Flow Visualization: Team First Report

MCEN 5151: Flow Visualization

By Michael Berrera
Assisted by Bradley Schumacher and Qisheng Lei

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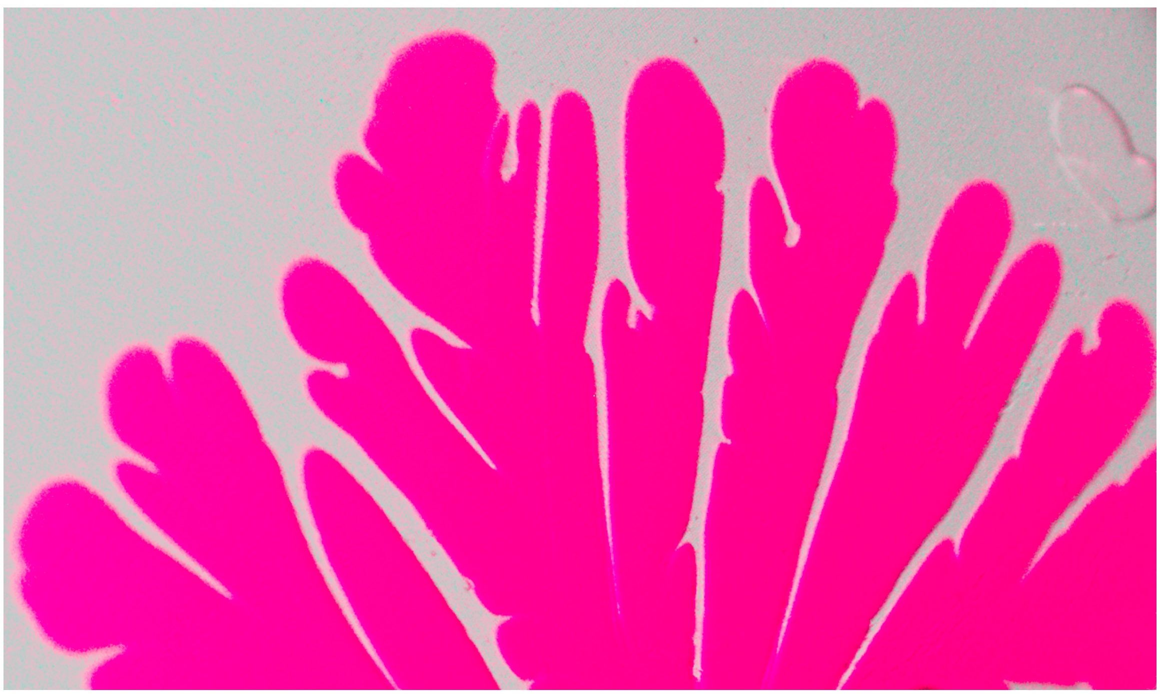


College of Engineering
And Applied Science
The University of Colorado Boulder

I Introduction and Background

Flow visualization plays a pivotal role in the fields of fluid dynamics and engineering, as it frequently provides invaluable insights into the behavior and attributes of fluid movement. Moreover, a significant portion of these experiments can be conducted with readily available, cost-friendly materials, resulting in captivating visual representations that illustrate the underlying physics. With this in mind, the overall purpose of this experiment was to collaborate with a team in order to capture a fluid phenomenon of our choice. As a team, we decided to showcase the Saffman-Taylor (ST) Instability which is characterized by a less viscous fluid being forced into a larger one within a confined geometry. The confined geometry in this case is a Hele-Shaw cell which consists of two parallel, transparent plates with a very narrow gap between them. This gap can measure to a few millimeters and essentially creates a controlled environment for fluid phenomena to develop. This results in a pattern that looks very similar to multiple flower petals or fingers. In short, the dampening effect provided by the more viscous fluid on the less viscous one allows for a more controlled flow. However, the less viscous fluid has the tendency to create instability between the fluid interfaces due to its capability of moving through more viscous fluids[4]. This creates a very interesting relationship that can be observed using several different combinations of fluids. In our case, we utilized honey and water which were the more viscous and less viscous fluids respectively. However, naturally, water would be very hard to see within honey and the visual effect is dampened. To address this, we incorporated a range of food coloring dyes, with red being the preferred choice due to its vibrant color. With the help of Bradley Schumacher and Qisheng Lei, I was able to successfully capture the ST instability.

