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Flow Visualization

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This vortex visualization was created for the second group project in Flow Visualization at the University of Colorado at Boulder. Our goal was to capture interesting vortices while draining water from a bucket and visualize the flow by seeding it with food dye. We also experimented with using two holes to capture multiple vortices, however, this was unsuccessful.

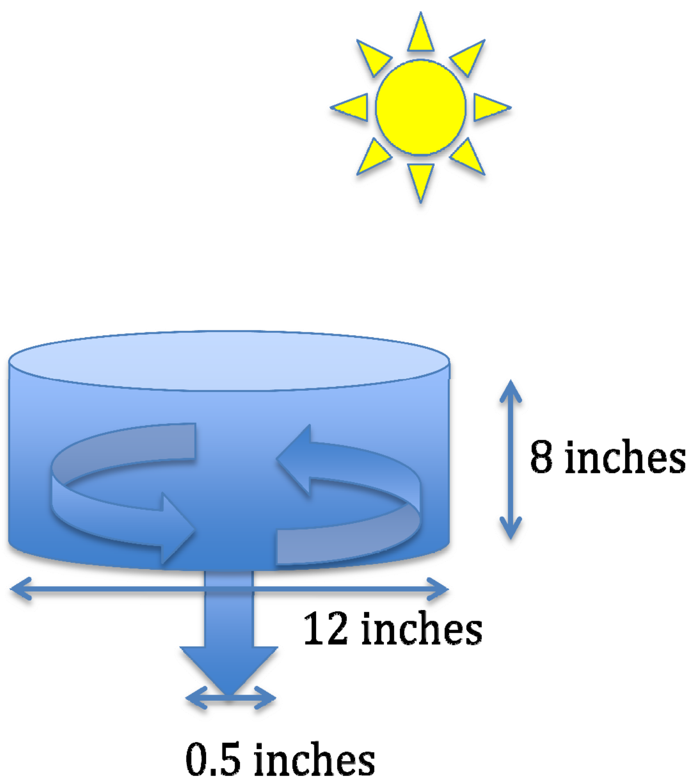

Figure 1. A vortex forms as water drains from a bucket that is open to atmospheric pressure and sunlight.

Water from a hose filled the bucket, and we allowed the water drain in batches through a 0.5-inch diameter hole in the center of the bucket. We can solve this problem for the time to drain the tank using a mass balance and Bernoulli's equation or Torricelli's Law. We can use a pseudo-steady-state approximation to say that the ratio of the velocity of the water at the top of the tank to the velocity of the water exiting the tank is zero. This will simplify Bernoulli's equation to exit velocity as a function of pressure and height. Because the pressure is atmospheric at the top and exit of the tank, Bernoulli's equation will relate the height of the water (its potential energy) to its velocity (its kinetic energy) by assuming friction is negligible. If we follow this analysis, we will derive Torricelli's Law for relating the velocity of the fluid to its height,

$$v = (2gh)^{1/2} \tag{1}$$

By trusting Torricelli, we can calculate the maximum Reynolds number (Re) for the fluid leaving the tank. If our assumption of the ratio of velocities is reasonable, we will find that flow is always laminar at the top surface of the liquid. The Reynolds number, defined

$$Re = v\rho D/\mu \tag{2}$$

where v is the velocity, ρ is the density, D is the diameter, and μ is the viscosity, describes the ratio of inertial to viscous forces in the fluid. A high Re gives to turbulent flow, low Re to laminar. Plugging in Torricelli's law for the velocity, we could calculate the ideal Re by neglecting entrance effects of the fluid leaving the tank and the cavity formed by the vortex. These effects will cause turbulence in flows that we would calculate to be laminar. We could instead look at Re for annular flow to replace D with a characteristic length scale, but the food dye alone discerns the turbulent/ laminar flow regions. By looking at the image we can discern that the flow is mostly laminar because mixing seems to be caused by diffusion alone, however, at the center of the tank, turbulence is giving to thorough mixing.

Gravity and centrifugal force acting on the fluid due to its circular motion cause a vortex. The angular momentum of the system is approximately conserved (it is consumed by turbulence at the center of the vortex and friction at the wall of the tank). This means that the angular velocity of the fluid increases toward the center of the tank. The increased centrifugal force (proportional to v^2/r) at the center of the tank causes the curved surface. It's steepness increases with centrifugal force until a cavity is formed[1]. The varying refractive index through the curvature causes a shadow under the vortex.

We seeded the flow with drops generic food dye on a warm sunny day so that sunlight was the only light source.

The picture was taken about 1 foot from the water's surface. The image field of view is about 28 square inches. Additional camera information is given in table 1. The image was initially 4272 x 2848 pixels and was cropped down to 3231 x 2028 pixels to focus the image on the vortex and dyed water. I increased the brightness and sharpness of the image to make the streamlines more apparent.

Table 1. Camera Specs

Camera type	Canon EOS Digital Rebel XSi
Focal length	135 mm
F-number	5.6
Exposure time	1/4000 s

I feel the physics are well revealed by differences in mixing through the image. The presence of mixed colors at the center of the vortex shows that the flow is turbulent because of the increase in fluid velocity. I like the wide range of color and flow depicted in the image. This idea could be further developed my adding another vortex to the system. We were unsuccessful in our attempts to create a second vortex, but placing the holes equally distanced from the tank center may allow this phenomenon to be captured.

Reference:

1. Bird, RB, Stewart, WE, Lightfoot, EN. Transport Phenomena: Second Edition. John Wiley & Sons, Inc; New York. 2002.