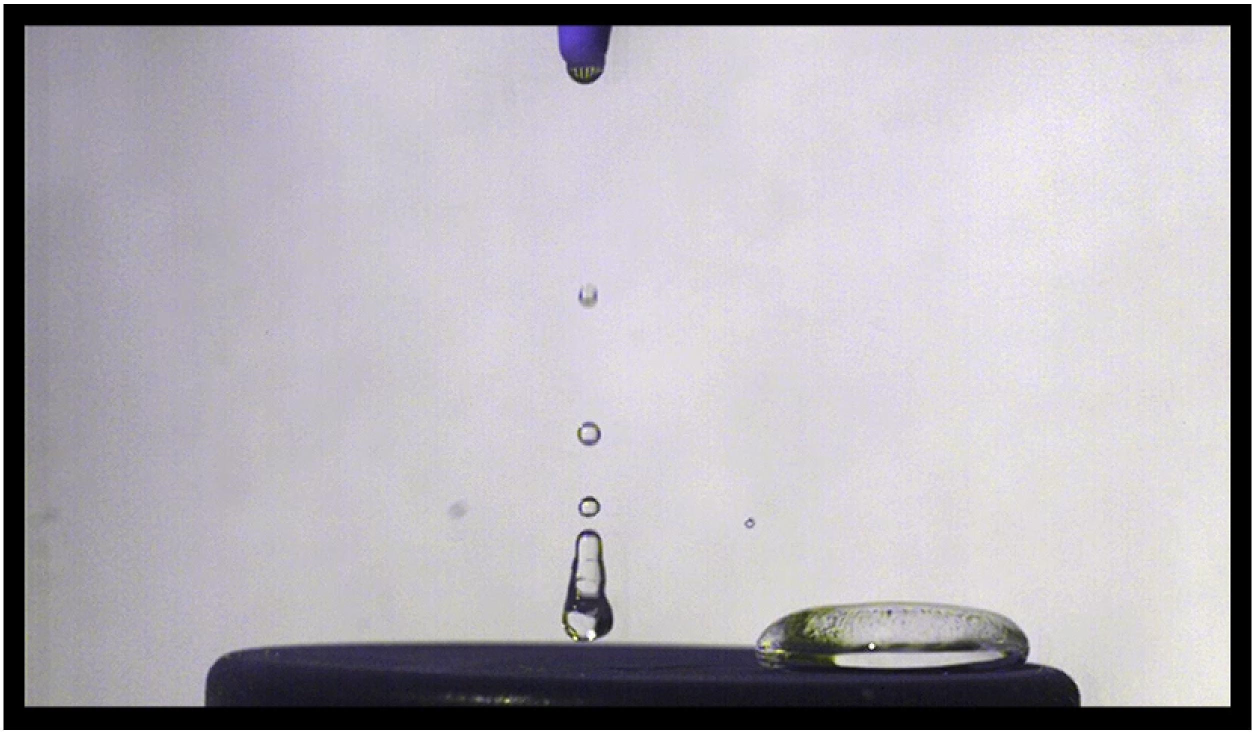
MCEN 5141: Flow Visualization

Team First



Andrew A. Van Der Volgen

1 Introduction

This project was intended to provide an opportunity for application of the techniques covered thus far in the MCEN5141 course curriculum. Its aim was to create a fluid flow indicative of an arbitrary fluid mechanic phenomena and image it effectively. The project was undertaken collectively by a group of four students who shared materials and expertise, but each student within the group produced their own unique final product. The team was comprised of Dylan Cook, Finn Ostrem, Kyle Samples, and the author.

It was ultimately decided that the group would image water interacting with superhydrophobic surfaces in order to showcase the effects of surface tension and the mechanics of hydrophobicity. This project utilized a high speed camera to capture those effects dynamically as water was dropped from height onto a superhydrophobic surface.

2 Major Materials

2.1 Superhydrophobic Coating

The most effective hydrophobic surfaces are those that are specifically engineered at micro scales to be inherently hydrophobic [4]. However, engineering a purpose built surface was beyond the scope of this project and so an acceptable alternative was found in the form of a commercially available aerosol product that can be applied to a variety of surfaces to make them artificially hydrophobic. The product, Rust-Oleum® NeverWet™, is available from most hardware stores for less than $20.

