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Flow Visualization: The Physics and Art of Fluid Flow

This photograph began through a search for an appealing visualization of any fluid flow. The possibility of visualizing human exhalation through smoke as a medium is a particularly captivating one, and led to this phenomenon being explored through multiple angles and lighting setups before the final image was created. The final image allows the physics of the exhalation to be explored, while maintaining an artistic appeal. This paper will identify the techniques used to create the image, as well as discuss the physics of the vortex ring at the bottom of the image.

Vortex rings are a fascinating phenomenon that can occur in various ways. In this experiment, a vortex ring was created out of smoke that was exhaled out of the human mouth. An "O" shape was formed by the lips of the smoker, and smoke was forced through this imperfect circular opening. The upward force was created by the lungs, pushing the smoke through the mouth. An equation that will be used to describe the ring is the Reynold's Number, a non-dimensional value given to certain flows to analyze their behavior. The equation for the Reynold's Number, Re, is seen below in equation (1), where μ is the viscosity coefficient, ρ is the fluid density, and V and L are the characteristic velocity and length scales of the flow. In this case, the characteristic length is equivalent to the exit diameter, or the diameter of the lips.

$$Re = \frac{\rho V L}{\mu} = \frac{\rho V d}{\mu} \qquad (1)$$

In order to use this equation, the approximate contents of human smoke exhalation have to be estimated. Room temperature air contains approximately 79% nitrogen, 20% O2, 0.04% CO2, as well as trace gases and water vapor. Exhaled air contains approximately 79% nitrogen, 16% O2, 4% CO2, as well as trace gases and water vapor [1]. Although smoke adds particulate matter, it does not significantly change the composition of exhaled breath. Therefore, the exhaled smoke will have approximately the same properties as room temperature air at a pressure of 1 atm: ρ is 1.20 kg/m^3 and μ is 1.8E-5 Ns/m^2 [2]. The estimated velocity of the vortex ring is 6 in/s, or .1524 m/s, and the estimated diameter of the mouth is 1 in, or .0254 m. The Reynolds number is then calculated below.

$$\text{Re} = \frac{\rho V d}{\mu} = \frac{\left(1.20\frac{kg}{m^3}\right)*\left(.1524\frac{m}{s}\right)*(.0254\text{m})}{1.8E{-5}\ {}^{Ns}/_{m^2}} = 258.06$$

Any Reynold's number in the range of 100 to 103 is a laminar flow, which can be examined in the image. This indicates that the layers of smoke remain parallel as they swirl from the inside of the mouth to form the ring. This Reynold's number describes the flow as it is leaving the mouth and changes as distance increases between the smoke and the mouth of the smoker.

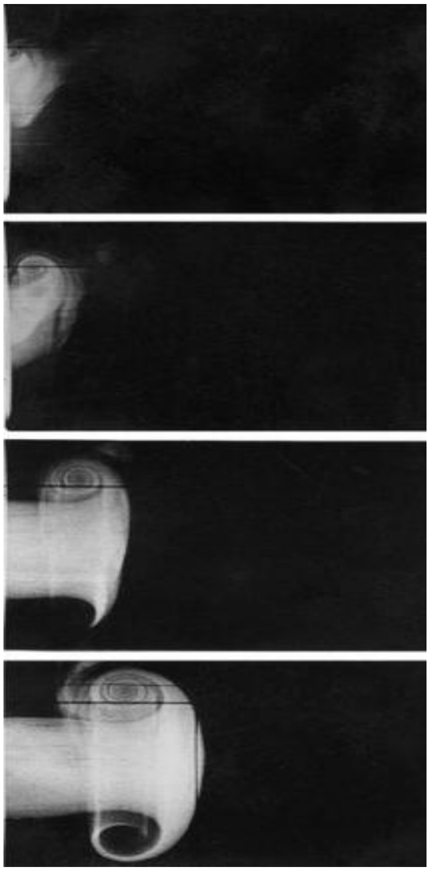


Figure 1: Formation of Vortex Ring [3]

