SHAKEN CROWN

TEAM THIRD, FALL 2023

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MCEN 5151 – Flow Visualization

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ACKNOWLEDGEMENTS
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Introduction

For the Team Third assignment for MCEN 5151 – Flow Visualization at the University of Colorado Boulder, I photographed the ejection of fluid off an elastic exercise band. Through this image, I hoped to capture the vibration-induced jets, droplet formation, and splashes generated by the acceleration and deceleration of the elastic band as it oscillates. My artistic intention was to capture a crisp image of the crown-like jets in a clean and striking black-and-white image.

Setup

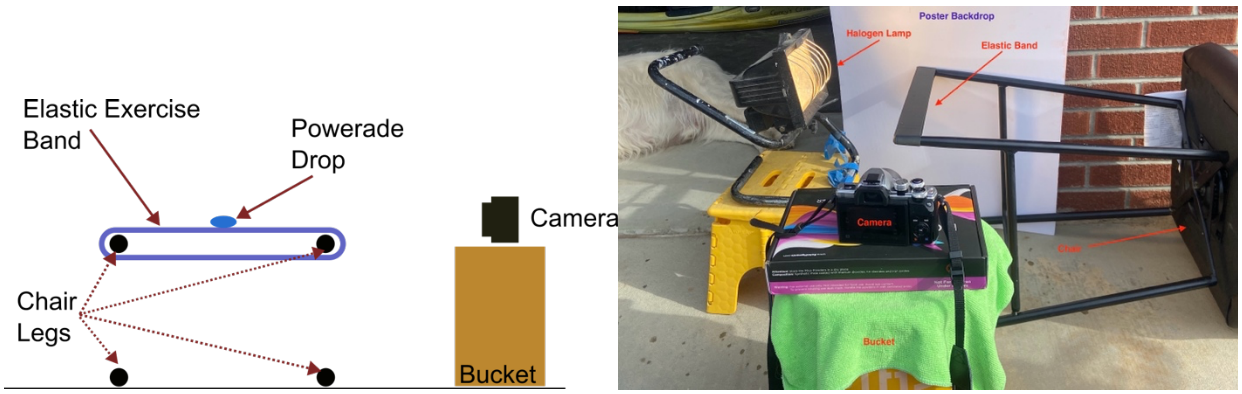

Figure 1: Setup of the Experiment. (LEFT) A schematic of the placement of the drop and the exercise band from the side where the halogen lamp was placed. (RIGHT) A photo of the actual setup.

To capture this image, I used a syringe to place about 1 mL of Mixed Berry (Blue) Powerade Zero near the center of an “X-Heavy” Black TechStone Resistance Band rated at 40 lbs (*Amazon.Com: TechStone Resistance Bands Set for Men and Women, Pack of 5 Different Levels Elastic Band for Home Gym Long Exercise Workout – Great Fitness Equipment for Training, Yoga – Free Carrying Bag : Sports & Outdoors*, n.d.). This drop of Powerade Zero occupied about a 1.5 cm diameter on the elastic band (as shown below). While I did not measure the droplet diameter with every trial, I did try to dispense the same amount of fluid with each trial (~1 mL). Using a barstool placed on its side, I wrapped the resistance band loop around the legs of the barstool. As such, the legs of the barstool supported the resistance band and extended the band until taut. To vibrate the upper surface of the band where the fluid drop lay, I pulled downward on the lower portion of the resistance band loop out of frame from the camera (approximately 8 cm below the equilibrium position). Every time I snapped the band, I used a ruler to measure how far I was pulling the band, targeting an 8 cm displacement below the “equilibrium” position of the band. Then, I released the lower portion of the resistance band, allowing it to swing upward rapidly and cause a collision with the upper portion of the resistance band. This collision caused an acceleration of the upper surface, thereby ejecting the drop of fluid from the band.

