This image was produced for the first project of Professor Jean Hertzberg's Flow Visualization course. The image was taken with intent of documenting the transition of smoke flow from laminar to turbulent.

The experimental apparatus was trivial. Incense was mounted on a plate and lit, and the resulting smoke plume was photographed. To see a diagram of the experiment/photograph set-up, consult Figure 2. Instead, we will discuss the fluid mechanics present in the annotated image depicted in Figure 1.

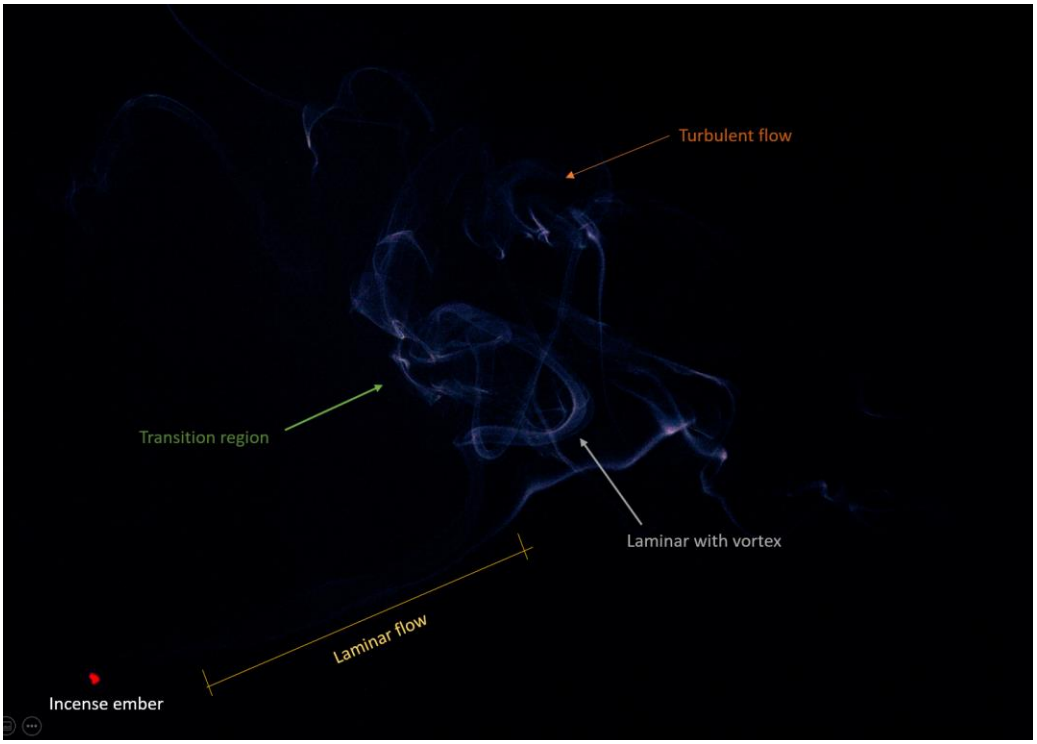

Figure 1: Final image with flow regions annotated.

The smoke rises due to buoyant forces. The ember heats the air in which smoke particulates are suspended. This air is less dense than surrounding air, and this discrepancy in buoyancy allows for the smoke to fill the volume above the ember. In this particular instance, drafts of air push the smoke laterally as it rises, causing the long laminar flow tube denoted in yellow text.

Just past this, the laminar flow starts to vortex due to the shear forces between the buoyant plume and the smoke and the surrounding air [1] [2]. Eventually, as the plume rises, its cross-sectional area increases due to diffusion. Diffusion is driven by entropy. As the smoke plume grows in volume, the particulates in the smoke and the air have more possible locations, which, according to the second law of thermodynamics, is favored. Since we know that laminar flow occurs at Re < 2100, we can estimate the velocity of the laminar flow by assuming the diameter was of the laminar flow was 2 cm, the kinematic viscosity was that of air 17.88 x10^-6, and the Re was 1500. $Re = \frac{uD}{v}$, therefore u (velocity) = 2 m/s , which is a reasonable solution.

