Team First Report - Flow Visualization

Wesley Caruso

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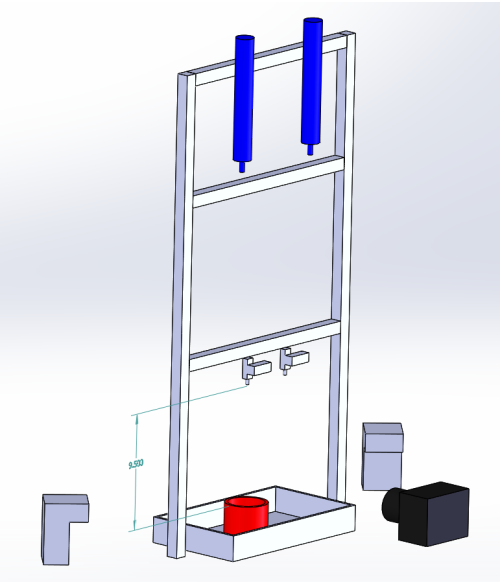
Figure 1: Final Image

1 Introduction

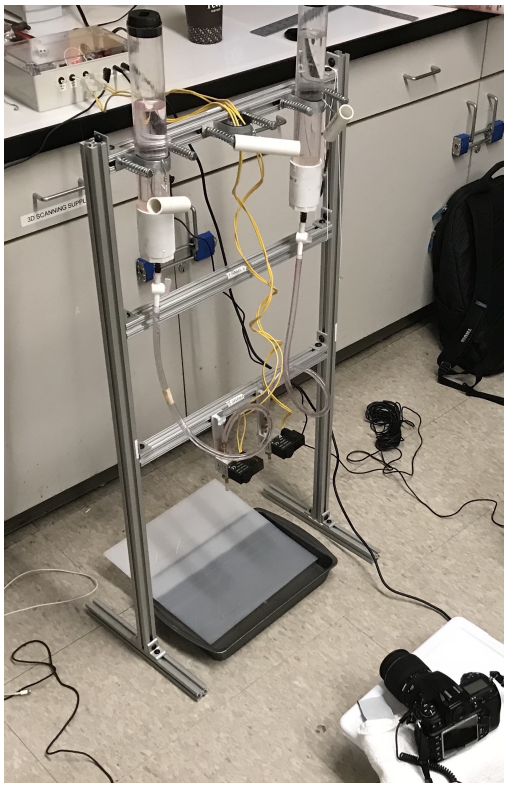
The image shown in Figure 1 was taken for the first team assignment in the MCEN-5151 Flow visualization course at CU Boulder. The purpose of this team assignment was to observe a real world flow and photograph its effects during experimentation. For this assignment, our team chose to examine two drops smashing into each other using a Drop Smasher apparatus. The intent of this image was to capture the Worthington jet phenomenon during the occurrence of two drops smashing into each other.

2 Flow Apparatus setup

The flow apparatus, Figure 2, was a drop smasher built by Kyle Hollis and Kyle Walters in 2016, as an independent study project for Flow Visualization [5]. This apparatus used electronic circuitry and actuators to control the timing of a drop via a Bluetooth app to trigger the flash and shutter of the camera. Without this electronically controlled timing, it would have been extremely difficult to capture the exact instance of this collision. The apparatus frame was constructed out of 8020 single slotted aluminum extrusion and contains a tank for storing the fluid connected to a electronic actuator to release the drops. For the focus of this experiment, a red coffee cup with a channel diameter of 0.089 meters was placed below the drop valve. The drops used in this final image were found to have an approximate diameter of 0.0035 meters when released from the valve.



