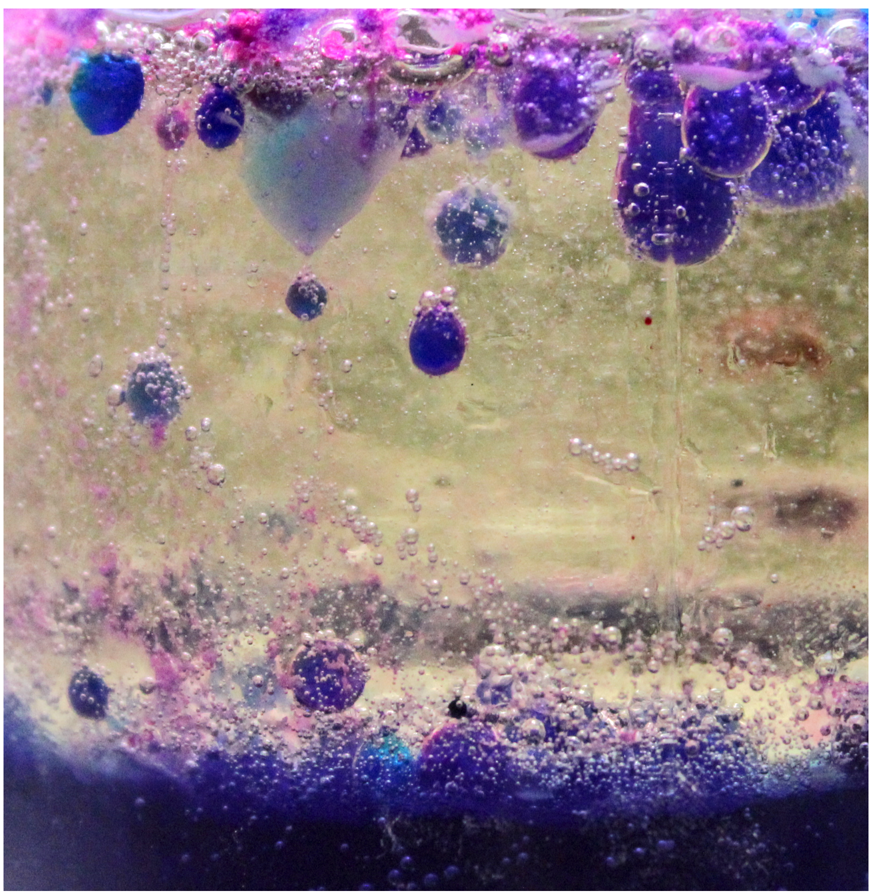
Get Wet

MCEN 5151: Flow Visualization

By Michael Berrera
Assisted by Bradley Schumacher
September 25th, 2023



College of Engineering
And Applied Science
The University of Colorado Boulder

I Introduction and Background

Flow visualization is a critical aspect of fluid dynamics and engineering as it often offers invaluable insights into the behavior and characteristics of fluid flow. Additionally, much of the experimentation can be done fairly easily without the use of costly materials, all the while providing beautiful imagery that showcases the physics behind it. The overall purpose of this assignment was to introduce ourselves to the world of flow visualization, practice the art of photography with higher-quality cameras, and begin recognizing the physics behind fluid flow. One of the many fluid flow phenomena that can be documented is the Rayleigh-Taylor (RT) instability. The RT instability can be described as the behavior of fluids with varying densities wanting to reduce their combined potential energy. Denser fluids will have the tendency to force themselves downwards whereas lighter fluids will attempt to climb up[2][5]. This was showcased in the experiment by mixing together three different fluids with varying densities which included oil, water, and oobleck in a clear mason jar. The addition of oobleck rather than a normal fluid denser than water was to see the effect of adding a non-Newtonian fluid into the mixture. In addition to this density experiment, food coloring dye and an alka-seltzer tablet were also used in order to further demonstrate the RT instability rather than have still fluids. To my surprise, this created what is known as a lava lamp experiment in which the density of fluid varies based on the creation of carbon dioxide (CO_2) which is further explained in Section II. Overall, with the help of Bradley Schumacher, I was able to successfully capture a photo and video of this fluid phenomenon with a few attempts.

