Team Second: Fog Laser

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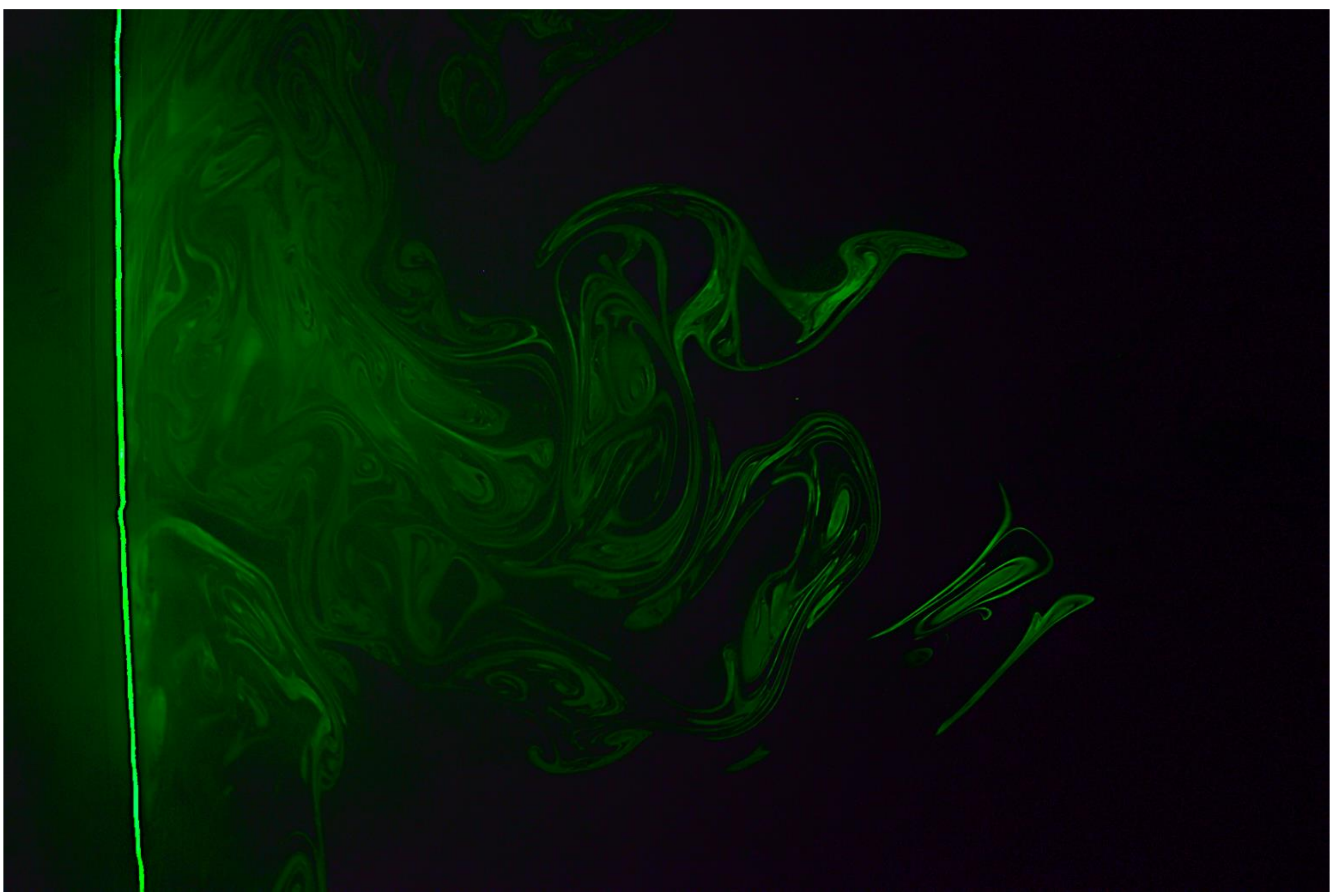

I. Introduction and Background

The primary intent of this image was to capture a 2D cross-section of a turbulent flow. Once we had established that we would accomplish this through a fog machine and a laser, I knew I wanted to make a somewhat darker image that would appear shadowy. On previous assignments, I edited my images heavily, often brightening and completely changing the color profile. In contrast, for this assignment I wanted to keep the editing fairly minimal and use it to highlight the shadows of the image and ensure the features of turbulence remained sharp and clear while making the image appear darker.