In Figure 1, left, the formation of a smoke vortex ring can be seen in depth. Although this experiment used a pipe to eject the smoke, the physics remain similar. The smoke begins to exit the opening without an obvious vortex formation. However, as the smoke emerges, the outer layers face shear from the sides of the pipe, or the sides of the mouth, and are slowed down. The inner layers move forward at a faster rate. The leading edge of the smoke represents the boundary layer between the two separate fluids, smoke and air, and the jet velocity at the leading edge is approximately half of the initial jet velocity. As the smoke moves forward in time and space, it mixes with the surrounding air and continues to rotate. This is the initial formation of the smoke ring. However, there is a notable difference when comparing Figure 1 and the final image. Air does not appear to penetrate the boundary layer in Figure 1. This is due to a larger pressure gradient. The surrounding pressure keeps the boundary layer undisrupted. Since the exhalation of human breath has approximately the same pressure as the surrounding air of the human smoking experiment, the air is able to penetrate the smoke and create the apparent vacancy in the center of the ring. This is demonstrated in Figure 2, right. Instead of showing the vortex ring moving forward into the air, this picture shows the air moving downward on the ring. The relative motion of these two scenarios is identical, and the cross section shows the rotation of the inner and outer layers of the ring. Air flows through the center of the ring as well as along the sides.

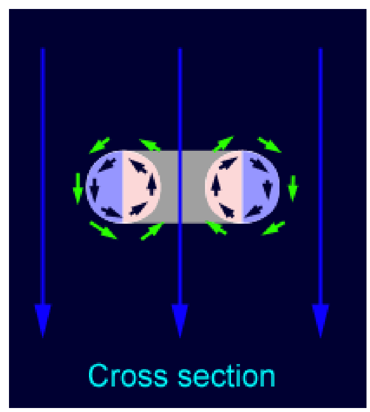


Figure 2: Fully Formed Vortex Ring [4]

To summarize the physics here, the smoke is acted on by a few main forces. Gravity slowly drags the fluid down, but acts uniformly over each particle, so does not disturb the rotation. The force from exhalation is a force of the human on the smoke, and it creates an upward acceleration. The relative densities of the smoke and the surrounding air are almost identical, so there is little buoyancy force. The smoke exits the mouth and separates due to the shear force acting on its outside layer. The vortex ring is a captivating demonstration of physics, and its artistic qualities will be displayed in the image below.

Final Image: Cigar smoke exhaled to form a vortex ring and cloud. This photo was exported from Lightroom 4 Beta in TIFF format at a size of 1,546 x 2,304 pixels.

This image was obtained by the following experimental setup. The camera was positioned 5 feet away from the face of the smoker at the height of the smoker. The smoker blows air straight up, and holds a light directly underneath the smoke, parallel to the direction of exhale (the thick arrow) about three inches from the face. The positioning of the smoker and the light can be seen below, in Figure 3. Cigar smoke was used for this experiment, although almost any type of smoke would be suitable. The light used for this experiment was a 75 lumen Black Diamond Spot headlamp.

