Imaging a Swirling Water Jet

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INTRODUCTION

The primary goal of this image was to effectively capture a fluid flow phenomenon in an aesthetically pleasing way which also has value for scientific inquiry. Swirling jets are fluid phenomenon that can be induced in both incompressible and compressible fluid flow by imparting angular velocity to a fluid jet before it exits an orifice. The flow condition is most often explained using a common 2 liter soda bottle filled with water. Simply inverting such a bottle with no cap starts a slow gurgling draining process because the liquid exiting the bottle must be replaced by air, requiring the two to be in counterflow through the same opening (Meyer,1). Swirl the water before it exits however, and it may have enough angular momentum to adhere to the walls of the opening, leaving a central pathway for the air replacing its volume so that both water and air may be in uninterrupted counterflow. This not only allows the water to drain more rapidly, but produces a beautiful axially-swirling free jet exiting the bottle. The aesthetics, mechanics, and ease with which this flow condition may be produced without special lab equipment all make it an excellent subject for photography. This report documents the process used to obtain this image.

PRODUCING THE SWIRLING JET

The basic process used to capture the flow is to induce the swirling jet from a bottle held in one hand above a marked focal plane, which will then be photographed using a timed shutter release on a camera. The jet was produced using the following steps:

1) Hold a 750ml glass bottle filled with tap water upside down over a liquid tight receptacle using a hand to plug the bottle opening.
2) Move the bottle in a circular fashion until the water begins to swirl.
3) Continue to swirl the bottle while releasing the water from the opening. Steady the bottle over the catchment area as the swirling jet forms into a somewhat steady state flow pattern, eventually emptying the bottle.

Circular flow requires a force to be exerted on the water to constantly change its direction. This force comes from the walls of the bottle before the water exits. For a constant velocity and fixed diameter, the Navier Stokes equations for conservation of momentum could be used to determine the radial force acting on the bottle from the fluid. In this case, the changing internal diameter of the bottle makes it difficult to approximate, but this radial resisting force is not present once the fluid leaves the orifice thus allowing an increase in the diameter of the jet as it exits. Since the jet remains continuous at this stage, the effects of surface tension cause gravitational force to have a narrowing effect on the jet after its initial diameter increase. Once the jet has narrowed significantly the bulb converges into a single stream where the fluid breaks down into droplets. It is likely that air reaches the inside of the hollow jet and ultimately the bottle through this point of convergence. Once separated from continuous flow, the droplets again spray outward, having no force to hold them in circular motion. This is similar to a well-studied fluid mechanics phenomenon referred to as vortex breakdown, in which the cylindrical film of water making up a swirling jet leaving an orifice is stretched by centripetal acceleration until the surface tension is overwhelmed and the stream separates into droplets (Liang,42). Swirling jets that include both a hollow bulb and a vortex breakdown section seem to be uncommon in fluid mechanics research, but it is believed that both these aspects are visible here.

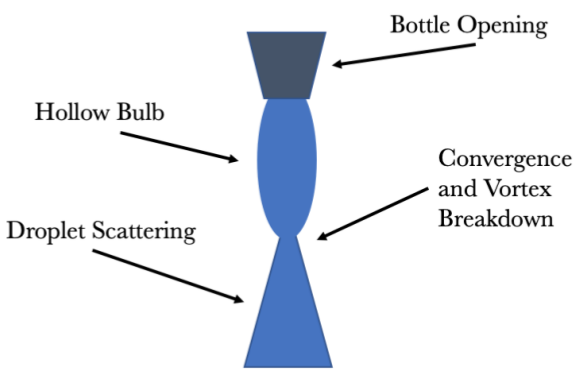

Figure 1: Diagram of the flow pattern swirling jet from a 750ml glass bottle used as the image subject.

