A study of the angular velocity in a liquid induced by a vortex in an emptying container

James Paul Hartman

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A STUDY OF THE ANGULAR VELOCITY IN A LIQUID INDUCED
BY A VORTEX IN AN EMPTYING CONTAINER

BY

JAMES PAUL HARTMAN, 1937-

A

THESIS

submitted to the faculty of the

SCHOOL OF MINES AND METALLURGY OF THE UNIVERSITY OF MISSOURI

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Degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

Rolla, Missouri

1963

Approved By

(advisor)  Charles L. Edwards

David W. Bunch
ACKNOWLEDGEMENT

The author wishes to express his appreciation to Dr. A. J. Miles, advisor in this work, and to Mr. B. L. Bramfitt for their valuable advise and criticism during the course of this investigation. He is also indebted to Mr. R. D. Smith for his assistance in the construction of the apparatus.
ABSTRACT

Previously a limited amount of investigation has been done to describe the rotational motion of fluid in a draining tank. To date tank design has been based on trial and error, since the physical mechanisms of actual draining have not been recognized.

This investigation has been made to develop a technique for the measurement of the motion of the fluid during the draining process and to present the results of the observed surface velocity of the liquid as a function of depth of fluid and its distance from the center of the vortex core.

Many previous investigators of vortex behavior have shown qualitatively the dynamics of flow, whereas this method of study was directed at numerical results and practical techniques for obtaining these results by direct measurement.
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I. INTRODUCTION AND LITERATURE REVIEW

When a tank containing a liquid is drained by means of an outlet located on the bottom, a phenomenon occurs which is known as vortexing. This action of the liquid can readily be observed, but the understanding of the vortexing motion of the liquid is still unexplained in its entirety.

Of the various liquid dynamic phenomena that may occur in a tank, the rotational motions of the liquid are of special interest because of the torque exerted on the tank through viscous action of the fluid, changes in inertial distribution, and reduction in flow rate during tank draining as a result of vortex formation.

The general study of vortices may in part give additional insight and information concerning these problems of liquid rotation, vortexing, and draining.

Most of the work that has been done in search for an explanation of the rotational motion has been mathematical analyses of the physical properties of the vortex and its surroundings. Even these studies are made with assumptions of ideal and unreal conditions.

Over a century ago Helmholtz (1) published his well-known paper on vortex motion. He established three basic theorems for this type of motion. The main content of these theorems were the conservation laws. He stated first that it is impossible to produce or destroy vortices, or, expressed in more general terms, the vortex strength is constant in time. Then he proposed that the vortex strength is constant along each vortex line or vortex
tube. His third theorem stated that the circulation is the same in all circuits embracing the same vortex tube.

Helmholtz studied the application of these theorems to certain practical cases, such as the interaction between several parallel vortices, the behavior of a vortex in the neighborhood of a fixed boundary, vortex sheets, and circular vortices.

Later, Lord Kelvin (2) added as a fourth theorem on vortex motion the fact that the circulation around a vortex core is constant and may serve as a measure for the strength of a vortex.

Probably one of the more complete summaries of vortex behavior has been written by Lamb (3) as he has given a fairly complete survey of the work done in the field up until the publication of his book. Although very few new developments were presented in his writings, this was the last complete publication that has taken into account all of the general aspects of vortices.

Recent studies have been made on specialized cases of vortex behavior, such as Oseen (4), who found a solution to the vortex problem which explains the decay of vortices. The same solution was found by other scientists from an analogy of the vortex motion to certain problems concerning the diffusion of heat.

