Stir Rod Vortex

Team Image 2, MCEN 4151, Flow Visualization

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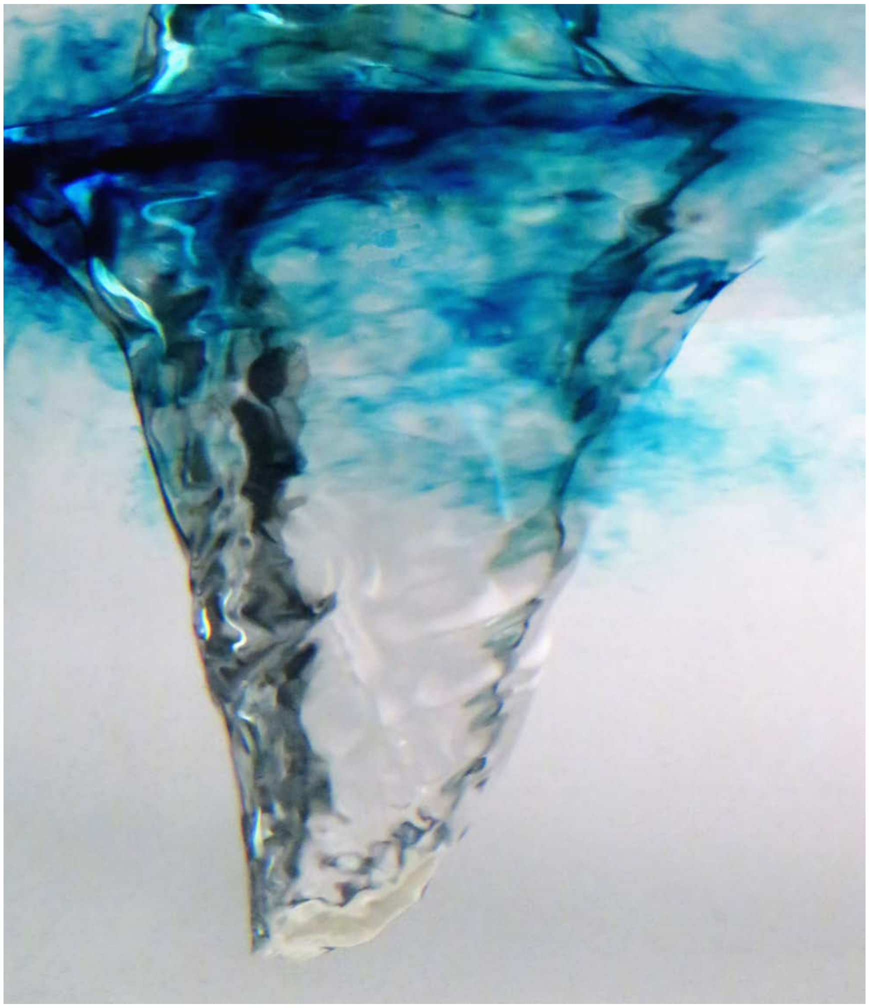

Introduction

For the second team image in Flow Visualization, I worked with Kristopher Tierney, Lael Siler, and Mark Voll to capture images of food dye in a water vortex. We looked at several pictures from the internet when deciding the subject for this assignment, and we liked the patterns that appeared in water vortices. Vortices appear in a wide range of fluid flow from bathtubs to the oceans, and despite their simple and graceful appearance, the mathematics describing vortices are complicated. I was particularly interested in using food dye to visualize the flow in the vortices, because I saw a beautiful image by Gary Velasquez for Flow Visualization in 2011 using a similar technique.[1]

Experiment and Flow Description

For this experiment, a clear plastic beaker was placed inside of a 10 gallon fish tank, and both were filled with water to the same height. The beaker had ports on the sides for use in chemical processing, so it did not seal on its own. By immersing it inside of a fish tank, the hydrostatic pressure of the water in the tank kept the water inside of the beaker. These two different surfaces of the water are responsible for the mirror effect seen near the top of the image. A magnetic stir rod was placed in the bottom of the beaker, and a magnetic stir plate (a Corning PC-351) was positioned directly beneath the fish tank. Two plastic tubs supported the tank from each end, and two white sheets of paperboard provided a neutral background for the image. See Figure 1 and Figure 2 below for a sketch and image of the experiment.

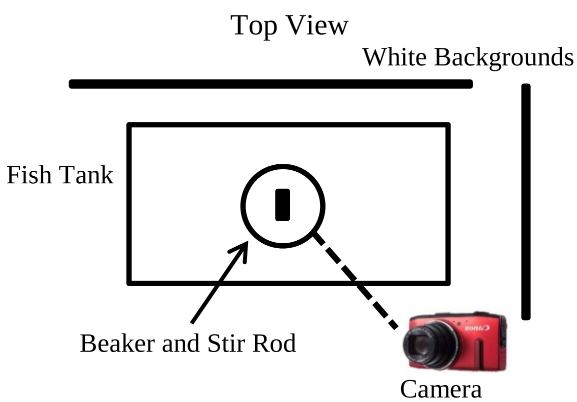

Figure 1: Top View Sketch of Experiment

Figure 2: Image of Experimental Set Up

The vortex was created by turning the stir plate on to the highest setting where the stir rod was stable. The rotating stir rod pulled water down to the bottom of the beaker and pushed water up the sides of the beaker. This created recirculation within the beaker in the vertical direction, and it was responsible for the well-defined vortex within the beaker. There was also circulation in the radial direction present throughout the beaker. The stir rod was set to its highest stable setting, because this created the largest vortex. Above this speed setting, the stir rod separated from the magnetic field and bounced chaotically within the beaker. The angular frequency of the stir rod is estimated below.