Our experiment was performed in Michael Becerra's basement, using a powerful laser pointed into a cylindrical prism to project a 2D vertical plane of light. This light was pointed at a solid black background and near this background, a fog machine was placed right next to the plane of light. When the lights in the room were turned off and the laser was the only source of illumination, we would activate the fog machine, creating a dense flow near the end of the light plane, seen on the left side of the above image. This flow was very turbulent and as it spread from the origin point, it dissipated through the air in the room. This also had the effect of making these flow sections dimmer since less fog particles were reflecting light.

It took several trials of the experiment to get images to come out crisp and clear. Our initial laser wasn't nearly as bright as the one used in the image above. This meant it was very difficult to get enough light to reflect off the fog to take well-lit pictures. We solved this image by moving the laser much closer and blowing fog into a small, reflective box to concentrate the fog particles and the intensity of the light. However, this required taking pictures at a very small scale and the fog swirled around very quickly in the box, making it difficult to capture an image that had a short enough exposure time and still properly bright. This issue disappeared when we began using a more powerful laser that provided far more light and allowed us to take pictures over a larger space, decreasing the speed of the flow and allowing us to take sufficiently fast and well-lit pictures.

II. Experimental Setup and Theoretical Calculations

The experimental setup can be seen below in Figure 1. As described above in Section I, we pointed a laser at a black background we hung from a shelf, directing the beam through a cylindrical prism in the transverse direction, projecting a vertically oriented 2D plane. The fog machine seen on the left side of Figure 1 was used to produce our flow. For each pass of the experiment, one member of the team would operate the laser and direct the light with the prism, making minor adjustments as needed. The other two team members stood to either side of the laser plane taking pictures while one also operated the fog machine with a foot switch on the ground. While the fog spreads omnidirectionally into the surrounding air, the distance from the laser to the background being roughly 8 ft and this was the only section of the flow that was highlighted. Even so, the region shown in the final image is roughly 3x3 ft.

Fig. 1: Experimental Setup Showing Laser and Fog Machine

To estimate the Reynolds number of this flow, we will be approximating the fog as flow over a flat plate. The fog was released very close to the floor in a parallel direction, so this assumption should be fairly accurate. I'd estimate the fog traveled about 1 ft, or 0.3048 m, before reaching the laser plane. According to Shavlov, "the viscosity of the fog could be ten times higher than the viscosity of pure air" [1]. However, it is also stated that "at large values of the gradient, the viscosity of the fog approached the viscosity of air" [1]. Because we are imaging very close to the origin point of the fog and early in the flow development, I will assume a fairly high gradient and will be estimating the viscosity of the fog as roughly 3 times the viscosity of air. According to Engineering Toolbox, the kinematic viscosity of air at 60°F is $14.66 * 10^{-6} \frac{m^2}{s}$ [2]. Multiplying this by 3 gives us $4.398 * 10^{-5} \frac{m^2}{s}$. The equation for Reynolds number over a flat plate is given by Eqn. 1 below [3]. Here V is the fluid velocity, L is the length of the plate, here we will be using the distance the flow traveled across the flow before reaching the laser plane, and v is the dynamic viscosity of the fluid.

