Applied Fluid Mechanics Lab Manual

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About Mavs Open Press

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About This Project

UTA CARES Grant Program

Creation of this OER was funded by the UTA CARES Grant Program, which is sponsored by UTA Libraries. Under the auspices of UTA's Coalition for Alternative Resources in Education for Students (CARES), the grant program supports educators interested in practicing open education through the adoption of OER and, when no suitable open resource is available, through the creation of new OER or the adoption of library-licensed or other free content. Additionally, the program promotes innovation in teaching and learning through the exploration of open educational practices, such as collaborating with students to produce educational content of value to a wider community. Information about the grant program and funded projects is available online.

Overview

This OER is designed for a junior-level lab in applied fluid mechanics (CE 3142) at UTA. The lack of standard material for the fluid mechanics laboratory course causes students to seek help from several textbooks in the subject area for the theoretical background of experiments, which costs them money and time; others seek out online resources for lab demonstrations. Even though free resources (e.g. lab manuals, videos, lab reports) are increasingly available on the Internet, they are too frequently inadequate and unreliable. This manual supports students by providing streamlined, vetted, and self-paced content, which frees students' time and saves them money. The OER includes customized lab manuals, educational videos, and an interactive lab report preparation workbooks for ten fluid mechanics experiments. Each section includes theory, practical applications, objectives, experimental procedure, and post-experiment questions. Preparation of result tables and charts are automated within the workbook for each experiment to facilitate answering post-experiment questions and writing lab reports.

Creation Process

In Summer 2017, Dr. Habib Ahmari taught the Fluid Mechanics Lab at UTA for the first time. He found students struggling with lab manuals that were prepared by previous instructors. Despite the fact that laboratory courses are considered essential components of engineering programs, there are no standard textbooks available for such courses. The lab teaching materials are usually developed by lab instructors (as handouts) or lab equipment manufactures as instruction manuals. These types of course materials are narratives and do not match very well with the nature of these courses; thus students rarely make connections with them. After teaching the course for two semesters, Dr. Ahmari realized it was very difficult for students to visualize the experimental procedures by reading these narratives. He also noticed that some students would videotape him or teaching assistants demonstrating the experimental procedure for future references. These observations triggered the idea of developing an OER for the course.

Dr. Ahmari was awarded a UTA CARES Innovation Grant in 2018 to develop an OER to support transitioning the traditional Fluid Mechanics Lab to a media-rich, student-paced learning environment. Shah Md Imran Kabir (graduate student) and Andrew Czubai, Ankur Patel, Nicholas Sopko (undergraduate students) were recruited for this project. This dedicated team worked on this project during the summer to make sure the platform would be ready for implementation for Fall 2018. Creation of the OER project included five steps. The first step was to shoot eleven educational videos of the lab experiments. For this work, two groups of two students were formed. The first group assisted with preparing scripts for videos, demonstrating experiments in the Fluid Mechanics Laboratory of the Civil Engineering Department, and providing voice over of the video. The second group performed video recording, editing, and adding closed captioning. In the next step, lab manuals for ten lab experiments were developed by Dr. Ahmari and his graduate student, Shah Md Imran Kabir. The lab manual was reviewed by a professional editor to enhance the quality of the material. Next, the team prepared the necessary workbooks for each of the experiments that can be used by students to record their raw data as input. The result tables and graphs will be automatically prepared within the workbook as output. All components of this OER (i.e. lab manuals, videos, and report preparing workbooks) were shared with students enrolled in Fluid Mechanics Lab in Fall 2018 via Blackboard. In Summer 2019, the manual was published in Pressbooks with videos and workbooks embedded in the text.

About the Authors

Habib Ahmari, Ph. D., P.E. is an Assistant Professor of Instruction and the Director of the Learning Center in the Department of Civil Engineering at UTA. He has more than 15 years of industry, education, and research experience. He has developed and taught several graduate and undergraduate courses in the area of water resources engineering.

Shah Md Imran Kabir is a graduate student in the Department of Civil Engineering at UTA. He completed his B.Sc. in water resources engineering from Bangladesh University of Engineering and Technology. He has 2 years of working experience in the water resources engineering industry.

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Acknowledgments

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About the Cover

Brittany Griffiths, UTA Libraries' Publishing Specialist, designed the cover for this OER. The image used is *Cascade and Ponds, Cooper Street, Arlington, Texas,* and was taken by the author, Habib Ahmari.

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Lab Manual

Basic knowledge about fluid mechanics is required in various areas of water resources engineering such as designing hydraulic structures and turbomachinery. The applied fluid mechanics laboratory course is designed to enhance civil engineering students' understanding and knowledge of experimental methods and the basic principle of fluid mechanics and apply those concepts in practice. The lab manual provides students with an overview of ten different fluid mechanics laboratory experiments and their practical applications. The objective, practical applications, methods, theory, and the equipment required to perform each experiment are presented. The experimental procedure, data collection, and presenting the results are explained in detail.

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Experiment #1: Hydrostatic Pressure

1. Introduction

Hydrostatic forces are the resultant force caused by the pressure loading of a liquid acting on submerged surfaces. Calculation of the hydrostatic force and the location of the center of pressure are fundamental subjects in fluid mechanics. The center of pressure is a point on the immersed surface at which the resultant hydrostatic pressure force acts.

2. Practical Application

The location and magnitude of water pressure force acting on water-control structures, such as dams, levees, and gates, are very important to their structural design. Hydrostatic force and its line of action is also required for the design of many parts of hydraulic equipment.

3. Objective

The objectives of this experiment are twofold:

- To determine the hydrostatic force due to water acting on a partially or fully submerged surface;
- To determine, both experimentally and theoretically, the center of pressure.

4. Method

In this experiment, the hydrostatic force and center of pressure acting on a vertical surface will be determined by increasing the water depth in the apparatus water tank and by reaching an equilibrium condition between the moments acting on the balance arm of the test apparatus. The forces which create these moments are the weight applied to the balance arm and the hydrostatic force on the vertical surface.

5. Equipment

Equipment required to carry out this experiment is the following:

- Armfield F1-12 Hydrostatic Pressure Apparatus,
- A jug, and
- Calipers or rulers, for measuring the actual dimensions of the quadrant.

6. Equipment Description

The equipment is comprised of a rectangular transparent water tank, a fabricated quadrant, a balance arm, an adjustable counter-balance weight, and a water-level measuring device (Figure 1.1).

The water tank has a drain valve at one end and three adjustable screwed-in feet on its base for leveling the apparatus. The quadrant is mounted on a balance arm that pivots on knife edges. The knife edges coincide with the center of the arc of the quadrant; therefore, the only hydrostatic force acting on the vertical surface of the quadrant creates moment about the pivot point. This moment can be counterbalanced by adding weight to the weight hanger, which is located at the left end of the balance arm, at a fixed distance from the pivot. Since the line of actions of hydrostatic forces applied on the curved surfaces passes through the pivot point, the forces have no effect on the moment. The hydrostatic force and its line of action (center of pressure) can be determined for different water depths, with the quadrant's vertical face either partially or fully submerged.

A level indicator attached to the side of the tank shows when the balance arm is horizontal. Water is admitted to the top of the tank by a flexible tube and may be drained through a cock in the side of the tank. The water level is indicated on a scale on the side of the quadrant [1].

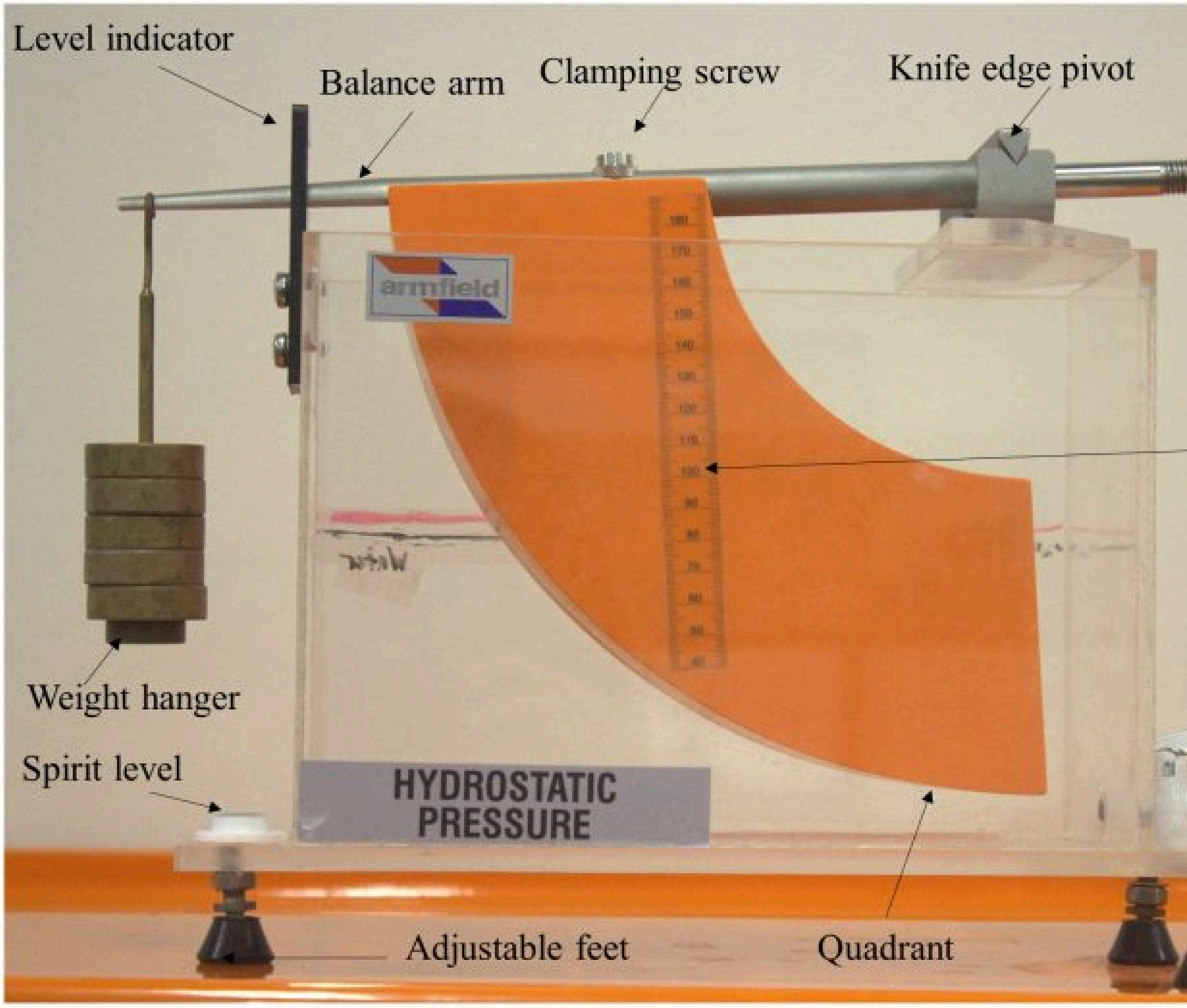


Figure 1.1: Armfield F1-12 Hydrostatic Pressure Apparatus

7. Theory

In this experiment, when the quadrant is immersed by adding water to the tank, the hydrostatic force applied to the vertical surface of the quadrant can be determined by considering the following [1]:

- The hydrostatic force at any point on the curved surfaces is normal to the surface and resolves through the pivot point because it is located at the origin of the radii. Hydrostatic forces on the upper and lower curved surfaces, therefore, have no net effect – no torque to affect the equilibrium of the assembly because the forces pass through the pivot.
- The forces on the sides of the quadrant are horizontal and cancel each other out (equal and opposite).
- The hydrostatic force on the vertical submerged face is counteracted by the balance weight. The resultant hydrostatic force on the face can, therefore, be calculated from the value of the balance weight and the depth of the water.

- The system is in equilibrium if the moments generated about the pivot points by the hydrostatic force and added weight (=mg) are equal, i.e.:

$$mg \times L = F \times y \qquad (1)$$

where:

m : mass on the weight hanger,

L : length of the balance arm (Figure 1.2)

F : Hydrostatic force, and

y : distance between the pivot and the center of pressure (Figure 1.2).

Then, calculated hydrostatic force and center of pressure on the vertical face of the quadrant can be compared with the experimental results.

7.1 Hydrostatic Force

The magnitude of the resultant hydrostatic force (F) applied to an immersed surface is given by:

$$F = P_c A = \rho g y_c A \qquad (2)$$

where:

P_c *:* pressure at centroid of the immersed surface,

A: area of the immersed surface,

y_c : centroid of the immersed surface measured from the water surface,

ρ : density of fluid, and

g : acceleration due to gravity.

The hydrostatic force acting on the vertical face of the quadrant can be calculated as:

- Partially immersed vertical plane (Figure 1.2a):

$$F = \frac{1}{2}\rho g B d^2 \qquad (3a)$$

- Fully immersed vertical plane (Figure 1.2b):

$$F = \rho g B D \left(d - \frac{D}{2}\right) \qquad (3b)$$

where:

B : width of the quadrant face,

d : depth of water from the base of the quadrant, and

D : height of the quadrant face.

7.2 Theoretical Determination of Center of Pressure

The center of pressure is calculated as:

$$y_p = \frac{I_x}{Ay_c} \qquad (4)$$

I_x is the 2nd moment of area of immersed body about an axis in the free surface. By use of the parallel axes theorem:

$$I_x = I_c + A{y_c}^2 \qquad (5)$$

where y_c is the depth of the centroid of the immersed surface, and I_c is the 2nd moment of area of immersed body about the centroidal axis. I_x is calculated as:

- Partially immersed vertical plane:

$$I_x = \frac{Bd^3}{12} + Bd\left(\frac{d}{2}\right)^2 = \frac{Bd^3}{3} \qquad (6a)$$

- Fully immersed vertical plane:

$$I_x = BD\left[\frac{D^2}{12} + \left(d - \frac{D}{2}\right)^2\right] \qquad (6b)$$

The depth of the center of pressure below the pivot point is given by:

$$y = y_p + H - d \qquad (7)$$

in which H is the vertical distance between the pivot and the base of the quadrant.

