effect in their 2013 paper [2]. This technique has its own benefits, however there are also significant drawbacks. Though the surface is superhydrophobic at low impact speeds, given enough kinetic energy, droplets may penetrate the micro-texture causing the surface to lose the desired hydrophobicity. This greatly limits the usefulness of micro-textured hydrophobic surfaces.

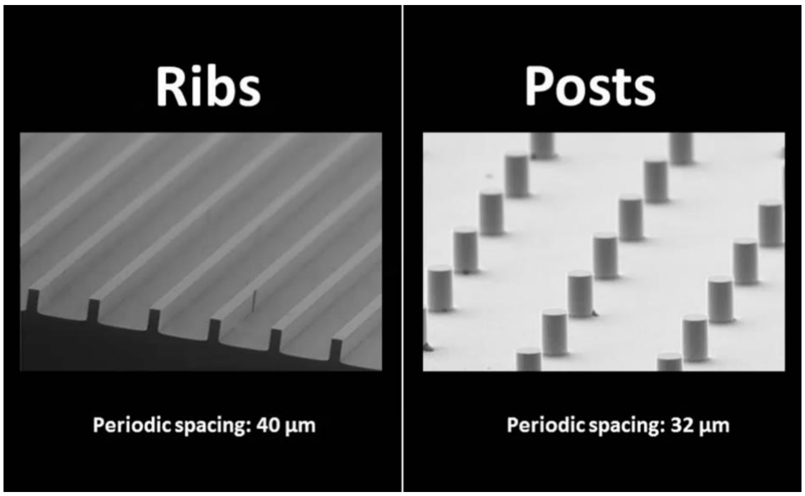


Figure 1: Different patterns of micro-textured hydrophobic surfaces. Image from Clavijo et al 2013 [2].

In 2013, James Bird et al published a study showing that a macroscopic ridge in an otherwise uniform hydrophobic surface reduced the amount of time a falling droplet remained in contact with the surface [1]. Our study expands on Bird's work and uses a needle instead of a ridge.

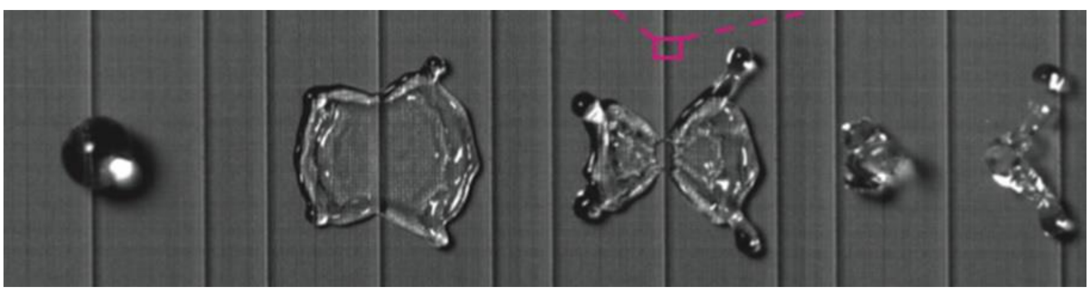


Figure 2: Stages of rebound as a droplet impinges on a ridge. Image from Bird et al 2013 [1].

Setup

Shown below is the setup used in this study.