II Experimental Set-up

For the experimental setup, I utilized a lightbox, a Mason jar, water, oil, oobleck, food coloring dye (red and blue), and an alka-seltzer tablet. To begin, The light box was set up on a countertop in order to house the mason jar with the fluids later on. This was a necessary component in order to provide the camera with the correct amount of light as the shutter speed of the camera was set to $\frac{1}{1000}$; Any less would result in a very dark photo.

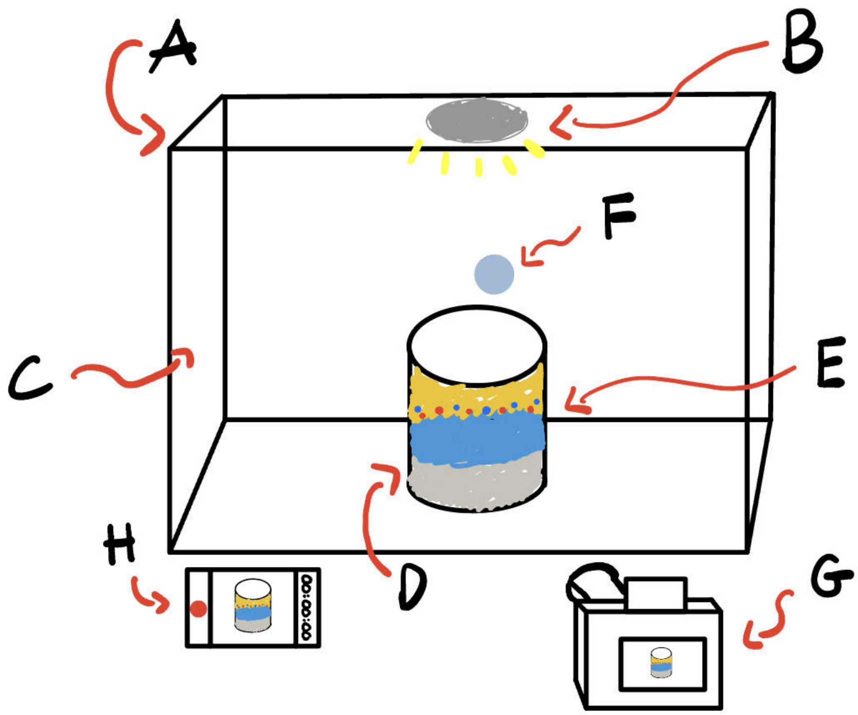


Figure 1: Final Experimental Setup to Showcase RT Instability

Figure (1) showcases the lightbox with all of the elements used inside of it and where cameras were located for the shot. Additionally, Table 1 below provides more in-depth information about what each of the components are.

Letter	Description
A	The lightbox which had a measured size of 12" x 24" x 12"
B	The light source which was a 5500K LED (White Light)
C	All interior walls were covered in diffusive material allowing for optimal lighting
D	The 16 Oz. lidless Mason jar used to store all the liquids
E	Oil (1st Layer) Red and Blue food coloring dye Water (2nd Layer) Oobleck (3rd Layer)
F	The alka-seltzer tablet I held and dropped into the jar
G	Bradley taking photos with a Cannon EOS 1500D (T7 Rebel)
H	Me recording a video with an iPhone 13 pro