II Experimental Set-up

For the experimental setup, I employed 2 transparent acrylic plates with a small drilled hole in the center of one (About 10 mm), a 20 mL syringe, water, honey, red food coloring dye, and 8 cloth pins. The dimensions of the acrylic plate were about 12" x 12" which provided ample amounts of space for the displacement of fluids later in the experiment.

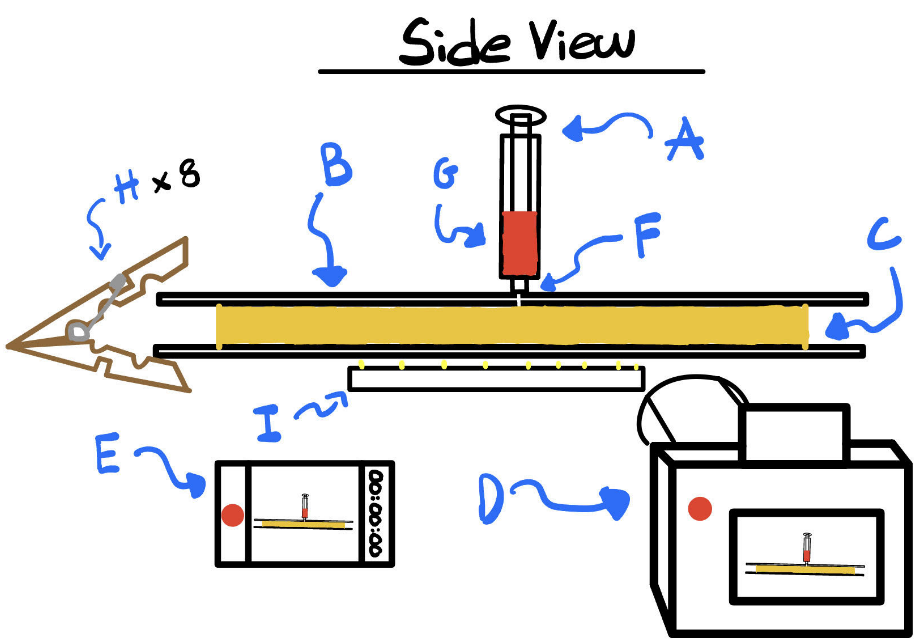


Figure 1: Side View of Hele-Shaw Cell Experiment

Figure (1) showcases the experimental set-up of the acrylic Hele-Shaw cell, a cloth pin position, the position of the cameras, and how the syringe was injected into the cell. The two acrylic plates are drawn further apart in order for the honey to be seen from the side. However, in reality, the two acrylic plates are nearly flat with only a few millimeters of space between them to create a necessary seal to create the ST instability. Figure (2) below represents the top view and better showcases the position of all 8 of the cloth pins which were used to further secure the cell beyond simply pressing down the two plates together.