Substitution of Equation (6a and 6b) and into (4) and then into (7) yields the theoretical results, as follows:

- Partially immersed vertical plane (Figure 1.2a):

$$y = H - \frac{d}{3} \qquad (8a)$$

- Fully immersed vertical rectangular plane (Figure 1.2b):

$$y = \frac{\frac{D^2}{12} + (d - \frac{D}{2})^2}{d - \frac{D}{2}} + H - d \qquad (8b)$$

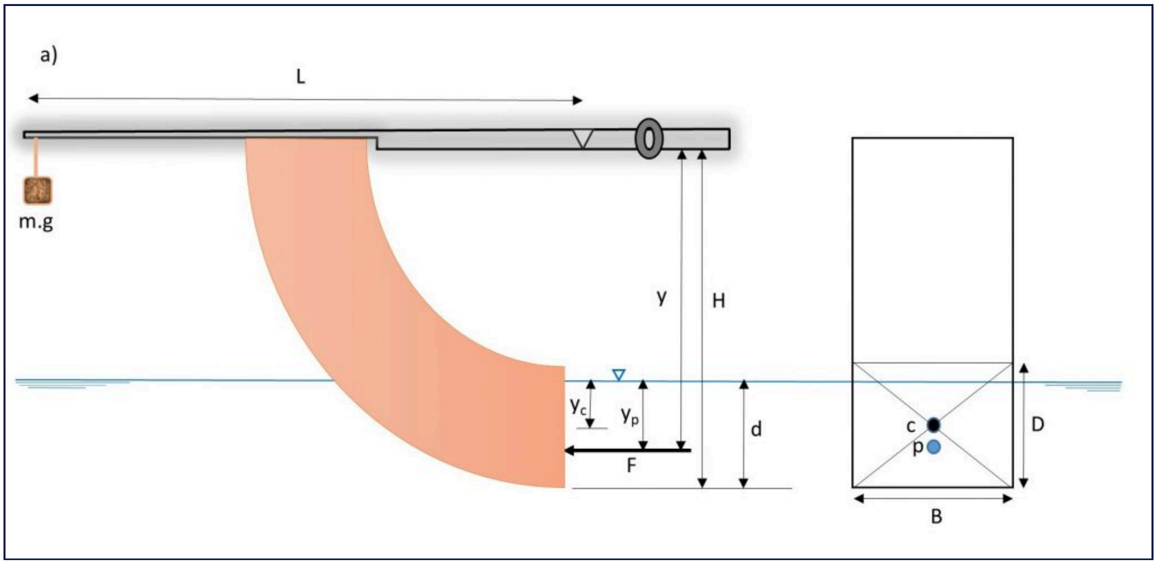


Figure 1.2a: Partially submerged quadrant (c: centroid, p: center of pressure)

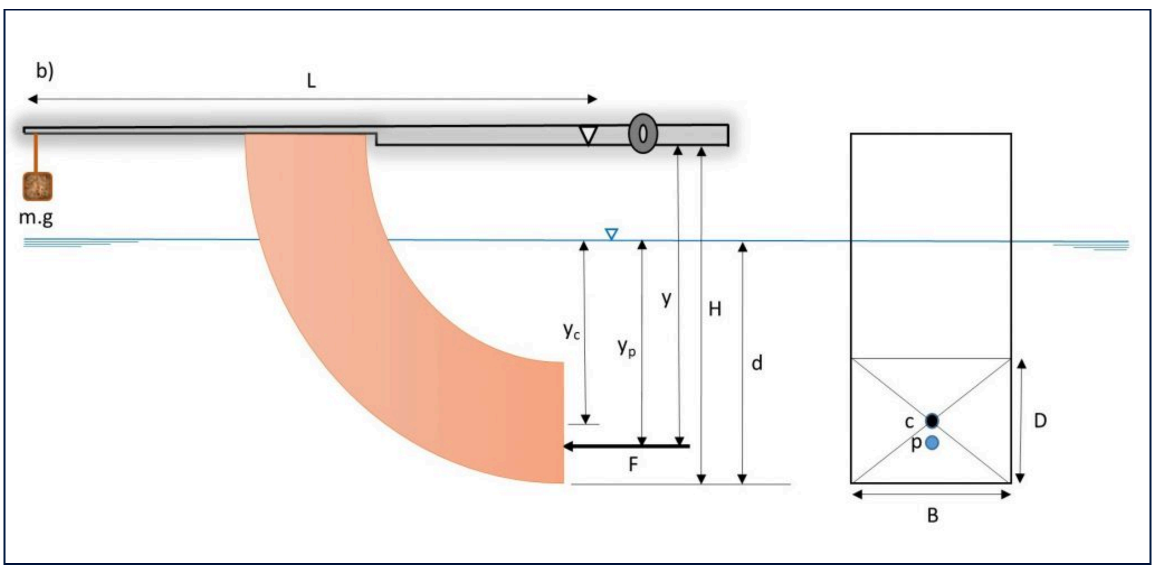


Figure 1.2b: Fully submerged quadrant (c: centroid, p: center of pressure)

7.3 Experimental Determination of Center of Pressure

For equilibrium of the experimental apparatus, moments about the pivot are given by Equation (1). By substitution of the derived hydrostatic force, F from Equation (3a and b), we have:

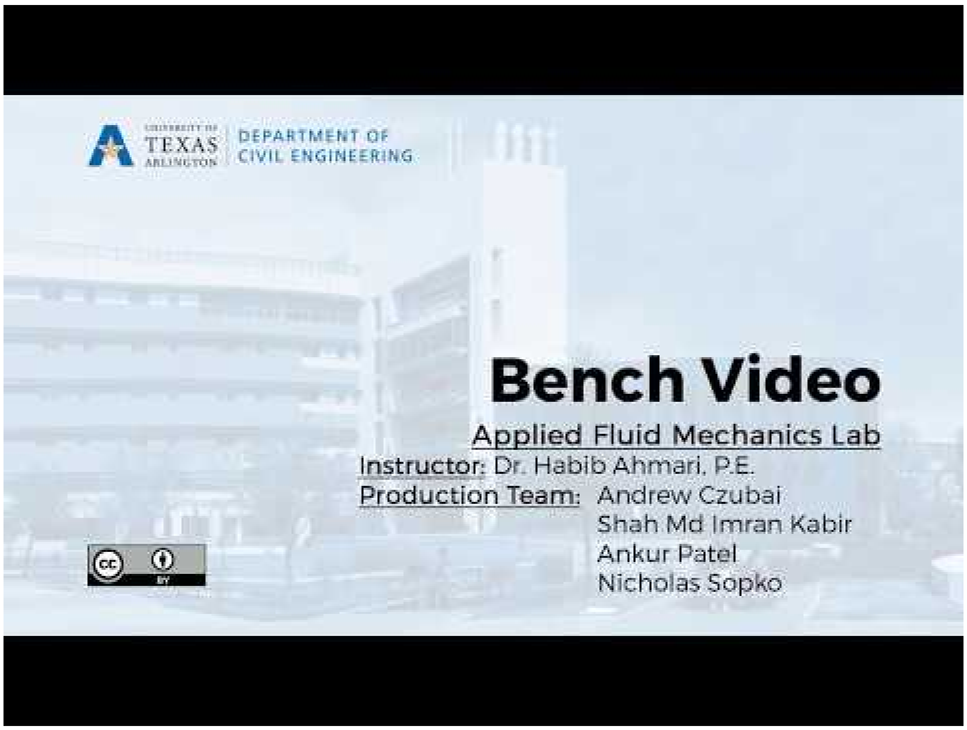
- Partially immersed vertical plane (Figure 1.2a):

$$y = \frac{mgL}{F} = \frac{2mL}{\rho B d^2} \qquad (9a)$$

- Fully immersed vertical rectangular plane (Figure 1.2b):

$$y = \frac{mL}{\rho BD(d - \frac{D}{2})} \qquad (9b)$$

8. Experimental Procedure



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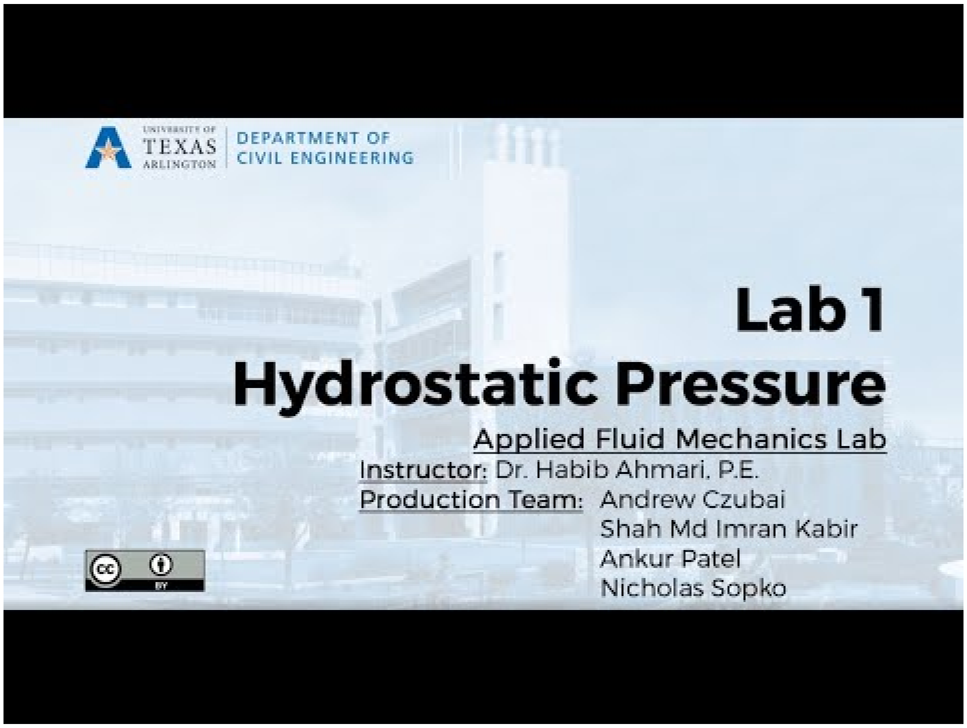

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Begin the experiment by measuring the dimensions of the quadrant vertical endface (*B* and *D*) and the distances (*H* and *L*), and then perform the experiment by taking the following steps:

- Wipe the quadrant with a wet rag to remove surface tension and prevent air bubbles from forming.
- Place the apparatus on a level surface, and adjust the screwed-in feet until the built-in circular spirit level indicates that the base is horizontal. (The bubble should appear in the center of the spirit level.)
- Position the balance arm on the knife edges and check that the arm swings freely.
- Place the weight hanger on the end of the balance arm and level the arm, using the counter weight, so that the balance arm is horizontal.
- Add 50 grams to the weight hanger.
- Add water to the tank and allow time for the water to settle.
- Close the drain valve at the end of the tank, then slowly add water until the hydrostatic force on the end surface of the quadrant is balanced. This can be judged by aligning the base of the balance arm with the top or bottom of the central marking on the balance rest.
- Record the water height, which displayed on the side of the quadrant in mm. If the quadrant is partially submerged, record the reading in the partially submerged portion of the Raw Data Table.
- Repeat the steps, adding 50 g weight each time, until the final weight of 500 g is reached. When the quadrant is fully submerged, record the readings in the fully submerged part of the Raw Data Table.
- Repeat the procedure in reverse by progressively removing the weights.
- Release the water valve, remove the weights, and clean up any spilled water.

9. Results and Calculations

Please visit this link for accessing the excel workbook for this experiment.

9.1 Result

Record the following dimensions:

- Height of quadrant endface, D (m) =
- Width of submerged, B (m)=
- Length of balance arm, L (m)=
- Distance from base of quadrant to pivot, H (m)=

All mass and water depth readings should be recorded in the Raw Data Table:

Raw Data Table

Test No.		Mass, m (kg)	Depth of Immersion, d (m)
Partially submerged	1		
	2		
	3		
	4		
	5		
Fully Submerged	6		
	7		
	8		
	9		
	10		

9.2 Calculations

Calculate the following for the partially and fully submerged quadrants, and record them in the Result Table:

- Hydrostatic force (F)
- Theoretical depth of center of pressure below the pivot (y)
- Experimental depth of center of pressure below the pivot (y)

Result Table

Test No.	Mass m(kg)	Depth of immersion d(m)	Hydrostatic force F(N)	Theoretical depth of center of pressure (m)	Experimental depth of center of pressure (m)
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					

10. Report

Use the template provided to prepare your lab report for this experiment. Your report should include the following:

- Table (s) of raw data
- Table (s) of results
- Plots of the following graphs:
    - Hydrostatic force (y-axis) vs depth of immersion (y-axis),
    - Theoretical depth of center of pressure (y-axis) vs depth of immersion (x-axis),
    - Experimental depth of center of pressure (y-axis) vs depth of immersion (x-axis),
    - Theoretical depth of centre of pressure (y-axis) vs experimental depth of center of pressure (x-axis). Calculate and present value for this graph, and
    - Mass (y-axis) vs depth of immersion (x-axis) on a log-log scale graph.
- Comment on the variations of hydrostatic force with depth of immersion.
- Comment on the relationship between the depth of the center of pressure and the depth of immersion.
- For both hydrostatic force and theoretical depth of center of pressure plotted vs depth of immersion, comment on what happens when the vertical endface of quadrant becomes fully submerged.
- Comment on and explain the discrepancies between the experimental and theoretical results for the center of pressure.

