Team First Report

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Introduction

My inspiration for the Team First assignment was simply to attempt a schlieren setup for a couple of common applications such as compressed air, and heat sources. None of us on the team had any experience with schlieren imaging and just wanted to learn more about the technique.

Out several flows which I tried, I liked the candle flame the best. The black and white nature of schlieren imaging can create a great feeling of depth in the flow, and the heat convection currents have fantastic smooth textures.

The structures in the candle flow are quite intriguing. Specifically, you can see distinct vortices where the whole plume flickers from left to right, as well as uniform pulses. Additionally, this visualization enables me to analyze some characteristics of the convection current like speed, size of the plume etc. One of my goals was to measure the speed of the flow to estimate the effects of turbulence via the Reynolds number.

Setup & Visualization Technique

To capture this image, I used a classic Z mirror schlieren setup. After using a phone flashlight to find the focal length of the mirrors, the setup was arranged as shown in Figure 1. My iPhone 14 flashlight was used as the light source. For a proper schlieren setup, a point light source is desirable. To emulate a point source, a small piece of foil with a hole was placed over the LED.

Instead of capturing an image of the light beam directly, I projected the light onto a flat background behind the knife edge and took a picture of that projection. One major factor that impacted this decision was the short focal length of my lens (55mm). When I attempted to capture images of the beam directly, the low zoom factor would cause the mirror to appear very small in the frame. Imaging the projection meant that I could fill the frame better but lose a ton of light due to material absorption.

The subject of my visual was a common “tea light” candle, placed just below the optical path of the mirrors. While you don’t see the flame itself in the video, this allowed me to fit more of the convective flow and wake into the FOV. In the context of this setup, FOV refers to the diameter of the collimated beam, which was measured at 3 inches.

The knife-edge cutoff was placed on the left side of the beam, blocking about 25% of the focused point. In this case, the use of a vertically aligned edge allows us to visualize density gradients in the horizontal (left-right) direction.

One final consideration here is that there may have been drafts in my test setup, which will affect the flame. Even small movements like walking around the room would disturb the flow.

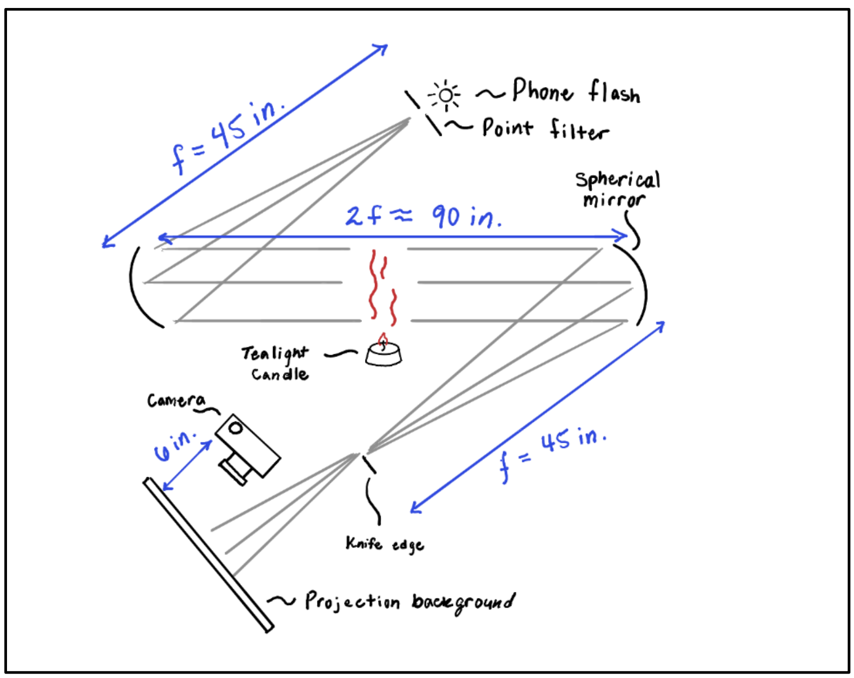


Figure 1: Setup Sketch

Analysis of Flow

The flow emerging from the candle flame is primarily driven by buoyant forces caused by the density difference of the hot combustion gas. As the flame heats the surrounding air, the fluid expands and its density decreases, producing an upward buoyant force [1] . This rising jet begins as laminar, but transitions to turbulent due to shear between the hot plume and surrounding quiescent air. The schlieren imaging reveals the unsteady nature of this shear layer, where small perturbations amplify into rolling vortices and mixing structures.

