MCEN 5151 – Flow Visualization Matt Phee

Team Project 3 Report

This image is my submission to the Team Project 3 assignment. It captures the Saffman-Taylor instability between fluids of different viscosities in a Hele-Shaw Cell. The Hele-Shaw cell consists of two flat planes between which subject fluids are injected. The intense colors were achieved by specifically choosing fluids that fluoresce underneath the ultraviolet radiation of a blacklight. The liquids used were laundry detergent with fabric softener which glows blue under blacklight and luminescent highlighter filler diluted in water which glows a very vibrant yellow.

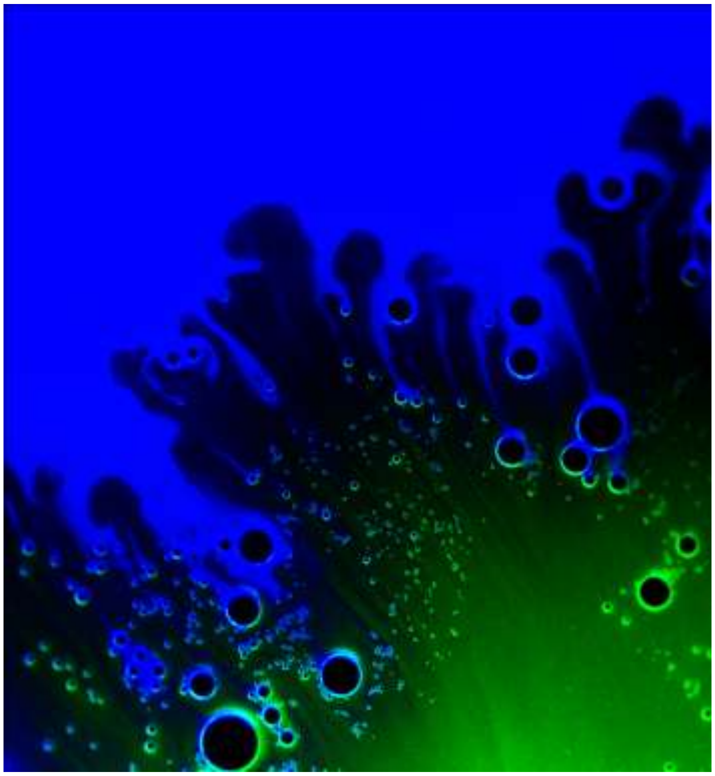

Figure 1: Saffman-Taylor instability in a Hele Shaw Cell

The experimental apparatus used for this project was primarily a Hele-Shaw cell assembled at the University of Colorado's Integrated Teaching and Learning Laboratory (ITLL). The Hele-Shaw cell consists of a wooden frame and PVC drainage system assembled in support of two horizontally stacked planes. The lower plane is a semi-translucent acrylic sheet designed to diffuse light emitted from bulbs underneath. The second plane is a transparent glass pane laid atop the acrylic. The thin channel formed between the planes is of variable width. An assembly of laboratory syringes and 2 mm plastic tubing was connected to the Hele-Shaw cell through a hole in the semi-translucent pane such that fluid could be injected up into the channel. The light sources used in the experimental were three 13 Watt Ecobulb® Blacklight bulbs, two of which were positioned below the semi-translucent lower pane and one of which was positioned above the cell and moved to highlight specific sections of the flow throughout shooting. The set-up was placed in the ITLL's Media Shack with the lights turned off and windows covered. No other lighting was used save for trace ambient light from the room's