Experiment #2: Bernoulli's Theorem Demonstration

1. Introduction

Energy presents in the form of pressure, velocity, and elevation in fluids with no energy exchange due to viscous dissipation, heat transfer, or shaft work (pump or some other device). The relationship among these three forms of energy was first stated by Daniel Bernoulli (1700-1782), based upon the conservation of energy principle. Bernoulli’s theorem pertaining to a flow streamline is based on three assumptions: steady flow, incompressible fluid, and no losses from the fluid friction. The validity of Bernoulli’s equation will be examined in this experiment.

2. Practical Application

Bernoulli’s theorem provides a mathematical means to understanding the mechanics of fluids. It has many real-world applications, ranging from understanding the aerodynamics of an airplane; calculating wind load on buildings; designing water supply and sewer networks; measuring flow using devices such as weirs, Parshall flumes, and venturimeters; and estimating seepage through soil, etc. Although the expression for Bernoulli’s theorem is simple, the principle involved in the equation plays vital roles in the technological advancements designed to improve the quality of human life.

3. Objective

The objective of this experiment is to investigate the validity of the Bernoulli equation when it is applied to a steady flow of water through a tapered duct.

4. Method

In this experiment, the validity of Bernoulli’s equation will be verified with the use of a tapered duct (venturi system) connected with manometers to measure the pressure head and total head at known points along the flow.

5. Equipment

The following equipment is required to complete the demonstration of the Bernoulli equation experiment:

- F1-10 hydraulics bench,
- F1-15 Bernoulli’s apparatus test equipment, and

- A stopwatch for timing the flow measurement.

6. Equipment Description

The Bernoulli test apparatus consists of a tapered duct (venturi), a series of manometers tapped into the venturi to measure the pressure head, and a hypodermic probe that can be traversed along the center of the test section to measure the total head. The test section is a circular duct of varying diameter with a 14° inclined angle on one side and a 21° inclined angle on other side. Series of side hole pressure tappings are provided to connect manometers to the test section (Figure 2.1).

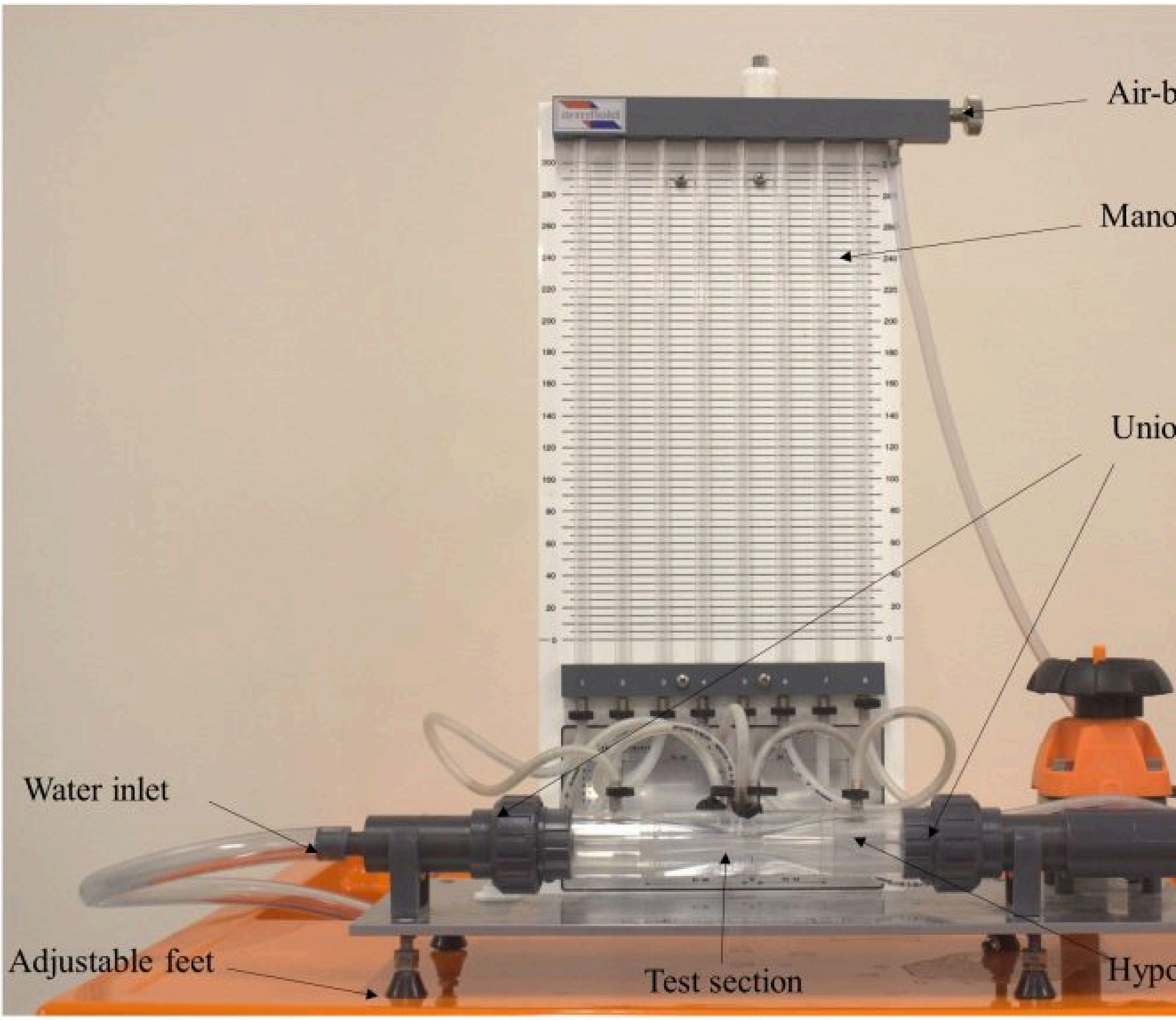
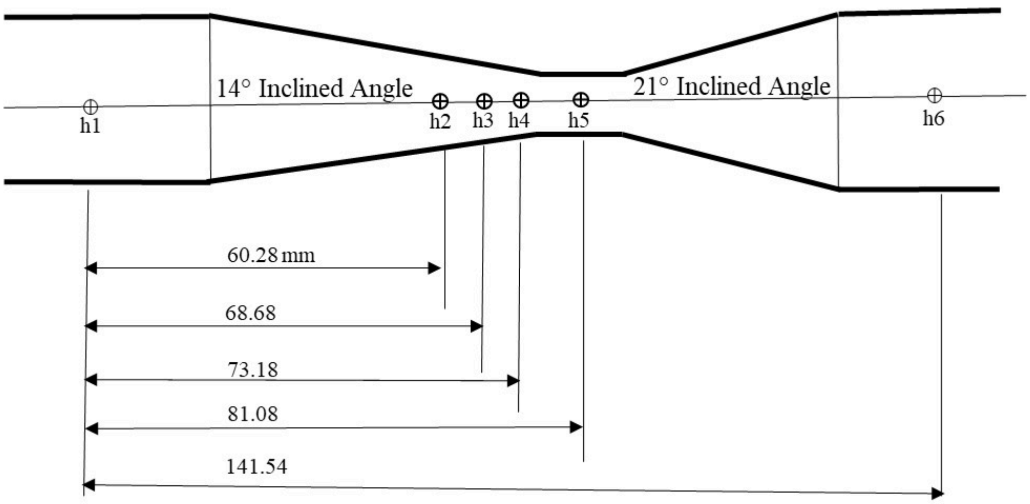


Figure 2.1: Armfield F1-15 Bernoulli's apparatus test equipment

Manometers allow the simultaneous measurement of the pressure heads at all of the six sections along the duct. The dimensions of the test section, the tapping positions, and the test section diameters are shown in Figure 2.2. The test section incorporates two unions, one at either end, to facilitate reversal for convergent or divergent testing. A probe is provided to measure the total pressure head along the test section by positioning it at any section of the duct. This probe may be moved after slackening the gland nut, which should be re-tightened by hand. To prevent damage, the probe should be fully inserted during transport/storage. The pressure tappings are connected to manometers that are mounted on a baseboard. The flow through the test section can be adjusted by the apparatus control valve or the bench control valve [2].



Manometer No.	Test section diameter (mm)
h1	25.0
h2	13.9
h3	11.8
h4	10.7
h5	10.0
h6	25.0

Figure 2.2: Test sections, manometer positions, and diameters of the duct along the test section

7. Theory

Bernoulli's theorem assumes that the flow is frictionless, steady, and incompressible. These assumptions are also based on the laws of conservation of mass and energy. Thus, the input mass and energy for a given control volume are equal to the output mass and energy:

$$Q_{in} = Q_{out} \qquad (1a)$$

$$E_{in} = E_{out} \qquad (1b)$$

These two laws and the definition of work and pressure are the basis for Bernoulli's theorem and can be expressed as follows for any two points located on the same streamline in the flow:

$$\frac{P_1}{\rho g} + \frac{v_1^2}{2g} + z_1 = \frac{P_2}{\rho g} + \frac{v_2^2}{2g} + z_2 \qquad (2)$$

where:

P: pressure,

g: acceleration due to gravity,

v: fluid velocity, and

z: vertical elevation of the fluid.

In this experiment, since the duct is horizontal, the difference in height can be disregarded, i.e., $z_1=z_2$

The hydrostatic pressure (P) along the flow is measured by manometers tapped into the duct. The pressure head (h), thus, is calculated as:

$$h = \frac{P}{\rho g} \qquad (3)$$

Therefore, Bernoulli's equation for the test section can be written as:

$$h_1 + \frac{v_1^2}{2g} = h_2 + \frac{v_2^2}{2g} \qquad (4)$$

in which $\frac{v^2}{2g}$ is called the velocity head (h_d).

The total head (h_t) may be measured by the traversing hypodermic probe. This probe is inserted into the duct with its end-hole facing the flow so that the flow becomes stagnant locally at this end; thus:

$$h_t = h + \frac{v^2}{2g} \qquad (5)$$

The conservation of energy or the Bernoulli's equation can be expressed as:

$$h_{t_1} = h_{t_2} \qquad (6)$$

The flow velocity is measured by collecting a volume of the fluid (V) over a time period (t). The flow rate is calculated as:

$$Q = \frac{V}{t} \qquad (7)$$

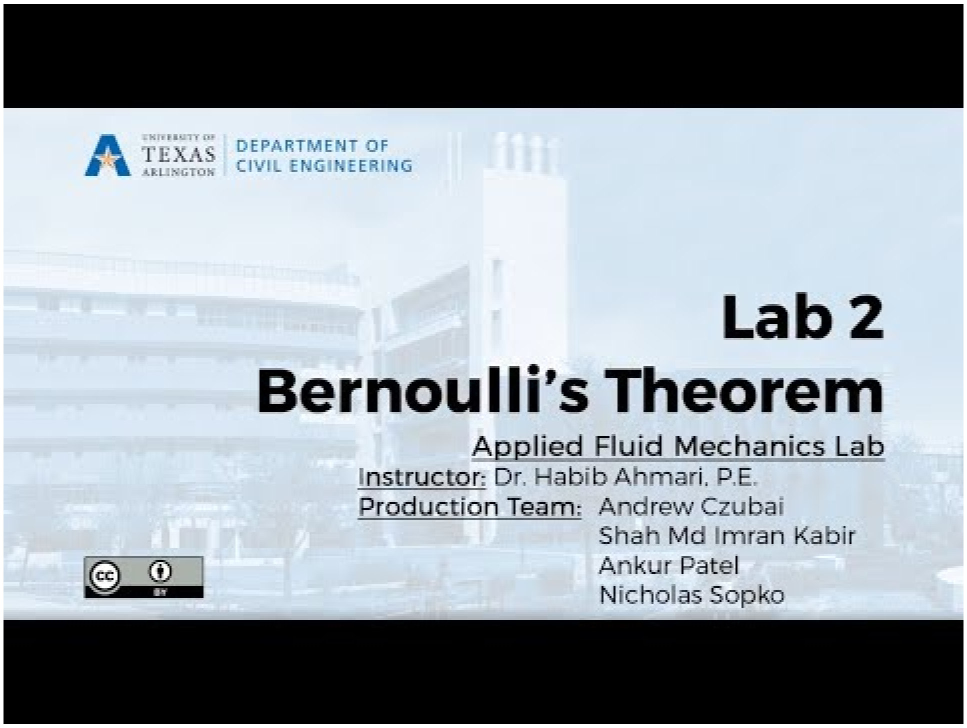
The velocity of flow at any section of the duct with a cross-sectional area of is determined as:

$$v = \frac{Q}{A} \qquad (8)$$

For an incompressible fluid, conservation of mass through the test section should be also satisfied (Equation 1a), i.e.:

$$A_1 v_1 = A_2 v_2 \qquad (9)$$

8. Experimental Procedure



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- Place the apparatus on the hydraulics bench, and ensure that the outflow tube is positioned above the volumetric tank to facilitate timed volume collections.
- Level the apparatus base by adjusting its feet. (A sprit level is attached to the base for this purpose.) For accurate height measurement from the manometers, the apparatus must be horizontal.
- Install the test section with the **14° tapered section** converging in the flow direction. If the test section needs to be reversed, the total head probe must be retracted before releasing the mounting couplings.
- Connect the apparatus inlet to the bench flow supply, close the bench valve and the apparatus flow control valve, and start the pump. Gradually open the bench valve to fill the test section with water.
- The following steps should be taken to purge air from the pressure tapping points and manometers:
    - Close both the bench valve and the apparatus flow control valve.
    - Remove the cap from the air valve, connect a small tube from the air valve to the volumetric tank, and open the air bleed screw.
    - Open the bench valve and allow flow through the manometers to purge all air from them, then tighten the air bleed screw and partly open the bench valve and the apparatus flow control valve.
    - Open the air bleed screw slightly to allow air to enter the top of the manometers (you may need to adjust both valves to achieve this), and re-tighten the screw when the manometer

levels reach a convenient height. The maximum flow will be determined by having a maximum (h_1) and minimum (h_5) manometer readings on the baseboard.

