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Flow Visualization
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Get Wet Report

The first assignment in Flow Visualization: A Course in the Physics and Art of Fluid Flow tasked the student with making a picture of fluid flow that was both a demonstration of the flow phenomenon being observed and a good picture. After considering several different kinds of flow phenomenon I decided to photograph smoke. I knew smoke would make for a great picture because of its intricate and beautiful flow patterns. Flowing smoke also has the potential to demonstrate both laminar and turbulent flow. Knowing this, I decided to attempt to capture an example of both laminar and turbulent flow in the same picture.

I first had to find a good source of smoke. I experimented with burning paper, matches, and incense sticks. I found that incense sticks produced the thickest and whitest smoke. Thick and white smoke would be vital to reflect enough light to produce a good image. I drilled several small holes in a piece of 2×4 to mount the incense sticks. After doing some experimentation I decided that using three incense sticks would make for the best photograph. I also observed that the three incense sticks would rarely produce exclusively laminar or turbulent flow, it was generally some combination of both; exactly what I wanted.

Before we go any further we must make an important distinction. I stated above that I wanted to photograph smoke. However, the smoke is only used to visualize the flow. Smoke is made up mostly of small particles which are carried upward by the flowing air. The real question is: Why does the air flow upward? First, we can define the flow apparatus as the air-filled room in which I took the pictures. We know that as a gas in a room heats up it will become less dense and will float on top of the cooler denser air due to buoyant forces. In this case the incense stick heats the air around it which rises upward at the same time as colder air from the room rushes in to replace the displaced hot air in a process called convection.[1] The flow of the hot air moving upward is visualized through the smoke particles carried upward with the air. Figure 1 on the next page shows the flow apparatus and the flow path of the smoke particles and the convection currents. Figure 3 on page 4 shows my final image. Looking at it we can see that as the smoke rises the flow becomes more turbulent. This is especially apparent on the left two incense sticks. The flow is becoming more turbulent because it is accelerating upward due to the unbalanced buoyant force acting on it. As a flowing fluid accelerates it becomes more turbulent. The Reynolds number of a fluid is a dimensionless number that gives the ratio of inertial forces to viscous forces acting on a fluid.[2] In general when the Reynolds number of a fluid increases the flow becomes more turbulent. In the next paragraph I will estimate the Reynolds number of the flowing air in my image.

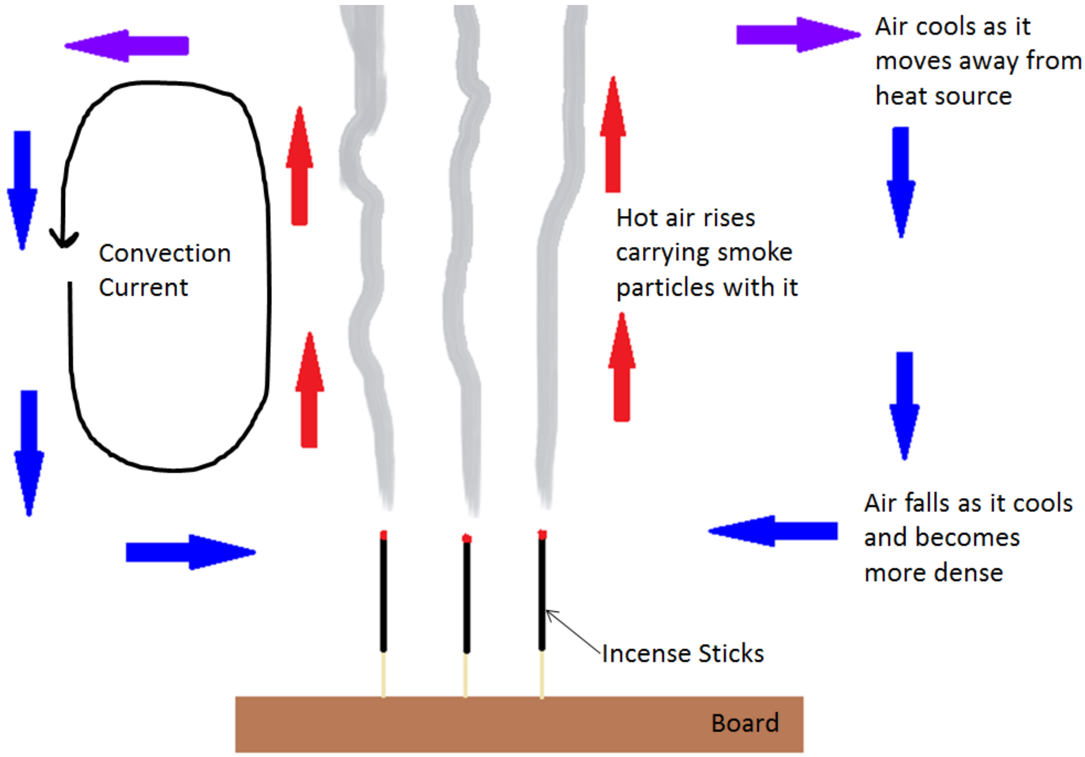

Figure 1

As stated above the Reynolds number gives the ratio of inertial forces to viscous forces acting on a fluid. It is defined as:

$$Re = \frac{UD}{v}$$

Where U = mean fluid velocity, D = hydraulic diameter, and *v* = kinematic viscosity. The kinematic viscosity of air at 300 K (about room temperature) is 15.68×10^{-6} m^2/s. Using the physical size of the image we can estimate the hydraulic diameter for the flow coming off the rightmost incense stick to be approximately 0.5 inches or 0.0127 m. Again using the physical size of the image we can estimate the mean fluid velocity of the flow coming off the rightmost incense stick to be approximately 0.508 m/s. Plugging in the numbers we get the Reynolds number for the rightmost flow pattern to be:

$$Re = \frac{(0.508\frac{m}{s})(0.0127\,m)}{15.68\times10^{-6}\,m^2/s} = 400$$

It is important to note that the formula used above is for calculating the Reynolds number for flow in a pipe. The situation here is different but if we assume the cold air surrounding the flowing hot air acts like a pipe then the formula above can be used. For pipe flow a Reynolds number less than 2300 indicates that the flow will be laminar.[2] We see that the flow coming off the rightmost incense stick is indeed laminar and we calculated a Reynolds number of 400. We are within an order of magnitude and therefore I believe the assumption has some validity.

As discussed above smoke was used to visualize the flow. To illuminate the smoke I used a powerful off-camera flash rented from Mike's Camera in Boulder. I mounted the flash on a tripod about four feet from the incense sticks and used rubber bands to mount blinders on the flash. This would ensure no direct light from the flash would enter the camera lens or illuminate the black sheet I hung as a background.

The field of view in the image is approximately 16 inches wide and 11 inches tall. This field of view leaves a lot of black space in the image which focuses the eye on the smoke and makes for, I believe, a more elegant photograph. In the image the smoke is approximately 18 inches from the camera lens. The focal length of the lens was 22.0 mm. The image was captured using a Canon EOS Digital Rebel XTi camera with a EF-S18-55mm f/3.5-5.6 lens. Both the original and final images are 3888 pixels wide and 2592 pixels tall. I decided not to crop because I wanted to follow the rule of thirds and keep the smoke off to the left side in the image. The aperture of the lens was f/10. A small aperture gives a greater depth of field. A large depth of field is important when photographing smoke because it will ensure that all of the smoke is reasonably in focus. I experimented with a range of f-stops and found that f/10 was about as small as I could go before the flash was not powerful enough to illuminate the smoke. The shutter speed was 1/200 second. I knew that a relatively fast shutter speed would be necessary because I didn't want the smoke to blur. A shutter speed of 1/200 second froze the motion of the smoke nicely and still allowed enough light to enter the lens. The ISO setting was 100. I chose an ISO of 100 because I wanted to eliminate all noise in the image. Any noise would destroy the fine lines of the smoke. An ISO of 100 also ensured that the background of the image would be a deep black. The original image can be seen below in Figure 2 and the final image can be seen in Figure 3.

Figure 2: Original Image

Figure 3: Final Image

Not much post-processing was done on the image but I did do several things to make the smoke appear brighter. First I used the auto-contrast feature in Photoshop. Then I used the dodge tool to brighten the middle range of tones. After that I zoomed in close on the image and removed any white particles on the black background. I believe these were probably due to pieces of lint or dust stuck to the black sheet which I used as a background.

The final image shows both laminar and turbulent flow. The smoke coming off the rightmost incense stick illustrates laminar flow. The left two incense sticks show both laminar and turbulent flow with the flow becoming increasingly turbulent as the smoke rises and accelerates. I believe the difference between laminar flow and turbulent flow is clearly illustrated in the image which was my original intent. After examining this image my biggest question is: Why do we see examples of both laminar and turbulent flow in incense sticks that are only inches apart? My best guess is that the flow is extremely sensitive to environmental conditions and minuscule currents in the air have a great effect on the flow. There is not much I dislike about the image. I was actually surprised at how well it came out and matched my original vision. Given the option to improve anything I would attempt to make the tiny wisps of smoke in the back of the image more visible using Photoshop. If I was to attempt this kind of image again I might try and get a picture of 20 or 30 incense sticks. I think if the flash was powerful enough this type of image would look great. I would also enjoy photographing different colored smoke using smoke bombs or colored incense sticks. In doing this project I began to get an understanding of the basics of photography. I hope to further expand that knowledge when doing subsequent projects for Flow Visualization.

<u>References</u>

[1] "Convection." *Wikipedia*. Wikimedia Foundation, Inc., 27 Jan. 2011. Web. 09 Feb. 2011. <http://en.wikipedia.org/wiki/Convection>.

[2] "Reynolds Number." *Wikipedia*. Wikimedia Foundation, Inc., 26 Jan. 2011. Web. 09 Feb. 2011. <http://en.wikipedia.org/wiki/Reynolds_number>.