University of Colorado - Boulder

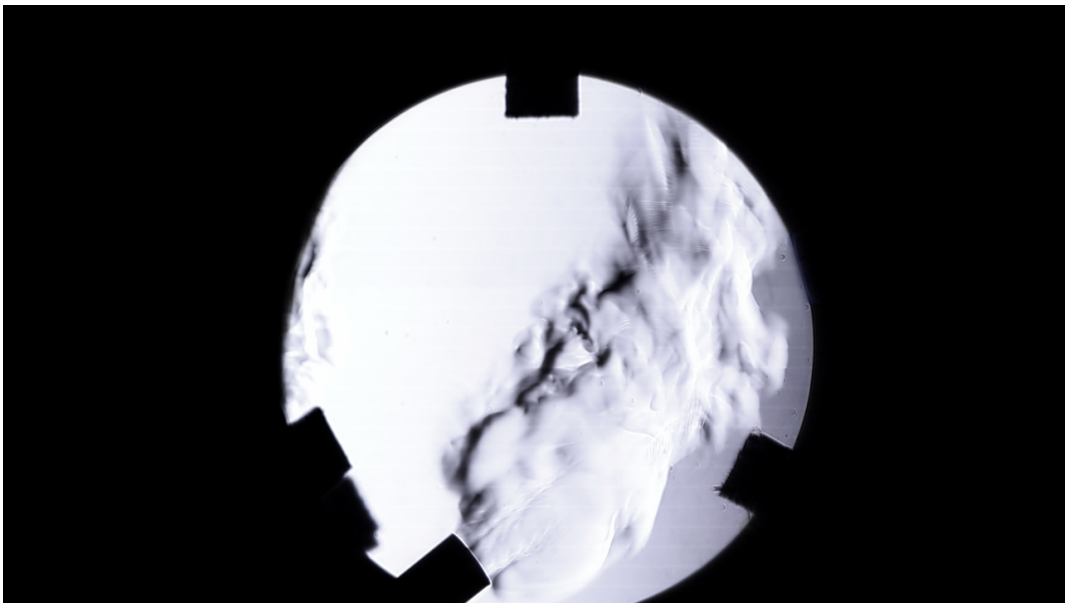
MCEN 5151
Flow Visualization

Team Second:
A Single Slit Experiment

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I Introduction

My group learned about using flashes to freeze fluid motion for our first team project. For the second we wanted to attempt a more challenging technique. We chose schlieren, which uses the refraction of light to show otherwise invisible changes in fluid density. An easy way to change the density of a fluid (like air!) is by manipulating the temperature. We each brought a different flame-creating device that we would hold in the test section so we could see the different ways they influenced the air around them. We did so in the middle of a parking lot, taking all of the necessary precautions to keep us and our test environment safe.

II Test Setup

We found ourselves in this parking lot knowing that schlieren was something you *could* do, but with little idea of the steps to set it up. Our supplies included a set of 4" mirrors marked Edmonton Industrial and a razor blade with a stand to hold it. We found a portion of an Edmonton manual for a 6" schlieren set that showed 45-60" between the mirrors. We then began a process of trial and error to get both the spacing and alignment for our setup.

We began with a bike light which we fixed to a small tripod. We made a small hole in a piece of tape and placed it directly over one of the two LEDs to make our point light source. With the light in place we lined up the first mirror at the lower end of the range provided in the manual since our mirrors were smaller, the distance ended up about 0.9 meters (40"). We then placed the second mirror the same distance away from the first, but next to the light source.

The camera was fixed upside down to a tripod so it was low to the ground, pointed at the second mirror. We could then begin our fine adjustments using 3 screws on the back of each mirror. Looking through the camera we moved the first mirror until we could see the second, then the second mirror until we could see the point light source.

Finally, with both mirrors aligned, we could see a dot of light reflected off of the second mirror. This dot came in and out of focus moving away from the mirror. We placed the razor blade (a slit or hole also work) at the point where the dot of light was smallest. We covered half of this dot before it reached the camera. This setup can be seen in Figure 1.

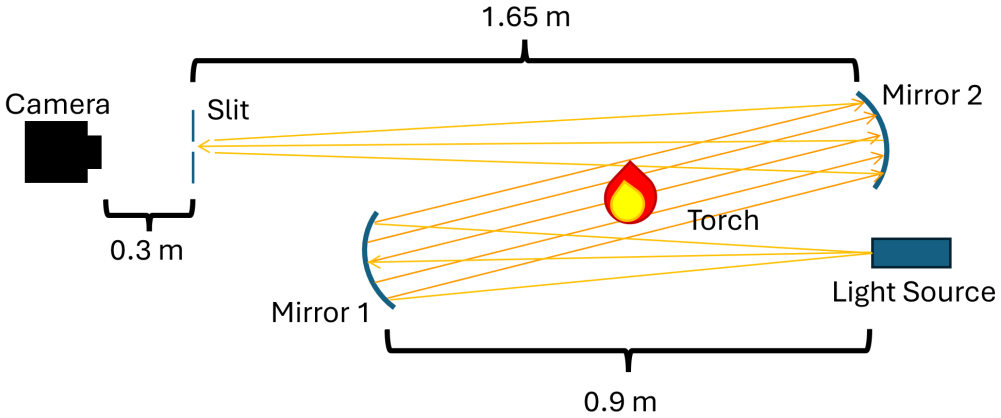


Figure 1: Experiment Setup

III Flow Phenomena

We have gone over our setup, but why does this work? The effect depends on the changes in refractive index as fluid temperatures change.

