# Team First Report

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## Context

This image demonstrates the cavitation and crown ripples formed when a droplet impacts both a pool of milk and a pool of water. This effect was accomplished through the use of a “DropSplash” apparatus designed and built by Kyle Hollis and Kyle Walters, two CU students, as in Independent Study project for the Flow Visualization course. The primary purpose of this apparatus is to release two drops of liquid in close succession, and to capture both the Worthington Jet of the first drop, and the collision between this jet and the second falling drop. I chose to instead focus on the physical interactions on only a single drop for my image.

## Flow Analysis

This flow was created through the initial cavitation effect that occurs when something is dropped into a pool of liquid. This action creates a divot in the pool of liquid that is quickly refilled. Subsequently, this rapid infill of water is what results in Worthington Jets. The image was backlit using two flashes with diffusers attached, as well as a flat diffuser in the water to further diffuse the flash. To ensure the sharpness and focus needed in this image the ISO was kept low and the lens used had a good zoom. To ensure consistent images the cameral was attached to a small tripod. The camera itself was situated roughly 1.5 feet away from the apparatus. The water is fed from a reservoir into a thin tube then into the solenoid valves used to regulate the drop flow. When these valves are released, the water droplets fall a certain distance into a small cup filled with either milk or water. This cup was also in a small cake dish filled with water that was used during calibration and testing. The setup for this experiment is outlined in Figure 1.

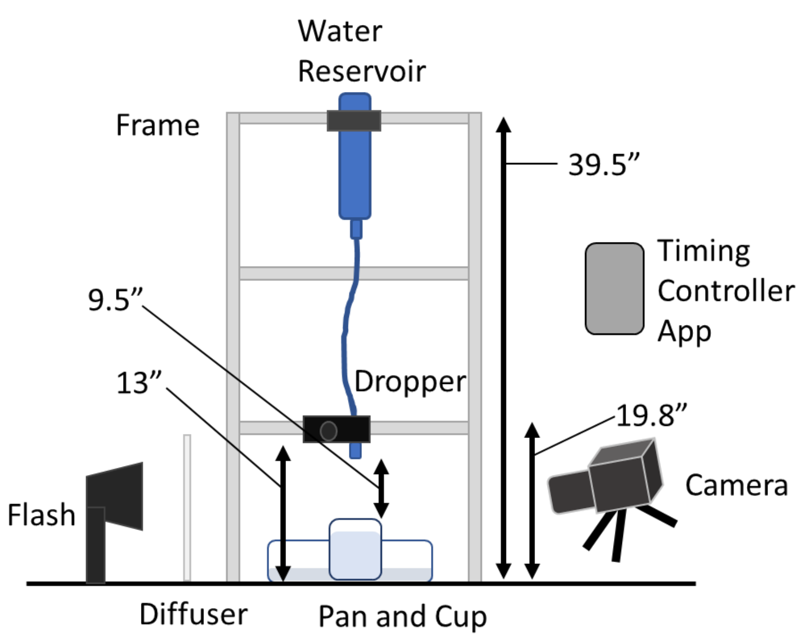


*Figure 1: Experimental Setup*

The apparatus used in this experiment included an Android App called ‘dropControllerBT’ which allowed for the control of drop, flash, and camera shutter timing. This app connected with the ‘Project Box’ which consisted of an Arduino to actually control all the timing[1]. Our actual setup can be seen in Figure 2.

*Figure 2: Actual Setup*

The flow pictured is the cavitation that is formed when a drop collides with a pool of liquid. As the splash of the droplet spreads out, the surface tension of this liquid pulls it back together into small filaments and droplets. These filaments, or ‘crowns’, can be observed in my image. The true cause of these crowns, and the ring that causes them is still in slight contention, but the filaments themselves are formed due to a Plateau-Rayleigh instability[2]. This instability is driven by the surface area of the liquid. When a stream of liquid is ejected as a vertical column, small variations create instabilities in the flow’s surface area that gradually tighten the radius of the flow at specific intervals until they are cut off entirely and separate into individual drops. This effect can be easily observed in the water that leaves a faucet at low flow rates, as seen in Figure 3.

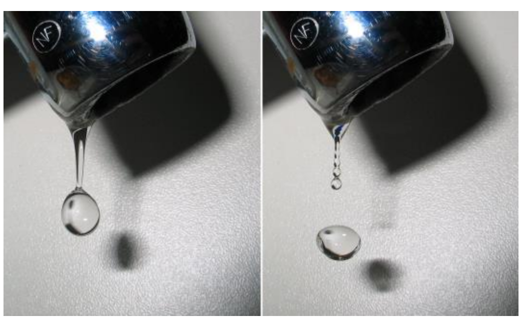

*Figure 3: Plateau-Rayleigh Instability demonstrated by dripping faucet[3]*

This phenomenon is not a new discovery, it has been known of for over a century, and the first time it was photographed was in 1908 by Arthur Mason Worthington[4], of whom the Worthington Jet was named after.

