Get Wet Flow Visualization - Spring 2018

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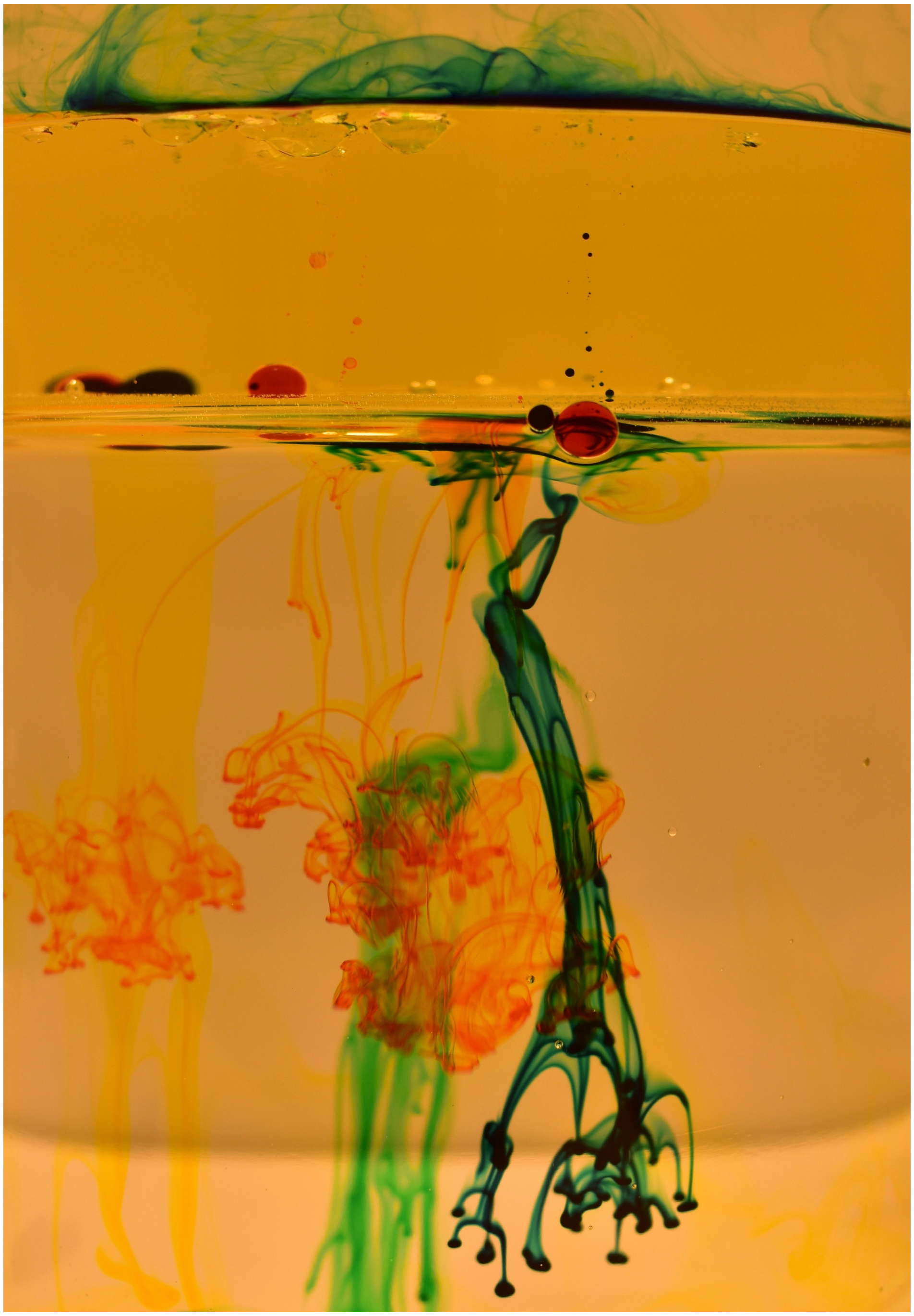