Shapiro (5) has systematically defined rotational flow and shown the connection between the rotation and the thermodynamic properties of the flow. The stagnation enthalpy, \( h_o \), is related to the velocity and enthalpy through the steady-flow energy relation,

\[
h_o = h + \frac{v^2}{2}
\]
or differentiating with respect to the radial direction,

$$\frac{\partial h}{\partial n} = \frac{\partial h}{\partial n} + \nu \frac{\partial v}{\partial n}$$

The thermodynamic relation for the entropy is

$$T \, ds = dh - \frac{1}{\rho} \, d\rho$$

This too may be expressed in derivative form as

$$\frac{\partial h}{\partial n} = T \frac{\partial s}{\partial n} + \frac{1}{\rho} \frac{\partial \rho}{\partial n}$$

The combination of these two thermodynamic equations then yields

$$\frac{\partial \rho}{\partial n} = -\rho T \frac{\partial s}{\partial n} + \rho \frac{\partial h}{\partial n} - \rho \nu \frac{\partial v}{\partial n}$$

Substituting this into Euler's equation for rotation

$$2 \omega = -\frac{\partial v}{\partial n} - \frac{1}{\rho \nu} \frac{\partial \rho}{\partial n}$$

Shapiro has obtained an expression relating the rotation of the fluid to the change of the thermodynamic properties of the fluid

$$2 \omega = \frac{1}{\nu} \left( T \frac{\partial s}{\partial n} - \frac{\partial h}{\partial n} \right)$$

In his derivation of an equation for vortex motion in a two-dimensional incompressible fluid, Dryden (6) has searched for an exact solution without neglecting the inertia terms, as is often done in such solutions to make the equations linear. Although the inertia terms complicate the problem somewhat, Dryden has shown that they must be included for the exact solution of the vortex motion problem.

Neufville (7) has attempted to correct some of the shortcomings of Helmholtz's vortex theory with the use of the Navier-Stokes
Equations. With the use of these equations, he has been able to present a set of solutions for axial symmetrical plane vortex motion. These solutions explain why the vorticity in a Helmholtz vortex slowly diffuses to infinity, so that in a finite region the fluid finally comes to rest. Neufville's investigation has indicated the need for a re-evaluation of the whole vortex problem in viscous fluids, including the related solutions and theorems available at present.

Though studying compressible fluid flow, Pai (8) has derived equations of the minimum radius for a vortex core which can be applied to incompressible fluids. These equations were based on Kelvin's Theorem that in a frictionless, homogeneous fluid without body forces the circulation along a closed fluid line remains constant with respect to time.

Dergarabedian (9), in a recent investigation, has gone to great lengths to derive the velocity components of a vortex system. Because of the intractable nature of the problem, many assumptions were made and the resulting answers were more nearly of a qualitative nature, rather than exact solutions.

A motion picture edited by Shapiro (10) reviews vorticity in general. It was based on experimental demonstrations of phenomena relating vorticity to circulation, and to the theorems of Crocco, Kelvin, and Helmholtz.

More recently, Abramson, Chu, Garza, and Ransleben (11) have presented the results of some experimental and theoretical studies of vortex formation while draining fluid from cylindrical tanks, and related liquid dynamic behavior. The experimental studies
were largely visual, through motion picture films. An analytical study of vortex formation in cylindrical tanks was also presented in an attempt to understand and delineate better the flow mechanisms involved. Also included were some data on time required for draining with various fluids, tank bottom shapes, and slosh and vortex suppression devices.

As a further attempt to understand better the basic mechanisms involved in vortex behavior in draining tanks, this investigation has developed a technique for the direct measurement of the angular surface velocity of the fluid surrounding a vortex core, and studies may be made of the vortex by using this method.

A study of vortex behavior is necessary to understand the details of tank draining which may be applied to tank and orifice designs.
II. THE DESIGN AND CONSTRUCTION OF APPARATUS

The apparatus used in this experiment was basically a large cylindrical tank with an orifice in the center of its bottom, and a system of devices to place an oil droplet at a predetermined point on the surface of the fluid being drained from the tank, and finally means to record the dynamic behavior of the droplet as it follows the moving fluid.

Figure 1 shows the flat-bottomed tank which was constructed of 22 gauge galvanized sheet steel, with inside dimensions of 48 inches in diameter and a depth of 16 inches. Located on the bottom of the center of the tank was an outlet of 1 inch diameter. This ratio of tank diameter to orifice diameter was large enough to eliminate the boundary layer effects caused by the walls for a study of the vortex core and the fluid motion in its immediate vicinity.