If needed, the manometer levels can be adjusted by using an air pump to pressurize them. This can be accomplished by attaching the hand pump tube to the air bleed valve, opening the screw, and pumping air into the manometers. Close the screw, after pumping, to retain the pressure in the system.

- Take readings of manometers h_1 to h_6 when the water level in the manometers is steady. The total pressure probe should be retracted from the test section during this reading.
- Measure the total head by traversing the total pressure probe along the test section from h_1 to h_6.
- Measure the flow rate by a timed volume collection. To do that, close the ball valve and use a stopwatch to measure the time it takes to accumulate a known volume of fluid in the tank, which is read from the sight glass. You should collect fluid for at least **one minute** to minimize timing errors. You may repeat the flow measurement twice to check for repeatability. Be sure that the total pressure probe is retracted from the test section during this measurement.
- Reduce the flow rate to give the head difference of about 50 mm between manometers 1 and 5 (h_1-h_5). This is the minimum flow experiment. Measure the pressure head, total head, and flow.
- Repeat the process for one more flow rate, with the (h_1-h_5) difference approximately halfway between those obtained for the minimum and maximum flows. This is the average flow experiment.
- Reverse the test section (with the **21° tapered section** converging in the flow direction) in order to observe the effects of a more rapidly converging section. Ensure that the total pressure probe is fully withdrawn from the test section, but not pulled out of its guide in the downstream coupling. Unscrew the two couplings, remove the test section and reverse it, then re-assemble it by tightening the couplings.
- Perform three sets of flow, and conduct pressure and flow measurements as above.

9. Results and Calculations

Please visit this link for accessing excel workbook for this experiment.

9.1. Results

Enter the test results into the Raw Data Tables.

Raw Data Table

Position 1: Tapering 14° to 21°

Test Section	Volume (Litre)	Time (sec)	Pressure Head (mm)	Total Head (mm)
h_1				
h_2				

h_3				
h_4				
h_5				
h_6				
h_1				
h_2				
h_3				
h_4				
h_5				
h_6				
h_1				
h_2				
h_3				
h_4				
h_5				
h_6				

Raw Data Table

Position 2: Tapering 21° to 14°

Test Section	Volume (Litre)	Time (sec)	Pressure Head (mm)	Total Head (mm)
h_1				
h_2				
h_3				
h_4				
h_5				
h_6				
h_1				
h_2				
h_3				
h_4				
h_5				
h_6				
h_1				
h_2				
h_3				
h_4				
h_5				
h_6				

9.2 Calculations

For each set of measurements, calculate the flow rate; flow velocity, velocity head, and total head, (pressure head+ velocity head). Record your calculations in the Result Table.

Result Table

Position 1: Tapering 14° to 21°

Test No.	Test Section	Distance into duct (m)	Flow Area (m^2)	Flow Rate (m^3/s)	Velocity (m/s)	Pressure Head (m)	Velocity Head (m)	Calculated Total Head (m)	Measured Total Head (m)
1	h1	0	0.00049						
	h2	0.06028	0.00015						
	h3	0.06868	0.00011						
	h4	0.07318	0.00009						
	h5	0.08108	0.000079						
	h6	0.14154	0.00049						
2	h1	0	0.00049						
	h2	0.06028	0.00015						
	h3	0.06868	0.00011						
	h4	0.07318	0.00009						
	h5	0.08108	0.000079						
	h6	0.14154	0.00049						
3	h1	0	0.00049						
	h2	0.06028	0.00015						
	h3	0.06868	0.00011						
	h4	0.07318	0.00009						
	h5	0.08108	0.000079						
	h6	0.14154	0.00049						

Position 2: Tapering 21° to 14°

Test No.	Test Section	Distance into duct (m)	Flow Area (m^2)	Flow Rate (m^3/s)	Velocity (m/s)	Pressure Head (m)	Velocity Head (m)	Calculated Total Head (m)	Measured Total Head (m)
1	h1	0	0.00049						
	h2	0.06028	0.00015						
	h3	0.06868	0.00011						
	h4	0.07318	0.00009						
	h5	0.08108	0.000079						
	h6	0.14154	0.00049						
2	h1	0	0.00049						
	h2	0.06028	0.00015						
	h3	0.06868	0.00011						
	h4	0.07318	0.00009						
	h5	0.08108	0.000079						
	h6	0.14154	0.00049						

3	h1	0	0.00049
	h2	0.06028	0.00015
	h3	0.06868	0.00011
	h4	0.07318	0.00009
	h5	0.08108	0.000079
	h6	0.14154	0.00049

10. Report

Use the template provided to prepare your lab report for this experiment. Your report should include the following:

- Table(s) of raw data
- Table(s) of results
- For each test, plot the total head (calculated and measured), pressure head, and velocity head (y-axis) vs. distance into duct (x-axis) from manometer 1 to 6, a total of six graphs. Connect the data points to observe the trend in each graph. Note that the flow direction in duct Position 1 is from manometer 1 to 6; in Position 2, it is from manometer 6 to 1.
- Comment on the validity of Bernoulli's equation when the flow converges and diverges along the duct.
- Comment on the comparison of the calculated and measured total heads in this experiment.
- Discuss your results, referring, in particular, to the following:
  - energy loss and how it is shown by the results of this experiment, and
  - the components of Bernoulli's equation ($\frac{P}{\rho g}, \frac{v^2}{2g}, z$) and how they vary along the length of the test section. Indicate the points of maximum velocity and minimum pressure.

3

Experiment #3: Energy Loss in Pipe Fittings

1. Introduction

Two types of energy loss predominate in fluid flow through a pipe network; major losses, and minor losses. Major losses are associated with frictional energy loss that is caused by the viscous effects of the medium and roughness of the pipe wall. Minor losses, on the other hand, are due to pipe fittings, changes in the flow direction, and changes in the flow area. Due to the complexity of the piping system and the number of fittings that are used, the head loss coefficient (K) is empirically derived as a quick means of calculating the minor head losses.

2. Practical Application

The term “minor losses”, used in many textbooks for head loss across fittings, can be misleading since these losses can be a large fraction of the total loss in a pipe system. In fact, in a pipe system with many fittings and valves, the minor losses can be greater than the major (friction) losses. Thus, an accurate K value for all fittings and valves in a pipe system is necessary to predict the actual head loss across the pipe system. K values assist engineers in totaling all of the minor losses by multiplying the sum of the K values by the velocity head to quickly determine the total head loss due to all fittings. Knowing the K value for each fitting enables engineers to use the proper fitting when designing an efficient piping system that can minimize the head loss and maximize the flow rate.

3. Objective

The objective of this experiment is to determine the loss coefficient (K) for a range of pipe fittings, including several bends, a contraction, an enlargement, and a gate valve.

4. Method

The head loss coefficients are determined by measuring the pressure head differences across a number of fittings that are connected in series, over a range of steady flows, and applying the energy equation between the sections before and after each fitting.

5. Equipment

The following equipment is required to perform the energy loss in pipe fittings experiment:

- F1-10 hydraulics bench,
- F1-22 Energy losses in bends apparatus,
- Stopwatch for timing the flow measurement,
- Clamps for pressure tapping connection tubes,
- Spirit level, and
- Thermometer.

6. Equipment Description

The energy loss in fittings apparatus consists of a series of fittings, a flow control valve, twelve manometers, a differential pressure gauge, and an air-bleed valve (Figure 3.1).

The fittings listed below, connected in a series configuration, will be examined for their head loss coefficient (K):

- long bend,
- area enlargement,
- area contraction,
- elbow,
- short bend,
- gate valve, and
- mitre.

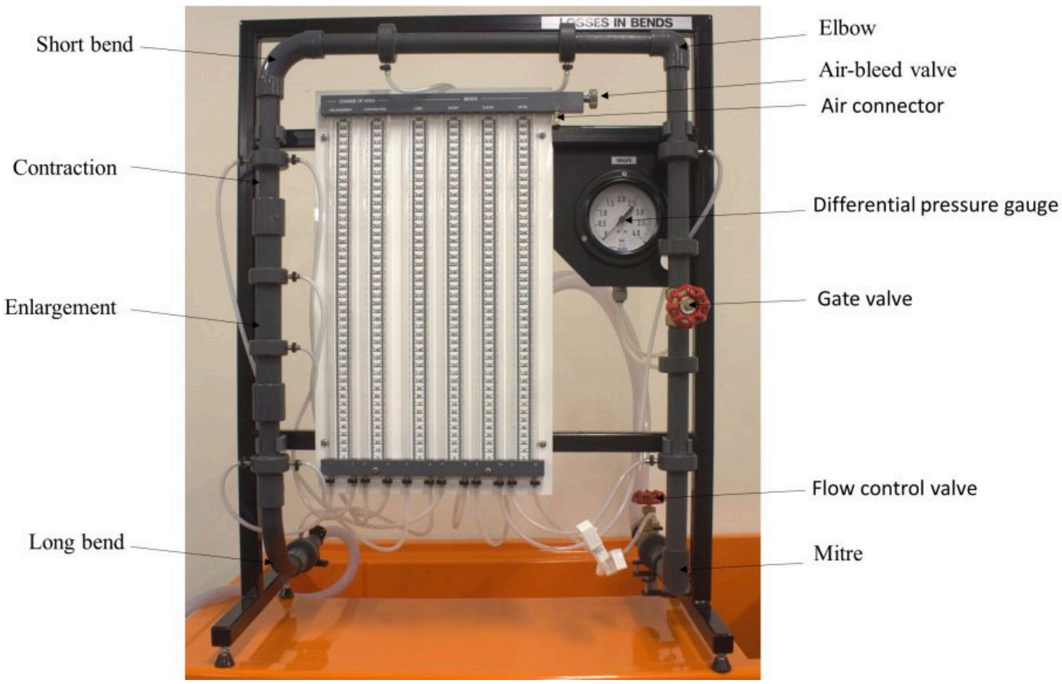


Figure 3.1: F1-22 Energy Losses in Pipe Fittings Apparatus

The manometers are tapped into the pipe system (one before and one after each fitting, except for the gate valve) to measure the pressure head difference caused by each fitting. The pressure difference for the valve is directly measured by the differential pressure gauge. The air-bleed valve facilitates purging the system and adjusting the water level in the manometers to a convenient level, by allowing air to enter them. Two clamps, which close off the tappings to the mitre, are introduced while experiments are being performed on the gate valve. The flow rate is controlled by the flow control valve [3].

The internal diameter of the pipe and all fittings, except for the enlargement and contraction, is 0.0183 m. The internal diameter of the pipe at the enlargement's outlet and the contraction's inlet is 0.0240 m.

7. Theory

Bernoulli's equation can be used to evaluate the energy loss in a pipe system:

$$[\frac{P}{\gamma}+\frac{v^2}{2g}+z]_{in}=[\frac{P}{\gamma}+\frac{v^2}{2g}+z]_{out}+h_L \qquad (1)$$

In this equation $\frac{P}{\gamma}$, $\frac{v^2}{2g}$, and z are pressure head, velocity head, and potential head, respectively. The total head loss, h_L, includes both major and minor losses.

If the diameter through the pipe fitting is kept constant, then $v_{in} = v_{out}$. Therefore, if the change in elevation head is neglected, the manometric head difference is the static head difference that is equal to the minor loss Δh through the fitting.

$$[\frac{P}{\gamma}]_{in} - [\frac{P}{\gamma}]_{out} = H_1 - H_2 = \Delta h \qquad (2)$$

in which H_1 and H_2 are manometer readings before and after the fitting.

The energy loss that occurs in a pipe fitting can also be expressed as a fraction (K) of the velocity head through the fitting:

$$\Delta h = K\frac{v^2}{2g} \qquad (3)$$

where:

K: loss coefficient, and

v: mean flow velocity into the fitting.

Because of the complexity of the flow in many fittings, K is usually determined by experiment [3]. The head loss coefficient (K) is calculated as the ratio of the manometric head difference between the input and output of the fitting to the velocity head.

$$K = \frac{\Delta h}{\frac{v^2}{2g}} \qquad (4)$$

Due to the change in the pipe cross-sectional area in enlargement and contraction fittings, the velocity difference cannot be neglected. Thus:

$$(H_1 - H_2) + ([\frac{v^2}{2g}]_{in} - [\frac{v^2}{2g}]_{out}) = \Delta h \qquad (5)$$

Therefore, these types of fittings experience an additional change in static pressure, i.e.:

$$([\frac{v^2}{2g}]_{in} - [\frac{v^2}{2g}]_{out}).$$

This value will be negative for the contraction since $v_{in} > v_{out}$ and it will be positive for enlargement because $v_{in} < v_{out}$. From Equation (5), note that Δh will be negative for the enlargement.

The pressure difference (Δh) between before and after the gate valve is measured directly using the pressure gauge. This can then be converted to an equivalent head loss by using the conversion ratio:

1 bar= 10.2 m water

The loss coefficient for the gate valve may then be calculated by using Equation (4).

