An Apparatus to Monitor and Control a Liquid Vortex

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Abstract

It seems that nature loves a vortex. Circular motion in nature occurs in weather patterns, meandering rivers, air off of airplane wings – both wing tips and trailing edges, and in liquid pools which are draining from the bottom. Yet in most of these cases, the fundamental physics behind the need to rotate is not very clear. Only in the case of airplane wing tip vortices and trailing edge wakes is the mechanism for the rotation understood- pressure differential in the case of tip vortices and combining airstreams of different speeds causing a rotating wake. As for tornadoes, it seems that the motion has to do with the updraft of air into a cloud to relieve the vacuum created from condensation of water vapor. This may explain the updraft, but what causes the rotation? In liquid vortexes, that are typically created in still reservoirs that have flow draining from a hole in the bottom, again the physics from the water draining (Torricelli's law) is straight forward, but the *rotation* of the exiting fluid column and the *rotation* of the remaining fluid in the reservoir is not explained. Even potential flow theory, which has its basis on the concept of a vortex[1], does not explain why the vortex is created but rather describes the motion of the elements if a vortex is created (conservation of angular momentum, irrotational vs rotational). To better view and study a liquid vortex, a Vortex Analysis Apparatus was built and housed in the lab of the College of Engineering at the University of Toledo. The apparatus was to allow experimenters to observe a liquid vortex in its formation and through to its maturity. Experiments were conducted in an to attempt to discover the characteristics of vortex formation

Introduction

One of the most difficult phenomenon of nature explain is one of the most common and one that most everyone has experienced. Water draining from an open hole in the bottom of a reservoir, such as a bathtub, often has the tendency to create a whirlpool. A whirlpool in a bathtub or a toilet is quite a curiosity. No matter how many times you see it, it always captures your attention. There is a power there which causes material to behave in a manner not before seen.

In fact, there are two aspects of a whirlpool, each equally fascinating. First, there is a dimple or a cone formed in the level surface of the liquid. Second, there is a clearly visible rotation of the fluid with a definite and significant rotational velocity. Both of these phenomena are hard to explain. Water seeks its own level, therefore why is there an indent in the surface of the water? Furthermore, the water is quiescent in most of the tank, therefore where did the energy come from to create the rotation, and why is this velocity in an isolated circular configuration?

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There is only one strongly held theory on how a whirlpool is produced, and that is almost certainly wrong. Yet, virtually everyone; layman, clergyman, physicist, will immediately offer this one suggestion on what causes whirlpools; the rotation of the earth. The 'theory' goes further to point out that the rotation of a whirlpool in the northern hemisphere is opposite that of the southern hemisphere. Not everyone will be able to quote which direction for which hemisphere but those that can, will usually predict counterclockwise for the northern hemisphere and clockwise for the southern.

In order to test this theory, and indeed to test for any cause-effect relationships concerning a vortex, a test apparatus was constructed at the College of Engineering of the University of Toledo that will give controlled conditions to observe and measure water vortexes. The design and construction of the apparatus (Vortex Analysis Apparatus VAA) was done by undergraduate engineering student for their senior project. Specifically we mean to study vortexes created in a 'static' reservoir which is exhausting some amount of fluid through an orifice at the base of the reservoir. We term this a 'gravity vortex' to draw the distinction to a 'pump suction vortex'. In fact, the practical use of the results of our studies may best be applied to pump suction vortexes, because such vortexes are of great interest to pump manufacturers[2] and pump uses [3] alike. Aggressive vortexes of this type can cause cavitation of pumps, with a corresponding loss of prime or, over a longer period, the destruction of the pump. However, it appears logical that the three primary parameters involved in the establishment of a vortex are the flow rate, the head over the exit (submergence), and the viscosity of the fluid. These three parameters are the same for a gravity vortex versus a pump suction vortex, with the distinction that the flow due to gravity is according to Torricelli's equation and the flow due to a pump is determined by the pump.