Table 1: Elements of the Experimental Setup

The next step of the experiment required the mixture of the three fluids with differing densities inside the mason jar. A variety of fluids could be chosen here but a classic mix of water and oil was picked due to the ease of obtaining these materials. Oobleck on the other hand required a little more effort as this requires water and cornstarch to make. The ratio of this was 1.5 cups of cornstarch to 1 cup of water while mixing vigorously to ensure a consistent batch that doesn't get too dry. The 16 Oz. Mason jar was then filled with water followed by oil then oobleck last to help prevent it from becoming further saturated by the water. Once this was done, the jar was centered right below the light source of the box to ensure an equal amount of light.
From here, water-based food coloring could be added which sunk below the layer of oil but didn't immediately mix with the water below it due to the surface tension between the two fluids. The final piece of the experiment was the alka-seltzer tablet which was added in once the food coloring droplets settled down. This tablet would ultimately mix with the water and create CO_2 filled bubbles which broke the surface tension between water and oil. This allowed for the food coloring to mix with the water and rise up in the bubbles due to the buoyant forces in play. During this time, my assistant Bradley would take multiple pictures during the reaction between the water and tablet which resulted in numerous photos until the tablet fully dissolved. Additionally, I was also recording the entire effect with an iPhone camera as I felt that a single picture wouldn't do this experiment justice. I wanted to showcase the fluid instability to its full potential and was able to capture this as well.

III Fluid Mechanics

The key physics that the photo displays is the Rayleigh-Taylor (RT) Instability highlighted earlier. To reiterate, it is when fluids with different densities attempt to lower their combined potential energy by moving around each other[2][5]. This was seen in the initial setup of the experiment where combining oil and water caused the water to sink due to gravity and oil rise from buoyant forces. Likewise, the oobleck displays similar behavior due to it being denser than both the water and oil which results in a layer at the bottom of the jar. Although this experiment could've been performed without oobleck, it was added to see if non-Newtonian fluids would have any additional effects. This is because non-Newtonian fluids behave quite differently from their Newtonian counterparts due to how they interact with stress. Oobleck in particular behaves as a dilatant fluid or shear-thickened fluid where increasing stress increases its viscosity[4]. Figure (2) showcases a general trend of the increase in viscosity when stress increases for non-Newtonian vs. Newtonian fluids.

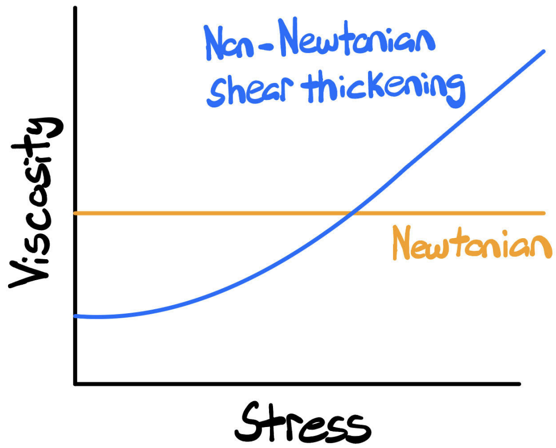
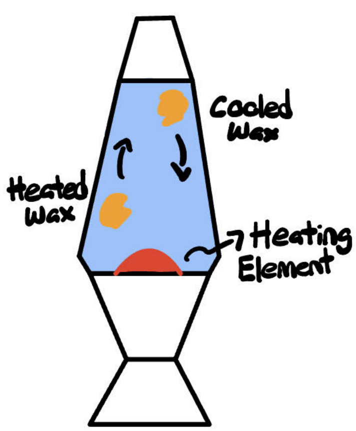
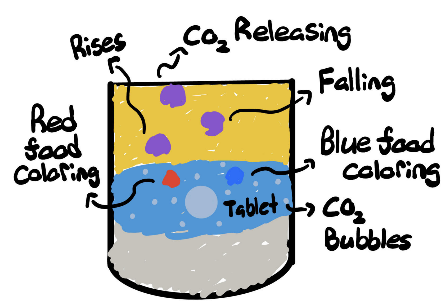


Figure 2: Viscosity of Newtonian and Non-Newtonian Fluids with Increased Stress[4]

