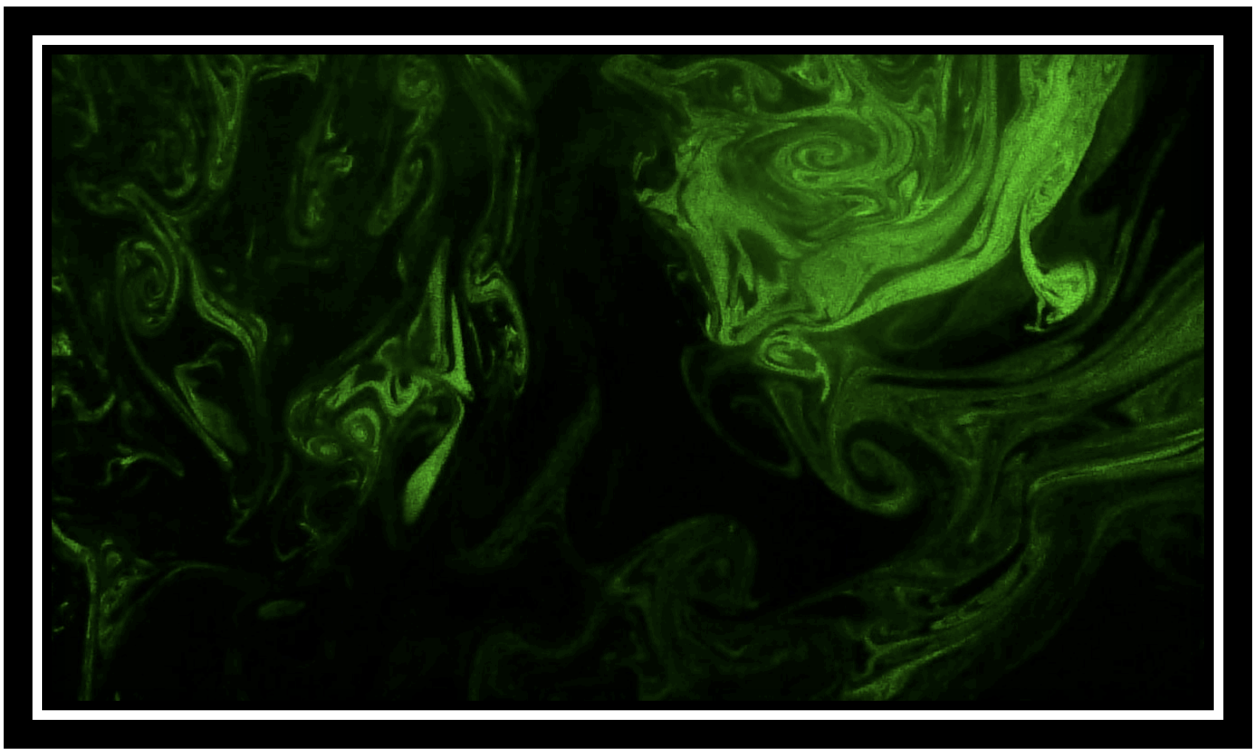
All Green Lights

MCEN 4151: Flow Visualization
April 4, 2011



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When fluid flows happen very rapidly or have small, intricate features it can be difficult to fully realize these flows and visualize them in a way such that information is not lost or interfered with. In this project we set out to utilize laser sheets to resolve flows on an extremely fine time scale as well as spatially. The original goal was to cut a turbulent plume of fog down to two dimensions by illuminating a plane with a high-powered pulse laser. This lead to exploration of what was possible to visualize with the laser sheet and eventually included vortex rings and ambient flow around a calm room. Our group utilized Professor Hertzberg's flow visualization laboratory and equipment to create these images and videos. This provided us with an ideal location to create a range of flows in a controlled environment with precision equipment. The results were nothing short of spectacular; we were rewarded with extremely fine time and spatial resolution in videos that captured the motion and physics of the flow superbly.

An extensive setup was not necessary for this visualization; just an enclosed room to shoot in, a laser, and a fog machine. For safety reasons laser trapping material was paramount. A backdrop was added to ensure a neutral background for shooting. These elements were placed as shown in Figure 1, though the fog machine was moved to the floor and shot upwards at an angle in the final setup. As seen in the figure the laser was placed upon a table and aimed at the laser trap to ensure that no strong specular reflections would be encountered. The fog machine was aimed upwards at an angle not incident to the laser to reduce the likelihood of forming small fog precipitates on the lens or internal components of the laser, which could disturb its operation and potentially damage it. The camera was placed perpendicular to the direction of the laser and across from it was the neutral backdrop.