Design and Construction

The basis of design for the apparatus was to create a tank in which a water vortex could be clearly viewed under controlled conditions. The tank should be large enough that the vortex should be unaffected by the sidewalls of the tank (no friction effects due to sidewalls). The amount of water that exhausts from the bottom should be able to be varied, and in a precise manner. The level of water over the exhausting orifice (submergence) should be able to vary and be precisely measured. The fluid shall be water but the viscosity should be varied by heating the water to elevated temperatures.

With these guidelines the VAA apparatus consisted of two large rectangular tanks; a water preparation and supply tank including submersible pump and water heaters and an observation reservoir (Figure 1). The observation tank was of sufficient size to eliminate any effects due to the sidewalls (90 cm x 90 cm at the base) and was tall enough (1 meter) to give sufficient submergence. The glass was 750 mm thick aquarium glass. It was determined that the strength of the glass with sufficient safety factor warranted that the tank be filled to only half of its depth and safety straps were positioned to give it lateral support. The exit hole in the base of the observation tank was piped directly to a control valve and then back to the supply tank.

The apparatus was meant to be used in two modes; an unsteady mode and a steady-state mode. In the unsteady mode, the observation tank was filled to a specific level and the control valve set for a specific rate. Once the test began, the water exiting the upper reservoir was not replaced and therefore the submergence was allowed to be reduced until a vortex became evident. In the steady state mode, once the first sign of a vortex became evident, the height of the water in the reservoir was closely monitored and made-up so that the level remained constant. In order to add the water in a manner that would not disturb or in any way ‘prejudice’ the vortex formation (create circulation in the reservoir), the fill water was introduced from the top and onto the glass sidewalls so that it could flow uniformly and in a sheet down to the sidewalls into the sump area.

(a) (b)

Figure 1 The Vortex Analysis Apparatus (a) the water preparation and supply tank including heaters and submersible pump is in the lower left, the back of the observation tank is in the upper right (b) the elevated observation tank. Notice in (b) the manifold system at the top to introduce water into the reservoir ina manner that would not ‘prejudice’ the circulation

Operation and Observation

While setting up the apparatus to collect data, the researchers were given the opportunity to observe vortex formation and vortex shapes *(Figure 2).* In particular, various forms of flow visual techniques were used. The two most successful were dye injection (food coloring) and trace particles. Granular plastic compounds were used for the trace particles, designed with a specific gravity to closely approximate water. Some very significant observations and conjectures were made.

The most important observation was that sometimes the vortex would be formed in the clockwise direction and sometimes it would form in the counterclockwise direction. In fact, the circulation of the vortex was extremely random, but for one exception. The researcher could force the direction of rotation by just a slight preliminary movement of the water in that direction. If we call this a ‘forced vortex’, then it is probably true that most liquid vortexes in nature have their direction of circulation forced on them by

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the surrounding. Certainly a toilet flushing is an example of a forced vortex. *Figure 3* illustrates a less obvious case of forced circulation. The waterfall fountain empties into a basin with submerged drains at opposite ends. The flow in the pond moves away from waterfall then divides going right and left. This rotational motion is more than sufficient to determine the circulation of the vortex over each drain. Notice that the circulation is opposite on each side.

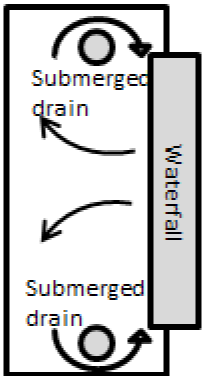

Figure 2 Vortex visualization in the VAA

Figure 3 An example of forced vortex circulation. There are two sump drains- bottom right and upper left. Each have different rotations

In the VAA, not only could we easily determine the direction of the vortex, but it seemed that the water actually had a 'memory'. That is, we could stop the drain and suppress the vortex, wait several hours, and then open the drain and the water 'remembered' the rotational direction from last time. With the dye and tracer visualization, we could actually see why water has such a memory. After several hours there was still significant movement in the tank, much of it random but still a distinguishable general rotation. The viscosity of water is so low that once in motion, it will remain in motion for extremely long times. Therefore we could surmise that even in the case of a draining bathtub, the motion of the water before the drain is pulled, is sufficient to determine the direction of circulation of the resulting vortex.