1 Introduction

The image shown above was taken for the first assignment in the MCEN-5151 Flow visualization course at CU Boulder. The purpose of this assignment was for students to "Get your feet wet" and combine techniques from photography to knowledge of fluid flows. For this specific project, the chosen topic was to observe the flow of dye through various liquid density layers. The intent of this image was to capture how liquid food dye interacts and disperses in fluids of different densities and the instability that occurs as a result. Light corn syrup was originally included in this experiment however, it would entirely expel the dyes into the layer above it and did not add beneficial aesthetics to the image or report. Red, green, blue and yellow dye were used for this experiment to observe the interaction with water, vegetable oil, and rubbing alcohol.

2 Flow Apparatus setup

The flow apparatus was setup using an acrylic canister, DSLR camera, counter top, white backdrop and desk lamp, which is modeled below in Figure 1. The 72 fluid ounce Oggi acrylic canister was purchased from Bed Bath and Beyond with an interior diameter of 4.72 inches and interior height of 8 inches. The acrylic canister was filled with 46.55 fluid ounces of water at a height of 4.8 inches, 11.64 fluid ounces of vegetable oil at a height of 1.2 inches, and 12.74 fluid ounces of 91% isopropyl rubbing alcohol at a height of 1.33 inches in the canister.

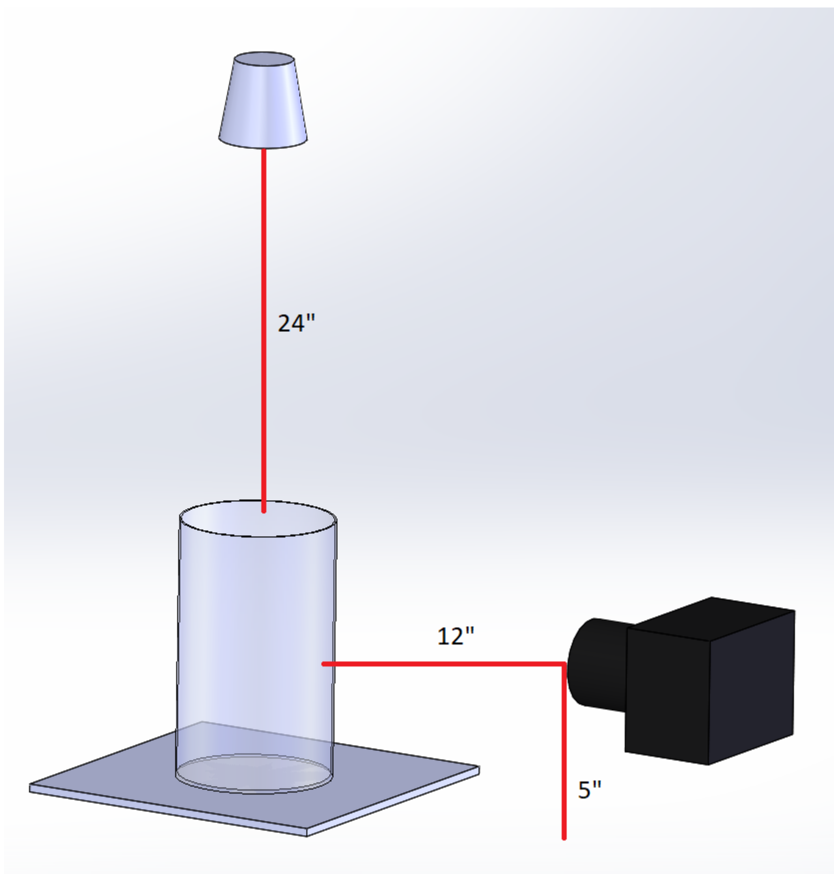

Figure 1: Apparatus Setup

The temperature of the water used in this setup was 75 degrees Fahrenheit which correlates to a kinematic viscosity of 0.0014173228 in^2/s according to engineering toolbox's calculator. The velocity of the dye was calculated using frame rate analysis from a simultaneous video recording during the experiment to obtain the velocity profile after the dye passed through the vegetable oil. Assuming the canister can be modeled as flow through a pipe, the Reynolds number for each velocity was calculated using Equation 1 with variables for velocity (u), hydraulic diameter (d_h), and the kinematic viscosity of water. A sample calculation for the first measurement is provided in Equation 1.

