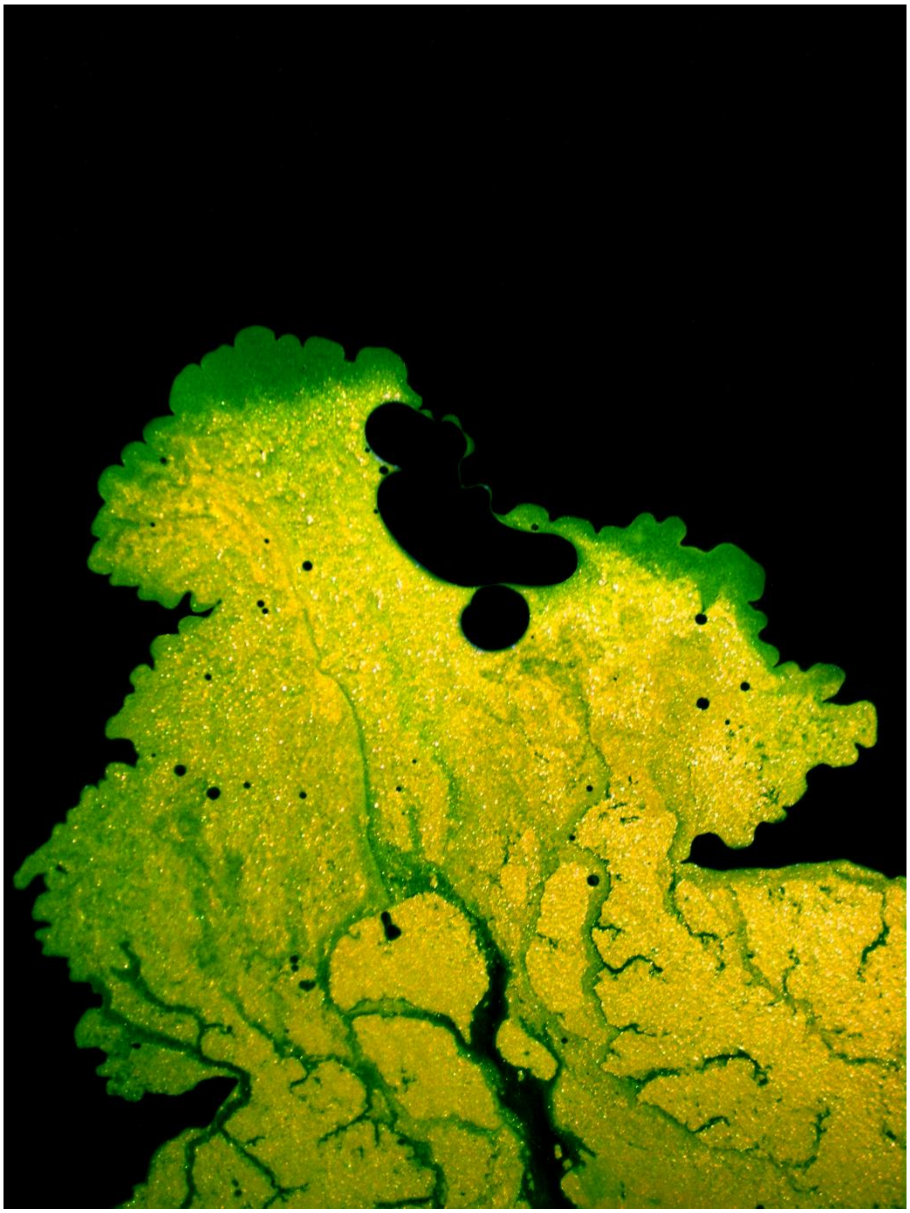
Group Photo #1:

Michael Chilton

3/22/12

Flow Visualization 2012



Introduction

For this assignment, I was not able to find enough time to work together with my group and needed to design a simple flow experiment which I could operate and capture on my own. To do this, I decided to create a Hele-Shaw cell and capture the effect of viscous fingering caused by the Saffman-Taylor Instability. I found typical examples of this experiment were designed to directly inject a less viscous fluid into a more viscous fluid under pressure between two plates of glass. To create a more unique flow and image, I decided to use an eye-dropper to layer a less viscous fluid on top of a more viscous fluid then place a plexiglass sheet on top of the fluid layers. This applied pressure will force the less viscous fluid to move displace the more viscous fluid, creating “fingers” on the fluid boundary. My hope was that this set-up would allow for a thicker fluid layer, compared to typical experiments, and create a more interesting flow image.