Data and Measurement

The first experiment that was designed for the apparatus was to determine the effects of viscosity on vortex formation. The VAA was used in its unsteady mode. Water was filled into the visualization reservoir at a specific temperature and then allowed to drain. The beginning of a vortex was defined by a slight surface swirl in the reservoir. The submergence of the drain at the initiation of the vortex was then recorded. This procedure was repeated 59 times with water temperature varying from 50degC to 150 degC. *Figure 4* shows the results.

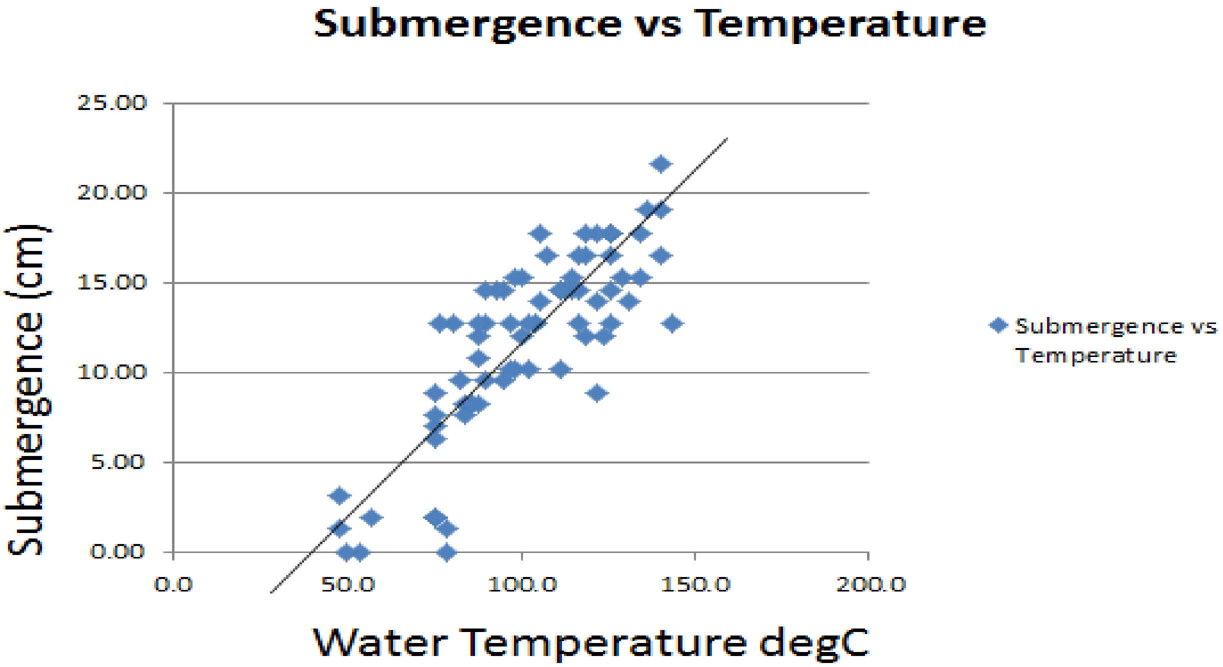

Figure 4 There was a trend that the vortex started earlier (greater submergence) for lower viscosity fluids

The first testing showed three things that were quite exciting. The first of them cannot be seen on *Figure 4*. Every data point on that graph represents a vortex and every vortex had a rotational direction. Of the 59 data points, the directions were almost evenly distributed between clockwise and counterclockwise. This is an amazing result; a vortex begins almost on a whim, but then increases in veracity to become a formidable phenomenon. In fact, often it occurred that once a vortex was formed and then the reservoir was allowed to drain, the next run would show a vortex in the same direction. It was as if the liquid, the water, had a memory and started in the same direction that the previous vortex had formed. If fact, we concluded that the direction of a vortex was determined by the preexisting condition of the fluid in the reservoir. If there was any general motion in the water, the vortex would initiate by following that motion.