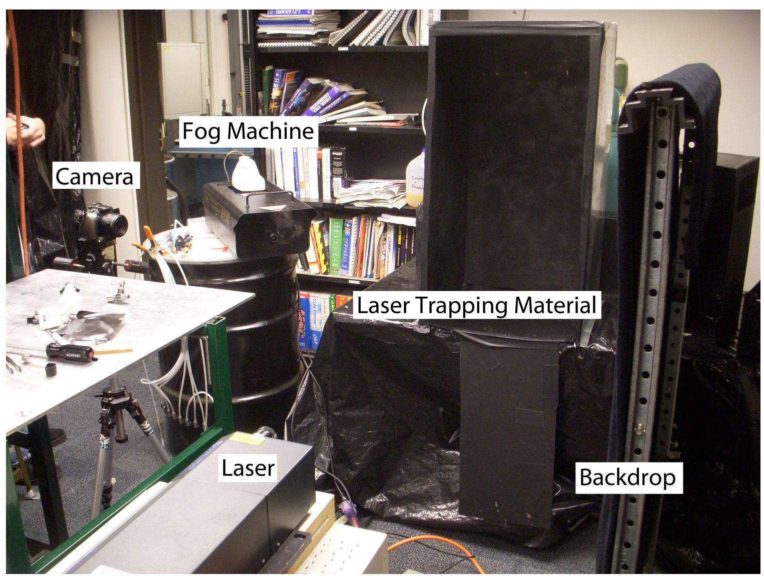

Figure 1: Flow Visualization Lab Setup

This setup allowed for a range of flows to be produced in the area between the laser and the laser trap. In this open space we were able to produce turbulent plumes by firing the fog machine upwards into the plane of the laser, vortex rings by firing a ”Mighty Blaster” by Zero Toys [1] into the plane of the laser, and ambient room flow by simply allowing residual fog in the room to move naturally across the plane of the laser. The laser plane was created by placing +1000mm, -15mm, and -25mm lenses on the laser. Using the thin lens equation,

$$\frac{1}{object\ distance} + \frac{1}{image\ distance} = \frac{1}{focal\ length} \qquad [3]$$

and a premade laser sheet calculator on the Wisconsin Shock Tube Laboratory [7] website it was calculated that at 914mm (~36in) from the laser we would have a 435.2mm (~17in) tall sheet with a spread of 27.50°. This allowed for substantial space to create the flows in, as the sheet continued to grow as it moved away from the laser. The final field of view in the video was only a section of this sheet, approximately 18 inches wide and 13.5 inches tall.

Within this plane it was possible to create the three different, unique flows. The first of these flows was the one decided upon to be visualized for this project: the turbulent plume. At its core this is a basic flow, nothing more than a jet of fluid through a nozzle into a less turbulent space. While the formation of such a flow is simple the physics behind it are complex and varied. First of all this flow happens in the turbulent region with a Reynolds