POSITIONING AND LIGHTING

The imaging setup was composed mostly of typical household items. A camera was set up on a tripod in a darkened room facing a focal area where the flow was to be captured. A large plastic box resting on a stand was used as a receptacle to catch the water draining from the bottle. A smaller container inside the box was used to catch the majority of the water for easier refilling and as a reference point for the focus region of the camera. A rectangular black canvas storage box was placed on a pedestal directly behind the subject viewing area. The box was angled such that the lighting would not fall on the back of the box. This simulates an infinite dark space behind the subject which bypasses the need for perfect uniformity in a backdrop surface. For a light source, several small LED penlights spaced about an inch apart, were fixed vertically to the edge of a music stand such that the edge of the stand blocked some of the light that would normally project into the box behind the subject. The lights were directed at the subject at approximately a 45deg angle relative to the axis of the camera lens in order to reflect as much light off the water into the camera. Since the flow was not being seeded or dyed to aid in visualization of the pattern, the quality of the final image was largely dependent on having adequate and appropriately controlled lighting as well as the dark background.

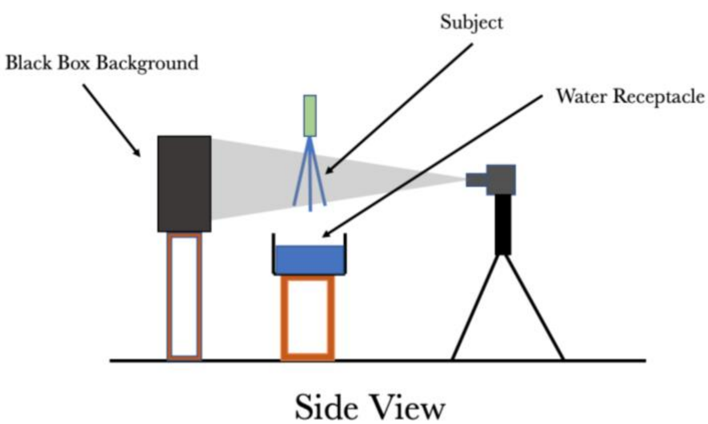

Figure 2: Side View of Basic Imaging Setup

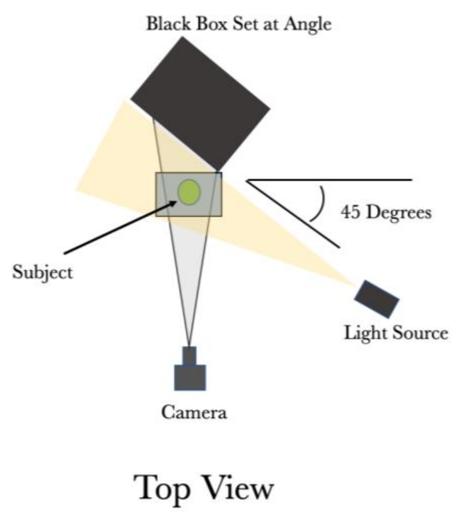

Figure 3: Top view of basic imaging setup

IMAGE ACQUISITION

The image was taken using a Canon Rebel T5i, DSLR camera mounted firmly to a tripod for stability. Since the bottle had to be swirled and emptied by hand, a 10s timed shutter release was used. Unless a remote shutter release is available, use of a timed shutter release is generally recommended since any disturbance from touching the camera has time to dissipate prior to the exposure. As mentioned previously, a smaller container within the water catchment box was positioned below the focus region as a reference for where to hold the bottle. Printed text was used to manually focus the camera at that depth, in this case 0.52m away from the lens. The close positioning was meant to maximize the image definition by filling the frame as much as possible with the subject, yielding an FOV of about 0.25m. The final image was chosen out of many takes which varied shutter speed and ISO experimentally. Some motion blur was desired in order to show higher velocity regions, with the condition that clarity of image on the smooth reflective portions of the jet would be maintained. A shutter speed of 1/30 with an ISO of 3200 was used on the final image which seemed to accomplish both these goals. A shutter priority setting was used which automatically regulated the aperture to f/4.0, bringing in adequate light especially given than no ambient light was present. The effectiveness of the shadowed black background and lighting setup used meant that few adjustments were deemed necessary in post-processing. The already image compensated of exposure of +5EV was boosted slightly in the edit an additional 1.12EV, brightening darker portions of the flow. Minor cropping of the image and use of the noise reduction functionality built into the Darktable software were the only other manipulations to the image.