In addition to buoyancy, gravity and viscosity also play a role in shaping this flow. Gravity provides the restoring force necessary for buoyant effects, and viscosity diffuses the momentum of the plume thereby creating turbulent structures [2]. At the small length scales of a candle flame, Reynolds number is typically in the transitional regime (100's – 1000's). This explains the coexistence of coherent rising structures alongside turbulent mixing.

The flow is also strongly time dependent, with vortex shedding and oscillations generated as the hot gases interact with the surrounding cooler air. Specifically, flickering arises from vortex shedding at the plume boundary, a common instability in buoyant diffusion flames [1].

After analyzing the video, I estimate a parcel of traverses the circle of light in about 5-6 frames. This correlates for a speed estimate of 0.38 – 0.46 meters/s. (18 in/s). Combined with an estimate for the viscosity and density of the hot combustion products, we can calculate the Reynolds number as follows:

$$Re = \frac{\rho U L}{\mu} = \frac{(0.27\ \frac{kg}{m^3})\left(0.38\ \frac{m}{s}\right)(0.0762\ m)}{4.8 * 10^{-5}\,\frac{kg}{m * s}} \approx 200$$

This result matches nicely with the phenomena observed. 200 is firmly in the transitional regime, where you might see features of both laminar and turbulent flow.

Photographic Technique

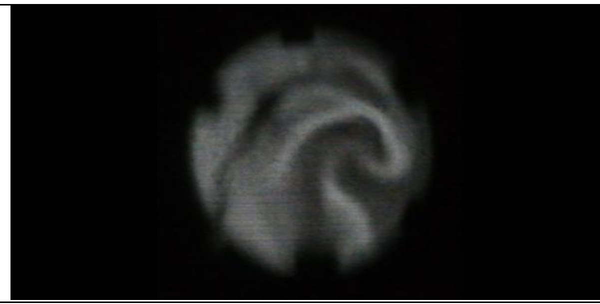
The camera settings used to capture this visual are summarized below in . This was a tough shot, since it was so heavily constrained by the amount of light. ISO was set to the camera maximum, and a fast shutter speed or framerate was necessary to capture the fast moving flow. This setup made for some very grainy, low-resolution stills. So, I opted for a video instead. Since I had somewhat poor spatial resolution, the video compensate with a lot more temporal resolution.

Camera	Fujifilm X-E4
FOV	8 in. frame width
Subject-Camera Distance	6 in.
Focal Length	55 mm
Aperture	f/4

ISO	12800
Resolution	1920 x 1080 (px)
Framerate	30 (fps)

Table 1: Camera Settings

Editing was fairly light, I added a slight blue tint, adjusted contrast and cropped the video. I also chose to slow down the video to ½ speed. This made it easier to see the rolling vortices and other structures, since they are moving quite quickly.

	
Unedited Frame	Edited Frame

Reflection

Based on the video and the Reynolds number for the flow, it seems like the convection currents are barely in the turbulent regime. There are a couple moments in the flow where the oscillations pause, and it seems like the plume almost becomes laminar. It's a nice regime to image, since you can see some vortex shedding and other instabilities, but it's not so turbulent that the physics become indecipherable.

Overall, I'm happy with the visual. Although there's room for improvement, I believe the physics are shown well. If I were to do this again, I would use a longer focal length lens and point my camera into the beam of light. This would fix a lot of my photography issues and produce a much shaper picture. It would also be interesting to have a larger setup, so that you could fit more within the test section. I found that a lot of my flows were quite long, so you only get to see a piece of them.

Contributions

I want to thank my teammates Will and Nick for their enthusiasm to give Schlieren imaging a shot. Although Nick used a different setup from mine, he gave a lot of great advice. For his part, Will sacrificed a whole afternoon with me attempting to set up the mirror system for the first time. Although we didn't get any images from that session, it helped us understand the process of aligning the optics.

References

[1] S. R. Tieszen, “On the fluid mechanics of fires,” *Annual Review of Fluid Mechanics*, vol. 33, no. 1, pp. 67–92, 2001, doi:10.1146/annurev.fluid.33.1.67.

[2] E. E. Zukoski, *Fluid dynamic aspects of room fires*, in *First International Symposium on Fire Safety Science*, Int. Assoc. Fire Safety Sci., 1985, pp. 1–30. Available: https://publications.iafss.org/publications/fss/1/1/view/fss_1-1.pdf