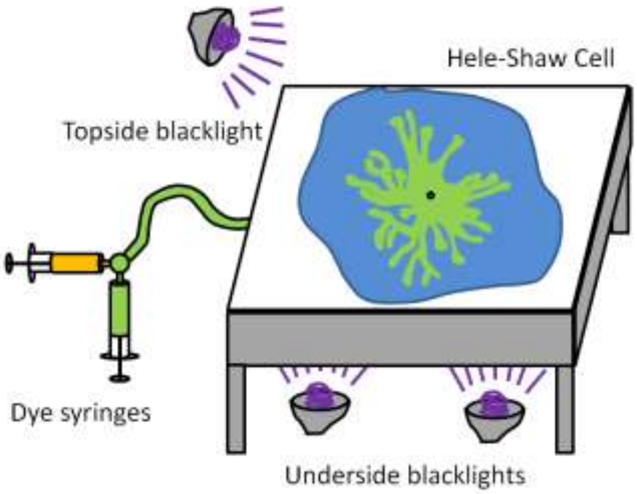

Figure 2: Diagram of experimental apparatus

imperfectly covered window. Laundry detergent with fabric softener and yellow and orange highlighter filler diluted in water were used to achieve the instability. Figure 2 shows the basic layout of the experiment as viewed from the perspective of the photographer, and the general procedure used is as follows. Both panes were cleaned thoroughly to reduce visible distractions and facilitate more uniform flow conditions. A 1.5 cup pool of viscous detergent was poured directly onto the lower pane roughly centered around the injection port. The upper, clear glass pane was set in place uniformly dispersing the detergent. Several highlighters were disassembled and the luminescent ink within was diluted in 1.5 cups of tap water. This mixture was loaded into the syringe assembly and injected into the cell. As the low viscosity water mixture displaced the higher viscosity detergent, the Hele-Shaw fingering instability, also known as the Saffman-Taylor instability, developed. Variable injection speeds were experimented with, though all flows were halted for photography. The process was repeated several times with slightly different fluid ratios. It should be noted that the final image in Figure 1 was taken during the team's first experimental run in which relatively large volumes of air bubbles were entrained in the flow. Later trials were amended to eliminate the presence of air, though the flow interaction with the bubbles in this earliest trial was a source of decidedly interesting photographic subject matter.

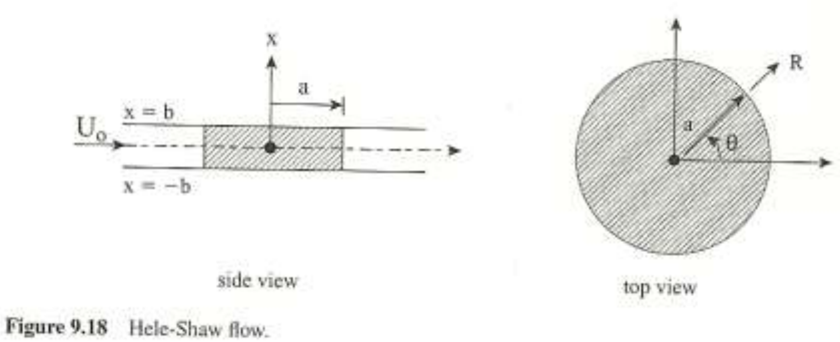

Figure 3: Hele-Shaw flow diagram from Kundu, *Fluid Mechanics* [1]

Two clear fluid phenomena common to Hele-Shaw systems are depicted in this experiment. Hele-Shaw flow is defined by Kundu to be "flow about a thin object filling a narrow gap between two parallel plates," and it is characterized by Reynolds numbers less than one [1]. The solution to Kundu's equation represents the highly laminar flow that develops around a thin cylindrical object bounded between plates such that fluid is forced around its curves [1]. Such an object is shown in Figure 3. In the Figure 1 image, such flow appears clearly around the entrained air bubbles near the fluid interface, the velocity potential of which is represented by (1). See [1] for a full solution of (1).

