UNIVERSITY OF COLORADO - BOULDER

Flow Visualization

Team Project #1

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The purpose of the "Team Project #1" assignment was to meet with our group members and capture an image that clearly exhibits the fluid dynamic phenomenon being observed. The group aspect of the project encourages communication and allows students to attempt to image more complex fluid phenomena's. This image was created for Professor Jean Hertzberg's flow visualization course at the University of Colorado in the spring of 2012. The original intent of the image was to capture the sequence of a smoke ring as it propagates through the air. However, after a substantial number of photographs that were blurry and didn't clearly demonstrate the phenomena, it was decided to try a different approach. The chosen image captures the shape of a smoke ring as it forms from a vortex ring generator. Specifically, the image displays the behavior of a vortex ring as it propagates through the air.

In order to produce the image, a dark ambiance was created in the light and vibrations room of the ITLL by turning off all of the surrounding lights and placing two 500 watt work lights head on at 72 inches from the vortex ring generator. The equipment used to create the fluid phenomenon was the vortex ring generator (length = 15.25 inch. diameter = 12.5 inch.) with the square hole (2.5 inch. x 2.5 inch.) in front of the opening, stage fog machine, and a black background. To create the smoke ring, the chamber of the vortex generator was first filled with smoke from the stage fog machine. Then the moveable diaphragm of the generator was pushed forward to displace the smoke (displacement = 2 inch). This displacement forced the smoke to flow out of the square opening at the other end of the vortex ring generator, creating a smoke ring with about a 3.5 inch diameter in the final image. The ring is formed because as the smoke exits the vortex ring generator the flow at the edges are slowed due to the square opening, while the smoke in the middle of the opening continues moving at the initial constant velocity. This rotation initiated by the opening continues in a circular pattern after exiting the vortex generator causing a constant circulation of smoke. Additionally, low pressure at the center of the vortex holds the smoke ring together as it propels through the air [1]. Figure 1 below shows the set up that created the final image.

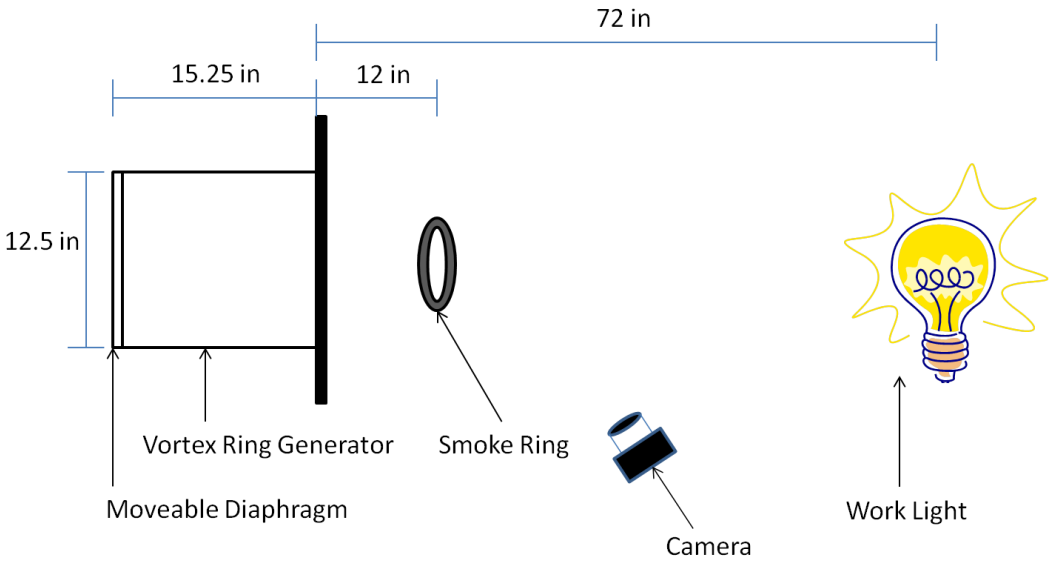

Figure 1: Final image setup

By analyzing high speed burst images of the smoke ring as it propagated through the air, the distance that the smoke ring traveled during the exposure of the photographs was estimated to be about 6 inches, which equals 0.1524 meters. Since the shutter speed of the high speed burst camera was 1/40 second the flow rate of the smoke ring was approximately 6.096 m/s. The Reynolds number can be roughly calculated using equation 1 below. Where v= average gas velocity (estimated to be 6.096 m/s), ρ= density of the fluid (density of air at 70°F is1.028 kg/m^3), η= dynamic viscosity of the fluid (dynamic viscosity of air at 70°F is 2.052E-5 kg/m*s), and D_h= hydraulic diameter of the flow [2]. Since the cross section of the tube is a square, the hydraulic diameter is used in calculating Reynolds number.

$$Re = \frac{\rho v D_h}{\eta} \tag{1}$$

The hydraulic diameter of the flow was estimated using equation 2 below. Where A_c is the cross-sectional area of the opening (0.00403m) and p is its perimeter (.254 m). From equation two, the hydraulic diameter can be determined to be 0.0635m.