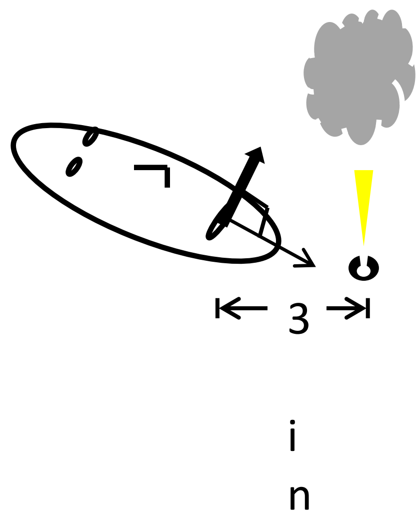
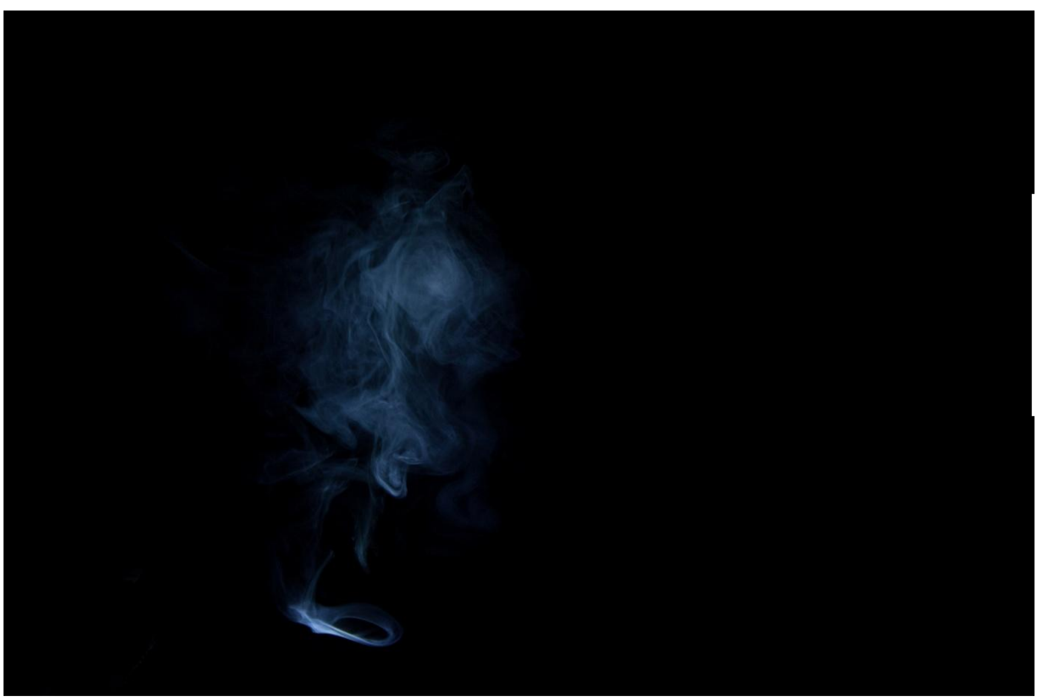


Figure 3: Lighting Setup. Not Drawn to Scale.

The camera used was a Canon Digital Rebel XT. The lowest ISO that could still produce a clear image was used to maintain clarity and eliminate graininess, set at 400. The aperture was set at f/7.1 to focus on the smoke, but nothing else in the background. A 1/100 sec shutter speed allowed the image to be captured with some streaking, but for the slower moving section (the vortex) to appear still. The lens is an 18-55mm Canon EFS, with a 55mm focal length. The distance from the object to the lens is stated above as 5 ft and the field of view was about 4 ft. Adobe Lightroom 4 Beta Edition was used to process the original image, shown below. It was cropped, the exposure was increased slightly, a small puff of smoke was removed from the top, and the color temperature was dropped to 2854 K to achieve the blue hue.



Original Image: Captured in CR2 RAW format at a size of 3,456 x 2,304 pixels.

Although this report focused on the vortex ring phenomenon, this is a small section of the physics captured in the final image. Other visible phenomena include expansion of the cloud, swirling vortices, shearing, separation of the smoke, etc. These physics could be studied in depth from the photo. I liked the orientation of the plume, how it was not perfectly perpendicular to the frame. I also was happy with the clarity of the photo and the lack of graininess even when it was blown up to a display size using a projector. In developing this idea further, it would be possible to take more pictures with the same setup and examine other phenomenon, as well as studying all the physics in this image in more detail and depth. It was a lengthy process to produce this image, but I am pleased with the final result.

Sources

1. "Respiratory System." *Ambulance Technician Study*. Web. 15 Feb. 2012. <http://www.ambulancetechnicianstudy.co.uk/respsystem.html>.
2. White, Frank M., and Sanford Klein. *Fluid Mechanics*. New York: McGraw-Hill, 2011. Print.
3. "Vortex Rings." *Scribd*. Web. 15 Feb. 2012. <http://www.scribd.com/doc/45029852/Vortex-Rings>.
4. "Deep Ocean Diving - Science, Technology and Medicine Related to Scuba Diving." */deepocean*. Web. 15 Feb. 2012. <http://www.deepocean.net/deepocean/index.php?science09.php>.