Image/Video 2 Report

MCEN 5151

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1 Introduction

For this assignment I wanted to capture an image of the crown instability which occurs as part of the drop-splash problem. In fluids research these types of drop-splash problems aren't well understood, so I wanted to dive into the physics and understand why that is. I also wanted to capture an artistic image of the phenomenon.

2 Apparatus

To produce this instability, tap water, red food dye, and corn starch were mixed together in a large glass bowl. The bowl was placed on a white bed sheet on top of a dining table to help lighten the image. The bowl was illuminated using an LED flashlight and an iPhone XR light. The flashlight was placed against the left side of the bowl and the iPhone light was placed at the back of the bowl. The camera was mounted on a tripod on the floor in front of the table about 6 inches away. To create a droplet, a pipette was used to drop the liquid back into the bowl. Below are schematic diagrams of the setup as well as a photo.

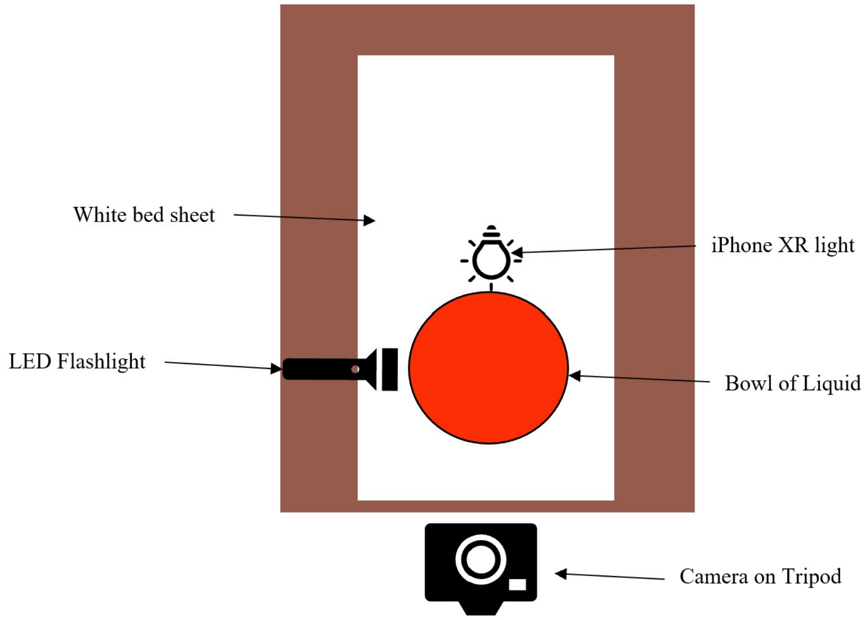

Figure 1: Diagram of experimental setup from above.

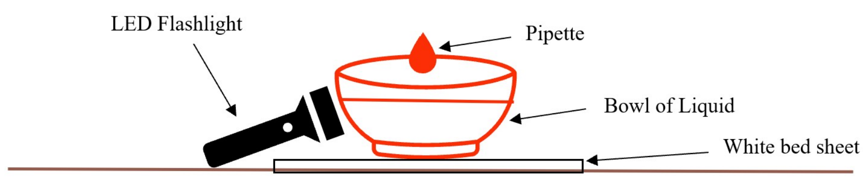

Figure 2: Diagram of experimental setup from plane view.

Figure 3: Photo of experimental setup without the iPhone XR light.

3 Physics Explanation

The crown instability is part of a larger class of problems. These problems are collectively called drop-splash problems. This class of problems begins when a droplet impacts a liquid surface [1]. The three main steps of a drop-splash problem are illustrated below in figure 4, which was taken from reference [3]. The three main steps are inertia-dominated impact, formation of ejecta, and crown evolution. This study mainly focused on the third step which lends to the crown instability.

