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Mixing Up a Vortex

MCEN 5228 – Flow Visualization

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Get Wet Abstract: The purpose of this experiment was to capture a visually appealing image of a vortex that also captured the physics of the fluid flow itself. A magnetic mixer was used to create a vortex within room temperature tap water, while green food dye was added for visual effect. The flow was modeled by the general geometry of a circular Rankine vortex, despite deviating from the ideal.

Introduction:

In many laboratories, the most common way to effectively stir a liquid mixture is by using a magnetic mixer, also known as a magnetic stirrer. A magnetic mixer consists of a rotating magnet (the stir bar) covered in an inert material, coupled with an electric motor that produces a magnetic field. The magnetic field causes the magnet to spin, which in turn generates fluid motion (a vortex) that is utilized to quickly and efficiently mix liquid mixtures. This method is also preferred in general because of its sterility, lack of moving parts, quiet operation, and ease of clean up.

Physics Background:

Many will recognize the vortex within the beaker as a visual analog to a tornado [3], or, perhaps, water flowing down a drain. At its most simplified level, the basic physics of the vortex created by the magnetic mixer is described by the Rankine vortex model. This model consists of a swirling flow in a viscous fluid, characterized by the forced vortex (caused by the mixer, in this case) in the center, surrounded by a free vortex. Assuming an ideal vortex, the Rankine vortex best describes this phenomenon. (The velocity profile of an ideal vortex in inviscid fluid consists entirely of the free vortex). [1] While this describes the flow that does not account for the visible funnel, it does describe the fluid flow around and below it. [2]

Procedure:

A 140mL Pyrex glass beaker was used for the container in this experiment due to its excellent properties as a transparent and inert container. Room temperature tap water was chosen to be the base (or background) fluid because of its ubiquity, easy clean-up, environmentally benign properties, and propensity to mix. A store-bought variety of Kroger™ food dyes was used for a variety of effects. A PMC Electric Mixer and 1-inch stir bar were utilized to create the vortex.

The backdrop and image capture required additional materials. A two-head halogen shop lamp was set up approximately three feet away from the beaker, angled such that it was firing downward at a slight (approximately 30 degree) angle. Each head of the lamp contained a 500 Watt bulb that operated at 110V and 60Hz. Simple printer paper was used for the breaker to sit upon as shown below in Figure 1 as well as to form a clean, featureless background. A classroom-standard dry erase marker board was used to reflect back some of the light from the shop lamp for aesthetic purposes. Photos were taken from approximately one foot away from the beaker, approximately level with the top surface of the water, and one foot left of the shop lamp.

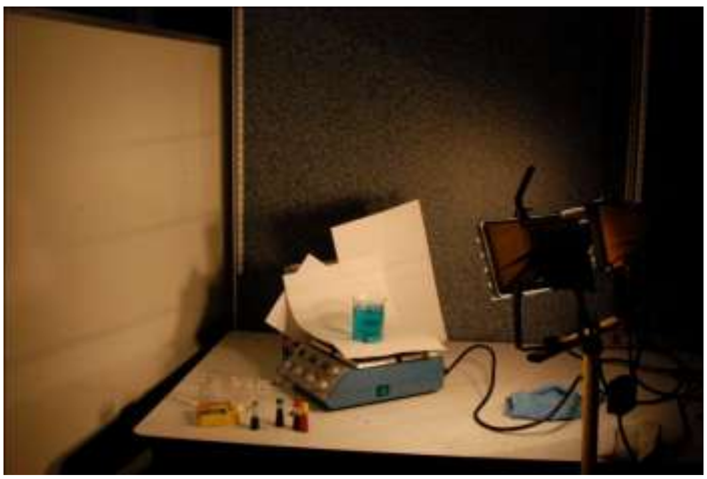

Figure 1 – Laboratory Set-Up

The set-up of the experiment was to set the magnetic mixer to various levels and drop single droplets of an estimated volume of 0.2 ml into the vortex at differing positions (the position that created the photo is shown in Figure 2) within the vortex. The stir bar was kept statistically stationary at a single position near the center of the base of the beaker. This allowed for variance within velocity fields, funnel depth, funnel radius, and stability. [2]

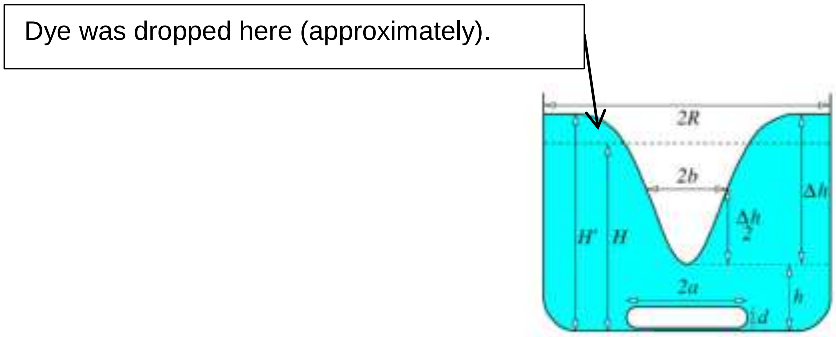

Figure 2 – Sample System [2]

Additionally, these variations propagate into differences in spread pattern and mixing rate depending on where the food dye was injected into the vortex funnel, how large the droplet was, and even which color was used (darker colors such as green and blue were observed to disperse more quickly than the lightest color, yellow).