Light leaves the point sources and is collimated by the first mirror, meaning all the rays travel parallel to each other. The second mirror focuses the rays back down to a point, this is where we placed the razor blade. The subject must be between the two mirrors. Changes in fluid density between the mirrors bend the light rays such that, after hitting the second mirror, they miss the focus point and are caught by the razor blade instead. This causes these regions of varying density to appear as darker on the camera placed behind the blade.

The change in refractive index can be described by the Gladstone–Dale relation [1], which is as follows:

$$\frac{n-1}{\rho} = \sum km$$

Where n is the index of refraction, ρ is the density of the fluid, k is the Gladstone-Dale coefficient (2.3×10^{-4} m^3/kg, near constant for visible light [2]), and m is the mass fraction of the component. For simplicity we can assume that the air is the only component, but you can see faint changes in the video when the propane is turned on before it is ignited.

$$n - 1 = k\rho$$

The placement of the razor changes how the light is stopped. If we had placed the blade aligned with the horizon then we would be interested in how the light was perturbed in the vertical direction. In our case the blade was oriented with the vertical axis, so we are interested in how the rays are perturbed in the lateral direction [3]:

$$\delta = \int \frac{\partial n}{\partial z} \partial s$$

Here s is the path of the light ray. We can take the partial derivative of n with respect to z and solve for the perturbation δ.

$$\begin{aligned} n - 1 &= k\rho \\ \frac{\partial n}{\partial z} &= k\frac{\partial \rho}{\partial z} \\ \delta &= \int_0^L k\frac{\partial \rho}{\partial z} \partial s \\ \delta &= [k\frac{\partial \rho}{\partial z} S]_{S=0}^{S=L} \\ \delta &= k\frac{\partial \rho}{\partial z} L \end{aligned}$$

We integrated from 0 to L, which is from the start to end of the density disturbance parallel to the light. The density gradient is taken perpendicular to the light rays. Now we can estimate the perturbation of the light passing through the propane torch. A propane

torch burns at nearly 2000°C. Treating it as an ideal gas and assuming it is still at atmospheric pressure, the standard atmosphere has a density of 1.225 kg/m^3 and the air at 2000°C has a density of 0.155 kg/m^3. If this change in density takes place over 1cm vertically, then the gradient could be:

$$\frac{\partial \rho}{\partial z} \approx \frac{0.155 - 1.225}{0.01\text{m} - 0} = -107\text{kg/m}^3/\text{m}$$

Let us assume the propane jet is a similar scale of 1 cm:

$$\begin{aligned}
\delta &= k\frac{\partial \rho}{\partial z}L \\
\delta &= (2.27 \times 10^{-4}\ \text{m}^3/\text{kg})(-107\ \text{kg/m}^4)(0.01\text{m}) \\
\delta &\approx -2.43 \times 10^{-4}\ \text{radians}
\end{aligned}$$

This is a very rough estimate, but the scale makes sense. It is large enough that it would miss the focus point and get caught by the razor without being unreasonable.

Finally, we can calculate the non-dimensional Gladstone-Dale coefficient [4]. This non-dimensionalization uses a reference density, where we can once again use the standard atmospheric density of 1.225 kg/m^3:

$$k^* = k\rho_{ref} = (2.27 \times 10^{-4})(1.225) = 2.78 \times 10^{-4}$$

This project used air temperature to manipulate and visualize density, but there are plenty of other ways fluid density can change. For example, when pressure changes in shocks. Sun, Gan, and Wu [5] used a high speed camera to measure shock waves and boundary layer interactions. They found that larger ramp angles lead to more intense low-frequency unsteadiness in the shock wave. Other materials can also be used, for example Mohsenimehr *et al.* [6] use schlieren to visualize plasma when analyzing the ion wind produced by surface dielectric barrier discharges. There are many useful applications of schlieren imaging, it is a relatively simple setup that allows otherwise invisible fluid dynamics to be visualized.

IV Visualization Technique

The schlieren setup was our visualization technique for this project, which has already been discussed plenty. It allowed us to see the changes in air density caused by a change in temperature. We used two Edmonton Industrial 4" Parabolic Mirrors for this.