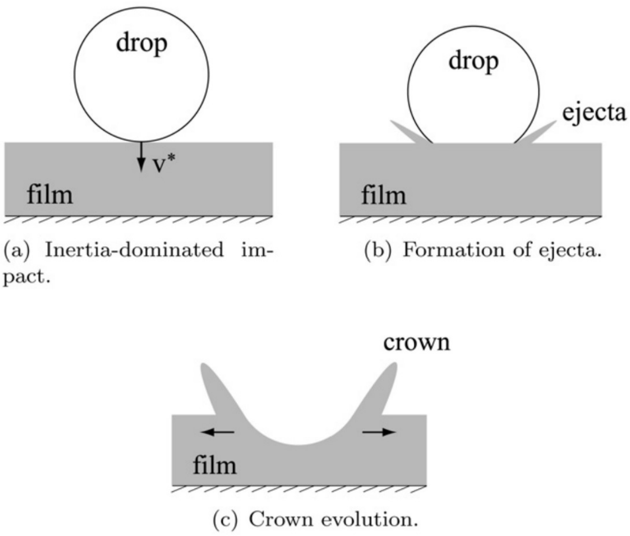

Figure 4: Thee key elements of the drop splash problem. See reference [3].

The governing equations of a liquid-liquid impact are the Navier-Stokes equation (1) and the continuity equation (2) [2].

$$\rho(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u}) = -\nabla p + \rho \mathbf{g} + \mu \nabla^2 \mathbf{u} \tag{1}$$

$$\nabla \cdot \mathbf{u} = 0 \tag{2}$$

We must also consider the surface tension forces. These forces are necessary to balance the stresses at the free surface [2]. In this case, the free surface is the liquid in the bowl. This balance can be expressed by equation (3) and shown in figure 5.

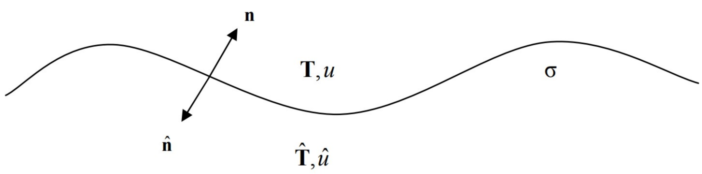

Figure 5: Schematic of surface tension force balance. Variables with carats represent properties of the lower fluid. See reference [2].

$$\mathbf{n} \cdot \mathbf{T} \cdot \mathbf{n} - \mathbf{n} \cdot \hat{\mathbf{T}} \cdot \mathbf{n} = \sigma(\nabla \cdot \mathbf{n}) \tag{3}$$

$\mathbf{T}$ is the stress tensor, while $\mathbf{n}$ represents the normal vectors as indicated by figure 5. σ is the surface tension value. It is important to note that this is a slight simplification in the complexity of this problem since we are only considering normal forces [2].

Due to the complexity of these governing equations, it is more useful to look at some dimensionless values such as the Reynolds number, the Froude number and Weber number [2]. These are defined as:

$$Re = \frac{\rho U L}{\mu} = \frac{Inertia}{Viscosity} \tag{4}$$

$$Fr = \frac{U^2}{gL} = \frac{Inertia}{Gravity} \tag{5}$$

$$We = \frac{\rho U^2 L}{\sigma} = \frac{Inertia}{SurfaceTension} \tag{6}$$

These dimensionless parameters aid in understanding which types of forces are more important in this interaction. The liquid used for this experiment was composed of water, food dye and cornstarch. Since the main ingredient in food dye is water and the ratio of cornstarch to water is small, it is reasonable to assume a complete water make-up. We will also assume the water was at 20 degrees Celsius (room temperature). Assume that the density ρ, viscosity μ and surface tension σ are those standard of water at 20 degrees Celsius. These values are tabulated below. U, which is the velocity of the droplet can be calculated by $U = gt$ where t is the fall time and g is the acceleration due to gravity. t is approximately 0.01 seconds, while $g = 9.8 \frac{m}{s^2}$ so the velocity is estimated at 0.098 $\frac{m}{s}$. L is the characteristic length, which is typically defined as the diameter of the droplet [1]. This will be estimated as 2 mm. Tabulated estimates of the variables for equations 4 through 6 are presented below.

Variable	Value	Units
ρ	997	$\frac{kg}{m^3}$
U	0.098	$\frac{m}{s}$
L	2	mm
μ	1.0016	mPa
g	9.8	$\frac{m}{s^2}$
σ	72	$\frac{mN}{m}$

Plugging the values from the above table into equations 4 through 6 yields:

$$Re = \frac{\rho U L}{\mu} = 195.10 \tag{7}$$

$$Fr = \frac{U^2}{gL} = 0.49 \tag{8}$$

$$We = \frac{\rho U^2 L}{\sigma} = 0.27 \tag{9}$$

From the analysis of the Reynolds number, we can conclude that Inertial forces dominate. From the Froude number, we see that gravity dominates. Finally, from the Weber number we see that Surface Tension dominates. This is consistent with what we expect since water is a low viscosity fluid with relatively high surface tension and the main force arises from a free-fall impact.