$$\varphi = R\cos\theta\left(1 + \frac{1}{R^2}\right)\frac{(1-x^2)}{2} \tag{1}$$

Hele-Shaw flow around entrained bubbles is a convenient addition to the image, however the intended focal point of this image is the Saffman-Taylor fingering instability that characterizes mixing of fluids with different viscosities in a Hele-Shaw cell. As Daripa explains, when a fluid of viscosity $\mu_i$displaces a fluid of viscosity $\mu_j > \mu_i$, the flow boundary suffers from Saffman-Taylor instability [2]. 1n 1958 Saffman and his colleague Taylor pioneered research in this area and verified the instability that now bears their names. A paper by Saffman presents (2) as the two-dimensional velocity of a fluid with viscosity μ between parallel plates with spacing b at pressure P [3].

$$u = -\frac{b^2}{12\mu} grad(P), \qquad div(u) = 0 \tag{2}$$

(2) gives the flow velocity for a single fluid in a Hele-Shaw channel. For cells in which a second fluid displaces the viscous fluid, surface tension imbalances along the interface give way to the formation of fingers as displacing fluid pursues the path of least resistance. Saffman explains that as displacement continues, some fingers grow at the expense of their neighbors. Eventually, only one large finger is sustained as the development of all others is stunted [3]. More recently, Alimov investigated the competition between fingers. Bensimon's group suggested that capillary forces between fingers are the cause for destructive competition, though Alimov proposed and experimentally verified a model which refutes this claim. In his 2007 paper, Alimov shows that finger competition in the Saffman-Taylor instability can develop in the absence of capillary forces [4].

The visualization technique used for this flow was the photo-luminescent material property of the chosen fluids, detergent and highlighter ink. When impacted with ultraviolet electromagnetic radiation emitted from a black light, these fluids fluoresce magnificently in the visible spectrum. The detergent and fabric softener mixture emits a bright electric blue and the yellow highlighter solution emits a brilliant and eerie, neon yellow color. Under normal light conditions, these fluids are unremarkable and in fact difficult to distinguish from one another. An image of Hele-Shaw flow illuminated by typical visible light would be boring and utterly pointless without a seeding or dye technique. On the other hand, under a blacklight, these fluids are a thrill to behold. The team's intent here was not only to create a flow involving a clear and beautiful fluid phenomenon, but to emphasize the often undervalued importance flow visualization techniques. I believe it is important to consider that the most beautiful art or groundbreaking science may not achieve the desired impact if it is not viewed under the proper light, in a literal and figurative sense respectively.

Fluorescence in these fluids is similar to that which occurs in fluorescent light bulbs. In fluorescent bulbs, ultraviolet light is emitted by way of electric stimulation of mercury in a rare gas environment of argon, neon, or krypton. Phosphor powders lining the bulb fluoresce in the visible spectrum when excited by the ultraviolet radiation [5]. In this experiment, ultraviolet light was supplied continuously by the blacklights and the chemical makeup of the fluids used caused them to fluoresce similarly to phosphor.

The photographic technique used to capture this flow was digital color photography using a Canon EOS Digital Rebel T2i DSLR camera with an EF100mm macro lens. The field of view of the original image was roughly 1 x 2 ft. The camera lens was positioned one to two feet from the subject depending on the shot. This particular image was taken two feet away, but the macro lens enhances zoom considerably. The original image was captured at 18 Megapixel (3456 x 5184 pixels) resolution. A 1/125 second exposure time was used to allow better exposure as the fluorescence of the subject fluids was the only light source. Graininess was an issue in the image already, so a low sensitivity of ISO-250 was used. Additionally, the camera was set at a focal length of 100 mm and f/2.8. The original, unedited images were rather dark, had less than desirable contrast, and did not convey just how bright these fluids fluoresce under UV stimulation. After importing the images into Adobe Photoshop Elements 8©, the image was cropped and rotated and the saturation and contrast were enhanced automatically using the program's Auto-Levels, and Auto-Contrast features. These changes can be inferred by viewing