To better grasp the physics behind this cavitation and splash, the best method to use is to calculate the Weber Number. This dimensionless value denotes the

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[1] Hollis, K., & Walters, K. (2016). Project DropSplash [Scholarly project]. In Flowvis.org. Retrieved from http://www.flowvis.org/wp-content/uploads/2018/01/DropSplash-QuickStart-and-Documenation.pdf
[2] F. (2013, December 02). Fuckyeahfluiddynamics. Retrieved February 28, 2018, from http://fyfluiddynamics.com/post/68785232957/when-a-water-drop-strikes-a-pool-it-can-form-a
[3] McLassus, Roger. “Detaching Drop.” Wikipedia, 21 Jan. 2006, commons.wikimedia.org/wiki/File:2006-01-21_Detaching_drop.jpg.
[4] Worthington, A. M. (1908). Study of splashes. Devonport: The Royal Naval Engineering College.

ratio between the inertial force and the surface tension force between two different liquids and indicates whether the kinetic or surface tension energy is dominant. This value is expressed through the equation

$$W_e = \frac{\rho v^2 l}{\delta}.[5]$$

In this equation $\rho$ is the liquid density, *v* is the velocity of the drop at impact, *l* is the characteristic length, and $\delta$ is the surface tension. In this case, we know the density of water to be $1000\ \frac{kg}{m^3}$. The droplet velocity is found though the equation $v = \sqrt{2gh}$, where g is $9.81\ \frac{m}{s}$, and h is the distance between the dropper nozzle and the liquid pool. Using the experimental setup in Figure 1 we know this to be 9.5 inches, or $0.2143\ m$. Inputting these values, $v = \sqrt{2gh} = \sqrt{2 * (9.81\ \frac{m}{s})(0.2413\ m)} = 2.175\ \frac{m}{s}$. The characteristic length is given as the diameter of the drop, which is assumed to be roughly 0.5 cm. Finally, the surface tension at room temperature is found through a value table to be $7.28 * 10^{-2}\ \frac{N}{m}$.[6] Putting all these values together, we find

$$W_e = \frac{\left(1000\,\frac{kg}{m^3}\right)\left(2.175\,\frac{m}{s}\right)^2 (0.5\ cm)}{7.28*10^{-2}\,\frac{N}{m}} = 325.$$

When analyzing the Weber number, we can classify the droplets into three primary phenomena: “The drop ‘bounces’ then ‘floats’ on the surface of the pool, the drop ‘coalesces’ into the pool, or the drop ‘splashes’ onto the pool, creating a ‘crown’ around a crater”.[7] The threshold for this crowning splash is known to be above roughly 84. Comparing this to this experiment’s calculated Weber number it is clear to see that my team’s DropSplash setup resulted in crowning splash phenomena.

Another relevant value that can be examined is the Reynolds number of the flow. This value is related to the turbulence of the flow, and is calculated through the equation $Re = \frac{v*l}{\upsilon}$.

Both *v* and *l* were already calculated, and assuming viscosity, $\upsilon = 1.6438 * 10^{-6}\,\frac{m^2}{sec}$, *Re* is calculated as

$$Re = \frac{v*L}{\upsilon} = \frac{2.175\,\frac{m}{sec}*0.5cm}{1.6438*10^{-6}\frac{m^2}{sec}} = 6616.$$

A flow is considered turbulent at an Re greater than 20,000, so the flow in this experiment was well in the laminar flow region. This observation is also reflected in the regular droplets that my team saw during experimentation and testing during the setup for this experiment.

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[5] (n.d.). Retrieved February 28, 2018, from https://www.engineeringtoolbox.com/weber-number-d_583.html

[6] (n.d.). Retrieved February 28, 2018, from https://www.engineeringtoolbox.com/water-surface-tension-d_597.html

[7] When a drop of water falls into water, where do the splashes come from? (n.d.). Retrieved February 28, 2018, from https://physics.stackexchange.com/questions/156339/when-a-drop-of-water-falls-into-water-where-do-the-splashes-come-from

## Setup

To create this image the only materials used were tap water with regular blue food dye added to it, a cake pan filled with this same tap water, one blue mug also filled with this water, and finally a red mug filled with whole milk. Two flashes were hooked up behind a diffuser to backlight the pool of water, and a camera was provided to us to capture the images. The image was taken in a standard room temperature room, at a standard Colorado level of humidity. The water was also roughly room temperature. The images were taken in a closed room with all the lights turned off.

## Photographic Technique

To take this image, many the camera's settings were suggested to us in the 'DropSplash QuickStart and Documentation' report. We used a zooming lens about a foot and a half away from the dropping. The photos were at an aperture of f/16, a shutter speed of ½ sec, and an ISO of 200. We used a Nikon D700 to capture the images. The flash, shutter, and droplet release timing were all controlled through an App as previously mentioned, and an example of the setting used can be found in Figure 4.