4 Visualization Technique

To help capture this image, cornstarch was added to the water to reduce the glare and transparency of the mixture. I added 2 teaspoons of cornstarch to 2 L of tap water, which made the liquid much more opaque. To color the liquid, I used 6 drops of Kroger's red food dye.

5 Photographic Technique

Below is a table summarizing the camera settings used for this image. The phenomenon was extremely fast so a quick shutter speed was necessary. The photos from this experiment were also shot in continuous mode in order to capture the different formations over time. The flash on the camera was not utilized as this created a large glare in the image.

Property	Value
Shutter Speed	1/3200 sec
Focal Length	55 mm
ISO	1600
Aperture	f/5.6
Pixels	6000 x 4000

5.1 Post Processing

To exaggerate the focus of the image, it was cropped around the instability. The brightness and saturation were also increased. By cropping out some of the brightness from the LED flashlight at the left of the image, I was also able to adjust the levels to better define the shadows and highlights. Below is the original image as well as the image after post processing.

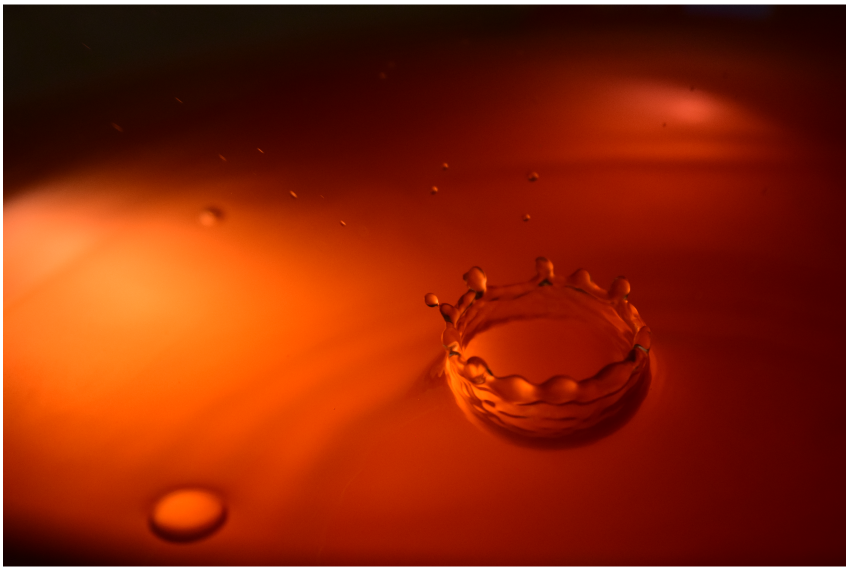

Figure 6: Original image without edits.

Figure 7: Final image including edits.

6 Final Thoughts

This image successfully captured the crown instability. Upon further research, a seemingly simplistic phenomenon was revealed to be quite complex. The fluid dynamics to accurately describe this phenomenon is very involved. As for the photo, I'm very proud of the lighting in this image. The use of multiple light sources helped to draw the eye towards the instability. I am also very happy with the clear focus, which was difficult to achieve. If I were to recreate this photo, it would be nice to have some sort of automated system to initiate the droplets. Since I was simply using a pipette, my timing wasn't always consistent.

7 References

[1] Agbaglah, G., and R. D. Deegan. “Growth and Instability of the Liquid Rim in the Crown Splash Regime.” Journal of Fluid Mechanics, vol. 752, 2014, pp. 485–496., doi:10.1017/jfm.2014.240.

[2] Cole, David. “The Splashing Morphology of Liquid-Liquid Impacts.” JCU EPrints, James Cook University, 2007, https://researchonline.jcu.edu.au/2065/2/02Chapters1-2.pdf.

[3] Krechetnikov, Rouslan, and George M Homsy. “Crown-Forming Instability Phenomena in the Drop Splash Problem.” Journal of Colloid and Interface Science,
http://www.math.ualberta.ca/ rkrechet/files/publications/jcis2009.pdf.