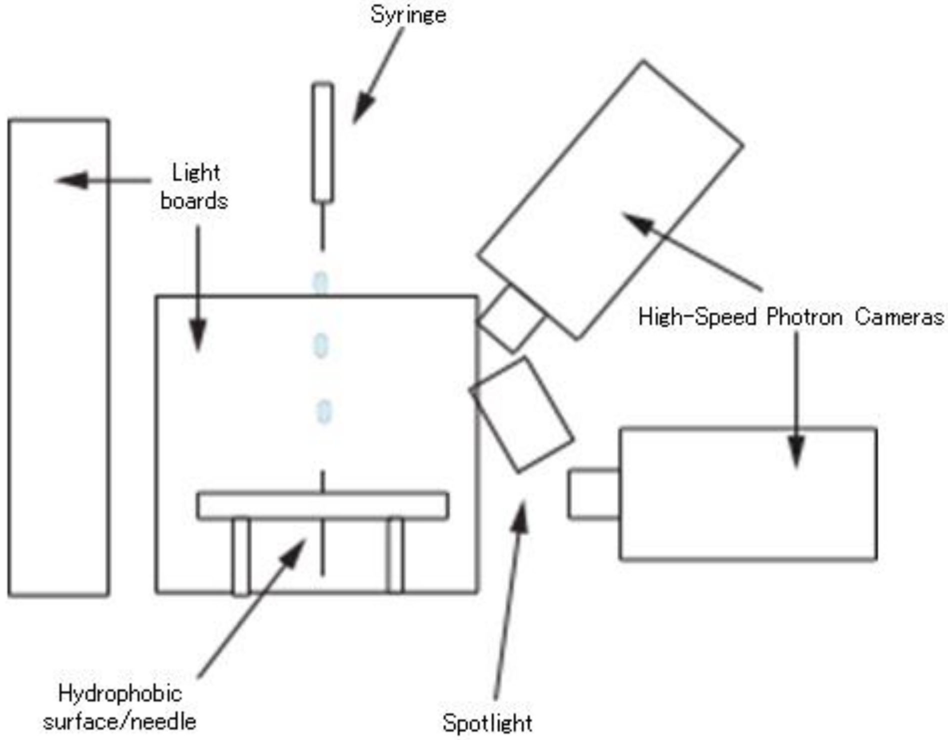


Figure 3: Three different needle sizes with base diameters of .40, 1.09, 1.55 millimeters were tested. A fourth needle with a triangular tip was also tested (diameter of 1.57 mm).

Procedure

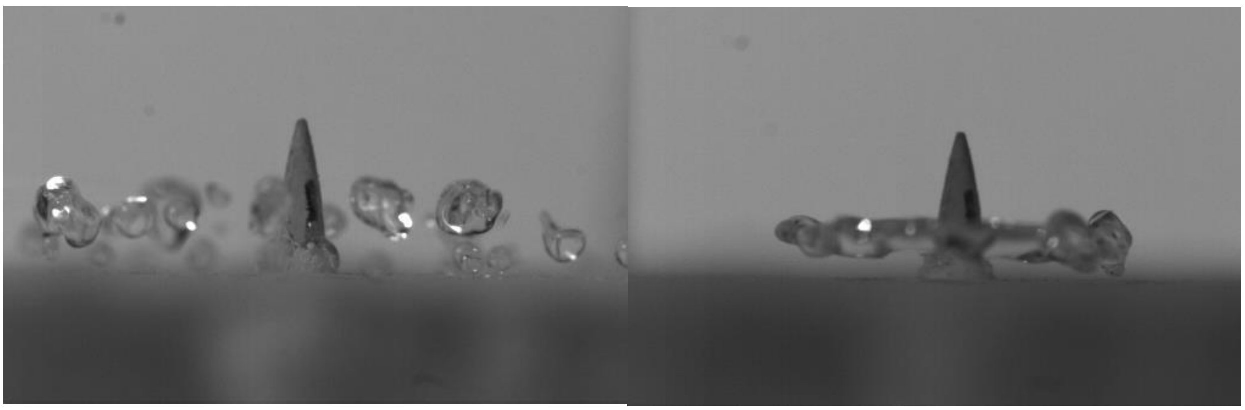
The hydrophobic surface was created using foam board. After cutting the board into the appropriate size, a needle was pushed through and set at the appropriate height. Needle heights of 1, 2, and 4 mm were investigated. Once the needles were positioned properly, the entire surface was sprayed with WX2100 in order to create a hydrophobic layer.

In order to better understand the phenomena, three different impact modes were tested. The first mode consisted of direct hits, with two additional cases in which the center of the impacting droplet fell at increasing distances from the needle. To observe the impact and rebound process, three high speed cameras were placed as shown in Figure 3, the third camera directed into the page. This gave a complete picture of what happened during impact.

The high speed footage was then analyzed. By using the shutter speed of the camera and the number of frames between impact and liftoff, total contact time was calculated. This was the primary metric for determining the effectiveness of the needles.

Interpreting Liftoff Time

Finding the liftoff frame was a simple matter at low impact speeds. However, at higher drop heights, the droplet did not coalesce, instead splitting into many smaller satellite droplets. This made it difficult to find the exact frame of liftoff, leaving some amount of subjectivity in the measurements. In order to correct for this ambiguity, a standard procedure was adopted to determine liftoff time. The frame of liftoff was defined as the frame after which the last satellite droplet left the surface. In instances where one or more satellite droplets remained in contact with the surface indefinitely, those droplets were ignored.



<u>Figure 4:</u> The frame on the left is of a droplet rebounding after falling from a height of 32 inches. The droplet has split into countless smaller droplets, some of which never fully leave the surface. On the right, the droplet fell from only 8 inches and there is a clear frame of liftoff since the droplet rebounded without splitting apart.

Results

Steps were taken to non-dimensionalize the variables being considered. For consistency's sake, the equation from Richard et al 2002 [3] for non-dimensional time was used. This is the same equation used by Bird and is shown below, with t^* being non-dimensional time, R, the droplet radius, ρ, density of water, and γ, the surface tension of water.