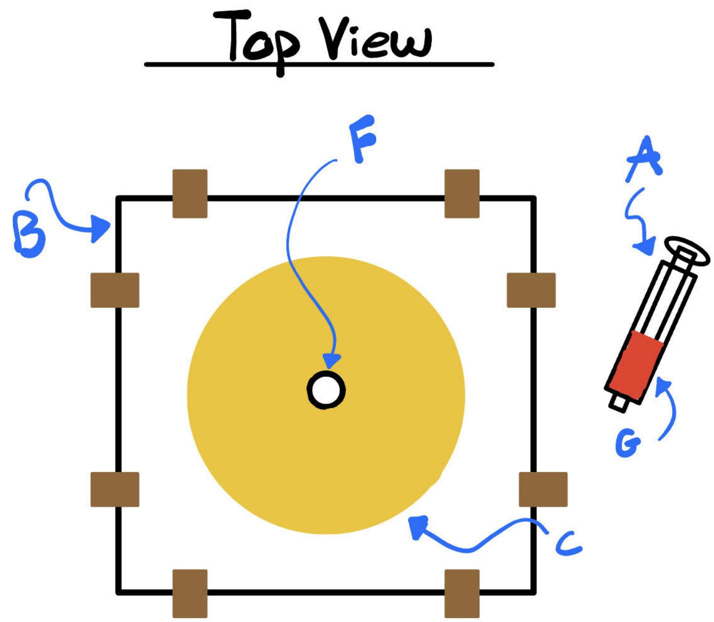


Figure 2: Top View of the Hele-Shaw Cell Experiment

Table (1) below represents a further explanation of each element seen within Figures (1) and (2).

Letter	Equipment
A	20 mL syringe with a smaller diameter than the top acrylic plate hole
B	2 12"x12" transparent acrylic plates that are about 1/8" thick
C	A cup and a half of honey spread out on the non-drilled acrylic plate
D	Cannon EOS Rebel T7
E	iPhone 13 Pro
F	10 mm drilled hole on the top acrylic plate
G	Water with red food coloring
H	8 Cloths pins to secure the Hele-Shaw cell
I	iPad w/ 1000 nit screen

Table 1: Elements of the Experimental Setup

To begin, about a cup and a half of honey was spread on one side of the acrylic plate without the hole. This gives a base fluid for the less viscous water to flow through when it is injected later on. The acrylic plate with the hole is then pressed on top of this layer of honey in order to further spread it out. Eight cloth pins were then used to ensure the plates would not shift and compromise the experiment. Two of these were used on each side and 4 inches apart if they were on the same side to allow for a more equal distribution of pressure. During this time, due to pressing a hole on top of the honey, some of it may exit through this hole. As such, it's advised to bring a towel to wipe out any excess honey.

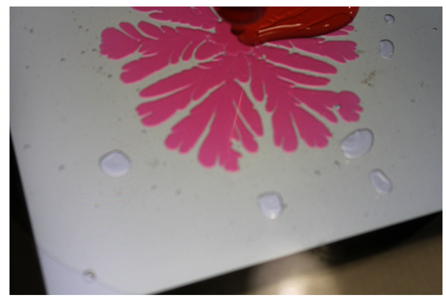
Water was then mixed in a plastic cup with red food coloring dye to produce a more vibrant colored fluid to flow through the honey. To quantity this mixture, it was about 5 drops of food coloring mixed with 1 cup of water. This was then inserted into the 20 mL syringe that had a larger tip diameter compared to the hole on the acrylic plate. The larger diameter was to ensure that the less viscous fluid entered the cell easily and also to consider that finding a tip smaller than 10mm was difficult in our case.

Now that everything for the experiment was prepared, the next step of trying to capture the phenomena was able to commence. I had one of my team members (Qisheng) hold the syringe tip flat to the hole on the acrylic plate and slowly press down at a steady rate. Initially, the less viscous water had trouble entering and would seep through the small crack between the tip of the syringe and the plate. It was important to not push too hard here as this would also cause the water to rebound back toward the person injecting the fluid. However, with about two careful injection attempts, with the first being used to water down the honey, the red-colored water would be able to break through the layer of honey. This would begin the process of the ST instability and create a stunning visual of viscous fingering.