A gate valve was located directly beneath the drain outlet and was operated by an extended stem which lets the valve manipulation be made from the control table. A gate valve was favored for this experiment because of its straight line flow design with a minimum of valving fluid friction. The elongated valve stem was connected to the valve using a neoprene universal joint and the stem was supported rigidly by the tank support assembly. This combination gave a vibration-free operation of the valve necessary to insure any unnecessary disturbance of the fluid in the tank. From the valve, the draining fluid was directed through a flexible 2 inch reinforced rubber hose.
Figure 1

APPARATUS
The apparatus to place the oil droplet on the moving water surface consisted of a leg set on each side of the tank constructed of 1 inch angle iron and were connected to one another by two round 1/2 inch hollow steel tubes. These tubes served not only as braces for the rigid system, but acted as burette clamp guides for the horizon positioning of the burette containing the oil.

For the precise adjusting of the burette, the burette clamp was attached to a threaded solid steel rod which parallels the brace rods. This threaded rod had 28 threads per inch and was rotated by a 1/15 horsepower General Electric AC-DC electric motor that had a rewired armature to provide for reversal of shaft rotational direction. By this means, the burette was displaced 1/28 inch horizontally per motor revolution. On the opposite end of the threaded shaft, above the control table, a counter was employed to enable the investigator to maintain an exact control on the positioning of the burette. The motor speed was regulated by a Superior Electric Company 0-135 volt powerstat that varied the armature and field voltage input. Also on the control table was a two-way switch that reversed the armature current for reverse rotation of the motor.

A permanent record of the oil droplet behavior once it had been placed on the surface of the rotating fluid was accomplished by means of a Kodak 8 motion picture camera (Figure 2). This camera uses an 8 millimeter film and photographs 16 pictures per second. The photoelectric exposure meter which automatically set the exposure time for the shutter was ideal for this experiment inasmuch as the reflections from the oil droplet change constantly from the ever changing position of the droplet.
Figure 2

KODAK 8 MOTION PICTURE CAMERA
The camera was firmly mounted above the tank from an adjustable tripod constructed of 1 1/2 inch angle aluminum. The camera release was activated by the investigator with a cord attached to a lever arm which was an intergal part of the tripod mounting.

Two General Electric 150 watt white floodlights provided the illumination for the photography. This was only 1/2 the amount of light recommended by the manufacturer of the Kodak Type A indoor film used in the investigation, but because of reflections from the bottom of the tank, this was the most satisfactory light combination for photography of the rotating liquid.

It was found that SAE 90 outboard motor gear lubricant was the most suitable oil for use as the tracer. This type of oil was very insoluble to water and the dull blackish-green color was especially photogenic.
III. EXPERIMENTAL PROCEDURE AND RESULTS

The experimental procedure used in the determination of the angular surface velocity around a vortex core in an emptying tank with the apparatus previously described was one of finding the most accurate and reliable method possible.

The most important consideration that must be respected was the ability to place the oil droplet traced in the rotating fluid at a precise point and recording the dynamic action instantly at that position and immediately afterwards. Inasmuch as the water level of the draining tank changes very slowly, the problem of positioning the droplet at a predetermined water level was small. This was accomplished simply by watching a calibrated scale on the inside of the tank. As the surface of the water draining from the tank reached a level on the scale in which a velocity measurement was desired, an oil droplet was released and a recording made on the camera.

On the other hand, the locating of the tracer at a fixed horizontal distance from the center of the vortex core required a static structure with a means to adjust the radius of the burette from the center of the tank. Before the start of an experimental run the position of the burette was determined, hence throughout the run the horizontal position could be changed with the motor that was attached to the threaded rod on which the burette clamp was carried. By counting the revolutions turned by the threaded rod, an exact position of the burette was always known.

To begin a run, the tank was completely filled to the 16 inch
depth mark and allowed to settle until the visually apparent sloshing motion had ceased. Since the tank was always filled in a counterclockwise direction with respect to an observer looking down into the tank, a small initial angular velocity was apparent at the beginning of an experimental run. The only effect this initial velocity had on the vortex behavior was to hasten the forming of the vortex core. The velocity of the rotation caused by the vortex was many times stronger than the initial rotation. This was observed by recording the angular surface velocity at a particular point with various initial velocities of the water. These velocities did not vary an appreciable amount.