Experimental Set-up

The flow apparatus used for this study was Hele-Shaw cell. The cell comprises of two plexiglass sheets laid on top of one another with the fluid mixture placed between them, as shown in Figure 1. The cell was placed on top of a black background to provide contrast and definition to the flow. In contrast to typical Hele-Shaw experiments, a hole was not drilled into the plexiglass and the secondary fluid was not injected directly into the more viscous fluid. For this study the more viscous fluid would be applied directly onto the free surface of the lower plexiglass. The less viscous fluid would then be placed directly on top of it using an eyedropper. The upper plexiglass sheet was then layered directly over the fluids, applying an even pressure while maintaining a certain fluid thickness. The flow was lit by using two desk lights with white paper placed in the light path to diffuse the direct light. I was not able to fully remove the glare onto the upper plexiglass sheet, however, by placing the lights on opposing sides of the cell and utilizing ambient light in the room, the glare was minimized. The image was captured by placing the camera directly over the cell surface and shooting without the built-in flash. Many different fluids were tested to find the best demonstration of the flow. Yellow pearlescent liquid acrylic ink and laundry detergent were chosen for the more viscous and less viscous fluids, respectively.

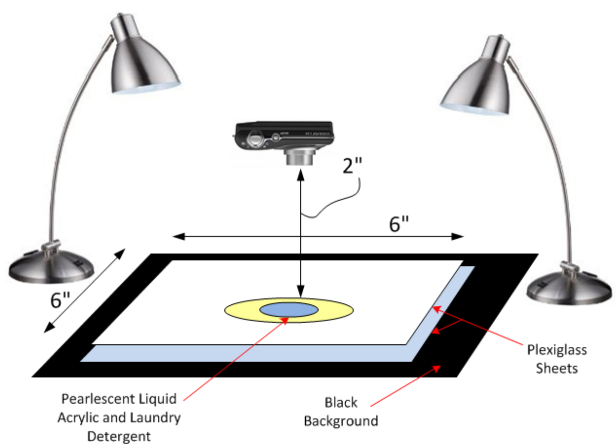


Figure 1: Experimental Set-up of Hele-Shaw Cell

Flow Analysis

The principle flow phenomena occurring within the Hele-Shaw cell is viscous fingering caused by the Saffman-Taylor instability. The purpose of the Hele-Shaw cell is to investigate two-dimensional flow between fluids of differing densities and viscosities. This difference in chemical structure provides for the fingering effect represented in the image, as caused by the more viscous fluid displacing the less viscous fluid. As the top plexiglass plate is unrestrained, a pressure gradient is created in the more viscous fluid, while the other fluid's pressure is nearly constant. This difference in pressure is the cause of the Saffman-Taylor instability, causing the displacement and fingering, as described previously. Displacement in these regions increased the pressure gradient in the more viscous fluid and thus increased the propagation of fingers. If not for the existence of capillary forces, the curved finger geometry would be in the form of sharp points. The motion of these fluids under the pressure gradient, ∇p, is governed by Darcy's Law, as shown in Equation 1, where b is the spacing of plates, μ is the fluid viscosity, and V is the velocity of the fluid front.[1]

$$V = -\frac{b^2}{12\mu}\nabla p \tag{1}$$

A completely accurate prediction of these formations and their propagation is still not completely understood, however it can be relatively approximated. Saffman and Taylor determined that the width of the finger was a function of the capillary number approaching half the channel width, λ=1/2, where λ represents the ratio of finger width to channel width. A graphical representation of the problem is shown in Figure 3.[2] Using an estimated viscosity of 900 cp, plate spacing of 2mm, and a approximate characteristic velocity of 0.25 mm/s, the pressure gradient can be found through Equation 1 to be -1350 Pa/m.[3]