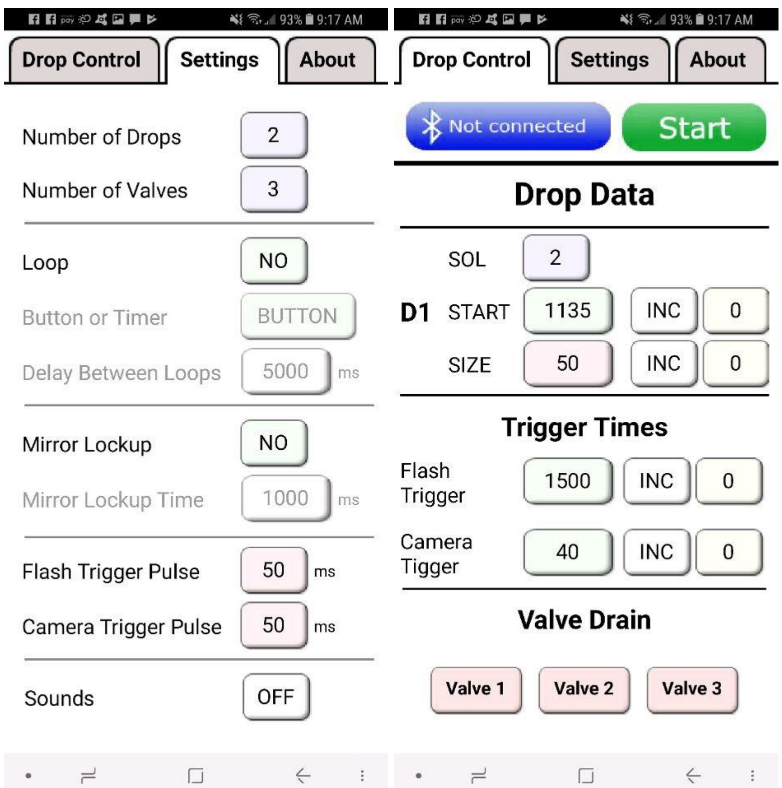


*Figure 4: App Droplet Timing Configuration*

The initial images pixel sizes were both 4256x2832, and the final combined image was 6461x1993.

For post-processing, I exported the image to Adobe Lightroom 6. Because I decided to do a comparison and was not confident in my ability to equally color balance both photos the most editing I did to each image was some cropping to better focus on the flow, and putting both images into one. Even so, the act of cropping did adjust to color distribution of each image. A comparison between the colors can be seen in Figure 5.

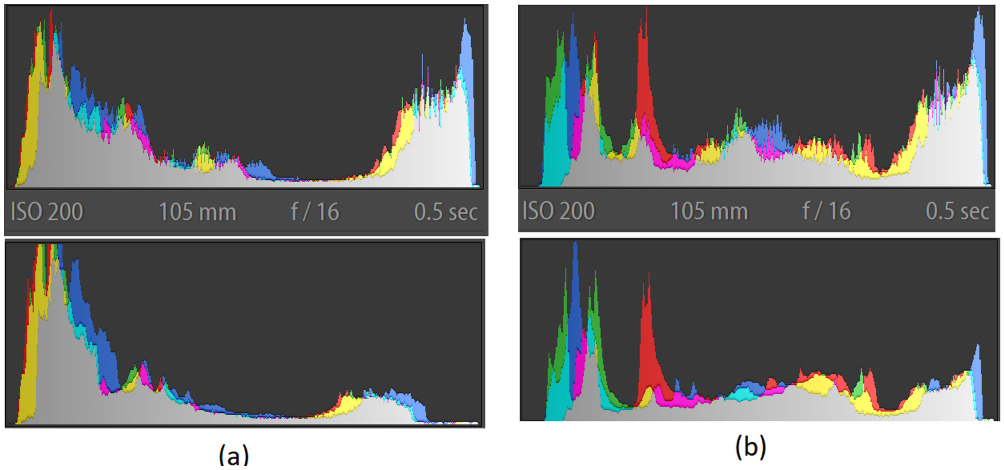


*Figure 5: Histogram comparison of before and after cropping. (a) is water and (b) is milk*

A comparison between the initial and final images can be seen in Figure 6.

*Figure 6: Before and After Images*

## Conclusion

This image demonstrates the crowning due to a high velocity low viscosity droplet impact onto a pool of liquid. The flow is laminar, and the crowning effect is the result of a Plateau-Rayleigh instability. I like how the image is well focused, and how both the milk and water offer different ways to see the flow and the food dye in the water. I think I could have used a lighter colored mug for the water because I think it is a bit difficult to see what is happening. I would also like to adjust the background and amount of flash, because in the water image you can see a bit of smudge that was created because the flashes were too close and bright. I think this image shows the fluid physics very well, and the comparison helps the audience spot the differences and similarities in the respective flows. If I was to develop this further I would like to shoot a video of this flow with a high definition slow motion camera to better grasp the droplet flow interactions. I would also like to try experimenting with other liquids and colors to see what type of splashes I could get.