After the lateral oscillations had ceased in the fluid, the valve on the outlet of the bottom of the tank was opened, allowing the water to start draining. As the water level began to fall, the rotational motion of the liquid began to accelerate and the vortex core started to form on the surface of the water. In the same manner, the core lengthened until it reached the mouth of the outlet on the bottom of the tank (Figures 3 and 4). Immediately the flow of water from the tank was reduced by over 75 per cent. Normally the vortex core was completely developed by the time the water level had fallen to 14 inches. To allow the rotation of the fluid surrounding the core to become stabilized and to become a complete function of the vortex strength, data was not recorded until the water depth had fallen to 10 inches. At this level an oil droplet (Figure 5) was released from the burette and a photographic recording was taken of its rotational displacement. As the
Figure 3

A VORTEX FORMING
Figure 4

A FULLY DEVELOPED VORTEX CORE
AN OIL DROPLET ON THE SURFACE OF THE ROTATING FLUID
water level dropped to 9 inches, a similar procedure was followed. In a like manner, recordings were made at one inch increments of depth to the bottom of the tank. Then the burette was moved to a different radius from the center of the tank and the procedure followed again.

Three experimental runs were made for each position in which the rotational velocity was desired.

Due to the fact that the top of the vortex core was rounded, there was a limit to the minimum radius in which the surface velocity could be calculated.

With the use of a slide projector and a special slide that allowed the manual projection of individual frames from the films of the oil droplet movement, the position of the rotating fluid was determined at 1/16 second intervals. To calculate the angular velocity of the fluid at a particular position, sixteen consecutive frames of the oil droplet were recorded on the projection screen. The angular velocity can be measured directly in degrees per second.

This procedure involved the reviewing of approximately 16,000 pictures for the three runs that were recorded.

From the data, which is graphically illustrated on Figures 6 through 15, it was apparent that the angular velocity of the fluid increased exponentially toward the core of the vortex. It was also apparent from this data that at distances from the center of the vortex core greater than 5 inches there was an almost linear relationship for the decrease in angular surface velocity at all fluid depths. This was shown even better on Figure 16, a relief of the angular surface velocity as a function of the depth of water and the distance from the vortex core. Calculations by Dergarabedian
## Table 1

EXPERIMENTAL DATA

ANGULAR SURFACE VELOCITY (DEGREES/SECOND)

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NOTE: * R = 1.75
Figure 6.

ANGULAR SURFACE VELOCITY OF A VORTEX
WATER DEPTH 1 INCH

Angular Velocity (Degrees/Second) vs. Distance From Center (Inches)
Figure 7

ANGULAR SURFACE VELOCITY OF A VORTEX
WATER DEPTH 2 INCHES

Distance From Center (Inches)
Figure 8

ANGULAR SURFACE VELOCITY OF A VORTEX
WATER DEPTH 3 INCHES

Angular Velocity (Degrees/Second)

Distance From Center (Inches)
Figure 9

ANGULAR SURFACE VELOCITY OF A VORTEX
WATER DEPTH 4 INCHES
Figure 10

ANGULAR SURFACE VELOCITY OF A VORTEX
WATER DEPTH 5 INCHES
Figure 11

ANGULAR SURFACE VELOCITY OF A VORTEX
WATER DEPTH 6 INCHES

Angular Velocity (Degrees/Second)

Distance From Center (Inches)
Figure 12

ANGULAR SURFACE VELOCITY OF A VORTEX
WATER DEPTH 7 INCHES
Figure 13

ANGULAR SURFACE VELOCITY OF A VORTEX
WATER DEPTH 8 INCHES

Distance From Center (Inches)

Angular Velocity (Degrees/Second)
Figure 14

ANGULAR SURFACE VELOCITY OF A VORTEX
WATER DEPTH 9 INCHES

Angular Velocity (Degrees/Second)

Distance From Center (Inches)
Figure 15

ANGULAR SURFACE VELOCITY OF A VORTEX
WATER DEPTH 10 INCHES

Angular Velocity (Degrees/Second)

0 1 2 3 4 5 6 7 8 9 10

Distance From Center (Inches)
have shown that the center of the core has a theoretical angular velocity of infinity. The data which had been taken from the rotating fluid surrounding the core has given evidence that this may very well be true.