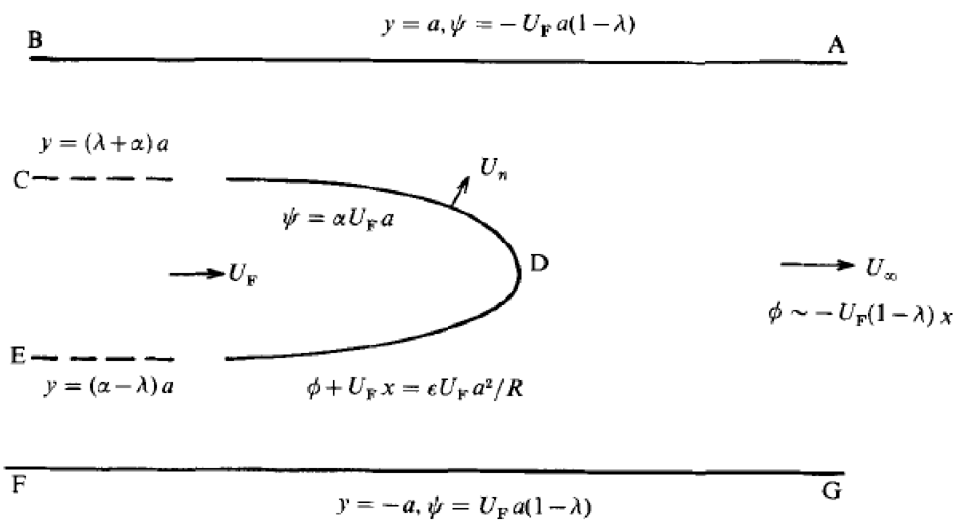


Figure 3: Sketch of geometry for a finger advancing into a Hele-Shaw cell, and the values of the velocity potential and stream function on the boundary in a frame moving with the finger

Using the previously stated values for viscosity and velocity, along with a surface tension measure estimate of 39 dyne/cm, the Capillary number for the flow is found to be 0.02308, following Equation 2.[4][5]

$$Ca_1 = \frac{\mu V}{\gamma} \tag{2}$$

Visualization Technique

To best demonstrate the flow and remove distracting elements, the visualization techniques used were focused on amplifying the flow properties and creating definition within the liquids. I chose to use a pearlescent liquid acrylic ink for the more viscous fluid, as the reflective properties would be increased and a seemingly granular look would be achieved. The laundry detergent was chosen as the less viscous fluid due to its translucence, which would help to create a layered effect within the liquid acrylic. The most difficult part of properly visualizing this flow was getting close enough to capture definition within the acrylic. The camera used did not allow for very accurate macro-level images, and getting the picture in focus was a challenge. Two opposing desk lamps were used to provide lighting to the Hele-Shaw cell, and a black sheet was placed underneath the cell to provide contrast against the color of the acrylic. The camera was moved around to numerous places in an effort to decrease the amount of glare being reflected off the upper plexiglass plate. After trying numerous angles, the camera was finally moved directly over the cell and it was determined the glare would need to be removed in post-processing.

Photographic Technique

The image was taken using a Nikon Coolpix S200 camera. The camera's F-stop was set at f/3.1 and the exposure time was 1/14s. The ISO was tweaked numerous times in order to find the best balance of sensitivity and sharpness. The focal length was 6mm and the aperture was 3.3. The image's field of view is approximately 1in. by 1in. Final dimensions for the image were 2304 pixels wide by 3072 pixels tall. Because of the amount of glare in the original image, there was a lot of post-processed necessary to bring out the flow definition and create a better image. Within Photoshop, I first increased the contrast and sharpness, then adjusted the color curves to take out the lighter shades and bring out darker colors. Once I had a suitable black within the image, I used the clone and brush tool to wipe away any leftover glare or color gradients outside of the flow boundary. I sharpened the edges of the flow boundary as well by using the brush tool at a high zoom level. I adjusted some of the colors within the flow to bring out definition in the layered areas, creating an image that more resembled a landscape. Figure 2 compares the original image with the final image after post-processing.