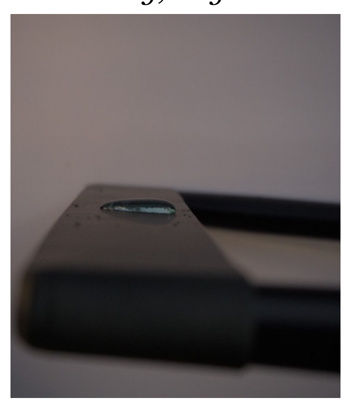

Figure 2: Placement of the Powerade Zero drop on the Elastic Band.

I photographed this image outdoors in direct sunlight using a white posterboard backdrop and an additional halogen work lamp approximately 10 inches away from the drop. Given the high shutter speeds required to capture the motion in this image, this image required a great deal of external lighting. Using the same setup on another overcast day, my images turned out incredibly underexposed.

After several trials with plain water, I experimented with different fluids, including mineral oil, Powerade Zero, and agave syrup. The mineral oil, which has a lower surface tension than water, accelerated too quickly for my camera shutter speeds, causing motion blur. The Powerade seemed to exhibit a slightly higher surface tension than the water, slowing the formation of jets to a speed that my camera was able to capture clearly at the highest shutter speeds.

PHYSICS

In this image, we see the formation of a crown or "coronet" splash with small "microjets" impinging around the periphery of the crown (Deegan et al., 2007). The crown is formed from a Peregrine sheet – a term that describes the sheet of liquid that travels outward after the impact of a splash on a surface (Deegan et al., 2007). Deegan et al. suggests Peregine sheets tend to form for Weber numbers greater than 40 and Reynolds numbers above 1300 (Deegan et al., 2007).

To measure the velocity of the fluid as it rises upwards, I captured a video of one trial recorded at 120 fps on my Olympus camera, using the same focal length and placement of the camera. In this video, I was looking for the velocity of the band – which I approximate as the velocity of the fluid jet. Upon release, the band traveled the ~8 cm back to equilibrium between 9 to 10 frames (across three trials). This means that the band was moving at 8 cm/10 frames * 120 frames per second = 96 cm/s = 0.96 m/s. For the sake of simplicity, I assume that the band is moving at the same speed as the fluid, though damping and fluid properties may alter the fluid velocity, U.

From this information, we can calculate the Reynolds number as:

$$Re = \frac{\rho D U}{\mu} = \frac{1.01 \text{ g/mL } (1.5\, cm)\ (53 \text{ cm/s})}{0.00089\, Pa - s} = 16{,}342$$

where the characteristic length D is the droplet diameter of 1.5 cm (measured as described above). The fluid velocity U is approximated as the same as the velocity of the band at 4.8 m/s. The density of the fluid $\rho\ is$ 1.01 g/mL for Powerade Zero (*Density of Beverages, POWERADE, Zero, Mixed Berry in 285 Units*, n.d.). The dynamic viscosity μ is $0.00089\ Pa - s$ for water, which was the closest approximation I could find for Powerade Zero (*Liquids - Dynamic Viscosities*, n.d.). These values give a relatively high Reynolds number, well above Deegan et al.'s threshold for crown formation.

The Weber number gives us the ratio of inertial forces to surface forces and can describe the formation of jets as we see around the periphery of the crown in my image. Arthur Mason Worthington first described what is now known as "Worthington Jets" in 1876 (Worthington & Clifton, 1876). Worthington described water drops colliding with a pane of glass. He noted that some droplet impacts created "free cylinders of liquid, …[that are] in equilibrium till the length bears a certain proportion to their diameter, after which they will tend to split each into a row of drops." Here Worthington is describing the impingement of a jet when a small droplet pinches off from the main "cylinder of liquid." The Weber number helps us describe when the inertia of the rising jet is sufficient to overcome that surface time and break off a small droplet (Hsiao et al., 1988).

