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Vortex Apparatus and Demonstrations

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Vortex flow, from millimeter to kilometer in scale, is important in many scientific and technological areas.[1] Examples are seen in water strider locomotion, from industrial pipe flow (wastewater treatment) to air traffic control (safe distance between aircrafts on a runway ready for takeoff) to atmospheric studies.[2-5] In this paper, we focus on a particular vortex known as bathtub vortex (BTV). It occurs when water is drained from a hole at the bottom of a container such as a bathtub or a sink under the action of gravity. The vortex has a funnel shape with a central air core, resembling a tornado. We have designed a portable apparatus to demonstrate bathtub vortex on a continual basis. The apparatus consists of a clear cylinder supported by a frame over a water reservoir and a submersible pump. Young and old have been equally amazed by watching the demonstrations at various public presentations held at the University of the Pacific recently. With material cost of less than $100, the apparatus can be easily fabricated and used at other universities. With a short set-up time, it is an ideal device for promoting science to the general public, and it can be used to enhance lectures in physics courses as well.

There has ben controversy regarding the natural direction of BTV differing in the Northern and Southern Hemispheres. Ascher Shapiro performed a series of experiments in a large but precisely fabricated tank of water (6-ft diameter, 6-in high) under highly controlled conditions. He showed that indeed the water undergoes a counterclockwise rotation as it drains out of the tank in Cambridge, MA, i.e., Northern Hemisphere.[6] Consequently, based on Shapiro's blueprints, researchers in Australia performed similar experiments and showed that the vortex direction is clockwise in the Southern Hemisphere.[7] Similar experiments were also carried out elsewhere.[8,9] The Earth's rotation and its Coriolis effect accounts for the different directions in different hemispheres. But the directional consistency can only be observed under controlled conditions or in large bodies of water. As for the water draining from relatively small containers, such as bathtubs, the vortex could be developed in either direction. The resulting direction depends on the container shape and any residual swirls that might be imparted on the water as a result of filling and/or removing the drain plug. Most people do not know these facts, and some tourists are taken advantage of by the locals who charge unsuspecting tourists to show them how a BTV behaves differently 20 ft north and 20 ft south of the equator!

More recent studies in BTV have dealt with investigations of outflow from fuel tanks[10,11] among others. Models of BTV have been installed in several science museums such as the Exploratorium in San Francisco.[12] However, museum models are limited in terms of what a visitor can do with them. For example, the one at the Exploratorium has a valve with which the visitor can change the air-core size, but nothing else can be done. In this paper an apparatus is described that can produce a BTV on a continual basis with which several demonstrations can be performed.

Bathtub vortex apparatus

Figure 1 shows the components of the apparatus, which is a simple and portable but durable device that can be set up and ready for use in 5-10 minutes, with negligible running costs. It can be fabricated in any machine shop equipped with a milling machine.

The apparatus consists of a clear acrylic cylinder (5-in diameter and 15-in high) closed at the bottom with an acrylic disk and open at the top. The cylinder is supported by a frame over a plastic bucket that serves as a water reservoir. Filling the bucket with two gallons of water is sufficient for demonstrations. A submersible pump (rated 300 gph at 0 head) supplies water to the base of the cylinder through an inlet tangentially drilled into its side. The disk at the bottom has a central hole (1-in diameter) for an outlet that is fitted with a ball valve to regulate the flow.

Figures 2(a) and (b) show steady BTV with fully and partially open outlet settings, indicating large and small air core, respectively.

Bathtub vortex demonstrations

Three new and intriguing demonstrations are presented here: (a) regulation of vortex height with a fixed bar, (b) illustration of color mixing with drinking straws, and (c) creation

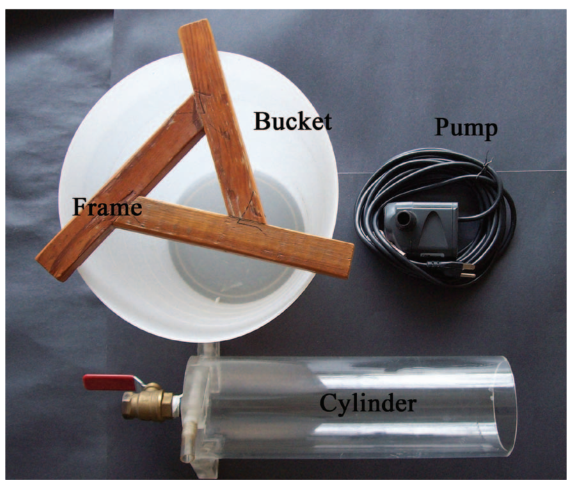

Fig. 1. Components of the bathtub vortex apparatus, with cylinder laid out horizontally to show the outlet valve. Plastic tubing (not shown) connects the pump to the cylinder.

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Fig. 2. Bathtub vortex with (a) fully open outlet and (b) partially open outlet.

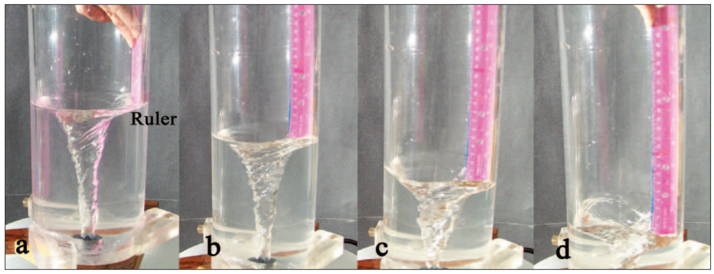

Fig. 3. Ruler's width aligned with (a) circumferential direction and (b, c, d) radial direction.

