Flow Visualization
MCEN 5228

Assignment: Team Project 2
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The Flow Visualization course taught by Dr. Jean Hertzberg at the University of Colorado in Boulder integrates the physics of fluids with fine art in hopes of capturing flow phenomena through photography. “Team Project 2” was the fourth assignment of the course. For the project, students worked together (or individually if desired – as chosen in this case) to artistically visualize a flow of their choice. I worked individually to capture the Rayleigh-Taylor Instability. In this event, a lighter fluid is accelerated upwards through a more dense fluid, causing fluid mixing. The physics of this is important in areas from pharmacology and medicine creation to nuclear weapons and fusion. This image attempts to slow down the acceleration in order to get a better look at the mixing by using highly viscous fluids.

The idea for the image came from an engineering demonstration presented to middle school-level females within the University of Colorado at Boulder. The demonstration was called *Expanding Your Horizons* and attempted to encourage young women to pursue an engineering or science degree once they reach the college level. A number of fluid phenomena were presented to them in the last week of February in 2009, one of which was entitled the *Density Rainbow*. The *Density Rainbow* consists simply of vase and a number of fluids with various physical properties. If done correctly, the fluids will stack themselves, arranged from the most dense liquids at the bottom to the least dense at the top, resulting in a picturesque demonstration of densities like that seen in Figure 1.

Figure 1: *Density Rainbow* Results when completed properly (Fizzics, 2009)

As shown in Figure 1, a beautiful color dissection is possible. However, when the fluids are poured into the vase in the incorrect density order, mixing occurs as the less dense fluid tries to rise to the top of the more dense fluid poured over it. This is the Rayleigh-Taylor instability and the resulting effect of one group of three middle-school girls when they placed shampoo underneath corn syrup. The results were later duplicated using the apparatus shown in Figure 2.

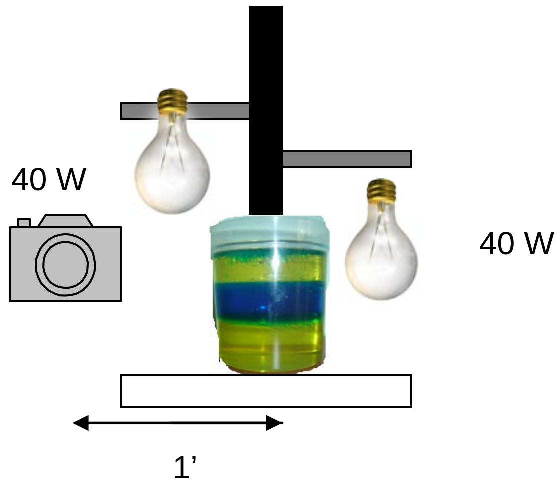

Figure 2: Figure of Apparatus Designed for Photo

Seen in Figure 2, the vase containing the separated liquid was placed on a stand that held two 40 Watt incandescent light bulbs placed on either side of the container. Each of these lights was placed eight inches away from the vase. The camera was placed slightly to the left of the vase, about a foot away, aimed downward at the mixing fluid layer.

To simulate the effect, Pantene Pro-V Volumizing Shampoo was placed in the bottom of the vase, dyed blue for easier visualization. An equal volume of Karo Light Corn Syrup, undyed, was placed over the top of it slow enough to avoid unnatural mixing. The vase, having a cross-sectional area of 4 inches square, allowed for 262 cm^3 of each liquid when poured one inch deep. Because of the varying densities, a natural instability occurs and the fluids try to exchange places. The shampoo, having a density of about 1063.34 g/L naturally wants to float on top of the corn syrup, which has a greater density of about 1238.6 g/L. The densities were determined by weighing known volumes of the liquids in the Durning Lab at the University of Colorado. Once the fluids were both in the vase, mixing began. The rate of mixing depends on many things, including the fluid viscosities and geometry of the container. This was a very slow process because of the high viscosities of both the corn syrup and the shampoo, and because of the small cross-sectional area of the vase. The resultant Reynolds number of the 0.25 inch dollop of shampoo seen in the photo rising through the corn syrup was 0.65. This is calculated from the equation for Reynolds number:

$$N_R = \frac{\rho V D}{\mu} \text{ (Smits, 29)}$$

where rho is density of the fluid, D is the descriptive diameter, V is the velocity, and mu is the dynamic viscosity of the fluid. The quarter inch dollop equated to a diameter of 0.0063 m, shampoo, similar to that of ammonia, has a viscosity of 2.2E-4 N*s/m (Smits, 493), a rate of 0.5 inches in ten minutes resulted in a velocity of 2.12E-5 m/s, and the density was 1063.34 kg/m^3, as stated previously. This low Reynolds number is the reason for the thick mixing layer between the fluids, which decreases in thickness with increasing turbulence. Therefore, the shampoo can be seen pushing through the syrup without actually penetrating and rising above it. To expedite the process, a pushing force of three pounds was quickly applied to the left side of the vase over a distance of four inches, causing a sudden upwelling of fluid on the left side due to the applied shear stress. That is why the shampoo is seen rising in the photo asymmetrically.