III Fluid Mechanics

The key physics that the photo displays is the Saffman-Taylor (ST) Instability highlighted earlier. To reiterate, it is when a fluid with a smaller viscosity attempts to displace a higher-viscosity fluid. Over time this creates an unstable interface between the two fluids and the less viscous fluid creates finger-like patterns in the higher one [4]. This was captured at the end of the experiment after several iterations as we initially injected the water into oil which failed to produce adequate results. This is due to how a substantial difference between the two fluids viscosity's is required to produce adequate amounts of finger growth. An example of the effect between water and oil in the cell is showcased in Figure (3a).

(a) ST Instability Attempt Between Water and Oil



(b) ST Instability Water and Honey

Figure 3: ST Instability Experiment Comparison

This happens when the viscosity between the two fluids differs but is still close enough to each other. On the other hand, when the viscosity differs enough, the result is what is produced in Figure (3b). Table (2) below represents the viscosity of fluids used in both experimental runs and the difference between water and the respective fluid it was injected into. This in combination with Figure (3) clearly illustrates the benefit of larger differences in viscosity for this experiment.

Fluid	**Dynamic Viscosity (cP)**	**Difference from Water**
Water	1	N/A
Canola Oil	42.6	+ 41.6
Honey	2000	+1999

Table 2: Fluid Dynamic Viscosity's

The growth of fingers in the STr instability can also be described by a mathematical model called Darcy's law. It describes the flow of a fluid through a porous medium as seen in Equation (1) below [1]:

$$q = \frac{k}{\mu} * \nabla P \tag{1}$$

Such that:

$$q = \text{Volumetric Flow Rate}$$
$$k = \text{Permeability of the Porous Medium (Honey or Oil)}$$
$$\mu = \text{Dynamic Viscosity of the Fluid (Water)}$$
$$\nabla P = \text{The Pressure Gradient Along the Cell}$$

Although all these values are important in this equation, the permeability of the porous medium, or in other words, the honey or oil that the water is flowing through, is quite influential. Assuming the dynamic viscosity was constant since water was the only fluid being injected, the permeability would play a large factor in the flow rate and pressure gradient. It can be understood that more viscous fluids generally have smaller permeability because they resist fluid flow, resulting in higher pressure, and vice versa. If the flow rate is too fast, meaning a higher permeability, this could potentially reduce the amount of time for the finger effects to develop leading to an underdeveloped ST instability. Although not a direct correlation, I assume that the closer the viscosity is, the more stable the system, as the water can freely and smoothly travel through the medium. However, in the case it is slower, this could give way for the effect to develop properly as seen in the differences in Figure (3). Additionally, in an experimental study done by Tabeling, Zocchi, and Libchaber in 1986, the increasing number of semi-circular fingers was found to be correlated to a lower velocity range in the interface [5].

Although a calculation could be made to compare the flow rate between both experimental set-ups, there was a big difficulty in obtaining permeability values for both honey and oil. However, I do expect the flow rate within honey to be much slower compared to the oil as the permeability in honey is expected to be much smaller. Despite this calculation being excluded, in place of it, we can find the Reynolds (Re) number to showcase laminar flow. The equation for the Re # is shown below in Equation (2).

$$Re = \frac{\rho * u * L}{\mu} \tag{2}$$

Such that:

$$\rho = \text{Density of the Fluid}$$
$$u = \text{Velocity of the Fluid}$$
$$L = \text{Length of the System}$$
$$\mu = \text{Dynamic Viscosity of the Fluid}$$

With water as the fluid, length as the approximate gap between the plates (0.01m), and assumptions for the velocity (0.01 $\frac{m}{s}$), it can be calculated as:

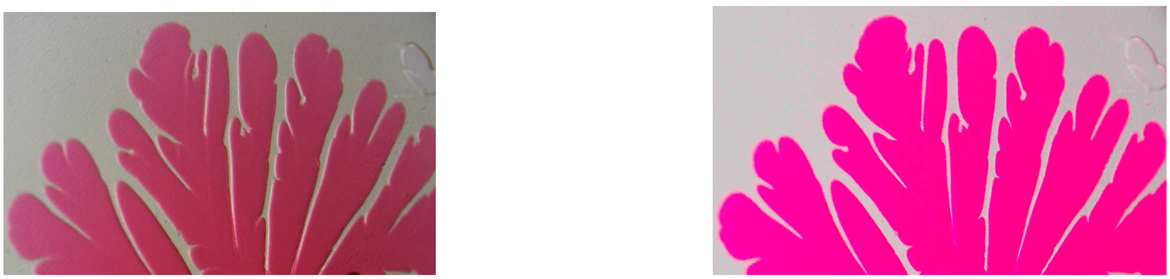
$$Re = \frac{1000 * 0.01 * 0.01}{10^{-3}} = \boxed{100 < 2000} \text{ and hence is a laminar flow.}$$

This would make sense as the flow of water in the more viscous honey doesn't visually produce a large turbulent effect and is relatively much smoother. This can be seen with the final image captured in the next section.

IV Visualization and Photographic Techniques

The photograph was captured by introducing a dye to the system to enhance the visibility of the marked boundary between the fluid and the surrounding honey [2]. However, a more transparent fluid than honey could've been used such as glycerol considering how the light yellow background seems to conflict with the beauty of the ST instability, hence why it was edited out in the final image. Additionally, the dye of the water helped the flow become visible considering how water is naturally transparent and would make it much harder to capture a video let alone a photo. The dye was also water-based and was purchased from Amazon.

Lighting was another critical component of this experiment as it was necessary for how dim the lighting was in the room. Rather than using natural lighting or the flash on the camera, a mini iPad was used underneath the acrylic plates. This iPad provided 1000 nits of white light which was quite beneficial in giving the red a more vibrant shade. The screen of the iPad was also centered as much as possible on where the phenomenon occurred. This minimized any shadow captured by the camera and enhanced the boundary between the two fluids.
As for photographic techniques, the photo was taken about a foot away from the experiment as there was quite a bit of difficulty in attempting to get a close-up with good focus. The photo was taken about 3 seconds into the process of injecting the water in order to allow for adequate development of viscous fingers, however not a moment too late as this would cause the effect to begin retracting. Additionally, due to the iPad screen being used for lighting, the photo was taken at an angle to reduce the moiré effect. This effect is quite common when taking a picture of a screen and the pixels don't align with the pixels on the device displaying the screen (i.e. The camera) [3]. 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 T7 Rebel which is a DSLR camera. The camera settings were set to ISO-500, with an aperture of f/5, a focal length of 40 mm, and a shutter speed of $\frac{1}{100}$. 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, due to converting to YouTube, the quality was reduced to 1080p with the same frame rate. The final image was then edited in Darktable where the contrast was adjusted to reduce the yellow in the background as well as highlight the red. Additionally, the RGB curve was also adjusted to enhance the color of the red and further mute the yellow honey. Due to some slight over-editing, the red did become vastly pink, but I liked this effect and kept it.

V Conclusion

Overall, by using boundary techniques, dye, and photo editing, an image of the Saffman-Taylor instability is able to be photographed. One aspect of the image I really like is the overall shape I was able to capture since the developing finger effect can be quite random depending on the set-up. However, one thing I disliked was the level of detail or the resolution as I felt it was a little blurry due to how I took the picture at an angle. With a better setup or a stand, I felt like I could've taken a higher-quality picture. Additionally, the use of an electronic screen for light does produce some unwanted effects like the moiré effect which could've been easily fixed by using a non-digital light source. Despite, this I felt like this effectively captured the fluid instability and the video recorded further supports the experiment we performed as a team. If I were to change this experiment, I would change the more viscous fluid to glycerol since it has a large enough viscosity difference from water to produce the same effect. It would also provide a transparent background for light to get through and possibly even highlight the effect further. Nevertheless, with some trial and error, it was a great experience working with others to capture this captivating fluid phenomenon.

VI References

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