# Get Wet

Scott Wieland
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## Purpose

This project was designed to help students understand the physics behind fluid flow phenomenon through the use of artistic photographic techniques and was completed for the Flow Visualization course taught by Professor Hertzberg at the University of Colorado at Boulder. The goal is to capture an interesting fluid flow that not only looks beautiful but also retains all relevant information to describe the physics. It was intended as the introduction to the techniques involved and was titled “Get Wet.” My personal goal was to capture the effects of a vortex generated by a magnetic stir plate at a high Reynolds number.

## Experimental Setup

To construct this experiment, a magnetic stir plate was utilized in conjunction with a cylindrical storage container filled with tap water. The cylinder was 11” tall with a radius of 2” and was filled with tap water to about 1.25” from the top. The 2” magnetic stir bar was then lowered into the cylinder and then the contraption was aligned so that the stir bar rested in the center of the vessel while also being held in place by the magnetic field of the stir plate. A desk lamp was then placed 4 inches above the cylinder, shining downwards into the liquid through a diffuser. A second desk lamp was placed 12” behind a 20” tall white backdrop located directly behind the vessel made of computer paper, which doubled as another diffuser. The final step was to emulsify Kroger brand food dye into Kroger brand vegetable oil. This emulsification was done manually and was accomplished by adding approximately 20 drops of either green or red dye into approximately 1 ounce of oil. The mechanical emulsification was then completed using a 2-speed immersion blender on its highest speed. Finally, each emulsified dye solution was placed into its own 10 ml syringe for use. The full experimental setup can be seen below in Figure 1.

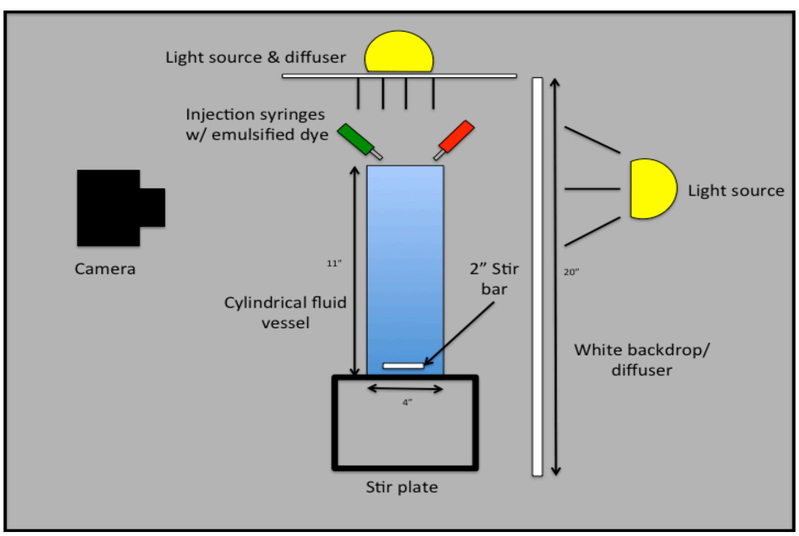


**Figure 1: The complete experimental setup for the stir plate vortex**

To actually conduct the experiment, the stir plate was first turned on, and the speed was slowly increased to its maximum rotational rate, approximately 2000 RPM. Once the maximum rotational speed on the stir plate was achieved, the mixing was allowed to occur until a turbulent steady state was reached. After reaching this state, both the red and green dye solutions were injected into the cylinder in approximately 0.5-1 ml quanta from opposite sides. This was done rapidly and until the syringes were empty. Finally, the camera was picked up and pictures were taken from around 6-12" away from the cylinder.