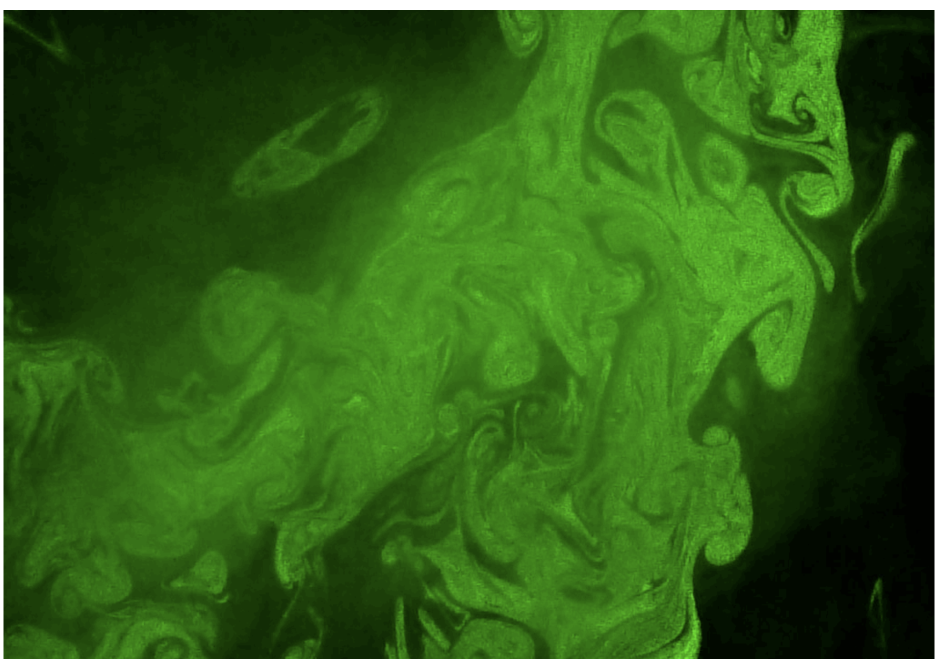

Figure 2: A turbulent plume moving from the bottom left to top right

number greater than 4000, which correlates to a velocity of at least .19 m/s for air. When the Reynolds number is this large the inertial forces dominate the flow instead of the viscous forces [2]. This can be seen in the chaotic nature of the flow, many different eddies are superimposed on one another and interact in a spontaneous and instable configurations. The result is a highly complex system of eddies and vortices which become unstable and dissipate as quickly as they form. Figure 2 shows an example of such a flow. Within the figure it is easy to see large and small eddies interacting with one another. The instantaneous direction in the flow can be seen at any point by observing the features around it and the direction in which the eddies are forming, though it may change at any time.

