IV2 – Fog Machine

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Context and Purpose

The intent of my photo was to demonstrate the fluid flow phenomena exhibited as vapor smoke is created and expelled from a consumer grade fog machine. While we were unsure going into this experimental setup what artifacts we were going to see, we were fairly certain due to multiple visual observations that under the correct conditions we would be able to capture fascinating phenomena. Personally, for IV1 I used a liquid medium infused with organic liquid chlorophyll 'dye' droplets to get visualization results, so I wanted to take a different direction and capture a gas flow within gas medium. The most interesting and accessible way that our group thought of doing this was through a fog machine at my house. Throughout the imaging process there was a lot of fog production periods, some of which served to give us an idea of the phenomenon we could capture and much of which was spent capturing images that didn't turn out as hoped. Half of the team, myself included, was more interested in the laminar artifacts that appeared a few seconds after fog production, and the other half of the team was more interested in using different lighting techniques to illuminate the fog clouds at genesis. After numerous attempts, I was able to fine tune the camera settings and properly capture some of the flows that we had seen with our eyes in their fleeting form. My teammates for this project were Robbie Cooper, Kendall Shepherd, and Lana Pivarnik, and I'd like to thank them for their assistance in setup of the flow apparatus. In this report, I will lay out the phenomena, techniques, and insights behind this beautiful fog flow development process.

Flow Apparatus

Below in Figure 1 is a diagram of the flow visualization apparatus used for this photo. A standard home use fog machine was used with "Low Lying" fog mix and was cooled by ice placed in a cooling tray on the top of the machine. Throughout experimenting with different apparatus configurations, we found that we were seeing the most interesting flow patterns when we left the cooling tray hatch open and allowed the fog to rise vertically out of the vents here as opposed to the spout that it typically would come out of on the front of the machine. A Petzl LED headlamp on its brightest white light setting was used to light the fog captured from a horizontal distance of about 4 inches, and about 3 inches above where the fog exits the cooling tray. The flow type visualized as the fog rises out of the cooling tray is that it starts as semi-turbulent flow with many individual clouds, small vortices, and eddies. However, after a few seconds the flow relaminarizes [1] into a mostly non-turbulent flow that can be considered to be averagely laminar regardless of lingering small turbulent aspects, such as very small vortices. The image was taken at a distance of 16.5 inches from the two fog artifacts most in focus in the image, and at a 120-degree angle from the light coming from the left side of the image. While, due to their transient nature, these artifacts weren't measured in terms of their size, based on the field of view of the image I would estimate the parabolic waves at the top to be about 3 by 2 inches in the plane of the image, and the bulbous jet at the bottom to be about 5 by 1.5 inches in the plane of the image.

Fluid Phenomena

After Prof. Hertzberg suggested that the artifacts seen in focus in the image, namely the parabolic shape at the top center and the jellyfish-like jet at the bottom center, were due to relaminarization, I reviewed two academic papers covering this subject. The first was the *Relaminarization of Fluid Flows by Narasimha and Sreenivasan* which corroborated what was seen during this experimental setup: that a flow can relaminarize due to a number of factors and that, "turbulent fluctuations need not necessarily have completely vanished in the relaminarized state; but that, if present, their contribution to mean flow dynamics is negligible." [1] It asserts that there are three different "reverting flows" and I postulate that my image captures those falling under the second class, in which "turbulence energy is destroyed or absorbed by work done against an external agency, such as buoyancy forces or flow curvature," for which the typical nondimensional parameter is the Richardson number. This then led me to the second referenced academic paper, *On the flux Richardson number in stably stratified turbulence by Venayagamoorthy and Koseff* which gave several definitions and quantifications of the Richardson number.[2] I referenced this paper in conjunction with a few Wikipedia articles which condense down some info on Grashof, Reynolds, and Richardson numbers, in order to gain a more complete understanding of these dimensionless numbers.[3][6][7] To further characterize the visualized flows, I calculate the Richardson number under Boussinesq approximation [4], in which density differences are small between the flows, as follows:

$$Ri = \frac{Gr}{Re^2} \qquad [2][3]$$

Where Gr is the Grashof number for bluff bodies and Re is the Reynolds number:

$$Re = \frac{\rho U L}{\mu} = \frac{(.7364*2.62)\frac{kg}{m^3}*0.25\frac{m}{s}*0.0762m}{.0000372\ Pa*s} = 990 \qquad [6]$$

$$Gr_D = \frac{g\beta(T_s - T_\infty)D^3}{\nu^2} = \frac{9.81\frac{m}{s^2}*\frac{1}{297.54°K}*(24.44°C - 22.22°C)*0.0762^3 m^3}{\left(\frac{.0000372\ Pa*s}{(.7364*2.62)\frac{kg}{m^3}}\right)^2} = 87100 \qquad [7]$$

In these equations I've assumed that the fog is represented by Propylene Glycol, one of the primary components in "Low Lying" fog solution [8], that the fog is an ideal gas for purposes of simplifying coefficient of thermal expansion, that the fog temperature is 76F (24.44C), that the bulk room temperature is 72F (22.22C), that the dynamic viscosity of the fog is twice that of air at 25C, that the characteristic diameter/length dimension for the artifact is 3in (0.0762m), its width against the direction of movement, and that the velocity of the fog is 0.25 m/s at the time of capture. I found that the density of Propylene Glycol is 2.62 times that of air [9] and air density at 5000ft and 25C is $0.7364\frac{kg}{m^3}$. I've calculated these values only for the parabolic vortex loop artifact in the upper center of the image because Prof. Hertzberg mentioned during image review that the jet like artifact is likely to be a 3-D artifact that would be much more difficult to characterize in a useful manner. Based on these calculated Reynolds and Grashof numbers the Richardson number must be:

$$Ri = \frac{Gr}{Re^2} = \frac{87100}{990^2} = 0.089 \qquad [2][3]$$

We know that if the Richardson number is much less than one that buoyancy is relatively unimportant in the flow.[2][3] The calculated Richardson number for this scenario is more than a magnitude less than one so it can be said that at the moment captured in the image buoyancy is unimportant in driving the flow of the fog and the relaminarized vortices within it. While there are several assumptions made in arriving at this Richardson number, it is congruent with what is observed in the image and visually at the point in flow development when this photo was captured. At the time of the image, while the flow continues to move and develop it is mostly fully relaminarized which makes sense as buoyancy forces are unimportant and therefore would no longer be driving turbulence within the flow. Additionally, a Reynolds number of 990 also supports that the flows visualized have largely relaminarized, and that the parabolic flow artifact is in fact very likely a vortex as laminar vortices can occur in a range of Reynolds numbers from 40 to 1000.[6] It was important to take the image in an unenclosed space a few seconds after the fog was created because this allowed the flows to develop over time and relaminarize resulting in the nondimensional numbers and visualizations seen. The relevant forces acting on the fluids within the framework of these principles that cause the flow to look this way are viscous forces, friction forces, gravitational forces, and buoyancy forces.

Visualization Technique

The primary visualization technique that I used to capture this image was by utilizing a "low lying" fog solution that was slightly more dense than other gaseous smokes or fogs that we're used to seeing. This fog solution was undiluted when inserted in the fog machine, however, a small amount of water vapor also is included likely included in the seen fog because of sublimation of the ice used to cool the machine. The fog was produced in a dark room with only one light source that lit the fog from the left side of the image. This means that the visualization technique was the marked boundary technique where the fog is the fluid with, "particles which scatter or absorb light," and the air in the room is the fluid which, "is transparent, not scattering or absorbing light." [5] This configuration works effectively in terms of visualizing the fog primarily because the rest of the room is very dark. As mentioned in the text, "contrast is heightened by keeping the rest of the room as dark as possible," [5] which we were sure to implement by doing the visualization at night and using only the headlamp from the left side of the image to the right. As is described in the Flow Visualization textbook to be necessary for this technique to work, these two fluids are relatively similar in density and presumably in viscosity.[5] In terms of sourcing of materials, the fog machine and fog fluid belong to my housemates who let me borrow it for the project, the Petzl headlamp is mine, and the image was taken in my apartment at approximately 8pm with all the lights turned off and the blinds closed. The camera was held by me approximately 16.5 inches from the subject while my elbows rested on the same table the fog machine was on. I was very slightly looking down from an elevated angle towards the section of the fog captured in the image and my groupmate Lana Pivarnik held the headlamp in position while I focused my efforts on capturing the desired moment of visualization.

Photographic Technique

The abstract technique that I used was taking an image of the flow visualization experiment with a zoomed in perspective. The size of the FOV was approximately 9 by 5 inches and the distance from the object to the lens, as stated previously, was 16.5 inches. The lens focal length was 44mm and the other lens specs are a thread diameter of 40.5mm, however I didn't use any lens filters. My camera is a Sona a-6500, it's a digital camera, and it was capturing images in RAW format, so my original photo is 6048 by 4024 pixels and 24 megabytes, and the exported high-quality photo is 5509 by 3518 pixels due to cropping. The aperture was 6.3, shutter speed was 1/2000, and ISO was 2000. In terms of post-processing on my image I used the RGB curve to lighten the smoke a little bit but also increase contrast between the lights in the image and the darks of the background and shadows. Additionally, I used the sharpen tool to make the lines sharper, the crop tool to remove empty black space around the edges and background, and the exposure tool to increase the visual difference between the foreground and background to make the smoke more visible. The FOV was chosen qualitatively to best show the artifacts that we were seeing with our eyes, the size of the image was the max that I was able to get in this camera setting exporting to RAW format, and I didn't mess with the aperture too much on this image so its sitting at the default value of 6.3. The ISO was chosen to both make the fog as visible as possible given that there was a single bright light source in a dark room, as well as maximize the amount of visual contrast between the plumes and vortices of fog and the dark background. The distance from the object to the lens was chosen as a combination of being the most practical distance for me to be able to kneel down and rest my arms on the table that the fog machine was on while taking the image, as well as a good distance given the aperture where

I could get a few inches of focus in the foreground of the image to highlight the artifacts there. Finally, the focal length was chosen through experimentation additionally to get these fog shapes in the clearest focus possible in the foreground of the image.

Image Insights

As stated in the Fluid Phenomena section this photo reveals the beauty of the relaminarization process and the interesting vortices, jets, and other flow artifacts that can result from proper flow development over time. My favorite parts of this image are the two previously mentioned artifacts in the foreground of the image, as one is clearly characterized by flow principles, and while the other occurs in the same field of view it appears to be the result of a separate set of processes and therefore cannot be as easily identified. In this way the image demonstrates the intriguing yet sometimes difficult nature of fluid physics; sometimes we can identify what's going on and sometimes we must appreciate artifacts for their beauty alone. Similarly, the main question that I am left with is what is causing this bulbous jellyfish reminiscent jet at the bottom of the image, and what type of flow is it. To further develop this concept of fog visualization in the future I think that it would be interesting to get an even brighter LED to allow for more extensive reflection of light off fog particles, and to further control the nozzle shape, size, and orientation through which the fog is exiting the fog machine. Ultimately, I have fulfilled the intent of this image to capture a beautiful visualization of gaseous flow development that normally is only visible to the eye in fleeting moments.

References

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