$$Re = \frac{VL}{v} \qquad \text{Eqn. 1}$$

For the flow velocity, I will be estimating based off strictly visual evidence a very rough value of 1 ft/s or 0.3048 m/s. Plugging in these values gives us $Re = 2112$, which is far too low to reliably guarantee turbulence. However, according to Brendan McGuigan, fog machines commonly get up to 400 °F [4]. Additionally, because the fog is initially very concentrated when exiting the outlet of the fog machine, the velocity is substantially higher. The fog is ejected from the machine by an internal fan. Making the assumption that the cross-sectional flow area is smaller by a factor of 20 when exiting the fog machine, the velocity is higher by a factor of 20. This new temperature results in a kinematic viscosity of $35.02 * 10^{-6} \frac{m^2}{s}$ for air [2] and $1.05 * 10^{-4} \frac{m^2}{s}$ for fog [1]. Additionally, the velocity is $6.096 \frac{m}{s}$. Finally, at this outlet, the characteristic length becomes the hydraulic diameter of the rectangular duct, which was roughly 3x15 cm. The equation for hydraulic diameter is given by Eqn. 2. With these measurements, we can calculate $D_h = 0.05\ m$. Plugging these values into Eqn. 1 and replacing L with D, the result is $Re = 2900$. Because this is now pipe flow, the condition for turbulence is that $Re > 2300$. This shows that the fog is sufficiently turbulent upon exiting the fog machine. Once it has exited the fog machine outlet, the fog begins to diffuse and spread throughout the room and remains turbulent.

$$D_h = \frac{4A}{P} \qquad \text{Eqn. 2}$$

The turbulence in the flow is very evident from the swirling vortices and the chaotic omnidirectionality of the flow. On the left side of the image, where the fog is the densest, clear patterns are difficult to make out. This could be for a few reasons. Because this is close to the point of origin of the flow, the density of fog in the air is far more uniform at this end, making it challenging to highlight specific flow patterns. Additionally, because this is the furthest point from the laser, the light has already passed through a significant amount of fog and may have reflected away. This would cause less light to reach the left side of the image and in turn could contribute to the relative blurriness in this region of the image. As the fog spreads out, it begins to coalesce into larger spirals and vortices that stand out much more clearly. As the fog moves into pure air, the tendency of the water molecules to attract each other helps the flow develop these features. Additionally, now closer to the light, these features are much better lit and stand out far more distinctly against the black background.

III. Visual Techniques and Camera Settings

As mentioned above, to visualize this flow we utilized a fog machine in Michael's basement which was roughly 60°F, potentially a bit colder due to periodically opening the windows to vent the fog out. A strong green laser was pointed through a cylindrical prism in the transverse direction to project a vertical 2D plane. This allowed us to visualize a 2D cross-section of the turbulent flow, simplifying the physics to a degree much easier to conceptualize than the full 3-dimensional flow. The drawbacks of this technique are primarily the blurring of the flow further from the light source as light begins to reflect off of fog particles and the fog grows denser. The particular settings on the Canon EOS Rebel 1500D (Rebel T7) used to take this picture are listed below in Table 1. Additionally, the original image is shown below in Fig. 2. The original image is 6020x4015 pixels while the final edited version shown on the title page is 1622x1080 pixels. This compression likely also effected the blurriness on the left side of the image.