To identify the flow regime through the fitting, the Reynolds number is calculated as:

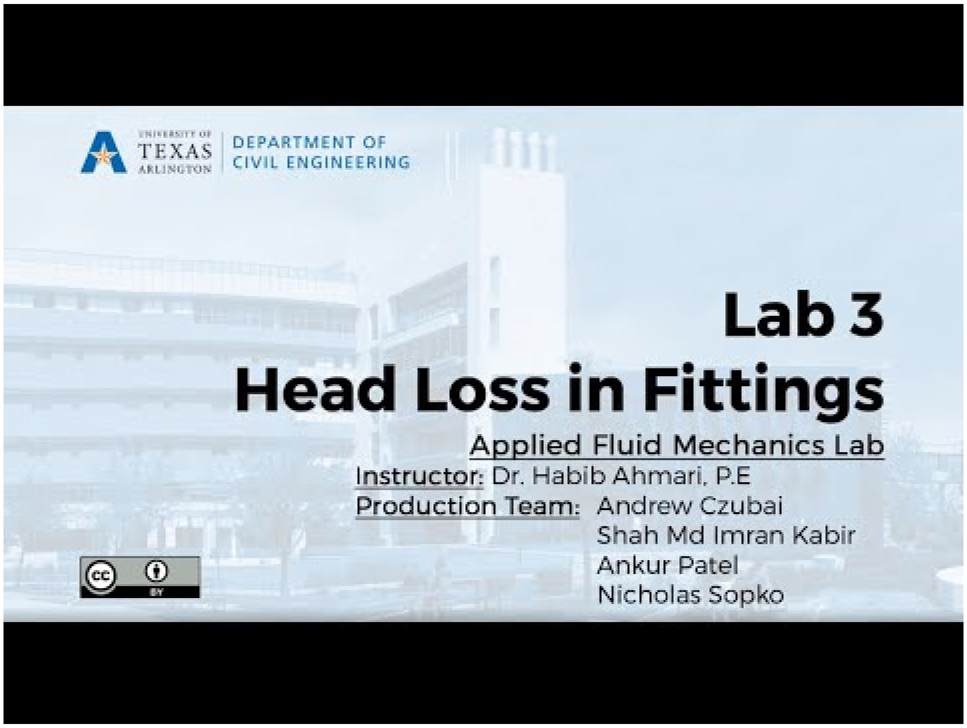
$$Re = \frac{vD}{\nu} \qquad (6)$$

where v is the cross-sectional mean velocity, D is the pipe diameter and ν is the fluid kinematic viscosity (Figure 3.2).

Temperature (degree C)	Kinematic viscosity v (m^2/s)	Temperature (degree C)	Kinematic viscosity v (m^2/s)
0	1.793E-06	25	8.930E-07
1	1.732E-06	26	8.760E-07
2	1.674E-06	27	8.540E-07
3	1.619E-06	28	8.360E-07
4	1.522E-06	29	8.180E-07
5	1.520E-06	30	8.020E-07
6	1.474E-06	31	7.850E-07
7	1.429E-06	32	7.690E-07
8	1.386E-06	33	7.530E-07
9	1.346E-06	34	7.380E-07
10	1.307E-06	35	7.240E-07
11	1.270E-06	36	7.110E-07
12	1.235E-06	37	6.970E-07
13	1.201E-06	38	6.840E-07
14	1.169E-06	39	6.710E-07
15	1.138E-06	40	6.580E-07
16	1.108E-06	45	6.020E-07
17	1.080E-06	50	5.540E-07
18	1.053E-06	55	5.110E-07
19	1.027E-06	60	4.760E-07
20	1.002E-06	65	4.430E-07
21	9.780E-07	70	4.130E-07
22	9.550E-07	75	3.860E-07
23	9.330E-07	80	3.630E-07
24	9.110E-07	85	3.420E-07

Figure 3.2: Kinematic Viscosity of Water (v) at Atmospheric Pressure

8. Experimental Procedure



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It is not possible to measure head due to all of the fittings simultaneously; therefore, it is necessary to run two separate experiments.

Part A:

In this part, head losses caused by fittings, except for the gate valve, will be measured; therefore, this valve should be kept fully open throughout Part A. The following steps should be followed for this part:

- Set up the apparatus on the hydraulics bench and ensure that its base is horizontal.
- Connect the apparatus inlet to the bench flow supply, run the outlet extension tube to the volumetric tank, and secure it in place.
- Open the bench valve, the gate valve, and the flow control valve, and start the pump to fill the pipe system and manometers with water. Ensure that the air-bleed valve is closed.
- To purge air from the pipe system and manometers, connect a bore tubing from the air valve to the volumetric tank, remove the cap from the air valve, and open the air-bleed screw to allow flow through the manometers. Tighten the air-bleed screw when no air bubbles are observed in the manometers.
- Set the flow rate at approximately 17 liters/minute. This can be achieved by several trials of timed volumetric flow measurements. For flow measurement, close the ball valve, and use a stopwatch to measure the time that it takes to accumulate a known volume of fluid in the tank, which is read from the hydraulics bench sight glass. Collect water for at least one minute to

minimize errors in the flow measurement.

- Open the air-bleed screw slightly to allow air to enter the top of the manometers; re-tighten the screw when the manometer levels reach a convenient height. All of the manometer levels should be on scale at the maximum flow rate. These levels can be adjusted further by using the air-bleed screw and the hand pump. The air-bleed screw controls the air flow through the air valve, so when using the hand pump, the bleed screw must be open. To retain the hand pump pressure in the system, the screw must be closed after pumping [3].
- Take height readings from all manometers after the levels are steady.
- Repeat this procedure to give a total of at least five sets of measurements over a flow range of 8 – 17 liters per minute.
- Measure the outflow water temperature at the lowest flow rate. This, together with Figure 3.2, is used to determine the Reynolds number.

Part B:

In this experiment, the head loss across the gate valve will be measured by taking the following steps:

- Clamp off the connecting tubes to the mitre bend pressure tappings to prevent air being drawn into the system.
- Open the bench valve and set the flow at the maximum flow in Part A (i.e., 17 liter/min); fully open the gate valve and flow control valve.
- Adjust the gate valve until 0.3 bar of head difference is achieved.
- Determine the volumetric flow rate.
- Repeat the experiment for 0.6 and 0.9 bars of pressure difference.

9. Results and Calculations

Please visit this link for accessing excel workbook for this experiment.

9.1. Results

Record all of the manometer and pressure gauge readings, as well as the volumetric measurements, in the Raw Data Tables.

Raw Data Tables

Part A – Head Loss Across Pipe Fittings

Test No. 1: Volume Collected (liters):		Time (s):
Fitting	**h_1 (m)**	**h_2 (m)**
Enlargement		
Contraction		
Long Bend		
Short Bend		
Elbow		

Mitre

Test No. 2: Volume Collected (liters): Time (s):

Enlargement
Contraction
Long Bend
Short Bend
Elbow
Mitre

Test No. 3: Volume Collected (liters): Time (s):

Enlargement
Contraction
Long Bend
Short Bend
Elbow
Mitre

Test No. 4: Volume Collected (liters): Time (s):

Enlargement
Contraction
Long Bend
Short Bend
Elbow
Mitre

Test No. 5: Volume Collected (liters): Time (s):

Enlargement
Contraction
Long Bend
Short Bend
Elbow
Mitre

Part B – Head Loss Across Gate Valve

Head Loss (bar)	Volume (liters)	Time (s)
0.3		
0.6		
0.9		

Water Temperature:

9.2. Calculations

Calculate the values of the discharge, flow velocity, velocity head, and Reynolds number for each experiment, as well as the K values for each fitting and the gate valve. Record your calculations in the following sample Result Tables.

Result Table

Part A – Head Loss Across Pipe Fittings

Test No:				Flow Rate Q (m^3/s):		Velocity v (m/s):	
Fitting	**h_1 (m)**	**h_2 (m)**	**$\Delta h = h_1 - h_2$ (m)**	**Corrected Δh (m)**	**$v^2/2g$ (m)**	**K**	**Reynolds Number**
Enlargement							
Contraction							
Long Bend							
Short Bend							
Elbow							
Mitre							

Part B – Head Loss Across Pipe Fittings

Head Loss (bar)	Δh (m)	Volume (m^3)	Time (s)	Flow Rate Q (m^3/s)	Velocity (m/s)	$v^2/2g$ (m)	K	Reynolds Number
0.3								
0.6								
0.9								

10. Report

Use the template provided to prepare your lab report for this experiment. Your report should include the following:

- Table(s) of raw data
- Table(s) of results
- For Part A, on one graph, plot the head loss across the fittings Δh (y-axis) against the velocity head (x-axis). On the second graph, plot the K values for the fittings (y-axis) against the flow rate Q (x-axis).
- For Part B, on one graph, plot the valve head losses Δh (y-axis) against the velocity head (x-axis). On the second graph, plot the K values for the valve (y-axis) against the flow rate Q (x-axis).
- Comment on any relationships noticed in the graphs for Parts A and B. What is the dependence of head losses across pipe fittings upon the velocity head?
- Is it justifiable to treat the loss coefficient as constant for a given fitting?
- In Part B, how does the loss coefficient for a gate valve vary with the extent of opening the valve?
- Examine the Reynolds number obtained. Are the flows laminar or turbulent?

Experiment #4: Energy Loss in Pipes

1. Introduction

The total energy loss in a pipe system is the sum of the major and minor losses. Major losses are associated with frictional energy loss that is caused by the viscous effects of the fluid and roughness of the pipe wall. Major losses create a pressure drop along the pipe since the pressure must work to overcome the frictional resistance. The Darcy-Weisbach equation is the most widely accepted formula for determining the energy loss in pipe flow. In this equation, the friction factor (f), a dimensionless quantity, is used to describe the friction loss in a pipe. In laminar flows, f is only a function of the Reynolds number and is independent of the surface roughness of the pipe. In fully turbulent flows, f depends on both the Reynolds number and relative roughness of the pipe wall. In engineering problems, f is determined by using the Moody diagram.

2. Practical Application

In engineering applications, it is important to increase pipe productivity, i.e. maximizing the flow rate capacity and minimizing head loss per unit length. According to the Darcy-Weisbach equation, for a given flow rate, the head loss decreases with the inverse fifth power of the pipe diameter. Doubling the diameter of a pipe results in the head loss decreasing by a factor of 32 (≈ 97% reduction), while the amount of material required per unit length of the pipe and its installation cost nearly doubles. This means that energy consumption, to overcome the frictional resistance in a pipe conveying a certain flow rate, can be significantly reduced at a relatively small capital cost.

3. Objective

The objective of this experiment is to investigate head loss due to friction in a pipe, and to determine the associated friction factor under a range of flow rates and flow regimes, i.e., laminar, transitional, and turbulent.

4. Method

The friction factor is determined by measuring the pressure head difference between two fixed points in a straight pipe with a circular cross section for steady flows.

5. Equipment

The following equipment is required to perform the energy loss in pipes experiment:

- F1-10 hydraulics bench,
- F1-18 pipe friction apparatus,
- Stopwatch for timing the flow measurement,
- Measuring cylinder for measuring very low flow rates,
- Spirit level, and
- Thermometer.

6. Equipment Description

The pipe friction apparatus consists of a test pipe (mounted vertically on the rig), a constant head tank, a flow control valve, an air-bleed valve, and two sets of manometers to measure the head losses in the pipe (Figure 4.1). A set of two water-over-mercury manometers is used to measure large pressure differentials, and two water manometers are used to measure small pressure differentials. When not in use, the manometers may be isolated, using Hoffman clamps.

Since mercury is considered a hazardous substance, it cannot be used in undergraduate fluid mechanics labs. Therefore, for this experiment, the water-over-mercury manometers are replaced with a differential pressure gauge to directly measure large pressure differentials.

This experiment is performed under two flow conditions: high flow rates and low flow rates. For high flow rate experiments, the inlet pipe is connected directly to the bench water supply. For low flow rate experiments, the inlet to the constant head tank is connected to the bench supply, and the outlet at the base of the head tank is connected to the top of the test pipe [4].

The apparatus' flow control valve is used to regulate flow through the test pipe. This valve should face the volumetric tank, and a short length of flexible tube should be attached to it, to prevent splashing.

The air-bleed valve facilitates purging the system and adjusting the water level in the water manometers to a convenient level, by allowing air to enter them.

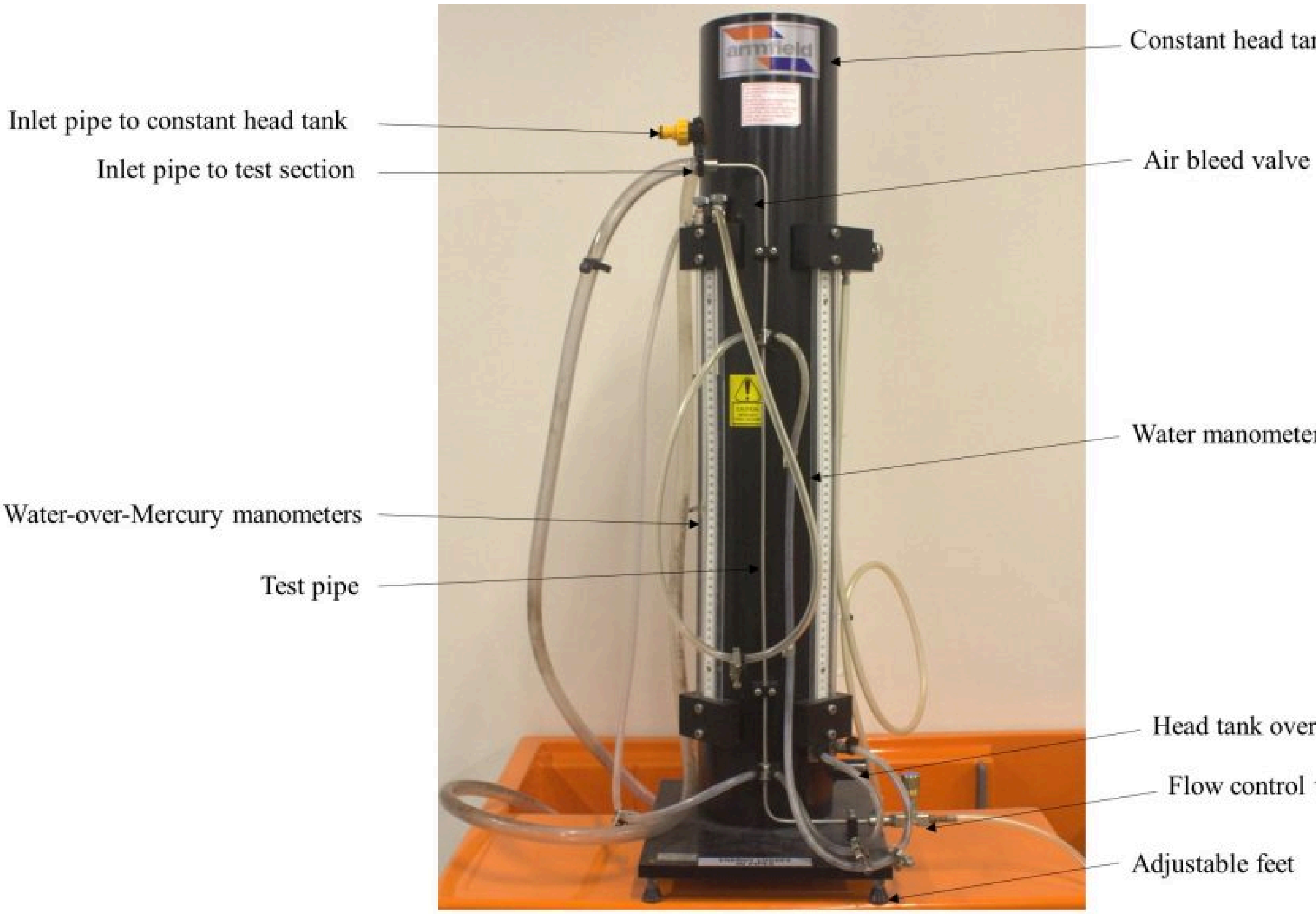

Figure 4.1: F1-18 Pipe Friction Test Apparatus

7. Theory

The energy loss in a pipe can be determined by applying the energy equation to a section of a straight pipe with a uniform cross section:

$$\frac{P_{in}}{\gamma} + \frac{v_{in}^2}{2g} + z_{in} = \frac{P_{out}}{\gamma} + \frac{v_{out}^2}{2g} + z_{out} + h_L \qquad (1)$$