(a) Modeled Setup



(b) Actual Setup

Figure 2: Modeled apparatus and actual setup

The flow from this experiment is described by the following actions. First, a drop from the valve was released from a height of 9.5 inches resulting in the Worthington jet seen in Figure 1. The milk had a surface tension of $0.0539\frac{N}{m}$ at 10 degrees Celsius as calculated in Equation 1 [1]. When the drop impacted the milk surface at $2.175\frac{m}{s}$, Equation 2, it broke the surface tension dragging the surface down, and formed a cavity as a result. When the water droplet reached maximum depth, the kinetic energy used to initially break the surface was converted into an upward force and created a Worthington jet [4].

$$\sigma_{milk} = 1.8 * 10^{-4}(T^2) - 0.163(T) + 55.6 = 0.0539\frac{N}{m} \tag{1}$$

The cylindrical cavity formed under the milk's surface eventually turning into a hemispherical crater where the initial drop deformed and lined the walls. A crown can form above the cavity if the Weber number is greater than 180, which happened prior to the instant the image was taken. When the crown subsided and the crater began to collapse, the Worthington jet formed as the upward force expelled it from the crater [6]. The threshold for a satellite drop to break off from the Worthington jet occurs when the Weber number goes beyond 84, resulting in the collision with the second falling drop, and an upward umbrella shape featured in Figure 1.

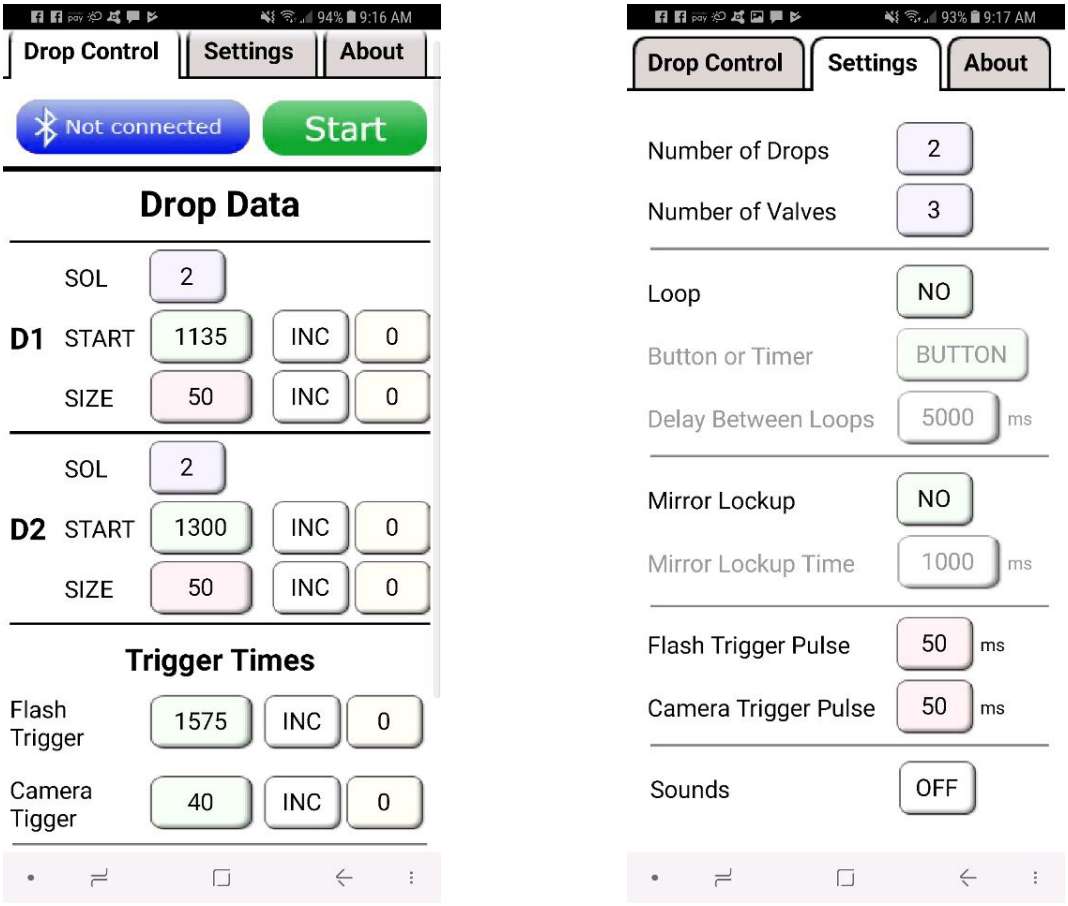
$$v = \sqrt{2(d)(g)} = \sqrt{(2)(0.2413m)(9.81\frac{m}{s^2})} = 2.175\frac{m}{s} \tag{2}$$