Shutter Speed	1/50
Aperture	f/4.5
ISO	ISO3200
Focal Length	32 mm

Table 1: Camera Settings

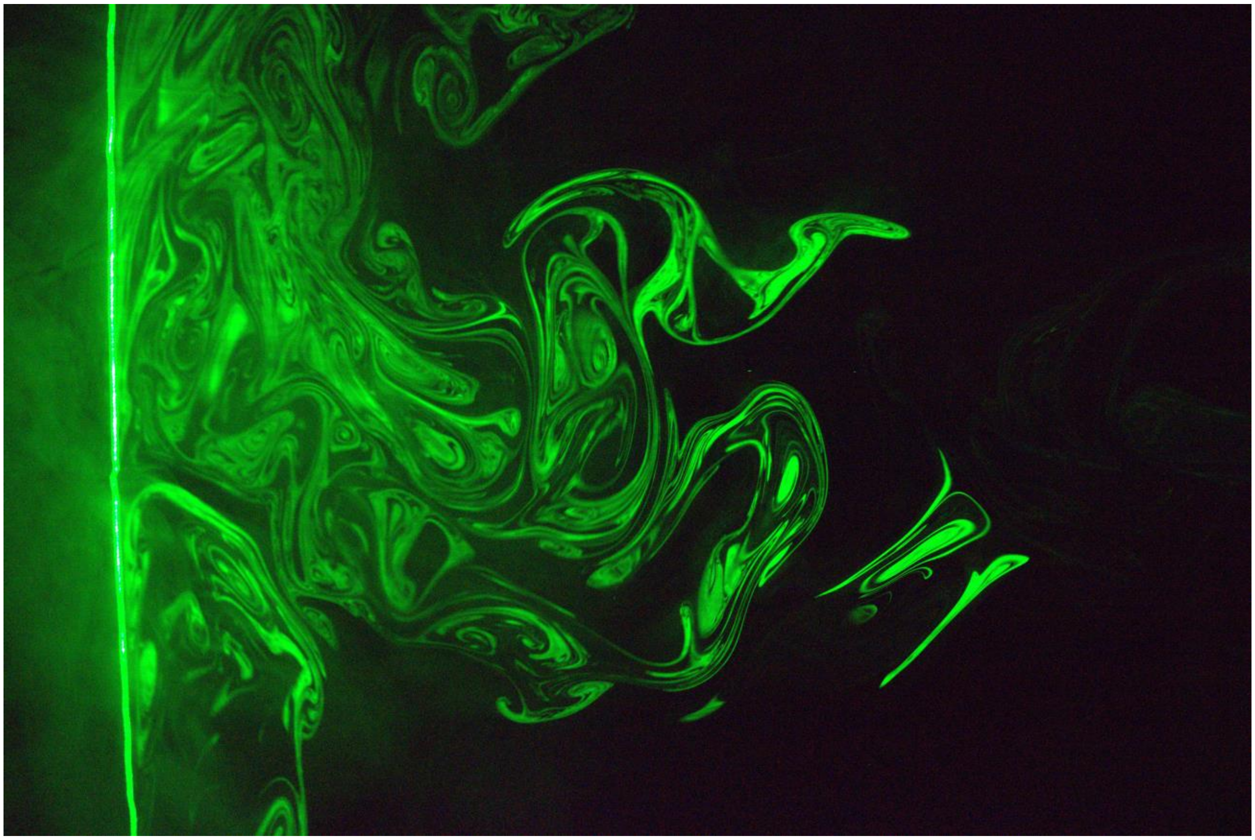

Fig. 2: Original (unedited) RAW picture

The image was taken from an approximate distance of 1 ft, the same distance from the laser plane as the fog machine since I was operating the fog machine via foot switch at the time of taking this picture. Additionally, the editing methods used to process the original RAW to the final version were fairly simple as I was trying to approach this picture in a more minimalistic way than my previous projects. The image was not cropped as I thought leaving in the laser boundary on the left side gave the image a better sense of scale. I mainly increased contrast and lowered the tones and white balance to darken the image. Finally, I increased the shadows and used the sharpen feature to clear up some of the blur, specifically on the left side of the image. I wanted to leave the color profile largely the same and edit the image mainly to darken it, embracing a murky, spooky vibe.

IV. Conclusion

I think this image reveals interesting insights into how turbulence behaves as a flow expands into a large space, dissipating from a dense, messy flow to more discrete features like vortices. I like the color palette of the image although I wish it was a bit sharper, which may simply be a feature of the experimental design. However, looking at the resolution of the original and the final image, this compression likely also had a lot to do with the final quality of the image and this issue could easily be resolved. If I were to reperform this experiment, I would vary the position of the fog machine and see how it affects the overall clarity of the flow throughout the image. I am not completely satisfied with the quality of this image although I do think the physics captured are interesting. Once again, given the feedback received from professors and fellow students, I have plenty of ideas on how to improve the experiment and the resulting image in the future.

References

"Air - Dynamic and Kinematic Viscosity." *Engineering ToolBox*, www.engineeringtoolbox.com/air-absolute-kinematic-viscosity-d_601.html. Accessed 7 Nov. 2023.

Brendan McGuiganLast Modified Date: October 06. "How Does a Fog Machine Work?" *Easy Tech Junkie*, 6 Oct. 2023, www.easytechjunkie.com/how-does-a-fog-machine-work.htm.

"Reynolds Number." *NASA*, NASA, www.grc.nasa.gov/www/k-12/airplane/reynolds.html. Accessed 7 Nov. 2023.

Shavlov, A.V., et al. "Non-Newtonian Viscosity of Water Fog." *Science Direct*, North-Holland, 26 Aug. 2022, www.sciencedirect.com/science/article/pii/S0375960122004765.