If the pipe is horizontal: $z_{in} = z_{out}$

Since $v_{in} = v_{out}$:

$$h_L = \frac{(P_{out} - P_{in})}{\gamma} \qquad (2)$$

The pressure difference (P_{out}-P_{in}) between two points in the pipe is due to the frictional resistance, and the head loss h_L is directly proportional to the pressure difference.

The head loss due to friction can be calculated from the Darcy-Weisbach equation:

$$h_L = f\frac{L}{D}\frac{v^2}{2g} \qquad (3)$$

where:

h_L: head loss due to flow resistance

f: Darcy-Weisbach coefficient

L: pipe length

D: pipe diameter

v: average velocity

g: gravitational acceleration.

For laminar flow, the Darcy-Weisbach coefficient (or friction factor f) is only a function of the Reynolds number (Re) and is independent of the surface roughness of the pipe, i.e.:

$$f = \frac{64}{Re} \qquad (Hagen - Poiseuille\,equation) \qquad (4)$$

For turbulent flow, f is a function of both the Reynolds number and the pipe roughness height, ϵ. Other factors, such as roughness spacing and shape, may also affect the value of *f*; however, these effects are not well understood and may be negligible in many cases. Therefore, f must be determined experimentally. The Moody diagram relates *f* to the pipe wall relative roughness (ϵ/D) and the Reynolds number (Figure 4.2).

Instead of using the Moody diagram, *f* can be determined by utilizing empirical formulas. These formulas are used in engineering applications when computer programs or spreadsheet calculation methods are employed. For turbulent flow in a smooth pipe, a well-known curve fit to the Moody diagram is given by:

$$f = 0.316Re^{-0.25} \qquad (Blasius\ \ equation) \qquad (5)$$

Reynolds number is given by:

$$Re = \frac{\rho v D}{\mu} = \frac{vD}{\nu} \qquad (6)$$

where *v* is the average velocity, D is the pipe diameter, and μ and ν are dynamic and kinematic viscosities of the fluid, respectively. (Figure 4.3).

In this experiment, h_L is measured directly by the water manometers and the differential pressure gauge that are connected by pressure tappings to the test pipe. The average velocity, *v*, is calculated from the volumetric flow rate (Q) as:

$$v = \frac{Q}{\frac{\pi D^2}{4}} \qquad (7)$$

The following dimensions from the test pipe may be used in the appropriate calculations [4]:

Length of test pipe = 0.50 m,

Diameter of test pipe = 0.003 m.

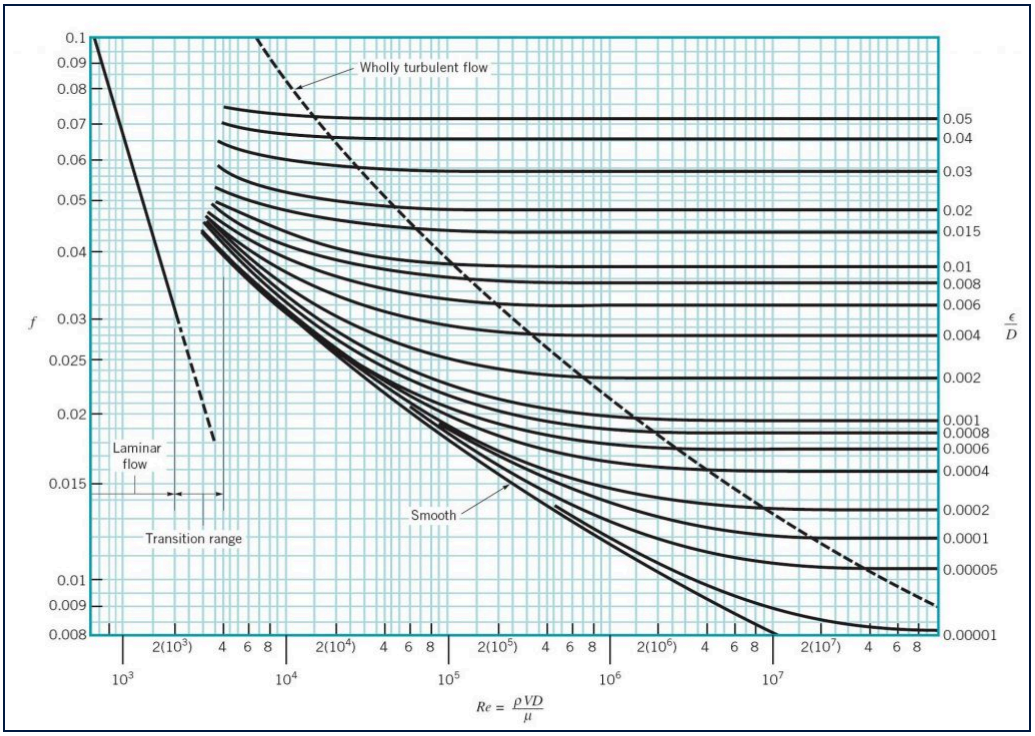

Figure 4.2: Moody Diagram

Temperature (degree C)	Kinematic viscosity v (m^2/s)	Temperature (degree C)	Kinematic viscosity v (m^2/s)
0	1.793E-06	25	8.930E-07
1	1.732E-06	26	8.760E-07
2	1.674E-06	27	8.540E-07
3	1.619E-06	28	8.360E-07
4	1.522E-06	29	8.180E-07
5	1.520E-06	30	8.020E-07
6	1.474E-06	31	7.850E-07
7	1.429E-06	32	7.690E-07
8	1.386E-06	33	7.530E-07
9	1.346E-06	34	7.380E-07
10	1.307E-06	35	7.240E-07
11	1.270E-06	36	7.110E-07
12	1.235E-06	37	6.970E-07
13	1.201E-06	38	6.840E-07
14	1.169E-06	39	6.710E-07
15	1.138E-06	40	6.580E-07
16	1.108E-06	45	6.020E-07
17	1.080E-06	50	5.540E-07
18	1.053E-06	55	5.110E-07
19	1.027E-06	60	4.760E-07
20	1.002E-06	65	4.430E-07
21	9.780E-07	70	4.130E-07
22	9.550E-07	75	3.860E-07
23	9.330E-07	80	3.630E-07
24	9.110E-07	85	3.420E-07

Figure 4.3: Kinematic Viscosity of Water (v) at Atmospheric Pressure

8. Experimental Procedure

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The experiment will be performed in two parts: high flow rates and low flow rates. Set up the equipment as follows:

- Mount the test rig on the hydraulics bench, and adjust the feet with a spirit level to ensure that the baseplate is horizontal and the manometers are vertical.
- Attach Hoffman clamps to the water manometers and pressure gauge connecting tubes, and close them off.

High Flow Rate Experiment

The high flow rate will be supplied to the test section by connecting the equipment inlet pipe to the hydraulics bench, with the pump turned off. The following steps should be followed.

- Close the bench valve, open the apparatus flow control valve fully, and start the pump. Open the bench valve progressively, and run the flow until all air is purged.
- Remove the clamps from the differential pressure gauge connection tubes, and purge any air from the air-bleed valve located on the side of the pressure gauge.
- Close off the air-bleed valve once no air bubbles observed in the connection tubes.
- Close the apparatus flow control valve and take a zero-flow reading from the pressure gauge.
- With the flow control valve fully open, measure the head loss shown by the pressure gauge.
- Determine the flow rate by timed collection.
- Adjust the flow control valve in a step-wise fashion to observe the pressure differences at 0.05 bar increments. Obtain data for ten flow rates. For each step, determine the flow rate by timed collection.
- Close the flow control valve, and turn off the pump.

The pressure difference measured by the differential pressure gauge can be converted to an equivalent head loss (h_L) by using the conversion ratio:

$$1 \text{ bar} = 10.2 \text{ m water}$$

Low Flow Rate Experiment

The low flow rate will be supplied to the test section by connecting the hydraulics bench outlet pipe to the head tank with the pump turned off. Take the following steps.

- Attach a clamp to each of the differential pressure gauge connectors and close them off.
- Disconnect the test pipe's supply tube and hold it high to keep it filled with water.
- Connect the bench supply tube to the head tank inflow, run the pump, and open the bench valve to allow flow. When outflow occurs from the head tank snap connector, attach the test section supply tube to it, ensuring that no air is entrapped.
- When outflow occurs from the head tank overflow, fully open the control valve.
- Remove the clamps from the water manometers' tubes and close the control valve.
- Connect a length of small bore tubing from the air valve to the volumetric tank, open the air

bleed screw, and allow flow through the manometers to purge all of the air from them. Then tighten the air bleed screw.

- Fully open the control valve and slowly open the air bleed valve, allowing air to enter until the manometer levels reach a convenient height (in the middle of the manometers), then close the air vent. If required, further control of the levels can be achieved by using a hand pump to raise the manometer air pressure.
- With the flow control valve fully open, measure the head loss shown by the manometers.
- Determine the flow rate by timed collection.
- Obtain data for at least eight flow rates, the lowest to give h_L= 30 mm.
- Measure the water temperature, using a thermometer.

9. Results and Calculations

Please use this link for accessing excel workbook for this experiment.

9.1. Results

Record all of the manometer and pressure gauge readings, water temperature, and volumetric measurements, in the Raw Data Tables.

Raw Data Tables: High Flow Rate Experiment

Test No.	Head Loss (bar)	Volume (Liters)	Time (s)
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			

Raw Data Tables: Low Flow Rate Experiment

Test No.	h_1 (m)	h_2 (m)	Head loss h_L (m)	Volume (liters)	Time (s)
1					
2					
3					
4					
5					
6					
7					
8					

Water Temperature:

9.2. Calculations

Calculate the values of the discharge; average flow velocity; and experimental friction factor, *f* using Equation 3, and the Reynolds number for each experiment. Also, calculate the theoretical friction factor, *f*, using Equation 4 for laminar flow and Equation 5 for turbulent flow for a range of Reynolds numbers. Record your calculations in the following sample Result Tables.

Result Table- Experimental Values

Test No.	Head loss h_L (m)	Volume (liters)	Time (s)	Discharge (m^3/s)	Velocity (m/s)	Friction Factor, f	Reynolds Number
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							

Result Table- Theoretical Values

No.	Flow Regime	Reynolds Number	Friction Factor, f
1		100	
2		200	
3	Laminar (Equation 4)	400	
4		800	
5		1600	
6		2000	
7		4000	
8		6000	
9	Turbulent (Equation 5)	8000	
10		10000	
11		12000	

12	16000
13	20000

10. Report

Use the template provided to prepare your lab report for this experiment. Your report should include the following:

- Table(s) of raw data
- Table(s) of results
- Graph(s)
    - On one graph, plot the experimental and theoretical values of the friction factor, *f* (y-axis) against the Reynolds number, *Re* (x-axis) on a log-log scale. The experimental results should be divided into three groups (laminar, transitional, and turbulent) and plotted separately. The theoretical values should be divided into two groups (laminar and turbulent) and also plotted separately.
    - On one graph, plot h_L (y-axis) vs. average flow velocity, *v* (x-axis) on a log-log scale.

- Discuss the following:
    - Identify laminar and turbulent flow regimes in your experiment. What is the critical Reynolds number in this experiment (i.e., the transitional Reynolds number from laminar flow to turbulent flow)?
    - Assuming a relationship of the form $f = KRe^n$, calculate K and n values from the graph of experimental data you have plotted, and compare them with the accepted values shown in the Theory section (Equations 4 and 5). What is the cumulative effect of the experimental errors on the values of K and n?
    - What is the dependence of head loss upon velocity (or flow rate) in the laminar and turbulent regions of flow?
    - What is the significance of changes in temperature to the head loss?
    - Compare your results for *f* with the Moody diagram (Figure 4.2). Note that the pipe utilized in this experiment is a smooth pipe. Indicate any reason for lack of agreement.
    - What natural processes would affect pipe roughness?