Figure 16 indicated the angular surface velocity to be a linear function of the water depth, except at shallow water depths. This non-linear variation was no doubt caused by the boundary layer effects of the tank bottom, as described by Rohsenow and Choi (12). They have derived an exact solution for boundary layer thickness over a flat plate, which has shown the thickness as an exponential function of the linear velocity of the fluid. Since the velocity of the fluid increased toward the center of the vortex core, the thickness of the boundary layer increased in a like manner. Because of the turbulence of the boundary layer, experimental results of the angular surface velocity at water depths below 1 inch could not be considered reliable.
IV. CONCLUSIONS AND RECOMMENDATIONS

The apparatus designed and used in this experimental investigation performed favorably in the measurement of the angular surface velocity of the vortex environment. Of the tests made at various water levels, consistent results were obtained except near the bottom of the tank where the boundary layer turbulence had a tendency to scatter the oil drops. Otherwise, the results in the laminar flow region seemed to be very reliable.

A difficulty that sometimes arose with the use of this apparatus was the tendency for the liquid to slosh. This was usually caused by some outside influence such as the vibration of other machinery in the laboratory. With a vibration-free environment, the vortex core was surprisingly stable. This in itself remains a large problem in the science of tank drainage as many vortex suppressors are ineffective because of the strong tendency of a liquid to form a vortex.

Though it is obvious that this analysis does not constitute anything like a complete description of the three-dimensional flow velocities, it was believed that the results show possibilities for adaptation and use in a more complete investigation of the behavior of the vortex.

With the use of the technique described previously, a complete study of boundary layer effects for various sized tanks should be possible. Not only could the tanks be dimensionally different, but they might be of different geometric design. These parameters will change the flow patterns considerably.
Along with the various sized tanks, the change in drainage outlet dimensions and the shape of the outlet is recommended for further studies. For this experiment a 1 inch round hole was located in the center of the tank. It is believed that an orifice that will constantly induce turbulence at the base of the vortex might tend to eliminate the entire core.

More studies might be made on the effects of the initial rotation of the liquid. This would require a tank similar to the one used in this experiment mounted on a table that could be rotated at known angular velocities. Naturally induced vortices may be eliminated by canceling the forces that cause them.

Another recommendation for the experimental tank design is to develop a method to replace the water in the tank as fast as the water is drained without disturbing the vortex or its immediate environment. This would require a tank boundary very far from the drainage outlet. One method that is thought to be feasible for this particular operation is to have the test tank contained in another tank of slightly larger radius. The entire side of the test tank would be perforated with small holes so that water could be added to space between the two tank walls and would then flow through these holes into the test tank, keeping the water level constant. This type of apparatus would be very helpful for two-dimensional flow studies.

A final recommendation would be to make a study of the vortexing of boiling liquids. In present day rocket engine design, this is a problem with the fuel tanks containing the cryogenic fuels. As the
liquid boils flow patterns are believed to change greatly.

The recommendations indicated are not meant to be a necessity, but are offered as a means to enable further vortex studies, in hope that a better insight may be derived on the various problems. With the technique developed in this investigation, the vortex behavior may be inspected very efficiently in any open tank.
V. BIBLIOGRAPHY


VI. VITA

The author, James Paul Hartman, was born on June 21, 1937 in Hannibal, Missouri. He received both his primary and secondary education in the public school in the same city, and his college education from the University of Missouri School of Mines and Metallurgy, Rolla, Missouri. A Bachelor of Science Degree in Mechanical Engineering was received from the University in May of 1959. Following graduation he was called to the services of the United States Army. After a tour of duty with the Army, he was employed by Lockheed Aircraft Corporation, Burbank, California. In February of 1962, he was granted a leave of absence by his employer to pursue his studies toward a Master of Science in Mechanical Engineering at the University of Missouri School of Mines and Metallurgy.