Equation 1:

$$\boldsymbol{t^* = \frac{t}{\tau} = \frac{t}{\sqrt{\rho R^3/\gamma}}}$$

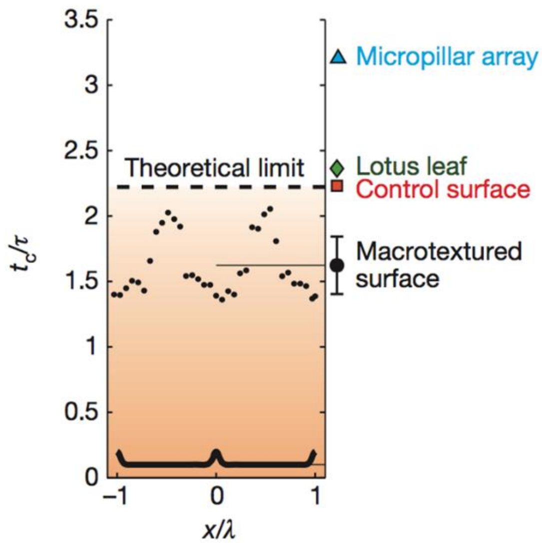


Figure 5: From Bird et al 2013 [1.] The y-axis shows non-dimensional time as obtained from Equation 1. The x-axis is non-dimensional distance, representing how far from a ridge the droplet impacted the surface. On the right is shown contact times of other comparable surfaces. Lotus leaves are naturally superhydrophobic and seen as a standard to beat.

The needles used in this study reduced the contact time in an almost identical fashion to Bird's ridges. In Bird's experiments, contact time reduction varied with the distance from the ridge. A direct impact yielded the greatest reduction of about 40%. Comparing Figures 5 and 6, it is clear that this result is matched, if not slightly exceeded by the needles.

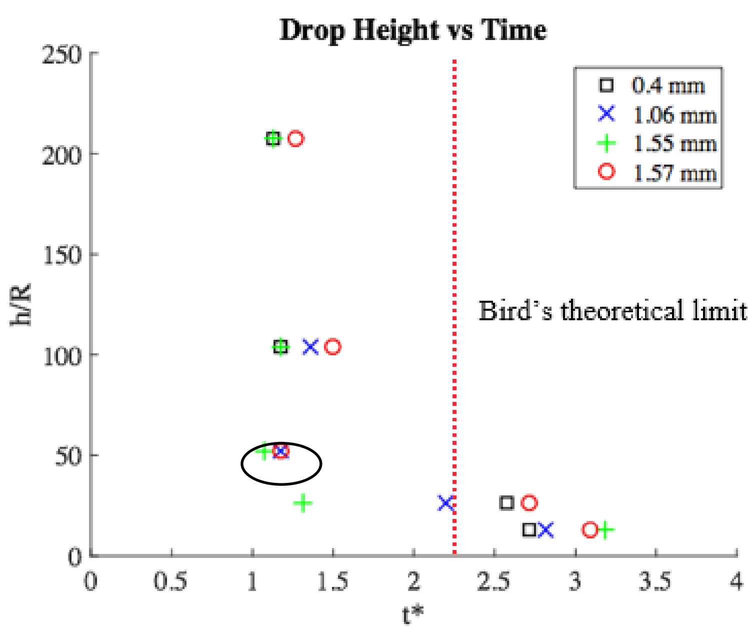


Figure 6: The y-axis shows drop height, h, non-dimensionalized using droplet diameter, R. The x-axis is non-dimensionalized time gotten from Equation 1. The different shapes depict different needle sizes. The largest needle, represented by red circles was triangular. It should be noted that each cluster of data points represents a drop height. Heights of 2, 4, 8, 16, and 32 inches were tested. The needles in this study achieved 50% contact time reduction at best.

One difference between this study and Bird's, is that Bird did not vary impact velocity. Figure 6 shows various drop heights, however, to be perfectly analogous, only droplets released from the same height as Bird's should be considered. For clarity, the points on Figure 6 which most closely replicated Bird's impact velocity have been circled. These points still fall well below the theoretical limit. The contact time reduction was comparable to Bird's.

Conclusion

Macroscopic textures and other features clearly change the way fluids interact with a surface. This study confirms that hydrophobicity does not end with chemical properties or microscopic texturing. Though several needle sizes and two different shapes were tested, every needle seemed to yield a similar reduction in contact time. Needle size and shape did not appear to significantly alter the contact time. Additionally, impact speed was critical. In future studies we hope to test droplets at or near terminal velocity. However, this possibility is limited by practicality as droplets become increasingly difficult to aim at higher drop heights.

Applications

This technology could prove useful in many different industries. In particular, it could be used to create ice-proof surfaces to mitigate damage from freezing rain or build more reliable anti-icing surfaces on airplanes. These are all instances in which micro-textured surfaces would be problematic due to the high impact speed of impinging droplets.

References

[1] Bird, James C., Rajeev Dhiman, Hyuk-Min Kwon, and Kripa K. Varanasi. “Reducing the contact time of a bouncing drop.” Nature 503. (2013): 385-388.

[2] Clavijo, Cristian, Daniel Maynes, and Julie Crockett. "Liquid Droplet Impact Dynamics on Micro-Patterned Superhydrophobic Surfaces." ArXiv.org E-Print Archive. Cornell University Library, Simons Foundation, 14 Oct. 2013. Web. 30 July 2015.

[3] Richard, Denis, Christophe Clanet, David Quéré. “Surface phenomena: Contact time of a bouncing drop.” Nature 417. (2002): 811-812.