Despite this, nothing abnormal came about when the tablet was mixed in water. Specifically, during the reaction between the Alka-Seltzer tablet and water, the food coloring is mixed with the water and creates this lava lamp effect without a heat source like conventional lava lamps[3]. When the Alka-Seltzer tablet mixes with the water it generates CO_2 in the form of bubbles. These bubbles break the existing surface tension between the water and oil which previously prevented the dye from mixing[5]. The dye-colored water and in this case purple since red and blue were mixed will also be carried by the bubbles. Additionally, these bubbles are less dense than the surrounding water and oil and thus will float to the top; This is caused by the buoyant forces pushing the less dense bubble up[5]. However, once it reaches the surface, the CO_2 is released and it becomes dense once again which sinks. One notable trait of the RT instability here is the generation of these finger or mushroom-like trails as the denser fluid moves down[2]. In essence, the CO_2 acts as a replacement for the heat source, and rather than cooling off, it loses the gas once it reaches the surface. Figure (3) showcases a sketch of the working of an actual lava lamp compared to the density experiment I performed and the aforementioned differences.



(a) Actual Lava Lamp



(b) Lava Lamp Experiment

Figure 3: Lava Lamp Using Heating Source vs. CO_2

The Reynolds (Re) number for the RT instability may also be found using some theoretical numbers based on what is known or estimated. For this specific experiment as the flow is fairly slow, the Re can be shown to be laminar using Equation (1).

$$R = \frac{\rho * u * L}{\mu} \tag{1}$$

Such that:

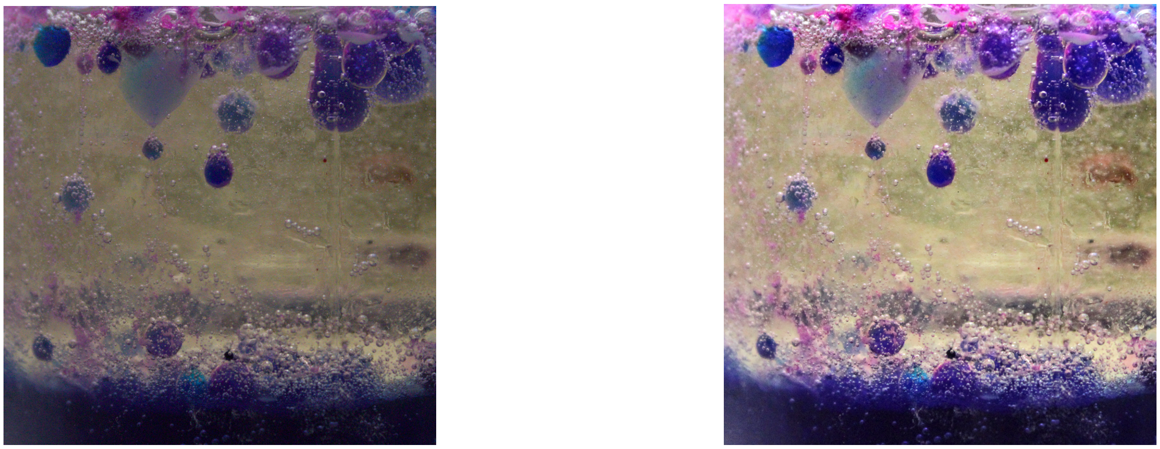
ρ = Density of the fluid
u = Flow speed
L = Length of System
μ = Dynamic viscosity of the fluid

$\boldsymbol{\rho}$ is an average between canola oil and water so it can be estimated as: $\rho = 950\frac{kg}{m^3}$.
u can be found by following 1 bubble and the distance it travels in one-second meaning: $u = \frac{0.00254m}{1s} = 0.00254\frac{m}{s}$
L can be found from the distance it travels from the layer of water to the surface of the oil so: $L = 0.127m$
$\boldsymbol{\mu}$ can be assumed to be water once again meaning: $\mu = 10^{-3}Pa{\cdot}s$

$$Re = \frac{950 * 0.00254 * 0.127}{10^{-3}} = \boxed{306.451 < 2000} \text{ and hence is a laminar flow.}$$