One of the keys for a schlieren setup is a point light source. We made the closest we could to this using a Lezyne Lite Drive 1000XL bike light. We covered both LEDs on the light with tape and poked a small hole directly over one of them. The light was set below its max 1000 lumen brightness, instead at 500 lumens.

V Photographic Technique

The video was taken at 120fps on a Canon R50. This requires enabling a specific high frame rate mode, which limits the camera to 1920x1080 and does not record any audio. The full zoom of the lens was used so the mirror took up all of the frame. The shutter speed used did not follow the 180 rule, which would have required it be 1/250 seconds. I instead used 1/320 seconds to avoid losing information in the bright parts of the image. The ISO was automatically set to the lowest value.

Camera	Canon R50		FOV	7° (@210mm)
Type	Mirrorless		Distance to Object	$\approx$ 2.4 m (reflected)
Original Image	1920x1080 pixels		Aperture	f/8.0
Final Image	1920x1080 pixels		Shutter Speed	1/320 second
Lens	RF-S 55-210mm f/5-7.1		ISO	AUTO (100)

Table 1: Photo Specifications

Davinci Resolve was used for video editing. The final video was shown at 30fps, and I changed playback speed from 1x to 0.25x at different points in the video. This means when the playback was slow every frame was being shown, but when play back was fast only every fourth frame was shown. I created a visual indicator that shows the speed as it ramps up and down using a coded Text+ box in Davinci. The video I recorded came out very blue. I tried modifying the white balance but realized one side of the frame was more orange than I had realized. Moving the white balance to reduce the blue brought out this orange too much, so I instead opted to cut the saturation of the whole video by half. This effectively stripped all color from the video, allowing the viewer to focus instead on the fluid flow.

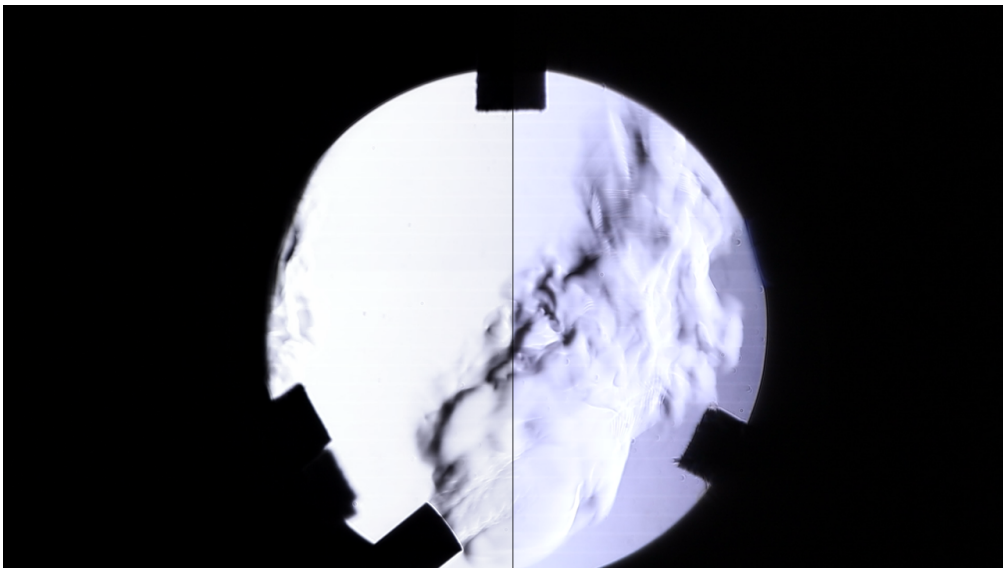


Figure 2: Comparison of stills from edited (left) and original (right) videos

VI Safety

Working with flames requires you to be careful and intentional to remain safe. The course outlines Combustion Experiment Guidelines that we followed.

1. The test was conducted in an empty parking lot. We cleared any flammable materials from the area and selected a location without any visible stains from potentially flammable liquids like motor oil.

2. We had a fire extinguisher on hand and within reach of a group member at all times.

3. With one group member at the camera and a second holding the test item, we had a third member free to observe and act in case anything went wrong.

4. PPE was not deemed necessary. The items used were matches, a lighter, and a propane torch. No fuels were handled and extra layer added when handling the lighter or matches could have decreased safety instead. The burner for the propane torch was very far from the control knob, ignition switch, and handle.

5. Shielding was not used. The camera operator was over a meter from the source of the flame. Shielding was not necessary for the individual holding the flame as these were all common household items designed to be operated safely as long as it is done carefully.

VII Conclusion

Schlieren is a very interesting visualization technique, I enjoyed learning how it works and succeeding in using it for my own experiment. I am very happy with the video that I created and think this was a great way to satisfy the video requirement for the course. This was one of my first attempts at video editing and enjoyed learning about each step as I worked through them in Davinci. I would like the opportunity to revisit this project using other ways to change air density, specifically compressed air. I have seen some videos online of small shock waves that I would like to recreate.

References

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