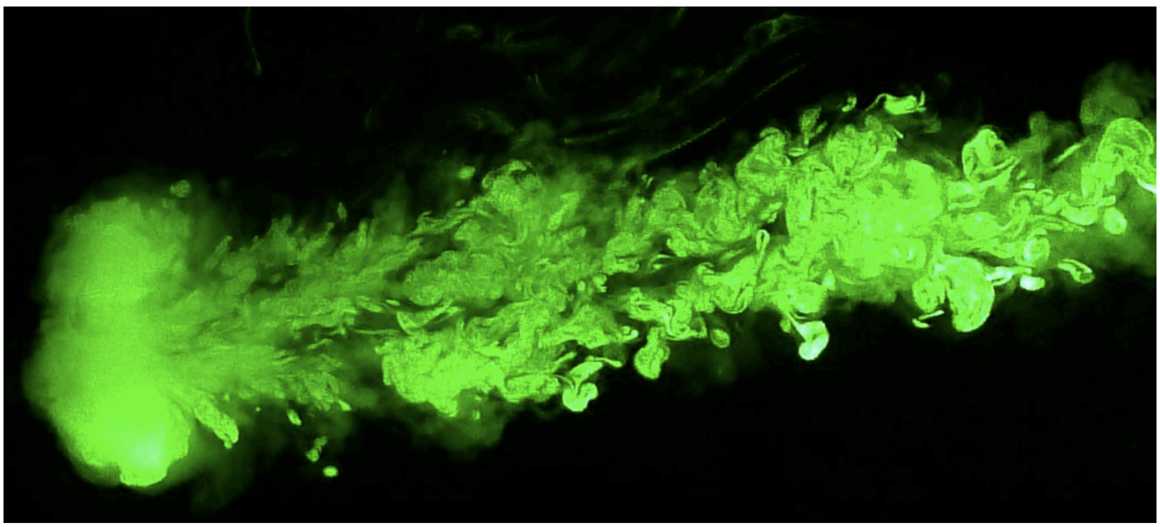

Figure 3: Vortex Ring and subsequent turbulent flow

The next flow that was observed was the vortex ring, or toroidal ring, as seen in Figure 3. This is a classic flow visualization phenomenon known widely as a smoke ring, though it can be formed out of other mediums as well. This flow occurs in the transient region, with a Reynolds number between 2300 and 4000. This means that the velocities within the ring are between .11 m/s and .19 m/s. Since it is in the transient region the flow is dictated by a combination of inertial and viscous forces [2]. The inertial forces drive the propagation of the ring and its movement forwards but the viscous forces give it a distinct shape. The vortex ring was generated using a “Mighty Blaster” from Zero Toys [1]. This device uses a piston to accelerate a column of air through a smaller opening. As the air passes through into open air it is endowed with forward motion from the piston and is also imparted with curl from the lip of the opening. This phenomenon is depicted in Figure 4. It is this combination of forces that act to form the ring. A column of air is pushing forwards through the center of the ring, moving it forwards. Inertial forces dominate this mechanic. A shear force is also acting along the outside of the ring, pushing it in the direction opposite of propagation. This induces more curl, spinning the outside of the ring into its distinct shape. The ring is formed by the combination of these elements, creating almost a 3 dimensional eddy, symmetric about the axis through the center of the ring. As the ring moves forwards air is pushed through the center of the ring and is subsequently pushed backwards by viscous shear forces, curling it back into the center column. This process is happening constantly as the ring moves forward and it will hold its shape until it slows down enough to become unstable [4].

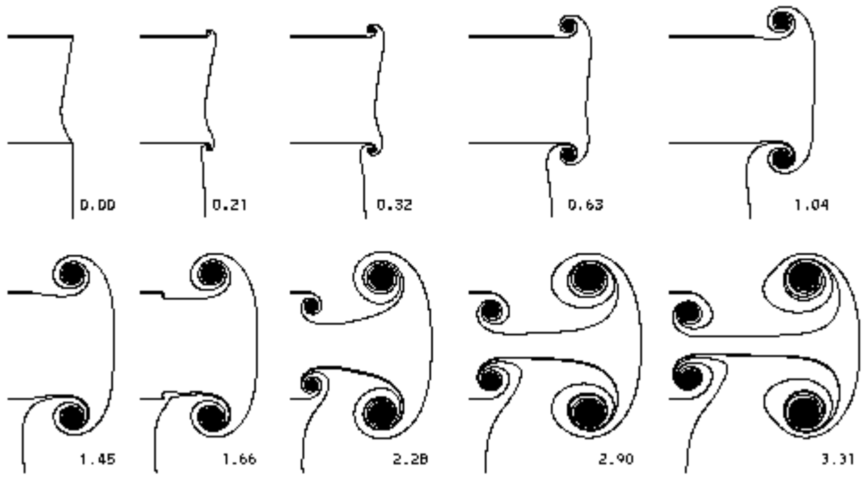

Figure 4: The formation of a vortex ring by a piston [4]

The final flow captured in the submitted video was laminar flow in a room. This was captured after a series of plumes had been fired into the laser, and was comprised of residual fog moving lazily about in the plane of the laser. While

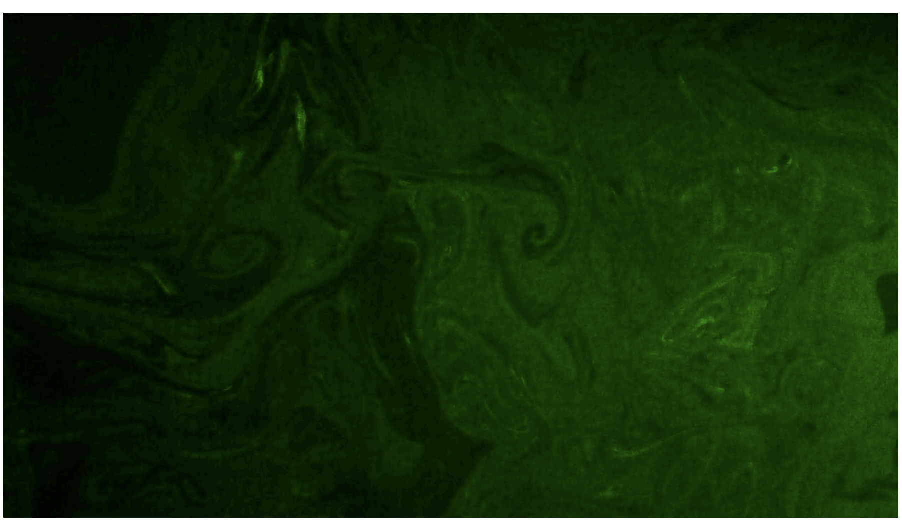
Figure 5: Laminar flow in a room

small eddies did form in this flow, most likely from perturbations caused by individuals moving around the room, the majority of the flow remained smooth and laminar. This flow exists in the laminar region, with Reynolds numbers under 2300 and velocities less than .11 m/s. In this flow viscous forces dominate the movement by trying to resist movement [2]. This is governed on a basic level by the interaction of molecules and their tendency to diffuse. There may be inertial effects giving the gas an initial velocity, but the majority of the forces are working to oppose this movement. The result of these integrations is a lazily moving flow that is trying to slowly oppose any movement but is periodically interrupted by turbulent features coming in to play. An example of this flow is shown in Figure 5, where a relatively calm flow is disturbed by turbulent interactions.