The Weber number in Equation 3 compares the kinetic and surface energies of the drop impact. For an increasing Weber number, the larger the deformation during drop impact becomes. "The threshold for a drop to detach at the top of the jet was reported to be $W_e = 84$," and "a crown is formed only if $W_e > 180$" [3]. Thus the value from the experiment is well beyond the threshold and the latter stages of these actions are shown in the final image.

$$W_e = \frac{\rho(v^2)(l)}{\sigma} = \frac{(1000\frac{kg}{m^3})(4.7306(\frac{m}{s})^2)(0.0035m)}{0.0539\frac{N}{m}} = 307.182 \tag{3}$$

3 Visualization Technique

The visualization technique was created by using milk as the base liquid in the red coffee cup in order to provide a better contrast for the droplets to fall into. The fluid being dropped from the actuator was water containing a diluted solution of McCormick blue food coloring. The two fluids blend nicely together due to the extreme difference in the blue and white colors. For lighting, the experiment was setup in a dark room to ensure that no additional light other than the flash would be exposed to the image. The artificial lights used for this setup were two Nikon SB AF speedlight flashes that were connected to the main control unit of the dropsplash apparatus. The flashes were triggered by user set timings configured in the drop controller Bluetooth application as shown below in Figure 3 [2].



(a) Drop Data Settings

(b) Drop Controller Settings

Figure 3: Drop Controller BT Application Settings

4 Photographic Technique

The photographic technique used was heavily reliant on the apparatus setup. A Nikon D70 camera was used with a 105.0 mm lens to capture the flow because it was equipped with a port that can be used for electronic triggering and a high enough resolution to visualize all the details in the fluids. The Nikon D70 was

connected to the electronic trigger system via the remote trigger port on the camera in order to efficiently take a picture at the exact instant desired to capture the drops colliding. The size of the field of view was set to capture just beyond the exterior of the cup where the drop was falling into, about 4 inches. The distance from the object to the lens was 18 inches at a focal length of 105.0 mm with a f/16 aperture. The camera was set at ISO 200 and a shutter speed of 1/2 second in order to capture the desired motion of the drop. The original image was taken at 4256 by 2832 pixels in RAW format to ensure loss-less compression of data. The final image was then cropped to 4256 by 1867 pixels and edited in Photoshop using the clone tool to remove miscellaneous background glare and extraneous drops that were present from splashes during collision. Comparison of the original and final image is shown in Figure 4 and Figure 1.

Figure 4: Original Image

5 Image Revelation

This image reveals the interesting phenomenon of a satellite drop from a Worthington jet colliding with a second falling drop, resulting in a umbrella formation. The most appealing aspect of this image is how from observation it is possible to visualize the various sequential motions of the flow which are described in the second section. Varying aspects of this experiment could provide interesting results if a third drop was added to the setup, although it might diminish the effect of the first two drops colliding. Another possible improvement to develop this idea further would be using the second actuator to release multiple drops next to each other. Overall, this image demonstrates the effects of water drops colliding in mid-air and the creation of a Worthington jet.

References

[1] A. Bertsch. "Surface tension of whole and skim-milk between 18 and 135 C". In: *Journal of Dairy Research* 50.3 (1984), pp. 259–267. DOI: 10.1017/S0022029900023098.

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[4] S. Gekle and J. Gordillo. "Generation and breakup of Worthington jets after cavity collapse. Part 1. Jet formation". In: *Journal of Fluid Mechanics* 663 (2010), pp. 293–330. DOI: 10.1017/S0022112010003526.

[5] Kyle Hollis and Kyle Walters. *Project Dropsplash: Full Documentation And Quickstart Guide*. URL: http://www.flowvis.org/wp-content/uploads/2018/01/DropSplash-QuickStart-and-Documenation.pdf.

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