$$R_e = \frac{(u)(d_h)}{v} = \frac{(0.30556\frac{in}{s})(4.72in)}{0.0014173228\frac{in^2}{s}} = 1017.58 \tag{1}$$

From the velocity profile in Table 1, we can see that the dye remains as a laminar flow from the point it enters the water as a droplet until it begins to display the Rayleigh-Taylor umbrella instability. The Rayleigh-Taylor instability appear as a natural occurrence in the real world, when two fluids of difference densities interact with each other. Two cases arise in this situation, "if the heavy fluid pushes the light fluid, the interface is stable, if the light fluid pushes the heavy fluid, the interface is unstable" [1]. In this experiment we encounter the second scenario, where as the food dye exits the vegetable oil layer, the water layer begins to push upward against the dye trying to rise above it. Instabilities like the Rayleigh-Taylor exhibit large traits of exponential growth. Starting out with small instabilities during interaction, the dye begins to slowly lose structure as the amplitude of the water continues to increase, forcing upward on the dye. These small instabilities inherently grow larger resulting in the unstable phenomenon shown by the umbrella effect in Figure 3.

Table 1: Velocity profile of blue drop interacting with water

Measurement	Distance Travelled (in)	Velocity (in/s)	Reynolds Number
1	0.30556	0.30556	1017.58
2	0.3611	0.240741	801.721
3	0.2778	0.237857	792.117
4	0.1389	0.237857	792.117

Specific gravity is the relation between a substance and the density of water, which allows the ability to calculate density of the substance by knowing the ratio to water. The food dye used in this experiment has an approximate specific gravity of 1.025, resulting in a density of 0.592491 oz/in^3 as shown in Equation 2.

$$\rho_{dye} = (\frac{SG_{dye}}{SG_{water}})\rho_{water} = (\frac{1.025}{1})0.57804\frac{oz}{in^3} = 0.592491\frac{oz}{in^3} \tag{2}$$

Table 2: Densities of fluids in experiment

Fluid	Density (oz/in^3)
Rubbing Alcohol	0.454337
Vegetable Oil	0.530753272
Water	0.57804
Food Dye	0.592491

Above, Table 2 shows how the layers remain in the order as they appear in the image. The most dense will naturally sink to the bottom and the least dense will rise to the top. The interaction between the dye and the rubbing alcohol is pretty mundane, since the low viscosity (2.04cP) and density of the rubbing alcohol does not create a net for the dye which causes a quick settling time. When the dye reaches the vegetable oil, the interactions become more interesting. Due to the high viscosity of the oil (30cP) and relatively close density, the food dye becomes trapped in a bubble-like cocoon as it settles to the bottom, where it is able to remain stable for a short period of time. Once the dye breaks through the surface tension of the oil, it begins to interact with the water and exhibit the Rayleigh-Taylor instability. Using the intrinsic properties of fluids, another way to examines their interaction appears with Atwood ratio number. This ratio predicts whether a buoyancy-driven flow can present the Rayleigh-Taylor instability, such as the one in this experiment, where the water is the upward driving force [2]. Therefore, by calculating the Atwood number in Equation 3, it becomes even more obvious that such a system will eventually become inherently unstable.

$$A_t = \frac{\rho_1 - \rho_2}{\rho_1 + \rho_2} = \frac{0.592491 - 0.57804}{0.592491 + 0.57804} = 0.012346 \tag{3}$$

For any Atwood number less than 1, just like this scenario, "the light fluid moves into the heavy fluid in the form of round topped bubbles with circular cross sections" [1]. In other words, the heavier fluid will form a pattern over the rising bubbles from the lighter fluid.