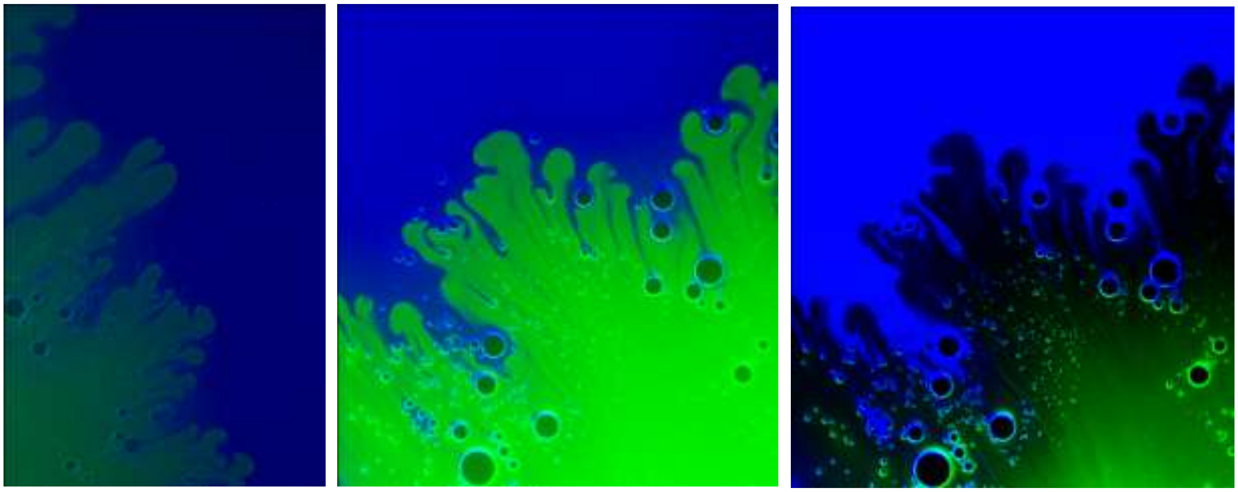

Figure 4: Image post-processing work

the differences between the first and second images of Figure 4. Then, the mid-level brightness was drastically reduced and highlights and shadows were tweaked slightly to yield the final image, reproduced in Figure 4. The image was manipulated in this way to showcase several of the team's observations including the Saffman-Taylor instability at the fluid interface, Hele-Shaw flow around entrained air bubbles, the streamlines within the highlighter/water mixture, the brilliant fluorescence of both fluids, and the lack of fluorescence seen in the entrained air bubbles.

Overall, I am pleased with this image. I was successful in capturing the fluid flow phenomenon I set out to create, and I was able to do so in an artistic and eye-popping way. Our team successfully overcame the challenges that came with shooting UV-fluorescent fluids in extremely low (visible) light conditions. I recognize that I performed a considerable degree of image post-processing, but I believe I was able to showcase some very interesting phenomena and present the flow in a visually surprising way without altering the observed physics of the Saffman-Taylor instability or Hele-Shaw flow impinging around entrained bubbles.

References

[1] Kundu, Pijush K., Ira M. Cohen, P. S. Ayyaswamy, and Howard H. Hu. *Fluid Mechanics*. 4th ed. Amsterdam: Elsevier/Academic, 2008. Print.

[2] Daripa, Prabir. "Studies on Stability in Three-layer Hele-Shaw Flows." *Physics of Fluids* 20 (2008). Print.

[3] Saffman, P.G. "Viscous Fingering in Hele-Shaw Cells." *Journal of Fluid Mechanics* 173 (1986): 73-94. Print.

[4] Alimov, M.M. "Competition between Fingers in Hele-Shaw Flows." *Fluid Dynamics* 43.5 (2008): 751-62. Print.

[5] Avallone, Eugene A., Theodore Baumeister, Ali M. Sadegh, and Lionel S. Marks. "12.5 Illumination." *Marks' Standard Handbook for Mechanical Engineers*. 11th ed. New York: McGraw-Hill, 2007. 12-90. Print.