## Fluid Physics

The vortex created by a stir plate is very similar to the phenomenon known as a plughole vortex. The most common occurrence of these plughole vortices occurs when fluid is going down the drain of a container such as a bathtub, in which a sink in the container is made while a constant inflow is applied. A stir plate will create a very similar flow, but without the mass flux of the inflow and outflow caused by the sink. The upper surface is defined as being free and the resulting flow creates a dip known as a downwell on the upper surface above where the sink or center of the vortex is located [1]. The velocity field around the sink can than be described in one of a few ways, either throw a potential flow theory analysis, or by modeling it as a Rankine or Burger's vortex [2,3].

The main features that develop to describe the flow are a negative radial velocity that pushes the fluid towards the center and a downward velocity in the center. These velocities actually are proportional to their corresponding direction, i.e. $u_r = -ar$ , and $u_z = bz$, where $a$ and $b$ are some constants, and the positive z direction is down [1–3]. These first two features can be described by the pressure gradient that develops in the flow. Essentially, the dynamic pressure is actually negative in the core of the vortex and enlarges to be positive as we get farther from the center. The resulting pressure field is the main cause of these motions [2].The last component of the velocity, the tangential velocity, decays as we get farther away from the center point. The typical way to model is proportional to $\frac{1}{r}$, but this has a singularity that does not hold mathematically. The improved result also decays at the center of the vortex, and looks like the following.

$$u_t = \frac{C_1}{r}\left(1 - e^{-\frac{r^2}{R^2}}\right)$$

In the previous equation $C_1$ is some constant proportional to the rotational speed of the stir plate, and $R$ is the radius of the cylinder [2,3]. Between these relationships with velocity, we can approximately describe a standard plughole vortex, but these models do not account for the flow to be wall bounded and have no mass flux through the system.

For the example we are working with, we must conserve mass and momentum, and also satisfy the boundary layers on the wall. The ending result is that we create a scenario that is almost reminiscent in appearance to that of a Rayleigh-Bernard convection. As the vortex causes a net velocity downwards in the center there is a point where it must become zero and then the radial velocity must change direction to push outwards. Then, this radial velocity must turn into an upward velocity as it approaches the wall. The resulting vertical cross section of velocity can be seen in Figure 2. The point at which this transition occurs is dependent on the Froude and Reynolds number. These definitions, and their estimations appear as follows.

$$Re = \frac{\Omega a^2}{\nu} = 21000, Fr = \frac{\Omega a}{(gR)^{\frac{1}{2}}}\left(\frac{d}{a}\right) = .47$$

In the above, $\Omega = 33\ s^{-1}, a = 2.54\ cm, \nu = 10^{-2} cm^2 s^{-1}, d = 1\ cm, g = 981\ cm/s^2,$ and $R = 5.08\ cm$, and they represent the rotational speed of the stir bar, the half length of the stir bar, the viscosity of water, the thickness of the stir bar, the acceleration due to gravity, and the radius of the container, respectively. The higher either nondimensional is, the deeper the transition point will be. The extraordinarily high Reynolds number is what allows me to get about 6 inches of immiscible dye bubbles penetrating down. This shows that the transition point must be about

Though no explicit relationship has been defined to find this transition point, it was determined that the lowest point in the visible downwell, i.e. the lowest point of the free interface, should depend on the same non-dimensional parameters. The found relationship is shown here.

$$h = Re * Fr * \frac{d}{\alpha x + \kappa} = 1.6\ cm$$

In this equation, the new variables are $\alpha = .58 * 10^3, x = 5.6,$ and $\kappa = 2.8 * 10^3$, where $\alpha$ and $\kappa$ are constants found by Halász, et al. and $x$ is the ratio of the height of the container to the radius of it. The measured downwell came out to be approximately 2 cm, so the relationship confirms the estimation of our non-dimensional parameters. That means this flow was highly turbulent because of the very large Reynolds number, and was dominated by body forces, which is evident by the very low Froude number [3]. Because of this, we know that in order to resolve this image in time, we should have an ideal shutter speed of $\frac{1}{Re}$, which equates to a very powerful high-speed camera. Similarly, to spatially resolve the image, we should cover about 5 orders of magnitude.