CONCLUSION

The final image seemed to meet the primary goals in that it provided an effective visualization of a very aesthetically pleasing flow phenomenon. The primary factor in the success was the iteration of the setup with an emphasis on excellent lighting and background. Acquiring the best possible original image should always be the primary goal in setting up to take a photograph. A 90 degree camera orientation would have been a better use of the T5i's cropped 22.3 X 14.9mm sensor. Although the tripod used did not have an additional pivot for accomplishing this, the up-down angle adjustment on the head reached 90 degrees meaning the camera could have been positioned at 90 degrees if the adjustment in the feet of the tripod were used to level and point the camera in the correct direction.

SOURCES

Liang, H. (n.d.). *Experimental Investigations of Swirling Jets*. ProQuest Dissertations, 2003. Retrieved September 28, 2020, from https://search-proquest-com.colorado.idm.oclc.org/docview/305320558/fulltextPDF/B851399A9164221PQ/17?accountid=14503

Mayer, H. (2019, October 11). Bottle Emptying: A Fluid Mechanics and Measurements Exercise for Engineering Undergraduate Students. Retrieved September 29, 2020, from https://www.mdpi.com/2311-5521/4/4/183/htm

Binnie, A. M., & Davidson, J. F. (n.d.). The flow under gravity of a swirling liquid through an orifice plate. Retrieved September 28, 2020, from https://royalsocietypublishing.org/doi/pdf/10.1098/rspa.1949.0147

APPENDIX

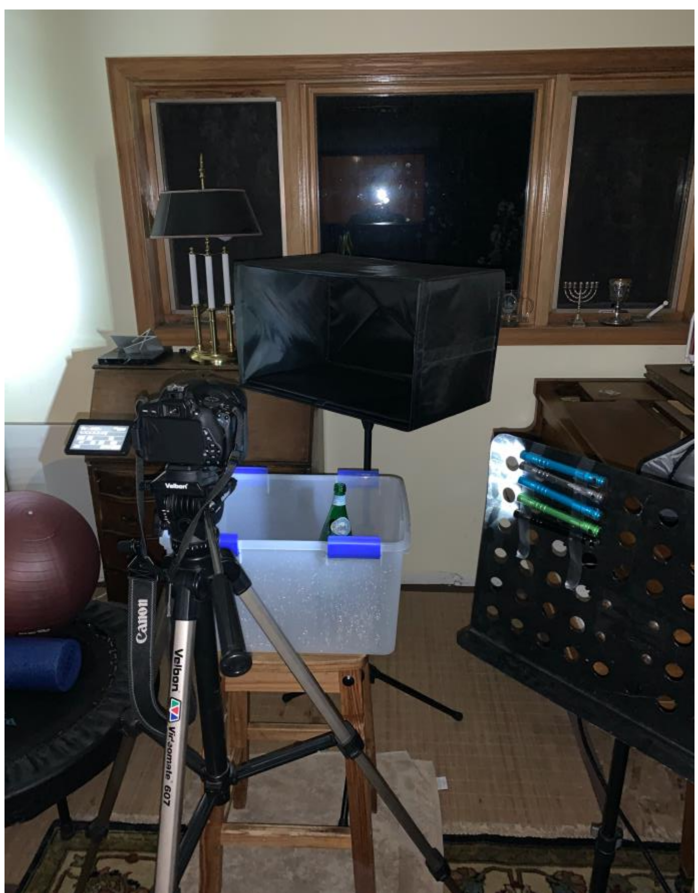

Figure 4: Picture of Final Imaging Setup from September 2020, with ambient lighting temporarily on for an experiment reset.