[1] Velasquez, Gary. "Mixing Up a Vortex." University of Colorado at Boulder, 9 Feb. 2011. Web. 31 Mar. 2014.

To visualize the fluid flow, one drop of blue food dye was added on the edge of the vortex next to the wall of the plastic beaker. Blue dye was used, because it provided more contrast than the other colors. Only one drop of dye was used, because more than would drop would introduce too much dye and obscure the flow around the vortex. The dye was introduced at the beaker wall, because the fluid motion pulled the dye from this location around the outside of the vortex in a beautiful way.

The flow in this experiment can be approximated as a Rankine vortex. Rankine vortices are an ideal model of a real vortex, and they assume that the circulation is constant in the radial direction.[2] The circulation of a vortex is representative of how much the velocity of the water changes as one moves outward from the center of the vortex. Therefore, constant circulation in a vortex means that the change in velocity is constant throughout the vortex. Mathematically, constant circulation occurs when the curl of the velocity field has the same magnitude throughout the beaker.

Certain parameters for a Rankine vortex can be calculated, but it is necessary to know the angular frequency of the stir rod within the plastic beaker. The camera had a high speed video setting that records 240 frames per second. By filming the stir rod mixing the water in the beaker in high speed, it was possible to review the footage in slow motion and calculate the angular frequency. It was observed that the stir rod completed 40 revolutions in 45 seconds leading to an angular frequency of 0.88 sec^{-1}.

With the angular frequency known, the Reynolds number of the vortex can be calculated. The Reynolds number of a flow is the ratio of the inertial forces to the viscous forces that are present in a fluid. High Reynolds number flows are dominated by inertial forces, and they tend to be turbulent with significant fluid mixing. Low Reynolds number flows tend to be laminar with minimal fluid mixing. For a vortex in a cylindrical breaker, the Reynolds number is defined with the following formula.[3]

$$Re = \frac{(angular\ frequency)(a^2)}{kinematic\ viscosity}$$

In this formula, the angular frequency was calculated above to be 0.88 sec^{-1}, and the kinematic viscosity is 0.89 mm^2/sec.[4] The parameter “a” is half of the length of the stir rod, which was 38.75 mm for this experiment. Substituting these values into the above formula, the Reynolds number can be calculated.

$$Re = \frac{(angular\ frequency)(a^2)}{kinematic\ viscosity} = \frac{(0.88\ sec^{-1})(38.75\ mm)^2}{0.89\ mm^2/sec}$$

$$Re = 1500$$

[2] Halász, Gábor, Balázs Gyüre, Imre M. Jánosi, K. Gábor Szabó, and Tamás Tél. "Vortex Flow Generated by a Magnetic Stirrer." *American Journal of Physics* 75.12 (2007): 1092-098. Print.

[3] Ibid.

[4] "Kinematic Viscosity of Water." *WolframAlpha Computational Knowledge Engine*. Wolfram Alpha LLC—A Wolfram Research Company, Web. 31 Mar. 2014.

This Reynolds number of 1500 is a relatively small Reynolds number, because it is less than 2300.[5] While the exact laminar to turbulent transition point differs for each flow scenario, the critical Reynolds number where the transition occurs is above 2300.[6] The calculated Reynolds number for this flow indicates that the vortex is mostly experiencing laminar flow. Given that the dye in these experiments diffused into the water in less than 3 seconds, there must be some mixing within the beaker despite the mostly laminar flow.

Estimation of the motion blur present in this image is possible by knowing the angular frequency of the stir rod, and assuming that the water at the center of the beaker is rotating at the same frequency as the stir rod. From the other pictures that were taken along with this image, the diameter of the vortex at its fastest point near the bottom is about 40 mm. Therefore, the radius from the center axis of the axis is 20 mm. Motion blur can be estimated with the following formula.

$$motion\ blur = \frac{(shutter\ speed)(angular\ velocity)(radius)(width\ of\ image\ )}{field\ of\ view}$$

Substituting values in yields:

$$motion\ blur = \frac{\left(\frac{1}{250}sec\right)(0.88\ sec^{-1})(20\ mm)(3000\ px)}{110\ mm} = 2\ px$$

A motion blur of 2 pixels indicates that very little motion blur is present in the image. Generally, a motion blur of less than 5 pixels is not noticeable by viewers.

