Image 2 || Smoke rings

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Figure 1: Final image of the smoke ring

Introduction:

Our team decided to use the second project to investigate the flow and physics of vortices. Our team was intrigued by the Zero-blaster smoke gun that was brought into class and we wanted to get a single image of the smoke rings that it produced. In the end the ring above was not actually from the Zero-blaster but from a homemade smoke ring machine as described in this report. With the assistance of Alex Kelling, David Milner, and Nathan Gallagher we were able to operate the smoke ring machine, adjust lighting, and capture images that detailed the movement and continuum of smoke rings.

Experimental Setup:

The physics behind smoke rings is intriguing because of its self-maintaining characteristics. As a smoke ring moves through the air, the opposing flows bring smoke back into the ring and continue its movement forward. Smoke rings are created when fluid is discharged from a containing volume through a small, round hole. Our experimental design is shown below.

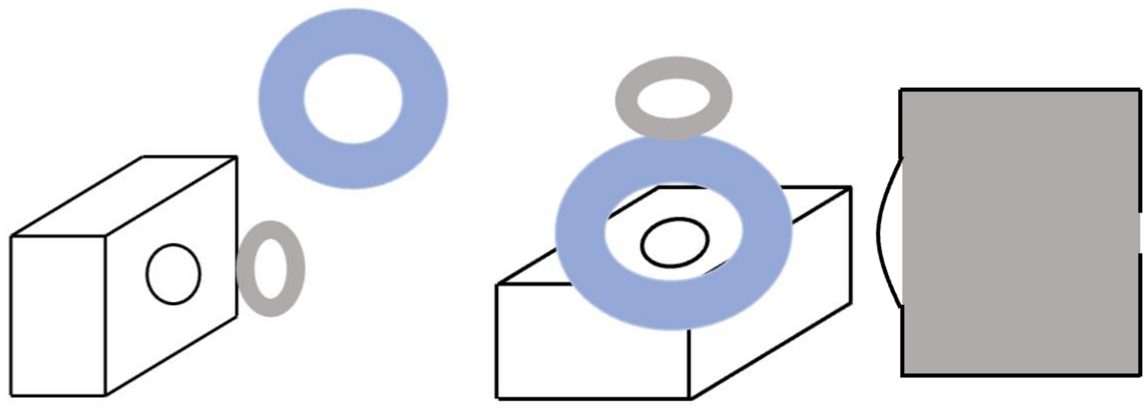

Figure 2: Experimental Setup. a) shows shooting smoke rings forward with the ring light illuminating from the side, figure b) shows the ring light resting on the box, illuminating the rings from the bottom. Figure c) shows a cut away of the box filled with smoke with the paper bellows on the left and the small opening on the right.

This was created by taking a small, 3”x6”x10” cardboard box and cutting 3 holes in it. The first was a small, 1” diameter hole in the center of the largest face. The second was a large square hole in the opposite face that removed nearly the whole face. This was to create a sort of “bellows” as we then taped a piece of paper against this opening and taped all sides of it to prevent any air from escaping. By leaving a kind of bubble in the paper when taping it, we could create better smoke rings by tapping the paper very lightly, decreasing the volume of the box and expelling air from the hole in the opposite side. The third hole was a 0.75”x4” hole that we taped a flap over. This was to allow the box to be inserted over the edge of a fog machine so that we could fill it with artificial smoke and then close the flap, trapping smoke inside to be released when the bellows were pressed. The ring was then lit up with a ring light supplied by Alex Kelling. We also used some external lighting in the form of flashlights, but these were supplementary and moved often to try and get the correct lighting.

This setup was then placed on a table in front of a black tablecloth. This allowed us to illuminate the ring exclusively and create a black background to provide enough contrast to see the ring. We then had multiple team members working together to get the shot. The first would tap the back of the box on the bellows and expel smoke, creating the smoke ring. Another member or two would then be taking pictures of the ring. If things weren’t working out one member would adjust the lighting to try and get a clear picture of the ring. Roughly every 5 minutes one team member would have to open the flap on the box and refill the box with smoke.