The product consists of a base-coat aerosol that serves as a surface sealant and adhesive for a proprietary silicone top-coat that imparts superhydrophobic properties to the surface on which it is applied [1]. The system is marketed as effective for application on wood, metal, concrete, PVC, fabrics, and most plastics.

2.2 Project Surface

Multiple surfaces were coated with NeverWet™ and the product performed best, by a marginal factor, on PVC. As a result, the exterior of a 76mm diameter black PVC end cap was chosen as a surface for the project. The black PVC end cap provided a high contrast surface for effective imaging and also exhibited a very slight concavity. This concavity ensured that water experiencing little to no friction against its surface would not simply roll off and out of frame.

2.3 High Speed Camera

Although a typical video camera would capture some of the unique behavior of water impinging on a surface, much of the dynamics occur on short time scales. For that reason, an Olympus I-Speed video camera was utilized in order to capture finer time resolution of the water/surface interaction.

The camera is capable of recording video at frame rates up to 1000 frames per second (fps) at its maximum resolution of 800×600. Filming at rates higher than 1000fps sacrifices video quality and, in the case of this project, captures little additional fluid flow information. As such, all video captured for this project was at 1000fps.

3 Setup and Video Capture

After treating the PVC end cap with superhydrophobic coating, the Olympus high speed camera was set up outdoors in direct sunlight on a basic photography tripod. The end cap was placed in front of the camera on a wooden stool and a plain white piece of A5 paper was placed behind the end cap in order to provide a bright, solid, background for the video. The camera was adjusted on its tripod so that the lens was at the same height as the horizontal PVC surface.

Ice water (the surface tension of water increases with decreasing temperature) was loaded into an eyedropper and several drops were deposited onto the surface of the PVC [7]. These drops were used to shim the end cap out of level with strips of paper until the water naturally collected on the right side (from the camera's perspective) of the PVC surface. The slight concavity of the end cap prevented the water from flowing off its surface despite being out of level. This created a circumstance whereby a water droplet impacting the center of the end cap would naturally flow away from the impact area to allow a clear surface for the next drop.

In this configuration video was taken of water being dropped from the eyedropper at a height of 4cm onto the center of the PVC surface. From this height the momentum of a drop impacting on the PVC was not enough to overcome surface tension effects, and the drops remained generally whole while rebounding off of the surface. After capturing several seconds (real time) worth of this behavior, the setup was reconfigured.

The strips of paper shimming the end cap were removed to level the PVC and the camera was raised on its tripod so that a 65° angle of depression was necessary to bring the end cap into frame. With this setup, video was taken of droplets dropped from a height of 15cm. From this height, water droplets impacting the end cap had enough momentum that significant portions of the drop would overcome surface tension and escape to form multiple smaller droplets.

For both configurations, video was recorded at 1000fps, 800×600 resolution, and with a f/4.2 aperture from a 25mm focal length prime lens. The field of view at the image plane for both configurations measured approximately 11×8cm.

4 Video Editing

The Olympus I-Speed camera outputs .AVI format files which were imported into Adobe Premiere Pro for editing. Individual droplet impacts that were redundant or less interesting than others were cut from the raw file to reduce run time. Premiere's *Levels* effect was utilized to adjust white levels in order to increase brightness and contrast, and the 4:3 aspect ratio of the raw video was cropped to 16:9.

Scenes showing droplets impacting from a height of 4cm were adjusted to play back at 30fps as that provided the best balance of time resolution and runtime. Portions of the video displaying impacts from 15cm were adjusted to play back at rates varying from 10-300fps in order to shorten runtime while slowing variably to provide increased time resolution where necessary.

Finally, a title screen was added to the beginning of the video and the final product was exported from Adobe Premiere to H.264 format. A side-by-side comparison of raw and edited video is shown in the frame captures below:

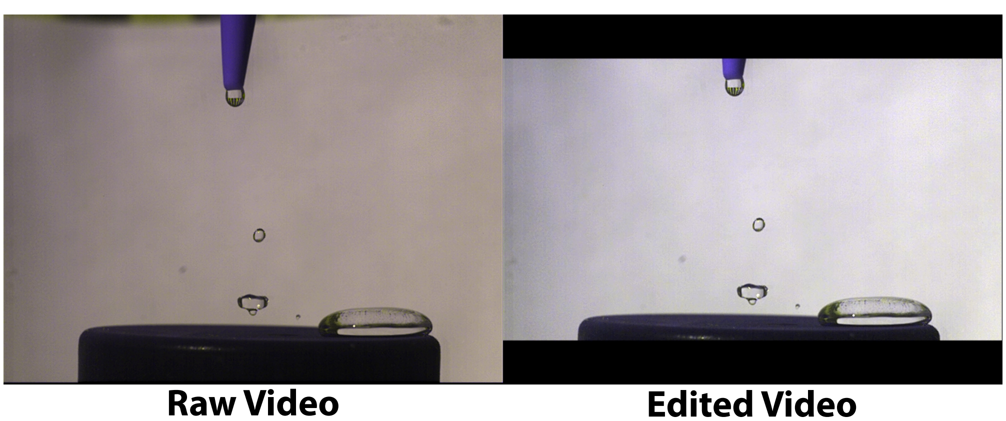


Figure 1: Video Editing Results

5 Fluid Mechanics

5.1 Superhydrophobic Surfaces

A substance's hydrophobic property is characterized by the contact angle made between the substance and a static droplet of water placed upon it as shown in Figure 2. The mechanism that governs the underlying hydrophobic property is related to Gibbs free energies of the system, which is beyond the scope of this report [5]. However, Wenzel's equation provides a relation between contact angle, surface roughness, and the interfacial energies of a system [8]:

$$\cos\theta_c = r\left(\frac{\gamma_{\mathrm{SG}} - \gamma_{\mathrm{SL}}}{\gamma_{\mathrm{LG}}}\right) \tag{1}$$

where $\gamma_{\mathrm{SG}}, \gamma_{\mathrm{SL}}, \gamma_{\mathrm{LG}}$ are interfacial energies of the solid-gas, solid-liquid, and liquid-gas boundaries, r is a roughness factor defined as the ratio of actual to projected surface area ($r = 1$ for a perfectly smooth surface, and $r > 1$ for a rough one), and θ_c is the contact angle (See Figure 2) . Substances exhibiting a contact angle $> 90^\circ$ are said to be hydrophobic.

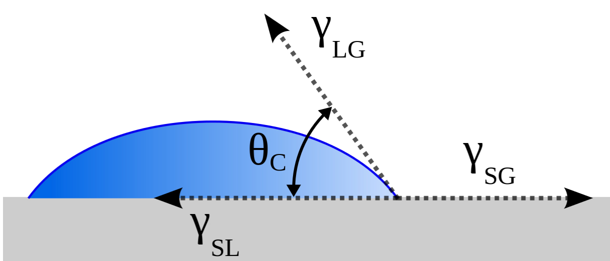


Figure 2: Contact Angle

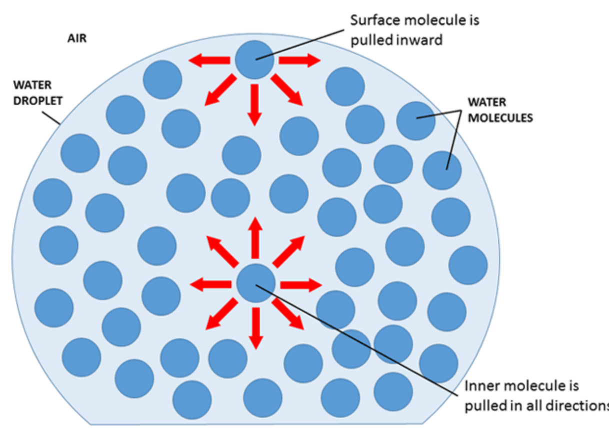


Figure 3: Surface Tension

From Equation 1 it becomes clear that a substance's contact angle can be artificially increased by introducing small scale roughness to its surface, increasing r. This yields the method by which most superhydrophobic surfaces are engineered: a substance with high hydrophobicity is used to construct a surface with micro scale roughness. If by doing so a contact angle $> 150^\circ$ is obtained, the surface is said to be superhydrophobic.

NeverWet™ is proprietary, but it utilizes a silicone based coating (silicone is inherently hydrophobic) that, by observation, clearly introduces small scale roughness to surfaces on which it is applied. This combination of inherent hydrophobicity and surface roughness limits interaction between the product and water that it comes in contact with. As a result, water's surface tension dominates the behavior of the system.