The Weber number gives us:

$$We = \frac{\rho V^2}{\sigma L} = \frac{\text{inertial force}}{\text{surface tension force}} = \mathbf{194}$$

where ρ is the density of the fluid (1.01 g/mL for Powerade Zero), V is the velocity of drop (value estimated above), L is diameter of drop, and σ is the surface tension of the impacted surface (72.0 mN/m for water). Here we see that the inertial force far exceeds the surface tension force of the water, which means we will likely see a jet or crown form. Hsiao et al. suggests that jets form in systems with Weber numbers greater than ~8 (Hsiao et al., 1988). With a Weber number of approximately 194 in the captured experiment, we can expect to see jets form around the periphery of the crown. (Deegan et al., 2007)

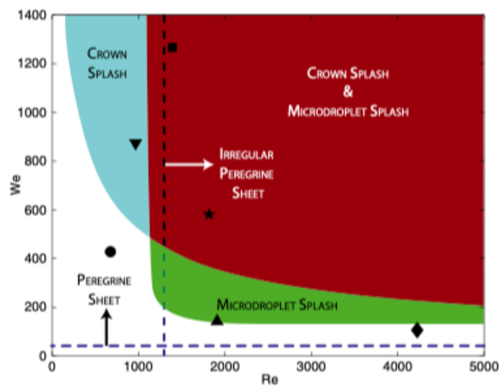

Figure 3. Phase diagram indicating the qualitatively different regimes of drop impact. The dashed vertical line indicates the Re beyond which the Peregrine sheet is disordered, and the horizontal dashed line indicates the We number above which a Peregrine sheet forms.

FIGURE 3:THE RELATIONSHIP BETWEEN REYNOLDS NUMBER AND THE WEBER NUMBER IN THE FORMATION OF PEREGRINE SHEETS, CROWN SPLASHES, AND MICROSPLASHES. (DEEGAN ET AL., 2007)

Deegan describes the relationship of the Reynolds number to the Weber number in the plot below. Generally, we can expect to see a Peregrine sheet in the "red" portion of this plot. However, in the image described in this report, our Reynolds number falls to right of the plot (off the chart). The lower Weber number of 194 in this image suggests we may see "microsplashes" in this image. To the right of my image, you will see a small droplet form above the crown, which is likely a microsplash.

FLOW VISUALIZATION

This image relies on the differences between the index of refraction of air and the index of refraction of the Powerade Zero to visualize the flow. The Powerade Zero has a blue tint to it, which in some ways acts as a dye. However, the flow in this image is moving so quickly that the blue hue was hard to detect in any of my images.

Photography

To generate this photograph, I used an Olympus OMD E-M10 Mark II Camera using the Manual mode with focal length of 42 mm, an aperture of f/5.6, exposure time of 1/10,000, ISO 1600, and manual focus as outlined in Table 1. I employed the Shutter Speed Priority mode on my camera. In this image, the camera lens lies about 12 inches from the location of drop on the elastic band (and about 6 inches away from the edge of the elastic band. Due to the high shutter speeds required to avoid motion blur, my image required a great deal of external lighting and higher ISO values than I typically use in other photographs. To time resolve the flow and avoid motion blur, I used a 1/10000 shutter speed. Given my estimated flow velocity of 96 cm/s, over the 1/10,000 s, the flow moved 0.0096 cm (96/10000). Since my frame accounts for only about 11 cm vertically (measured during these experiments), there should be minimal movement of the fluid during that exposure time. Finally, I used a burst mode (H) that captured 11 frames over 1 second to capture the various phases of the fluid ejection.

Table 1: Camera and Video Settings

Camera	Olympus OM-D E-M10 Mark II
Lens	M. Zuiko Digital 14 – 42mm 1:3.5-5.6
Light Source	Sunlight + Halogen Work Lamp
Focal Length	42 mm
ISO Speed Rating	1600
F number	f/5.6
Exposure	1/10,000
RAW Image Size	4608×3456
Edited Image Size	974×1503
Edited Resolution	72 pixels/inch