Flow Physics:

The actual smoke ring is formed when a fluid is expelled from a small opening like the round hole we cut in the box. When we press on the paper, decreasing the volume of the box, some of the smoke held inside is expelled due to this decrease in volume. Then when the bellows spring back into place the volume expands again and pulls air into the hole. When the bellows are tapped very lightly with a finger, this process happens in a fraction of a second. The boundary layer of the fluid at the edge of the opening holds the air flow close to the edge of the box so that it rolls around the corner when expelling. Then when the bellows spring back, it separates the boundary layer and this curling fluid flow continues forwards wrapping around itself in a circle around a axis normal to the opening. This is the vortex shown in figure 1. One can see the fluid rotating around a ring whose central axis exists in the page.

The mathematics behind this are explained by the Reynolds number of the fluid and its flow type. The Reynolds number is a dimensionless number that can be described by the ratio of internal forces to viscous forces[1]. This number can be used to characterize a fluid flow as laminar or turbulent. Laminar flow is described as a flow where all vectors of flow in a fluid are in a uniform direction. This means that the flow looks “smooth” whereas turbulent flow looks more like a chaotic flow with eddy’s and non-uniform flow paths. This means that we can expect the fluid in the smoke ring to be laminar because, when looking at a small portion of the ring, the flow paths are uniform and flowing in one direction, around the rings axis. Proof of this can be derived using the equation for the Reynolds number:

$$R_e = \frac{VL}{\nu} = \frac{\rho VL}{\mu}$$

Where R_e is the Reynolds number, V is the velocity of the fluid over a characteristic length, L, ρ is the density of the fluid, and μ is the dynamic viscosity of the fluid. In our system, the velocity, V was approximately $0.15\frac{m}{s}$, the density was that of air, $1.204\frac{kg}{m^3}$, and the viscosity, $\mu = 1.825 * 10^{-5}\frac{m}{s}$. For this equation we will use a length of 1 cm due to the approximate width of the “donut” being roughly 1 cm. Plugging these values into the equation above we get that $R_e = 98.96$

In fluids, a typical cutoff for turbulent vs laminar flow is a Reynolds number of 2100[2]. Anything below 2100 is considered laminar and anything above is assumed to be turbulent. This is an estimation and is not necessarily a hard cutoff but is a good rule of thumb to use. Since our Reynolds number is well below this value, we can assume that the flow in the vortex is laminar.

Photographical Techniques:

Since we had multiple people working to take pictures, there were multiple cameras used to get images. This image was taken on a Nikon D7000. The lens was a Nikkor 18-55m f/3.5-5.6 VR. The focal length for this picture was 36mm with a 1/1000 shutter speed, f/4.8, and an ISO of 5000. The original image was 4928×3264 pixels but was cropped to 1825×1822 in post processing. The original image, before cropping, is shown below. As one can see, this was taken with the box facing upwards and the light ring resting on top. The post processing involved cropping and rotating the image. I liked the diagonal line when rotating it and framing the ring better after cropping. There was also some contrast correction to get the white ring to pop off the black background and there were a few dead pixels that I removed. This was all completed in darktable.

[1] Rapp, Bastian E. (2017). Chapter 9 – Fluids. Microfluidics: Modelling, Mechanics and Mathematics
[2] Trinh, Tuoc. (2010). On The Critical Reynolds Number for Transition From Laminar To Turbulent Flow

Figure 3: Original image before post-processing. Shows the light ring and trail from the ring

When getting the image, we tried to use the automatic settings on the camera after focusing manually. We would have one team member hold their hand where the smoke rings were travelling and then focus on that before removing the hand and sending out smoke rings. Since the automatic exposure, shutter speed, and aperture settings were not working, we decided to set them manually. The problem with automatic settings was that they used a very long shutter speed and since the rings move through the air, they were very blurry. It took a lot of trial and error to get the settings right and each team member had roughly 400 photos by the end of the session. This ended up being my best image but other group members images can be seen on flowvis.org.

Conclusion:

I am very proud of this image of the vortex ring. The process of capturing this phenomenon took roughly 5 hours of continuous trial and error but in the end we were able to get one clear image of the vortex. In the future it would be really interesting to try and capture this with a slow-motion camera in an effort to fully visualize the complicated fluid flow demonstrated by vortex rings.