3 Visualization Technique

The visualization was created using McCormick Assorted Food Color to interact with Crisco Pure Vegetable Oil, 91% isopropyl rubbing alcohol, and water. Water was filled at the bottom layer of the container, with a small layer of vegetable oil above, and rubbing alcohol on top. When adding each layer, it was important to use the side walls of the container to fill the liquid in slowly, making sure to not mix the layers. The lighting used for this experiment was artificial lighting obtained from one desk lamp. The lamp was placed two feet directly above the container as previously described in Figure 1 and used a Eco-Smart 40W 2700K soft white LED bulb. It was important to have this setup completed prior to conducting the experiment because the time frame to capture the image of the dye is very small, ranging from three to fifteen seconds.

4 Photographic Technique

Figure 2: Original Image

For the original image shown above in Figure 2, the field of view was chosen to depict all the fluids from the bottom layer to the top layer. The camera was setup eight inches away from the container in order to frame the image at a focal length of 29mm. The type of camera used was a digital Nikon D3400 DSLR with a 18-55mm lens, which captured a 4000 by 6000 pixel original image, later edited down to 2834 x 4082 pixel image. The aperture was set at f/5.6 with a focal length of 29mm at a shutter speed of 1/10 second. A low ISO of 200 was used to ensure minimal the noise would appear in the image. The image was captured as a JPEG image, and edited in Photos to crop the image and focus in on a specific region. The final image is shown below in Figure 3 which was cropped to draw more focus to the interaction between the three fluid density layers to eliminate view of empty space in various parts of the fluids and the distracting background. This edit was also performed to capture a better section of the Rayleigh-Taylor instability.

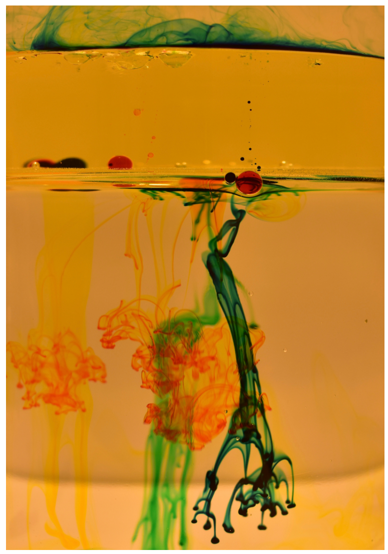

Figure 3: Final Image

5 Image Revelation

This image reveals the interactions between fluids of various density. These immediate effects can be easily observed as the food dye passes through each of the three density layers. The most appealing thing about the image is the chaotic nature of the Rayleigh-Taylor instability and how the instability trees begin to form as the buoyancy force drives upward onto the dye. Also, it is interesting how the dye interacts with the highly viscous vegetable oil resulting in entrapment at the bottom of this layer, which eventually passes through after breaking the layer tension. Aspects of this experiment that could be improved are likely a different setup of lighting to reduce the yellow hue that is apparent throughout the image. To develop this idea further, it might be interesting to see the how the dye travels through the layers in a smaller diameter container. It might also be interesting to find out what other fluids the dye will exhibit the instability pattern with. Overall, this image captures the Rayleigh-Taylor instability and shows how it appears only in water for this experiment but not the other two fluids.

References

[1] D.H.Sharp. "An overview of Rayleigh-Taylor instability". In: *Physica D: Nonlinear Phenomena* 12.1-3 (1984), pp. 3–5. DOI: https://doi.org/10.1016/0167-2789(84)90510-4.

[2] Stuart B. Dalziel Malcolm J. Andrews. "Small Atwood number Rayleigh–Taylor experiments". In: *Phil. Trans. R. Soc. A* 368.1-3 (2010), pp. 1663–1679. DOI: doi:10.1098/rsta.2010.0007.