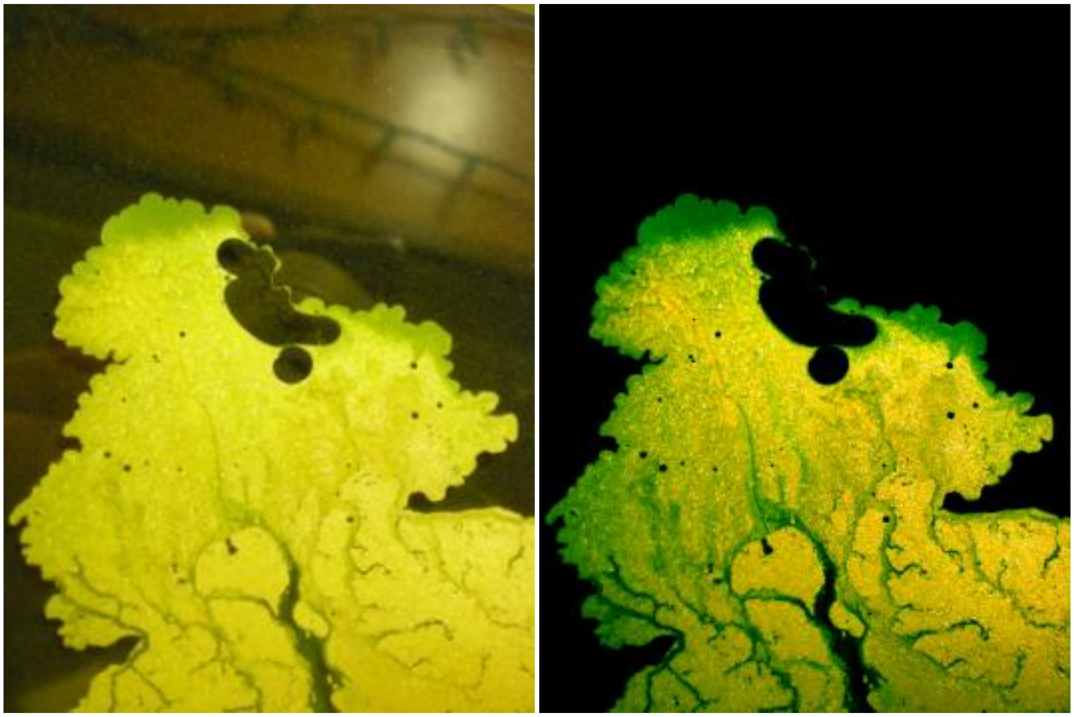


Figure 2: Original Image (Left), Processed Image (Right)

Conclusion

The captured image is a great expression of the Saffman-Taylor instability as seen within a Hele-Shaw cell. I am very pleased with the level of detail I was able to get out of the image and how much contrast was created through post processing. It was very interesting to see how easily this type of flow could be created and how clear of an image could be captured from it. If I was able to re-do this image, I would have like to use a better camera with a macro lens. Having a better camera and macro lens would have allowed me to get closer to the flow and capture much better definition of the layered properties. The image would have also been much sharper as the focal length would not have been so limited and manual focus could have been utilized. I was not able to find research covering a free hanging top cell plate, all research found dealt with different fluids and gases between plates held at a constant distance. I believe the added pressure of the top plate being suspended entirely by the fluids helped to propagate the instability faster than would have otherwise been done. It would be interesting to see this exact same study performed with a larger gap between the two plates, as I think this would create a much deeper flow with interesting features.

References

[1] Couder, Y. (1986). *Dendritic Growth in the Saffman-Taylor Experiment.* *http://iopscience.iop.org/0295-5075/2/6/005/pdf/0295-5075_2_6_005.pdf*

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

[3] *Beltran, Diane. "Measurement Techniques for Acrylic Artist Colors."* Measurement Techniques for Acrylic Artist Colors*. Paint and Coatings Industry Magazine. Web. 06 May 2012. <http://www.pcimag.com/articles/measurement-techniques-for-acrylic-artist-colors>.*

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