5.2 Surface Tension

Surface tension is a phenomena generated by the molecular cohesive force of a substance. In the case of water, its molecular polarity promotes hydrogen bonding between individual water molecules which results in relatively strong cohesive forces. A water molecule surrounded on all sides by other molecules will experience attractive forces in all directions, resulting in zero net force. However, a molecule at an interface is bordered only by a hemispherical region of neighboring molecules, which results in a net force on surface molecules

(Figure 3). This force compels a water droplet to contract to a minimum energy state which, in the absence of external forces, takes a spherical form [3].

In the video produced for this project, surface tension is seen competing against inertial forces to contract back to a spherical minimum energy state. These dynamics in the context of a water droplet impacting a rigid surface are fairly well studied and can be characterized by the Weber number [6]:

$$\mathrm{We} = \frac{\rho v^2 l}{\sigma} \qquad \text{where} \qquad \begin{array}{l} \rho \text{ is the density of the fluid (kg/m}^3) \\ v \text{ is its velocity (m/s)} \\ l \text{ is its characteristic length (m)} \\ \sigma \text{ is its surface tension (N/m)} \end{array} \tag{2}$$

This dimensionless parameter is a ratio of inertial to surface tension forces and is capable of predicting the characteristic behavior of a liquid droplet as it impinges on a surface. When $\mathrm{We} \approx 4$, waves form in the drop at impact but the drop remains intact. At $\mathrm{We} \approx 18$ a drop rebounds into a highly elongated vertical shape and smaller droplets escape from the bulk of the fluid. At $\mathrm{We} \gtrsim 120$, a droplet exhibits *corona splash* behavior and many satellite drops break off from the bulk fluid during impact spreading or surface tension driven retraction [2]. Each of these behaviors is evident in the project video.

5.3 Calculation of Applicable Weber Numbers

Water droplets in the video impacting from 4cm height had a characteristic Weber number [7]:

$$\mathrm{We} \approx \frac{(1000\frac{\mathrm{kg}}{\mathrm{m}^3})(0.875\frac{\mathrm{m}}{\mathrm{s}})^2(0.00476\mathrm{m})}{0.07495\frac{\mathrm{N}}{\mathrm{m}}} \approx 49$$

and from 15cm height:

$$\mathrm{We} \approx \frac{(1000\frac{\mathrm{kg}}{\mathrm{m}^3})(1.70\frac{\mathrm{m}}{\mathrm{s}})^2(0.00476\mathrm{m})}{0.07495\frac{\mathrm{N}}{\mathrm{m}}} \approx 185$$

The very small secondary droplets released from the eyedropper at 4cm have a Weber number:

$$\mathrm{We} \approx \frac{(1000\frac{\mathrm{kg}}{\mathrm{m}^3})(0.875\frac{\mathrm{m}}{\mathrm{s}})^2(7.94 \times 10^{-4}\mathrm{m})}{0.07495\frac{\mathrm{N}}{\mathrm{m}}} \approx 8$$

In each of these cases respective droplets exhibited the characteristic behavior predicted by the Weber number, which was made evident through high-speed photography. It should be noted that empirical evidence shows a reduction in Weber number characteristic transition thresholds when drops impinge on superhydrophobic rather than traditional surfaces. However, the effect has been shown to be negligible for Weber numbers $\lesssim 120$ and having only a marginal effect at ≈ 185 [6].

6 Conclusion

The Olympus I-Speed camera utilizes decade-old technology which makes filming with it time consuming and inconvenient. Its relatively small amount of internal memory prevents filming 'long' duration events, and yet, off-board transfer of the data stored in memory takes significant time due to outdated data transfer methods. It is also less light sensitive than current technologies which makes obtaining proper exposure during filming a serious concern. Nevertheless, if patient, the camera is capable of capturing high-speed events effectively and the resultant video can highlight dynamics not otherwise discernible in real time. The video produced for this project accomplishes that end for water droplets impinging on a rigid surface and the inclusion of superhydrophobicity creates visual appeal due to the novelty of the phenomena.

References

[1] Rust-Oleum Corporation. Material Safety Data Sheet: NeverWet Base/Topcoat. Technical report, Rust-Oleum Corporation, 2014.

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