To ensure that these flows were entirely visible and well resolved laser sheet visualization was utilized. This consisted of passing fog through the plane of the laser in any of the aforementioned manners. A fog machine that is available in the flow visualization laboratory produced the fog for this project. To ensure optimal performance and longevity the machine was cleaned, used, and then cleaned once again. The fog produced was nearly neutrally buoyant, as the particles were denser than air but they were at an elevated temperature after being vaporize in the fog machine. The temperature in the lab was approximately 20°C. The lighting was achieved solely through the use of the laser, which was set on low power and fired at approximately 10 Hz. This provided substantial lighting once the lab's lights had been turned off.

To capture the flow a Panasonic Lumix FZ35 was used. This 12.1 megapixel camera has a 27-486mm wide-angle 18x optical zoom. When used for recording, the product was a 3-megapixel resolution video for an overall size of 1280x720 pixels at 30 frames per second. This camera was set up on a tripod approximately 24 inches away from the laser sheet. No data was taken for the aperture, focal length, shutter speed, or ISO settings. iMovie was used to edit the various clips that were shot through a range of trials. This allowed me to cut out small sections of the flow that I found beautiful, entertaining, or informative. It was also used to stitch the clips back together using premade transitions. The video FX features were used to create the mirrored effects and adjust the playback speed, slowing it down, speeding it up, or even running it backwards.

When everything was said and done I was extremely proud of my final product. I had set out to capture an image of a turbulent plume, but by the end of shooting I knew that I wanted to use the film footage instead. The videos explained the physics and movement of the flow in ways that a still image never could. As this was my first endeavor in editing film it was a long and frustrating process at times, but as I became more familiar with the software I began to enjoy editing my movie. I had no stylistic approach when I began; I simply had a series of clips I wanted to present, so I set to combining them. As I was working a song came up on my iPod that fit the flow that I was working with. I was nearly halfway done with editing when I found this song that I wanted to add in, but the song fit so perfectly that nearly none of the first half of the video had to be revisited to be cued with the music. It worked out even better because the music, All Green Lights by Paper Diamond, is produced and distributed for free. This did lead to my video spanning the entire length of the 4 minute long electronic dance ballad, which took the focus out of the particular flows I wanted to show. But in the end I feel as though I created something that is approachable by anyone. It has almost a musical visualizer feel. Slow sections of the song were matched to plumes lazily expanding out, and the quick claps were matched to vortex rings quickly making their way across the frame. But even on a smaller scale the fast tempo of the beat matches so well to the variety of small turbulent flows found in almost every clip.

While the video could have been shortened to bring more attention to a particular few flows, it would lose the overall view of our project. This video shows a range of unique flows that fall into one of the three flow features as mentioned above. It is easy to lose oneself watching these beautiful flows take shape. To bring focus to a few of the more unique flows I revisited these clips throughout the film, showing them at different playback rates or with a visual effect. One such flow is the clip that the film starts to, where laminar flow is pushed out of the frame just before a vortex ring passes by. This happens so quickly that it is easy to think the film was cut there, but in fact the preceding wake of the vortex ring pushed the laminar flow out of the plane just before passing through itself. It is these small details that had me watching the film over and over, looking for small, intricate flows. And it was easy to show the flows so clearly when this visualization technique was used. The physics are readily visible throughout the entire film.

To develop this idea further I would first reduce the length of the video. It is simply too long to hold one's attention, especially with the lack of new flows to present. To this end I would focus on a few unique flows and try to showcase their physics through different playback speeds. I would also like to further explore the features that video editing software offer me to create an overall entertaining final product. In the meantime I am quite happy with the final video and have watched it multiple times since its completion.

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