5

Experiment #5: Impact of a Jet

1. Introduction

Moving fluid, in natural or artificial systems, may exert forces on objects in contact with it. To analyze fluid motion, a finite region of the fluid (control volume) is usually selected, and the gross effects of the flow, such as its force or torque on an object, is determined by calculating the net mass rate that flows into and out of the control volume. These forces can be determined, as in solid mechanics, by the use of Newton's second law, or by the momentum equation. The force exerted by a jet of fluid on a flat or curve surface can be resolved by applying the momentum equation. The study of these forces is essential to the study of fluid mechanics and hydraulic machinery.

2. Practical Application

Engineers and designers use the momentum equation to accurately calculate the force that moving fluid may exert on a solid body. For example, in hydropower plants, turbines are utilized to generate electricity. Turbines rotate due to force exerted by one or more water jets that are directed tangentially onto the turbine's vanes or buckets. The impact of the water on the vanes generates a torque on the wheel, causing it to rotate and to generate electricity.

3. Objective

The objective of this experiment is to investigate the reaction forces produced by the change in momentum of a fluid flow when a jet of water strikes a flat plate or a curved surface, and to compare the results from this experiment with the computed forces by applying the momentum equation.

4. Method

The momentum force is determined by measuring the forces produced by a jet of water impinging on solid flat and curved surfaces, which deflect the jet at different angles.

5. Equipment

The following equipment is required to perform the impact of the jet experiment:

- F1-10 hydraulics bench,
- F1-16 impacts of a jet apparatus with three flow deflectors with deflection angles of 90, 120, and 180 degrees, and
- Stopwatch for timing the flow measurement.

6. Equipment Description

The jet apparatus is a clear acrylic cylinder, a nozzle, and a flow deflector (Figure 5.1). Water enters vertically from the top of the cylinder, through a nozzle striking a target, mounted on a stem, and leaves through the outlet holes in the base of the cylinder. An air vent at the top of the cylinder maintains the atmospheric pressure inside the cylinder. A weight pan is mounted at the top of the stem to allow the force of the striking water to be counterbalanced by applied masses [5].

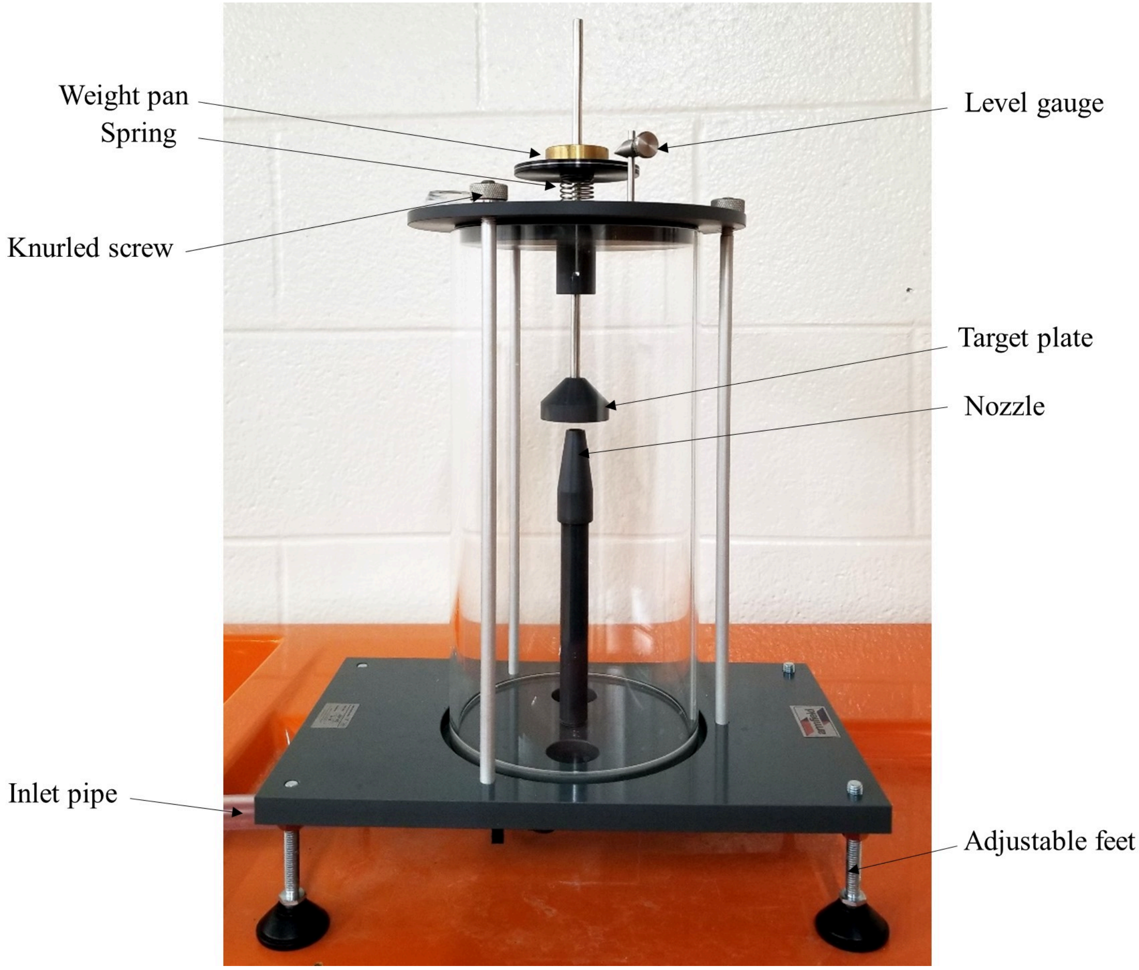


Figure 5.1: F1-16 Impact of Jet Apparatus

7. Theory

The velocity of the water (v) leaving the nozzle with the cross-sectional area (A) can be calculated by:

$$v = \frac{Q}{A} \qquad (1)$$

in which Q is the flow rate.

Applying the energy equation between the nozzle exit point and the surface of the deflector shows that the magnitude of the flow velocity does not change as the water flows around the deflector; only the direction of the flow changes.

Applying the momentum equation to a control volume encompassing the deflected flow results in:

$$F_y = \rho Q v (cos\theta + 1) \qquad (2)$$

where:

F_y: force exerted by the deflector on the fluid

ρ: fluid density

θ: $180-\alpha$, where α is the flow deflection angle (Figure 5.2).

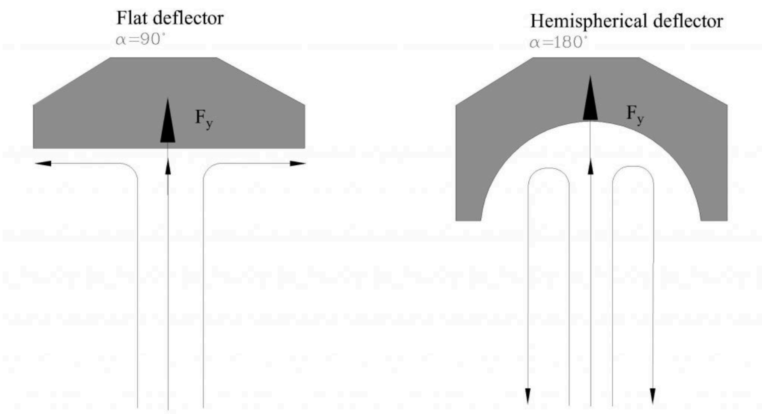


Figure 5.2: Examples of flow deflection angles for flat and hemispherical deflectors

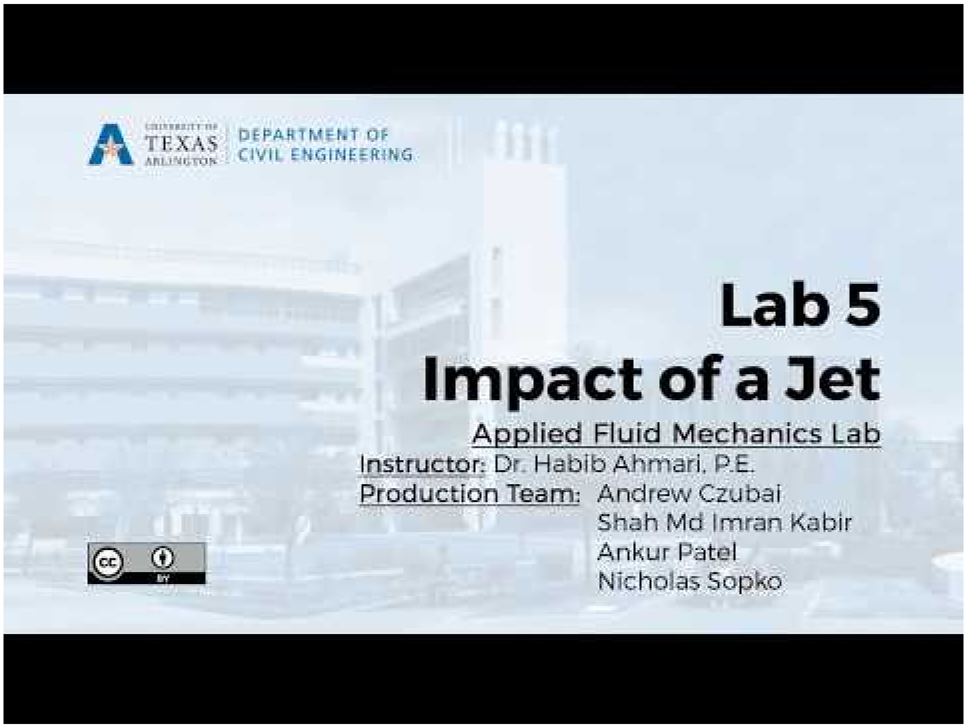
From equilibrium of forces in a vertical direction, F_y is balanced by the applied weight on the weight pan, W ($W = mg$, where m is the applied mass), i.e., $Fy = W$. Therefore:

$$W = \rho Qv(cos\theta + 1) \qquad (3)$$

Since $Q = vA$, this equation can be written as:

$$W = \rho Av^2(cos\theta + 1) \qquad (4)$$

8. Experimental Procedure



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Perform the experiment by taking the following steps:

- Remove the top plate (by releasing the knurled nuts) and the transparent cylinder from the equipment, and check and record the exit diameter of the nozzle.
- Replace the cylinder, and screw the 90-degree deflector onto the end of the shaft.
- Connect the inlet tube to the quick-release connector on the bench.
- Replace the top plate on the transparent cylinder, but do not tighten the three knurled nuts.
- Using the spirit level attached to the top plate, level the cylinder by adjusting the feet.
- Replace the three knurled nuts, then tighten in sequence until the built-in circular spirit level indicates that the top plate is horizontal. Do not overtighten the knurled nuts, as this will damage the top plate. The nuts should only be tightened enough to level the plate.
- Ensure that the vertical shaft is free to move and is supported by the spring beneath the weight pan.
- With no weights on the weight pan, adjust the height of the level gauge until it aligns with the datum line on the weight pan. Check that the position is correct by gently oscillating the pan.
- Place a mass of 50 grams on the weight pan, and turn on the pump.
- Open the bench valve slowly, and allow water to impinge upon the target until the datum line on the weight pan is level with the gauge. Leave the flow constant. Observe and note the flow behavior during the test.
- Measure the flow rate, using the volumetric tank. This is achieved by closing the ball valve and measuring the time that it takes to accumulate a known volume of fluid in the tank, as measured

from the sight glass. You should collect water for at least **one minute** to minimize timing errors.

- Repeat this procedure by adding an additional 50 grams incrementally, until a maximum mass of 500 grams has been applied.
- Repeat the entire test for each of the other two flow deflectors.

9. Results and Calculations

Please use this link for accessing excel workbook for this experiment.

9.1. Results

Use the following tables to record your measurements.

Raw Data Table

Test No.	Deflection Angles (degree)								
	90			120			180		
	Volume (Liter)	Time (s)	Applied Mass (kg)	Volume (Liter)	Time (s)	Applied Mass (kg)	Volume (Liter)	Time (s)	Applied Mass (kg)
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									

9.2. Calculations

The nozzle should be of the following dimensions.

- Diameter of the nozzle: d= 0.008 m
- Cross sectional area of the nozzle: A= $5.0265\times10^{-5}\ m^2$

These values may be measured as part of the experimental procedure and replaced with the above dimensions.

For each set of measurements, calculate the applied weight (W), flow rate (Q), velocity squared (v^2), force (F_y), and theoretical and experimental slope (S) of the relationship between W and v^2. The theoretical slope is determined from Equation 5, as follows:

$$S = \rho A(cos\theta + 1) \qquad (5)$$

The experimental value of S is obtained from a graph W of plotted against v^2.

Result Table

	Nozzle Diameter (m)=			Flow Area (m^2) =		Deflector Angle (degree)=	
Test No.	**Applied Weight (N)**	**Flow Rate (m^3/s)**	**Velocity (m/s)**	**Velocity^2 $(m/s)^2$**	**Force (N)**	**Theoretical Slope**	**Experimental Slope**
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							

10. Report

Use the template provided to prepare your lab report for this experiment. Your report should include the following:

- Table(s) of raw data
- Table(s) of results
- Graph(s)
  - Plot a graph of velocity squared, v^2, (x-axis) against applied weight, W, (y-axis). Prepare one graph, presenting the results for all three deflectors, and use a linear trend line, setting the intercepts to zero, to show this relationship. Find the slopes of these lines. Record the slopes in the Results Table, as the experimental slope.
  - Compare the slopes of this graph with the slopes calculated from the theoretical relationship from Equation 5.
  - Plot the measured force from the weights (W) versus the force of the water on the deflector (F_y) that is calculated by using the momentum equation, i.e., Equation 2.
- Discuss your results, focusing on the following:
  - Does this experiment provide a feasible means of verifying the conservation of momentum equation? Try to be quantitative in your comparison between the experimental and calculated results.
  - Would the results have been different if the deflectors were closer to the nozzle? Explain.
  - Comment on the agreement between your theoretical and experimental results, and give

reasons for any differences.
- Comment on the significance of any experimental errors.