Visualization Technique

The fluid flow was visualized with two techniques: blue food dye and refraction of light through the vortex. The food dye was a generic liquid dye purchased from a local grocery store, and it is primarily comprised of water and propylene glycol. The refraction highlights the edge of the vortex, and it is due to the change in the indices of refraction between the air and the water on the inside of the vortex.

This image required several different lights and backgrounds. First, the overhead fluorescent lights in the room were turned on. The work bench that was used also had some fluorescent lights above and behind the vortex, which were turned on as well. Finally, an incandescent light, which was warmer in color than the fluorescent lights, was clamped to a cabinet about 2 feet above the vortex. This light was directed down on top of the vortex. Two sheets of paperboard served as a plain white background. This diffused the light and helped light the vortex from behind. No flash was used.

Photographic Technique

The image was taken with a Canon PowerShot SX280 HS Digital Camera with 12.1 megapixels. The camera lens has a 4.5 - 90.0 mm focal length with an image stabilized 20 times

[5] Stepanyants, Yury A., and Guan H. Yeoh. "Stationary Bathtub Vortices and a Critical Regime of Liquid Discharge." *Journal of Fluid Mechanics* 604 (2008): 77-98. *Journal of Fluid Mechanics*. Cambridge University, June 2008. Web. 1 Apr. 2014

[6] Ibid.

optical zoom, and it can produce an aperture between 1:3.5 and 1:6.8. The camera supports an ISO from 80 to 6400.

The original image was 3000 by 4000 pixels with a bit depth of 24, and the field of view was about 11 cm across. In the experiment, the lens was 0.3 m from the vortex. Despite the numerous lights used, the image did not appear very brightly on the camera's image sensor. Therefore, a higher ISO of 1600 was used. I was interested in capturing the texture and depth of field around the vortex, so I used an F Number of 7.1. The high F Number (and small aperture) made the image darker, so I compensated by using a slightly longer shutter speed of 1/250 seconds. However, I did not want to make the shutter speed much longer because it would lead to motion blur in the vortex. The focal length was set to 11 mm.

This image required a substantial amount of post processing, which was performed with GIMP. First, the image was cropped to remove the stir rod and the distracting elements in the background, such as the water line and the gaps in the paperboard. The contrast was then increases to highlight the color and make the background whiter. There were many air bubbles on the side of the plastic container; these along with the most distracting reflections and were removed with the clone stamp tool. The final image is 2636 by 3058 pixels, and the original image is shown in Figure 3 below.

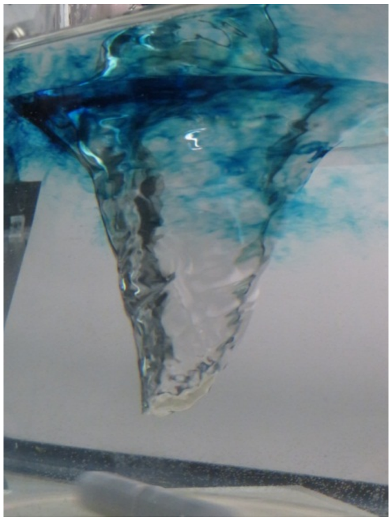

Figure 3: Original Image

Image Results

Overall, this image shows the fluid flow well. I like how part of the top of the vortex is reflected across the water line. This was a challenging subject to image, and I complicated the process by trying to take videos of the dye mixing with the water. The videos produced my camera did not have high enough resolution to show the fluid flow as clearly as I liked. If I were to do this experiment again, I would use the continuous shooting mode on my camera to take several images in quick succession as the dye hit the water and began to rotate. While the videos from my camera had a high enough frame rate to capture the fluid flow, the image size was smaller than the size of the still photos. If I used the continuous shooting mode, the images would be the full resolution (12.1 megapixels) that my camera is capable of producing. Furthermore, the mixing of the dye is beautiful when filmed in slow motion (240 frames per second or higher), and that would be an interesting approach to capturing this phenomena. One would need to make sure that the frame resolution is large enough and that the image is well lit.

References

[1] Velasquez, Gary. "Mixing Up a Vortex." University of Colorado at Boulder, 9 Feb. 2011. Web. 31 Mar. 2014.

[2] Halász, Gábor, Balázs Gyüre, Imre M. Jánosi, K. Gábor Szabó, and Tamás Tél. "Vortex Flow Generated by a Magnetic Stirrer." *American Journal of Physics* 75.12 (2007): 1092-098. Print.

[3] Ibid.

[4] "Kinematic Viscosity of Water." *WolframAlpha Computational Knowledge Engine*. Wolfram Alpha LLC—A Wolfram Research Company, Web. 31 Mar. 2014.

[5] Stepanyants, Yury A., and Guan H. Yeoh. "Stationary Bathtub Vortices and a Critical Regime of Liquid Discharge." *Journal of Fluid Mechanics* 604 (2008): 77-98. *Journal of Fluid Mechanics*. Cambridge University, June 2008. Web. 1 Apr. 2014

[6] Ibid.