Stage Fog Turbulence Visualization Using Angled Light Source

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Image/ Video 2

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Figure 1: Visualization of Turbulence Using Fog Machine

For this secondary Image/ Video submission, students were assigned into teams in order to work together to capture more complex fluid phenomenon. My group decided to visualize the flow of stage fog from a standard fog machine using various lighting techniques, and I was personally interested in capturing vortices and turbulence from the device itself. Figure 1 depicts the photo taken to visualize these phenomenon. Due to scheduling issues I was unfortunately unable to take photos alongside my teammates and instead ended up working primarily with my roommate. My teammate William Watkins, however, had checked out LED lights from the department beforehand and left them for me to use, which was greatly appreciated. My roommate, Edison Bai, and myself created the experimental setup from Figure 2.

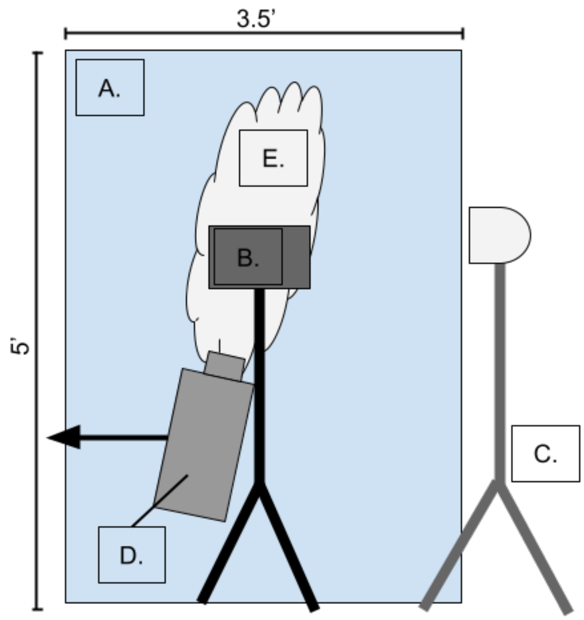


Figure 2: Experimental Setup for Figure 1

Figure 2 shows the experimental setup used to take Figure 1. The elements labeled are described in Table 1:

Table 1: Figure 2 Items and Descriptions

Item	Description
A	Black backdrop hung on wall behind subject
B	Camera mounted on tripod (facing into page)
C	LED Light on tripod
D	Rockville R720L Fog Machine pointed vertically (arrow denotes external support)
E	Fog dispensed by machine

Turbulence is a phenomenon that occurs in fluids when specific flow criteria are met that prevent the flow from being "smooth", or laminar. This is traditionally dictated by a quantity known as the Reynolds number, a dimensionless quantity that describes the turbulence of a given flow. The equation for Reynolds number depends on the fluid density (ρ), the flow velocity (u), characteristic length (L), and the dynamic viscosity (μ), and is shown below in Equation 1:

$$Re = \frac{\rho u L}{\mu} \tag{1}$$

To calculate the quantities in this equation, we require additional data regarding the fluid used. Fog machines typically use fog fluid that consists of a mixture of primarily water with glycerin in order to be visible once heated. The addition of glycerin should slightly increase the viscosity of the water, however a study by Dimotakis (1983) states that at sufficiently high Reynolds numbers, viscosity is not as important in determining the dynamics of the fluid's flow. This means that if the Reynolds number is high, the viscosity is not as critical in affecting the real-world model. Using this assumption, we will model the flow from the fog machine using the viscous properties of air, as the difference is likely to be negligible.

Using the website "Engineering ToolBox" to find data for air at a temperature of 72°F, the dynamic viscosity μ is found to be $0.3808 * 10^{-6} \frac{\text{lbf*s}}{\text{ft}^2}$, and the density is given as $0.07459 \frac{\text{lb}}{\text{ft}^3}$ [2]. Next, assumptions must be made about the characteristic length (diameter of exit), along with the flow velocity of the fog. For the Rockville R720L Fog Machine, the diameter was measured to be 0.1 inches (L), and the exit velocity was found from the manufacturer's website to be approximately $20 \frac{\text{ft}}{\text{s}}$ [3].

Given the exit diameter, 0.1 inches, we can calculate the area of the outlet using Equation 2:

$$\pi * r^2 = \pi * (0.1)^2 = 0.0079\text{in}^2 \tag{2}$$

Plugging in all of these values to Equation 1 results in the following:

$$Re = \frac{\rho u L}{\mu} = \frac{0.07459 * 20 * 0.1}{0.3808 * 10^{-6}} = 391754 \tag{3}$$

The Reynolds number is dimensionless, and for values greater than 2000 the flow is considered turbulent. Given the answer calculated, the flow is highly turbulent! From a functional perspective, it makes sense that the flow would be desired to be turbulent. This would allow for the fog to disperse among a greater area, rather than shooting directly in a straight line.

Another interesting feature from Figure 1 is the appearance of vortex rings around the center of the image. Figure 3 below is a useful visualization from the Journal of Fluid Mechanics (2000), and depicts the formation of vortices as they appear after a jet stream:

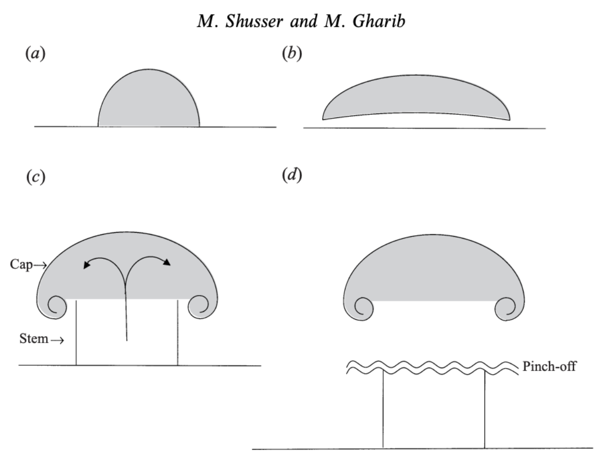


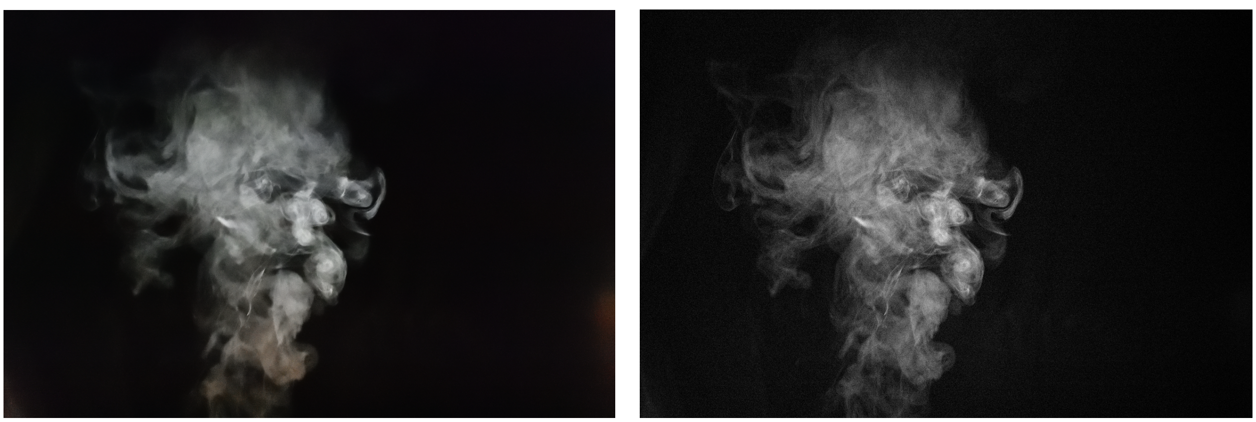
Figure 3: Different Stages of vortex ring formation (a) initial mass of a light fluid; (b) formation of the initial ring (stage I); (c) growth of the ring by flow from the stem (stage II); (d) pinch-off of the vortex ring. (Journal of Fluid Mechanics, 2000)

Based on this visualization, it appears that Figure 1 depicts every stage of the vortex ring formation, from the initial mass, formation of initial ring that resembles a mushroom cap, to the vortex stem curling around the edges, and finally full separation and curling present in the fog body. This is most visible around the center of Figure 1!

Initially, I had hoped to visualize a cross-section of fog that was dispensed from a fog machine– this would allow for the best imagery of the vortices that are present. Unfortunately, I did not have a thin or powerful enough light to make this work, so I settled for the LED light that had been checked out by my group. The procedure used was that Edison would hold the fog machine in a near vertical position with the spout near the edge of the camera's FOV, and he would activate the machine using the toggle switch for about a second before shutting it off again. I simultaneously was manning the camera, and would take several pictures as the flow dispersed. The key factor in the experimental setup that was eventually discovered was the need for lighting from the side. Over the span of several hours, I explored many different angles for the lamp's positioning, but satisfactory results were not produced until it was set up as shown in Figure 2. The static lighting from the side allowed for full illumination of the dispensed fog, while preventing reflections/ undesired lighting from the backdrop. This combination was crucial, as the detail present in the fog was so fine that it would be difficult to visualize (and edit) if any unnecessary elements were present. The bulb used was a SAVAGE brand 35W 5500K LED bulb with a white light setting producing 2130 lumens; no built-in camera flash was utilized.

This image was taken with a Nikon D3400 DSLR camera, using an 18-55mm f/3.5-5.6G zoom lens. The photo was taken with a focal length of 25mm at aperture f/4. The shutter speed was 1/250s, at ISO 25600. The goal of the framing of the image was to capture a region of fog flow with vortices clearly in the frame, and the background to be dark. The FOV of the image spans a region 12x8 inches (at 6000x4000 pixels), and the subject was approximately 24 inches away from the lens.

After taking the initial photo, I decided to apply a few digital alterations to highlight the fluid physics. I applied a monochrome filter to the image to remove the last bit of color, and then increased the exposure of the image. I then applied a vignette effect to remove some slight background reflections, increased the sharpness, and then ran everything through a soft denoise algorithm to remove a bit of grain. Figure 4 depicts the original, unedited photo compared with the altered version.



(a) Original Photo

(b) Edited Photo

Figure 4: Original vs. Edited Photo

In conclusion, this image highlights neat behavior of turbulent air leaving from a small nozzle. I am quite happy with the way that it turned out, in fact I think it is interesting the way that it seems to resemble a face! I believe that the fluid physics are shown well, with some vortices being extremely present. I was successful in fulfilling my intent with this image, however if I were to redo the experiment in the future I would be sure to use a plane laser for additional visualization. I would also use different ISO settings to prevent some of the graininess present in the final image.

References

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Engineering ToolBox, (2003). Air - Dynamic and Kinematic Viscosity. [online] Available at: https://www.engineeringtoolbox.com/air-absolute-kinematic-viscosity-d_601.html [Accessed 10 Oct. 2022].

Journal of Fluid Mechanics , Volume 416 , 10 August 2000 , pp. 173 - 185 DOI: https://doi.org/10.1017/S0022112000008727

Rockville R720L Fog/Smoke Machine. Rockville Audio, www.rockvilleaudio.com/r720l-v2-fog-smoke-machine/. Accessed 10 Oct. 2022.