Post-Processing

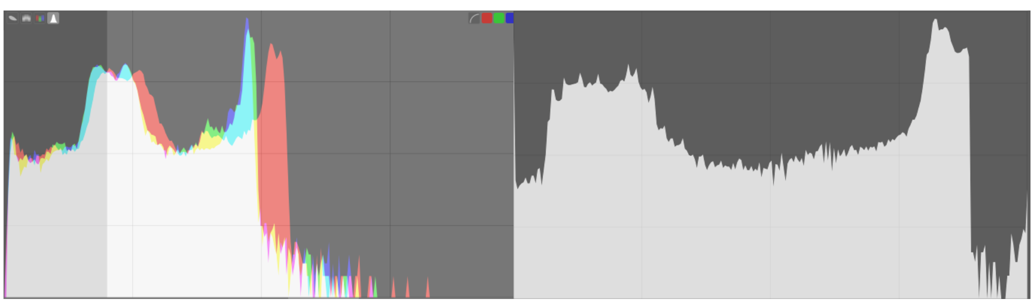

FIGURE 4: HISTOGRAM PLOTS OF THE IMAGE'S LIGHT LEVELS. (RIGHT) ORIGINAL IMAGE; (LEFT) FINAL IMAGE

To edit this image, I used DarkTable. In my original image (left below), the flow was pretty small relative to the size of the frame. Therefore, I cropped out a large portion of the original image to isolate the flow and spatially resolve the image. I played with the image contrast and tone curves to bring out some of the fluid ridges and make the background appear more white. Finally, I adopted a monochrome filter. I think the black-and-white coloring accentuates the drama of the crown and highlights the microsplashes.

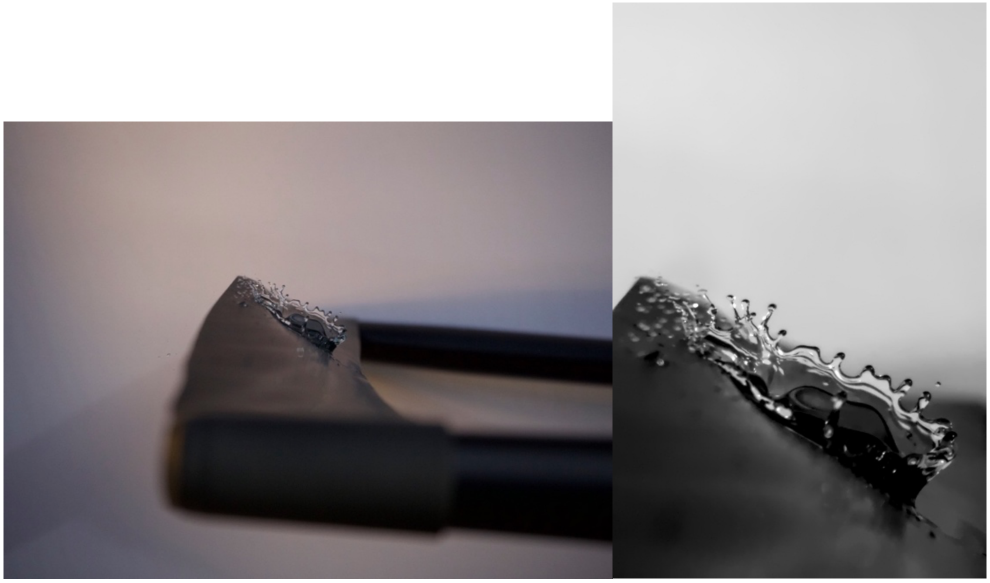

FIGURE 5: (LEFT) ORIGINAL IMAGE; (RIGHT) EDITED IMAGED

CONCLUSION

I find splash coronets to be compelling marvels of fluid dynamics. I am grateful to have captured this image, despite it not being my original intention. Originally, I set out to capture Vibration-Induced Atomization (James et al., 2003; Vukasinovic et al., 2007b, 2007a). However, as I did not have access to a microscope (i.e., the camera I would need to capture the scale on which vibration-induced atomization occurs), I approximated the physics with this larger-scale setup. Ultimately, I am still thrilled with the results of this change of course. Should I conduct this experiment again, I would try to get closer to the flow to avoid having to crop out quite as much of the image. Additionally, I would like to try this with a macro lens and a higher-speed camera with even more external lighting to try to get more consistent images without motion blur. While I was able to get an image that was largely in focus without much motion blur, I think I would have had a larger array of images to choose from with a more robust setup. Nevertheless, I still appreciate the striking beauty and captivating physics in this image.

ACKNOWLEDGEMENTS

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