IV Visualization and Photographic Techniques

The photo was taken using a dye in order to better visualize the marked boundary between the bubbles and the surrounding oil [1]. However, a more transparent oil could've been used as the bubbles that were formed with little dye are more difficult to see as they seem to blend in with the oil. On the other hand, the dye-colored ones clearly highlight the difference between the two fluids. More specifically, the amount of dye used was three drops of red and blue food coloring each prior to adding the tablet. The dye was also water-based so it would not mix with the oil and rather sit at the bottom oil layer; This was purchased from Amazon.
Lighting was another critical component of this experiment as it was necessary with the shutter speed the camera was set to. Rather than using natural lighting or the flash on the camera, a light box was purchased from Amazon. This light box provided 5500K white light along with all the interior walls being covered in diffusive material which helps in providing equal amounts of light to all areas and in turn minimizes shadows. The jar used in this experiment was placed right below this light source without the lid so that the reaction could be illuminated
As for photographic techniques, the photo was taken as a closeup of the experiment in order to get a better focus on the reaction happening. The camera lens was about 1-2 inches away from the Mason jar and the final photo was taken about a minute into the reaction happening. This is because the initial reaction with the tablet causes a lot to move at once which creates a problem for the camera trying to focus on one component. Due to this, a burst of shots were taken during this minute before more careful shots when the reaction slowed down. This helped a little more with the resolution of the image as previous images were quite blurry or didn't capture the effect I was looking for. Figure (4) showcases the unedited and edited version of the photo taken for comparison.



(a) Original Photo

(b) Edited Photo

Figure 4: Original vs. Edited Photo

The final photo was captured on a Cannon EOS 1500D (T7 Rebel) which is a DSLR camera. The camera settings were set to ISO-3200, with an aperture of f/5.6, a focal length of 40 mm, and a shutter speed of $\frac{1}{1000}$. The pixels of the final image were captured at 6000x4000 but sized down to 900x1300 in the cropped version. As for the video I recorded, it was originally captured at 4K with 60 fps, however, during conversions to YouTube, the quality was reduced to 1080p at the same frame rate. The final image was then edited in Darktable where the RGB curve setting was adjusted so that the color of the dye and oil would be highlighted more. Additionally, the contrast was also increased to sharpen the image even more.

V Conclusion

Overall, by using boundary techniques, dye, proper lighting, and photo editing, an image of the Rayleigh-Taylor instability is able to be captured. One aspect of the image I really like is how I was able to capture the bubbles rising and falling down simultaneously. However, one thing I disliked was the level of detail or the resolution as I felt it was a little blurry due to the camera trying to adjust to multiple points at once. Despite, this I felt like this effectively captured the fluid instability and the video recorded further supports this claim. If I were to change this experiment, I would change the type of glass I was using to one with a flatter surface rather than curved as this could've affected the photo quality. Additionally, I believe using a clearer oil such as baby oil could've provided a better contrast for the colored bubbles floating around. Nevertheless, it was a fun and interesting experiment that ended in a success.

VI References

[1] Hertzberg, J. (2023, July 13). Overview 2: Visualization techniques. Flow Visualization. https://www.flowvis.org/Flow

[2] Kull, H. J. (1991). Theory of the Rayleigh-Taylor Instability. Physics Reports, 206(5), 0–129. https://doi.org/10.1016/0370-1573(91)90153-d

[3] Lava lamps. Let's Talk Science. (2019, August 21). https://letstalkscience.ca/educational-resources/stem-explained/lava-lamps

[4] Non-newtonian fluids. Science Learning Hub. (2010, April 12). https://www.sciencelearn.org.nz/resources/1502-non-newtonian-fluids

[5] Sharp, D. H. (1984). An overview of Rayleigh-Taylor instability. Physica D: Nonlinear Phenomena, 12(1–3), 3–18. https://doi.org/10.1016/0167-2789(84)90510-4