The next observation, which can be seen in *Figure 4*, is that three times the vortex *never* occurred or started just before the water ran out. This attests to the random behavior of a vortex. But on four other occasions, at the same temperature and under the 'same' conditions, the vortex formed at between 6 and 9 cm of submergence. Although this data looks like it is not repeatable, it could be explained that the water had different preexisting conditions.

The third observation from this test is that it appears that with the lower viscosity (higher temperatures), the vortex started earlier (greater submergence). That is the straight line draw on the figure. It is interesting that viscosity, or the lack of it, surely must play a role in vortex creation, and this graph attests to the fact that the lower the fluid velocity, the earlier a vortex will form. However, with that said, the difference of the submergences for one specific viscosity is significant. For example, at 100 degC, some vortexes started with a reservoir height as high as 18 cm, while at other times the reservoir drained all the way down to 10 cm.

Conclusion

This paper announces and describes the Vortex Analysis Apparatus built in the College of Engineering of the University of Toledo. It also details some surprising first results from the apparatus. In particular it debunks the myth that there is a preferred circulation direction for a liquid vortex. In fact, the argument is made that all vortexes have a forced circulation direction based on preexisting motion in the reservoir.

Furthermore it illustrates that vortexes are created easier in less viscous liquids than in more viscous liquids. This is certainly consistent with logic that would indicate that vortexes do not form in very viscous liquids.

Research on this facility has just begun. In particular, what is reported here concerns the nature of the creation of the vortex. What has not been investigated is the strength of the vortex because, if the current research indicates that the direction of a vortex is determined almost on a whim, it is not true that once the vortex has direction, it remains a weak phenomenon. In fact, a vortex grows to be very violent. Future research with the VAA will attempt to determine where the energy comes from to generate such violence.

Also in the future agenda is to research concepts to delay or arrest vortexes. This is of primary interest to pump manufactures and users of liquid pumps. With the VAA, several different designs of vortex attenuators can be tested.

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Dr. Kamm is Professor of Engineering Technology at the University of Toledo. He has been the lead thermodynamics and fluid mechanics instructor in the Department and wholly responsible for the Thermodynamics and Fluids Laboratory . He is the author of a textbook in thermodynamics: HEAT AND POWER THERMODYNAMICS (Prentice Hall) which has been used for both introductory and advanced courses of thermodynamics for engineering technology. His text has been converted to a digital book and with streaming media. He has been honored on several occasions for his excellence in the classroom. In 1991, the Outstanding Teaching Award was presented by the National Institute for Staff and Organizational Development, University of Texas. In 2002, he was cited in Who's Who Among America's Teachers, and in 2009, we received the Outstanding Teaching Award from the University of Toledo. Dr. Kamm has established a rapport with the HVAC industry and became a member of the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) in 1976. He has served on various local ASHRAE chapter committees and in 1980 was nominated for a three year term as Regional Chairman of Educational Activities. In 1983, he was elected Regional Chairman. During his three year term, he was responsible for overseeing all the activities of 13 mid-western ASHRAE chapters and serving on the Society Board of Directors. After retiring from the ASHRAE Board, he served as chairman of the Toledo ASHRAE for four years, culminating in President in 1994. Dr. Kamm is a Life Member of ASHRAE and is the author of the ASHRAE on-Line learning course, *Fundamentals of Psychrometrics.* He has published many papers and has been interviewed numerous times on his research in energy related topics. Much of this comes from his constant involvement in undergraduate research through the Senior Technology Design capstone course. He has received a grant from the Ohio Biomass Energy Program (PUCO) to propose a new biofeedstock. His paper *'A New Class of Plants for a Biofuel Feedstock Energy Crop'* appeared in APPLIED BIOCHEMISTRY and BIOTECHNOLOGY, (2004) Humana Press.