Camera Settings:

Camera Model	**Nikon D80**
Lens	**28-80 mm**
F-Stop	**f/5.6**
Exposure	**1/160 sec**
ISO Setting	**ISO-200**
Exposure Bias	**0 step**
Focal Length	**80 mm (35mm equivalent = 120 mm)**
Aperture (Max)	**5**
Subject Distance	**Roughly 12 in ≈ 300 mm**

For the original photograph, a low ISO setting was chosen in order to reduce the graininess and pixelation that occasionally arise from higher sensitivity settings. The focus was set manually, and the photograph was taken from a short distance away (about 12 in). The motion of the stir bar was captured nicely, which maintains the experimental context that was desired for the final image. Below, the differences between the original and the post-processed final image are discussed. The scale of the vortex funnel is that it has a large diameter (taken at the top of the vortex) of one inch, and a depth of approximately 1.5 in.

Image Post-Processing:

Figure 3

Figure 4

Final Image Settings	**Original Image Settings**
Width - 2412 px	Width - 3872 px
Height - 3173 px	Height - 2592 px
Resolution - 72 dpi	Resolution - 300 dpi
Color Space - sRGB	Color Space - sRGB

The final image, Figure 3, was post-processed in the open-source program the GIMP (GNU Image Manipulation Program). It was cropped to the above dimensions in order to preserve the context of the experiment, while still narrowing the focus and scope. Since the original image (Figure 4) is a little bit dark and lacking in contrast, the levels were adjusted channel-by-channel: first red, then blue, then green, then red once again to return the background to a pearl-like white. The overall levels were raised, which increased the brightness considerably.

The markings that were inherent on the outside of the beaker were blurred by using a Gaussian Blur filter with selective boundaries, which uses the two dimensional Gaussian function

Equation 1

$$G(x,y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}}$$

where σ is the standard deviation of the Gaussian distribution, x is the distance from the origin in the horizontal axis, and y is the distance from the origin in the vertical axis. When applied in both dimensions, Equation 1 produces a surface with contours which are concentric circles with a Gaussian distribution from the origin. [4] This is what produced the softer, out-of-focus look of the backside of the beaker. In effect, the algorithm makes edges more difficult to detect. A simple sharpen filter was also utilized at the lowest setting, once. No further modifications were made.

Discussion:

The tangential velocity of a Rankine vortex is mathematically described as

Equation 2

$$u_\theta(r) = \begin{cases} \Gamma r/(2\pi R^2) & r \leq R, \\ \Gamma/(2\pi r) & r > R. \end{cases}$$

Where Γ is the circulation, R is the outer radius, and r is the inner radius. This describes a vortex that is under a Reynold's number of 2300 (laminar flow) [1], and gives the description of uniform vorticity along a cylinder of radius R with a central line as its axis. The vortex in the image is likely of Reynold's number greater than 5000 (it is visibly turbulent flow in a mixer), and it also contains a funnel that has velocities approximated by Equation 2. This model does not account for a fluid with a real viscosity (such as water), nor does it describe the course of streamlines taken by the food dyes. Also, because I did not measure velocities, a comparison cannot be accurately made.

What can be seen when looking at the image is that the droplet of green food dye, is that the vortex is not, in fact, uniform about a central axis. Some of the food dye can be seen escaping the walls of the vortex and entering the surrounding water. It can also be seen that the dye droplet does not disperse uniformly; instead, it has darker bands of concentration at various locations along the streamlines of the inner and outer walls of the vortex.

Some of the turbulent flow is also visible as the green moves in difficult to predict directions at the outer edges near the very top of the funnel. As it moves downward from the top of the vortex, it can be seen getting lighter (lower concentration) as it nears the bottom.

Conclusion:

In order to adequately describe the flow of the fluid, it would be important to take into account the surface tension effects of the water, the droplet of food dye, and possibly the ambient air. The turbulence induced by the magnetic mixer also complicates the system, which makes a mathematical model somewhat impractical. The basic geometry, however, was defined well by the Rankine vortex model. The naked eye can spot that the funnel appearsto take the form of Figure 2.

Suggestions:

Set up a digital timer circuit to take the photographs rather than trying to time it by hand, because it took nearly 800 photos to get the final photo that was used. Not all of the photos were poor (in fact, many were very good, albeit showcasing different vortices and flows each time), but it would have been nice to have more uniform photography and fluid flow. Also, finding a more precise way to limit the oscillation of the flow bar could eliminate some of the variability inherent in the system. Also, paying more careful attention to the parameters of the flow (velocity, etc.) as well as magnetic field analysis on the stir bar and mixer would allow for a more advanced analysis than what can be seen here.

Works Cited

[1] Acheson, D. J. Elementary Fluid Dynamics. Oxford: Clarendon, 2006. Print.

[2] Halasz, Gabor, Balazs Gyure, Imre M. Janosi, K. Gabor Szabo, and Tamas Tel. "Vortex Flow Generated by a Magnetic Stirrer." American Journal of Physics 75.12 (2007): 1092. Web.

[3] Mishra, A., D. James, and C. Letchford. "Physical Simulation of a Single-celled Tornado-like Vortex, Part A: Flow Field Characterization." Journal of Wind Engineering and Industrial Aerodynamics 96.8-9 (2008): 1243-257. Print.

[4] Nixon, Mark S., and Alberto S. Aguado. Feature Extraction and Image Processing. London: Elsevier, 2008. Web.