$$D_h = {}^{4A_c}/_{p} \tag{2}$$

The Reynolds number for the flow can be estimated to be 19651.1. This estimate is greater than 10000, verifying that the fluid flow is turbulent [2]. This turbulent flow is especially apparent in the trailing tail of the vortex ring as it exits the vortex generator. Additionally, the formation time of the smoke ring can be calculated to determine if a trailing jet will form behind the vortex. The formation time can be roughly calculated using equation 3 below. Where L = the length of the cylindrical column of fluid that is pushed through a hole of diameter D, and ΔV= the change in volume (estimated to be 0.006 m^3). Since a square hole was used the hydraulic diameter D_h (estimated to be 0.0635m) will again be substituted for D.

$$T = \frac{L}{D} = \frac{\Delta V}{\pi D^3} \tag{3}$$

The formation time for the flow was estimated to be 7.459. This estimate is greater than 4, therefore concluding that a trailing jet should have been formed behind the smoke ring [3]. After viewing the original image, a trailing jet was indeed made, thus verifying the calculations above.

The visualization technique used to capture the final image was the formation of a smoke ring as it propagates through the air. The fluid used in creating the smoke ring was stage fog, which is composed of a vaporized glycol-water solution. Since smoke rings are very hard to see a high concentration of stage fog was used in the vortex ring generator. The intent of the image was to have the smoke ring be visible and clear; however, since the rings are fairly opaque, the correct lighting was critical to capturing the fluid phenomenon. The lighting was produced by two 500 watt work lights that were positioned head on at six feet from the vortex ring generator. Additionally, the flash on the camera was used to help illuminate the smoke ring, creating a clearer image. Further room preparation consisted of turning off all of the surrounding lights and closing all of the doors so that the room would be as dark as possible. The air temperature of the room was approximately 73°F.

The field of view of the original image was approximately 4 feet (width) by 3 feet (height). A Sony DSLR-A230 digital camera was held slightly above the vortex ring generator at a distance of about 3 feet from object to lens. This provided an ideal viewing angle of the rings because it allowed us to see the trailing tail as well as the vortex ring generator opening that the ring came from. In order to prevent motion blur, the camera was held stationary on a tripod. This orientation created an original image with pixel dimensions of 3872 x 2592. The final pixel dimensions were 1872 x 724 after being cropped in Gimp. In order to attain a clear image the aperture was set to f/5.6 and a corresponding shutter speed of 1/60 sec was chosen by the camera to allow for sufficient light to enter the lens. Additionally, the image was taken with an ISO setting of 400 as well as a compulsory flash to increase the shutter speed in the low light setting, ensuring a clear capture of the smoke ring. Furthermore, the focal length of the lens was 40mm (35mm equivalent focal length = 228mm). The original image before being edited in Gimp can be seen in figure 2 below.

Figure 2: Original image before editing

After the original image was captured it was imported to Gimp and converted from RAW to a TIF file so that the image would maintain its format. The original image was then significantly cropped in Gimp to focus on the opening of the vortex generator and the smoke ring. Additionally, the curves tool was extensively used to brighten the white smoke and darken the blacks. The image was then enhanced by using the clone stamp tool to blend any blemishes created by the black fleece blanket in the background. The final edited image can be seen in figure 3 below.

Figure 3: Final edited image

Ultimately, the image reveals the formation of a developed smoke ring as it propagates through the air. By incorporating the orifice that the smoke ring developed from, I was able to create an image that is especially intriguing and exciting to look at because you don't expect round smoke rings to come from square holes. I really like the clarity of the smoke ring as well as the great contrast between the black background and the white smoke ring. However, because the background was a black fleece blanket the smoke ring appears to be a little pixilated due to the surface of the blanket. This texture of the blanket created the appearance of an unclear image. Additionally, there was a wrinkle in the blanket that can be seen in the original image, this created an uneven coloring through the trailing tail of the smoke ring. This made the editing of the photograph especially difficult as the curves tool had to be extensively used so that the fold in the blanket would become black. By increasing the curves so drastically, the trailing smoke ring tail washed out, which diminished the overall physics revealed by the photo. If the group were to do this again, we would pick a smoother background with no wrinkles or visible surface textures. This would ultimately allow us to more easily edit the images, while maintaining the structure of the smoke ring as well as its trailing tail.

Works Cited:

[1] "ZeroToys.com - Science." *Products: Zero Toys Online Store*. Web. 21 Mar. 2012. <http://www.zerotoys.com/shtml/science.shtml>.

[2] Çengel, Yunus A., and Afshin J. Ghajar. *Heat and Mass Transfer: Fundamentals & Applications*. New York: McGraw-Hill, 2011. Print.

[3] Mohseni, K., Ran, H. Y. & Colonius, T. 2001 Numerical experiments on vortex ring formation. J. Fluid Mech. 430, 267–282.