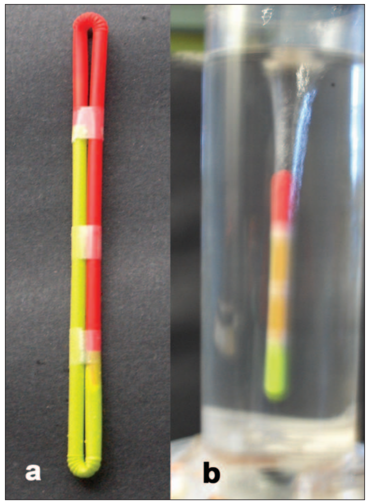

Fig. 4. (a) Loop made of green and red straws. (b) Spinning loop, note yellow in the middle. Slow shutter speed (1/15 s) was used to reveal color mixing in the photo.

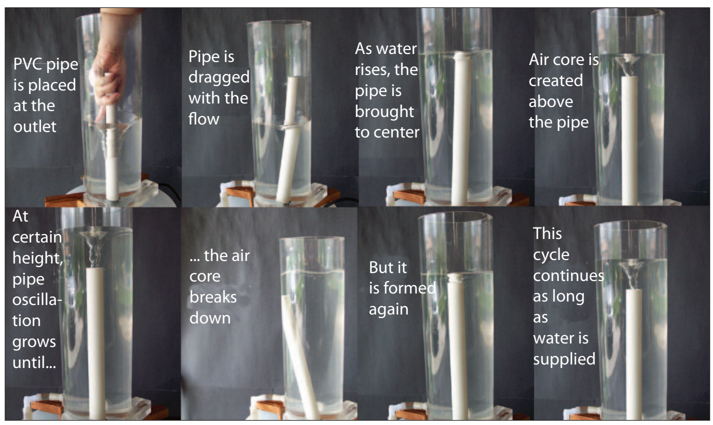

Fig. 5. The sequence of self-induced vibration of a pipe in BTV. Photos to be viewed from left to right, top row first.

of self-induced vibration of a pipe placed within the vortex. To the author's knowledge such demonstrations have not been reported in the literature. More demonstrations have been performed with the apparatus but due to space limitations are not included here.

(a) Height regulation

Consider a plastic ruler. If its width is aligned with the azimuthal (circumferential) direction and inserted adjacent to the cylinder wall in the vortex, nothing happens, as shown in Fig. 3(a). However, when aligned with the radial direction and inserted in the vortex, the water level immediately drops down to the end of the ruler, as shown in Figs. 3(b)-(d). As a result the ruler can be used as a simple level regulator. The ruler insertion in the radial direction forces more water towards the central axis and therefore more water flows out, causing a drop in the water level. As the ruler is pulled out, the water level rises to its previous level.

(b) Color mixing

It is well known that when two colors are mixed, a third color results. Two bendable drinking straws—one green and one red—are used to make a loop as shown in Fig. 4. If the loop is dropped into the vortex while the outlet is fully open, it will be immediately pulled into the vortex and out through the drain hole. This effect demonstrates the strong suction (i.e., low pressure) present at the drain hole, similar to the eye of a tornado. By partially closing the outlet valve, the loop can be made to stay in the vortex and spin along the central axis. While spinning, the loop shows colors of red at the top and green at the bottom, but yellow color is perceived in the middle (combination of green and red). This is a fascinating demonstration that most people enjoy watching. A paper by Halász et al., which describes a vortex created by a magnetic stirrer, recommends using drinking straws to observe rotation of elongated objects in the vortex.[13]

(c) Self-induced vibration

This demonstration is explained below and depicted in a series of sequential snapshots in Fig. 5. Consider a 10-in long piece of ½-in PVC pipe. It is inserted into the vortex by setting its bottom end freely at the drain hole. This insertion breaks down the air core, and as a result more water flows out, causing the water level to drop below the pipe's top end. The incoming flow then drags the pipe with it around the cylinder, while the pipe's bottom end remains at the drain hole. Eventually, the pipe is oriented vertically along the central axis due to radial pressure gradients, i.e., higher pressure at larger radius as prescribed by Euler's equation of motion for inviscid fluid on a circular path (due to centripetal acceleration). Now, as soon as the water rises above the pipe, the air-core vortex is reformed above and through the pipe. The water level keeps increasing to about 2.5 in above the pipe. At this point air-core instabilities become large enough to induce oscillations to throw the pipe's top end off center. This action destroys the air core again and more water drains out, lowering the water level. Then, the above sequence is repeated and it continues as long as the flow is maintained. A video clip of this demonstration was shown at the 2007 Gallery of Fluid Motion sponsored by the Fluid Dynamics Division of the American Physical Society. A copy of the video is available at the repository maintained by Cornell University.[14]

End result and conclusion

Youths and adults have been equally amazed by observing these demonstrations at several public events held at our campus recently. The observing groups included girls aged 12-18 attending "Expanding Your Horizon," boys and girls with their parents attending our university Open House, and a group of retired men in a coffee club. A few of the comments made by the observers best describe the value of the apparatus as a tool to promote science and engineering. A young boy said he wanted to make a similar device for his room. A young girl asked several thoughtful questions. An adult expressed that it was hypnotic for him to watch the BTV.

Based on 23 years' experience of performing show-and-tell presentations with various devices to the general public, the author feels this apparatus has been one of the best devices for him in attracting the public's attention and interest in science and engineering. Any reader interested in replicating these demonstrations is welcome to contact the author to obtain an engineering sketch of the apparatus.

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4. efluids.com/efluids/gallery/gallery_pages/trailing_vort2_page.jsp. This link shows flow visualization of a wing-tip vortex that contributes to strong downwash left behind as a C-17 Globemaster takes off.
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14. hdl.handle.net/1813/9460. This link has a two-minute video of the self-induced vibration presented in the third demonstration.

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