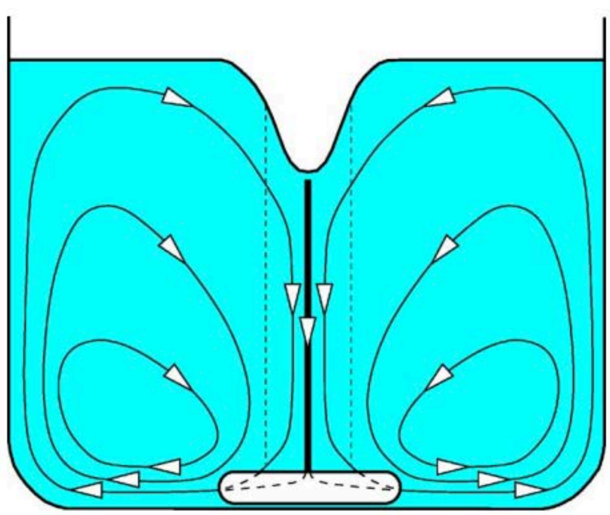

**Figure 2: The resulting convection like current do to the wall bounded flow** [3].

## Photographic Technique

To obtain the resulting photograph, a Nikon D70 with a Nikkor AF-S DX Zoom lens was used. The ISO was set to 1600, the shutter speed was set to 1/200 of a second, the focal length 46mm, and the f/ was 4.5. The picture was taken roughly 6" from the container and the original image shows a section of cylinder roughly 4" wide and 6" tall. The original image is 2000 pixels by 3008 pixels and comes to 6 MB in size. My overall goal was to make the bubbles of dye appear like glass beads, and to do this I needed the fastest shutter speed I could get to freeze the flow, and ideally, a higher level of exposure. I used GIMP to make many changes, as is visible in Figure 3. First, I cropped the image to about 1400 by 2400 pixels. Secondly, I put a standard S-curve on the entire shot to get more contrast on all levels. Then I forced more of the dark channels to be green and more of the bright channels to be red so that there would be a stark difference in the two colors. All of these color edits were done using curves. Next, from increasing the contrast, graininess started appearing from the high ISO setting, so I applied a wavelet de-noising filter to try to clean it up. Finally, I applied an unsharp-mask with a radius of 5 and amount of 2.5 to try to give the image a more crisp feeling.

**Figure 3: The original image, left, and the edited image, right.**

## Conclusion

It was my intention to capture interesting vortex dynamics in a unique and creative way. My goal was to display how a fluid that is immiscible with water will get pulled into the center and downwards when a strong vortex is formed. I believe the phenomenon is captured well and is relatively easy to see. I also believe, however, that my equipment limited my artistic skills. I was unable to spatially or temporally resolve the flow, so in turn, my original image suffers from a soft focus and some motion blur. To solve this, there are many approaches. Adding more lighting or using a standalone flash could help me solve the problem by allowing me to lower my ISO and increase my shutter speed. I also may have been able to achieve a better focus if I had a macro lens instead of a zoom lens since the spatial features were so small. I believe, however, that I was highly limited by my camera. Seeing as it is about 10 years old at this point, it is quite outdated in terms of camera technology. With a newer camera, I would be able to push the ISO even higher than 1600 without having to worry about graininess and that alone would probably have helped me achieve the shutter speed I really needed to completely time resolve the image. Finally, I may be able to obtain some interesting images using a nice quality high-speed camera. In the end, though, my hope is that before the end of the semester, I will be able to borrow or check out any of the aforementioned equipment to try to improve the final product.

## Bibliography


[1] Q.-N. Zhou and W. P. Graebel, J. Fluid Mech. **221**, 511 (2006).

[2] N. Rott, ZAMP Zeitschrift Für Angew. Math. Und Phys. **9**, 543 (1958).

[3] G. Halász, B. Gyüre, I. M. Jánosi, K. G. Szabó, and T. Tél, Am. J. Phys. **75**, 1092 (2007).