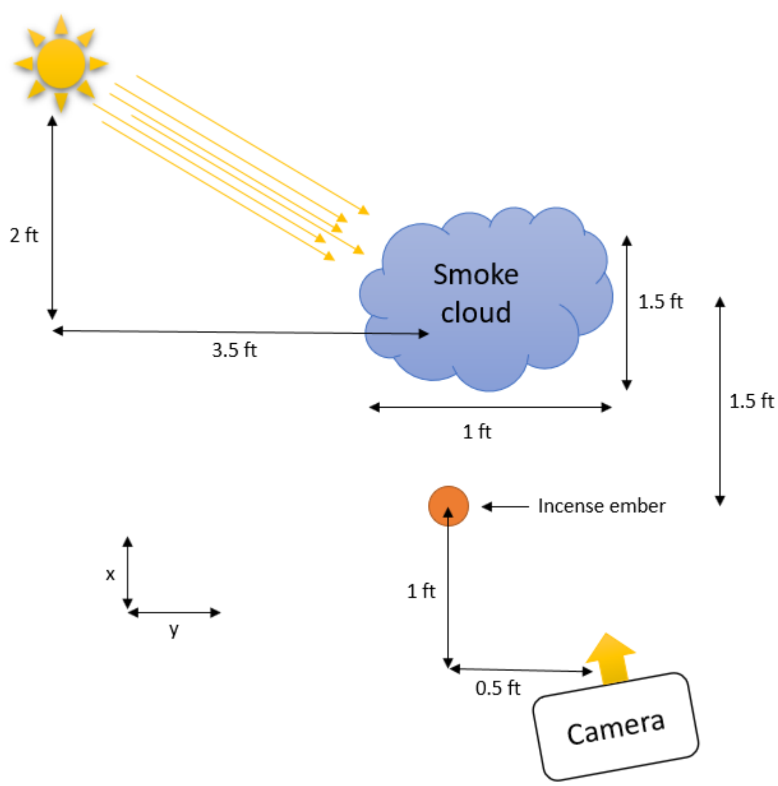

Figure 2: Top-down (Bird's eye) view of the photograph set-up. Due to unpredictable drafts in the shooting location, the smoke did not rise directly above the burning incense. Dimensions in the diagram portray dimensions in the x and y direction, but not the z direction (elevation). The camera and incense ember were positioned 0.5 ft off the floor. The center of the smoke cloud was estimated to be 1.5 ft from the floor, and the light source was positioned 3 ft from the floor.

The specific type of incense used is unknown- it was found in a junk drawer and repurposed for this project. The light for the image was provided by a 300 lumen LED headlamp that was mounted at the distances specified in the diagram from the smoke cloud. The headlamp was not operating at peak brightness- the best estimation is that 200 lumens of light were needed to create the image. Note that the headlamp was able to create a relatively focused beam, so in order to recreate the image, one should use a focused light source, not a diffused one.

A Sony α6000 mirrorless camera was used to take the photo. An F-stop of f/9, a shutter speed of 1/60 sec, and a ISO of 12800 were used to capture the image. The F-stop was specified by trial and error. Any smaller of a F-stop and only a small portion of the volume of smoke was in focus. The shutter speed was also settled on by trial and error- it was the longest shudder speed tested before the smoke became blurry from movement. The ISO setting was set to auto in hopes the software in the camera would decide the best ISO. Focus was set manually with a ruler before the lights were turned off to take the image. The image was heavily edited in post-production. Not only was the image heavily cropped, the denoise algorithm was utilized to undo the noise created by the high ISO value. Color was added by removing all the red form the image, as well as boosting the blues by 15% and removing 30% of all greens.

Figure 3: Before and after editing using Darktable. Notice not only the change in color, but the change in integrity of the black background.

The image reveals my inexperience in photography. The largest mistake I made was using the auto ISO feature. This made the RAW file grainy, and it took a lot of effort in Darktable to reduce the graininess and the noise. I am proud of the post-processing work I did on the image. Not only did I learn a lot about Darktable, I think the final image is more aesthetically pleasing and makes the fluid dynamics more clear. The laminar flows and turbulent regions are more pronounced, but the image does not look over processed. Because I captured the laminar to turbulent transition, I fulfilled my intent. However, knowing what I do now, I could have done so much better. For one, I should have used a dark background instead of relying on darkness for the image. This would have made shooting much less difficult (operating in the dark is non-trivial) and would allow me to reduce the ISO. It also would allow me to better illuminate the laminar region. To further this idea, I would reshoot the smoke in a less drafty region. This would keep the smoke flow vertical, allowing me to increase the aperture but maintain clarity.

Citations

[1] ROSENFELD, M., RAMBOD, E., & GHARIB, M. (1998). Circulation and formation number of laminar vortex rings. Journal of Fluid Mechanics, 376, 297-318. doi:10.1017/S0022112098003115

[2] SHUSSER, M., & GHARIB, M. (2000). A model for vortex ring formation in a starting buoyant plume. Journal of Fluid Mechanics, 416, 173-185. doi:10.1017/S0022112000008727