Archimedes of Syracuse, born in 287 BC, was fascinated with geometry in fluid mechanics. In his studies, he helped develop the four propositions which turned into the famous Archimedes Theorems. The third theorem states that if a lighter fluid is totally and forcibly immersed in a denser fluid, the lighter fluid will have an upwards thrust equal to the difference between its weight and the weight of an equal volume of the heavier fluid (Smits 448-449).. Due to the equal volumes of fluids, the weight of each fluid could be calculated from their densities. The syrup weight of 2.73 N subtracted from the corn syrup weight of 3.18 N resulted in the shampoo having an upwards thrust of 0.45 N naturally. The three pounds of force applied to the left side of the vase, however, adds another 13.35 N of force acting upwards through the corn syrup once the shampoo is routed upwards by contact with the side of the vase. A total upwards thrust of 13.80 N is then seen acting on the corn syrup; still not enough to penetrate its one inch thickness.

For the photograph, no special visualization technique was used; the fluid was shot in its natural state in nominal conditions of about 28 degrees Celsius. Both the shampoo and the corn syrup were purchased at the King Soopers store off of 30th St. and Arapahoe Ave. in Boulder to simulate the different densities. Pantene Pro-V was chosen due to its original white color which made it easily dyeable. The square vase was found in Dr. Jean Hertzberg's lab within the Stores and Labs hallway at the University of Colorado at Boulder, and the remaining items, including the lights and the stand, were found within the storage rooms of the Engineering Center's ITTL basement. The two 40 Watt incandescent light bulbs provided the lighting in conjunction with the flash from the camera. The Sony digital camera used comes equipped with a flash range of (0.2-7) m wide x (0.9 to 5.6) m tall and a Carl Zeiss Vairo-Tessar 10x zoom lens.

A digital Sony DSC-H10 was used to photograph the stacked fluids on February 28, 2009. Enabling the macro setting on the camera allowed for the close-up view of the fluid flow, with a final image field of view of 0.9 inches. Figure 2 shows the camera being placed a distance of 12 inches from the vase, slightly zoomed for a focal length of 6.3 mm (0.248 in.). This results in an image distance of 0.253 inches, using the equation:

$$\frac{1}{FocalLength} = \frac{1}{ObjectDistance} + \frac{1}{ImageDistance} \qquad \text{(Eq. 1)}$$

For a high sensitivity, an ISO setting of 125 was used. Additionally, an F-stop of f/8, a maximum aperture value of f/3.5 and a shutter speed of 1/1600 were used. With the given velocity of 2.12E-5 m/s, the shampoo could then rise 1.32E-8 m (5.12E-7 in.) within the exposure time. From the given distance, the original image had pixel dimensions of 3264 pixels wide by 2448 pixels high. This image contained the whole vase and all of the fluid layers in motion. The image was cropped in Adobe Photoshop to 884 pixels wide by 251 pixels high to focus the attention of the viewer on the thickening mixing layer: the extra fluid layers were removed along with the vase, leaving the mixing layer between the shampoo and corn syrup. In addition to cropping, the *Curves* function was used to heighten the contrast of the image, giving it a full light to dark spectrum. This amplified the green-yellow tint of the corn syrup and darkened the shadows where the mixing indentations can be seen. Also, *Clone Stamp* was used to remove the reflection of the flash on the fluid and any fingerprints on the glass.

Overall, the picture demonstrates clearly the boundary mixing layer between two fluids during Rayleigh-Taylor instability. This is specifically shown for two viscous fluids with a low Reynolds number, creating a very slow-moving, thick layer between them. The size of the image, however, may be out of the zooming capabilities of my particular lens. To capture such a small effect, the camera needed to be moved to the closest possible distance where everything was in focus. The desired image, then, needed to be cropped from the whole. This resulted in a very small image that becomes pixilated when viewed zoomed in. Fortunately, however, the physics can be seen unobstructed, with the main portion of the cropped image in focus. The next step in pursuing this phenomena would be to use a lens fit for closer imaging to achieve a less pixilated result. The Rayleigh-Taylor effect, though, can be seen well in either case.

References

1. Fizzics Education Pty. Fizzics Education. "Making Layered Liquids." www.Fizzicseducation.com.au. Fizzics Education Pty Ltd. 2009

2. Smits, Alexander J. A Physical Introduction to Fluid Mechanics. "Laminar and Turbulent Flow." pg. 29. John Wiley & Sons, Inc. New York City, NY. 2000