6

Experiment #6: Orifice and Free Jet Flow

1. Introduction

An orifice is an opening, of any size or shape, in a pipe or at the bottom or side wall of a container (water tank, reservoir, etc.), through which fluid is discharged. If the geometric properties of the orifice and the inherent properties of the fluid are known, the orifice can be used to measure flow rates. Flow measurement by an orifice is based on the application of Bernoulli's equation, which states that a relationship exists between the pressure of the fluid and its velocity. The flow velocity and discharge calculated based on the Bernoulli's equation should be corrected to include the effects of energy loss and viscosity. Therefore, for accurate results, the coefficient of velocity (C_v) and the coefficient of discharge (C_d) should be calculated for an orifice. This experiment is being conducted to calibrate the coefficients of the given orifices in the lab.

2. Practical Application

Orifices have many applications in engineering practice besides the metering of fluid flow in pipes and reservoirs. Flow entering a culvert or storm drain inlet may act as orifice flow; the bottom outlet of a dam is another example. The coefficients of velocity and discharge are necessary to accurately predict flow rates from orifices.

3. Objective

The objective of this lab experiment is to determine the coefficients of velocity and discharge of two small orifices in the lab and compare them with values in textbooks and other reliable sources.

4. Method

The coefficients of velocity and discharge are determined by measuring the trajectory of a jet issuing fluid from an orifice in the side of a reservoir under steady flow conditions, i.e., a constant reservoir head.

5. Equipment

The following equipment is required to perform the orifice and free jet flow experiment:

- F1-10 hydraulics bench;
- F1-17 orifice and free jet flow apparatus, with two orifices having diameters of 3 and 6 mm;
- Measuring cylinder for flow measurement; and
- Stopwatch for timing the flow measurement.

6. Equipment Description

The orifice and free jet flow apparatus consists of a cylindrical head tank with an orifice plate set into its side (Figure 6.1). An adjustable overflow pipe is adjacent to the head tank to allow changes in the water level. A flexible hose attached to the overflow pipe returns excess water to the hydraulics bench. A scale attached to the head tank indicates the water level. A baffle at the base of the head tank promotes smooth flow conditions inside the tank, behind the orifice plate. Two orifice plates with 3 and 6 mm diameters are provided and may be interchanged by slackening the two thumb nuts. The trajectory of the jet may be measured, using the vertical needles. For this purpose, a sheet of paper should be attached to the backboard, and the needles should be adjusted to follow the trajectory of the water jet. The needles may be locked, using a screw on the mounting bar. The positions of the tops of the needles can be marked to plot the trajectory. A drain plug in the base of the head tank allows water to be drained from the equipment at the end of the experiment [6].

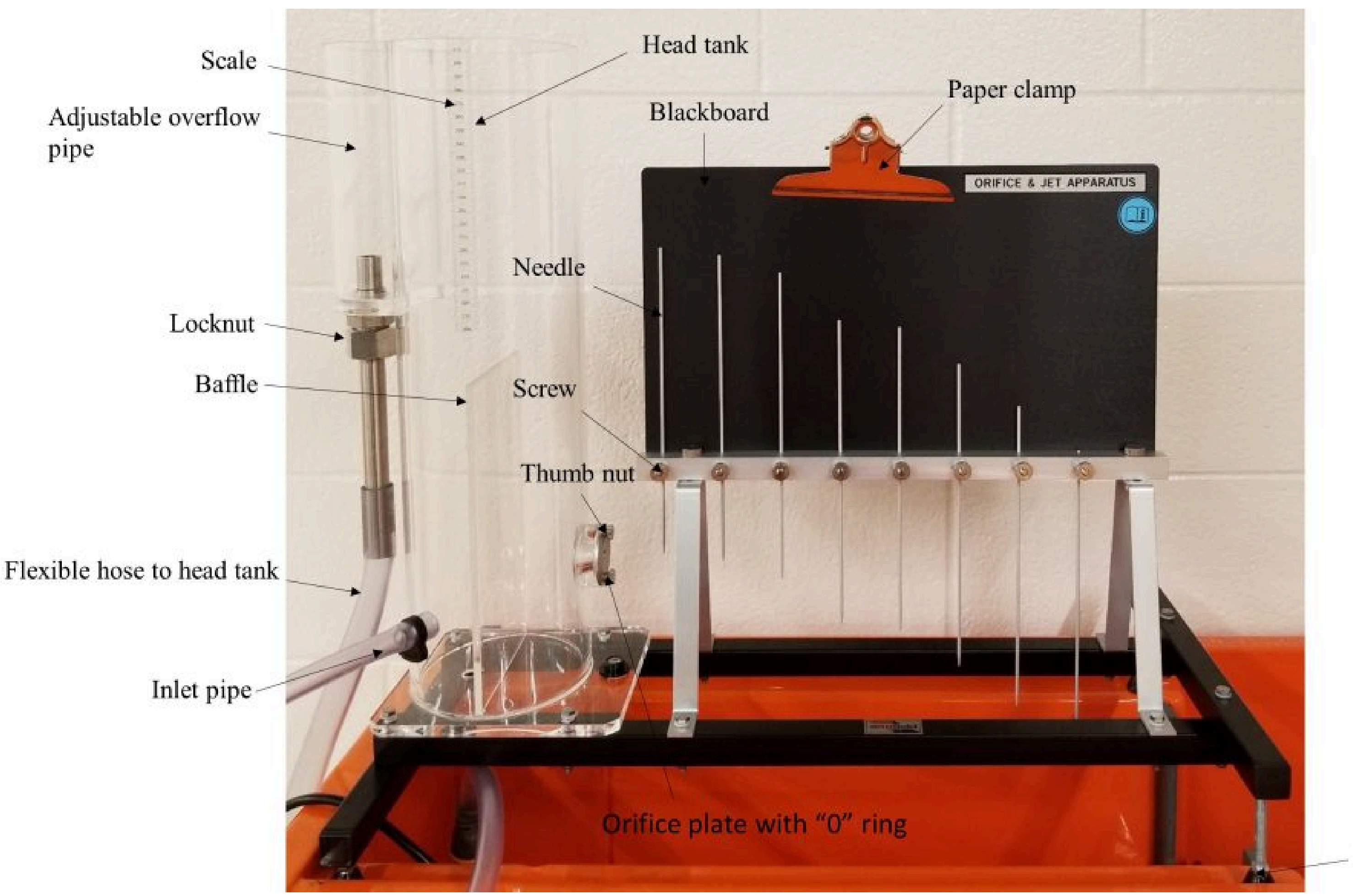


Figure 6.1: Armfield F1-17 Orifice and Jet Apparatus

7. Theory

The orifice outflow velocity can be calculated by applying Bernoulli's equation (for a steady, incompressible, frictionless flow) to a large reservoir with an opening (orifice) on its side (Figure 6.2):

$$v_i = \sqrt{2gh} \qquad (1)$$

where h is the height of fluid above the orifice. This is the ideal velocity since the effect of fluid viscosity is not considered in deriving Equation 1. The actual flow velocity, however, is smaller than v_i and is calculated as:

$$v = C_v\sqrt{2gh} \qquad (2)$$

C_v is the *coefficient of velocity*, which allows for the effects of viscosity; therefore, $C_v < 1$. The actual outflow velocity calculated by Equation (2) is the velocity at the **vena contracta,** where the diameter of the jet is the least and the flow velocity is at its maximum (Figure 6.2).

The actual outflow rate may be calculated as:

$$Q = vA_c \qquad (3)$$

where A_c is the flow area at the vena contracta. A_c is smaller than the orifice area, A_o (Figure 6.2), and is given by:

$$A_c = C_cA_o \qquad (4)$$

where C_c is the coefficient of contraction; therefore, $C_c < 1$.

Substituting v and A_c from Equations 2 and 4 into Equation 3 results in:

$$Q = C_vC_cA_0\sqrt{2gh} \qquad (5)$$

The product C_vC_c is called the coefficient of discharge, C_d; Thus, Equation 5 can be written as:

$$Q = C_dA_0\sqrt{2gh} \qquad (6)$$

The coefficient of velocity, C_v, and coefficient of discharge, C_d, are determined experimentally as follows.

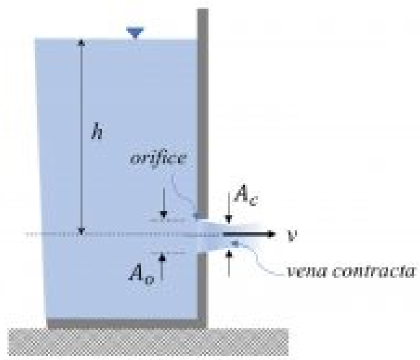


Figure 6.2: Orifice and Jet Flow Parameters

7.1. Determination of the Coefficient of Velocity

If the effect of air resistance on the jet leaving the orifice is neglected, the horizontal component of the jet velocity can be assumed to remain constant. Therefore, the horizontal distance traveled by jet (x) in time (t) is equal to:

$$x = v.t \qquad (7)$$

The vertical component of the trajectory of the jet will have a constant acceleration downward due to the force of gravity. Therefore, at any time, t, the y-position of the jet may be calculated as:

$$y = \frac{1}{2}gt^2 \qquad (8)$$

Rearranging Equation (8) gives:

$$t = (\frac{2y}{g})^{0.5} \qquad (9)$$

Substitution of t and *v* from Equations 9 and 2 into Equation 7 results in:

$$x = C_v\sqrt{2gh}(\frac{2y}{g})^{0.5} \qquad (10)$$

Equations (10) can be rearranged to find C_v:

$$C_v = \frac{x}{2\sqrt{yh}} \qquad (11)$$

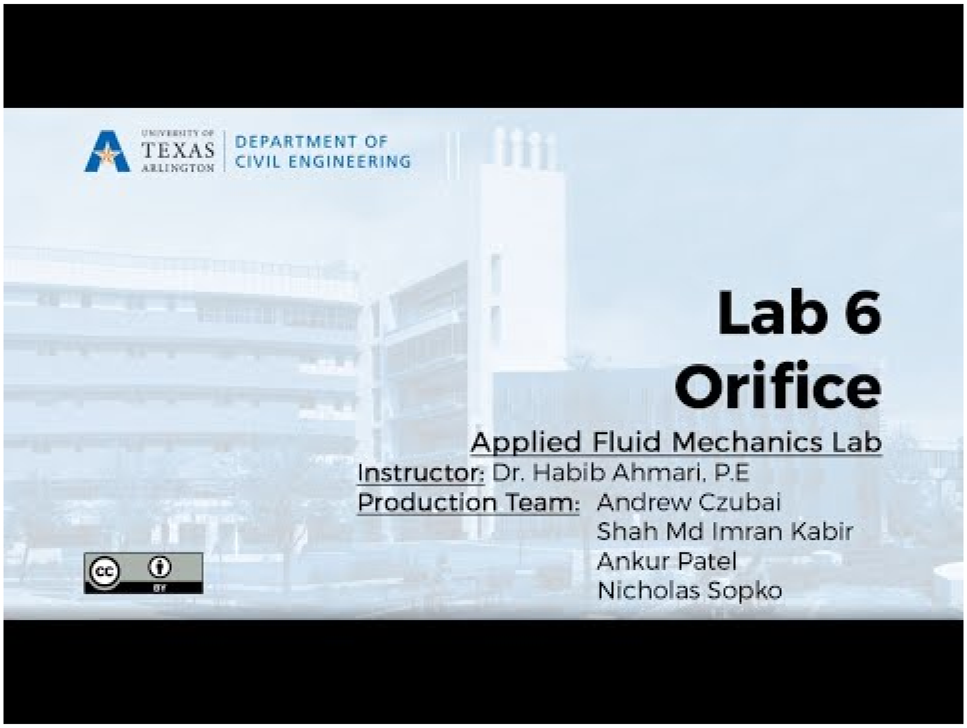
Therefore, for steady flow conditions (i.e., constant h in the head tank), the value of C_v can be determined from the x, y coordinates of the jet trajectory. A graph of *x* plotted against $\sqrt{yh}$ will have a slope of $2C_v$.

7.2. Determination of the Coefficient of Discharge

If C_d is assumed to be constant, then a graph of Q plotted against $\sqrt{h}$ (Equation 6) will be linear, and the slope of this graph will be:

$$s = C_d A_o \sqrt{2g} \qquad (12)$$

8. Experimental Procedure



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This experiment will be performed in two parts. Part A is performed to determine the coefficient of velocity, and Part B is conducted to determine the coefficient of discharge.

Set up the equipment as follows:

- Locate the apparatus over the channel in the top of the bench.
- Using the spirit level attached to the base, level the apparatus by adjusting the feet.
- Connect the flexible inlet tube on the side of the head tank to the bench quick-release fitting.
- Place the free end of the flexible tube from the adjustable overflow on the side of the head tank into the volumetric. Make sure that this tube will not interfere with the trajectory of the jet flowing from the orifice
- Secure each needle in the raised position by tightening the knurled screw.

Part A: Determination of coefficient of velocity from jet trajectory under constant head

- Install the 3-mm orifice in the fitting on the right-hand side of the head tank, using the two securing screws supplied. Ensure that the O-ring seal is fitted between the orifice and the tank.

- Close the bench flow control valve, switch on the pump, and then gradually open the bench flow control valve. When the water level in the head tank reaches the top of the overflow tube, adjust the bench flow control valve to provide a water level of 2 to 3 mm above the overflow pipe level. This will ensure a constant head and produce a steady flow through the orifice.
- If necessary, adjust the frame so that the row of needles is parallel with the jet, but is located 1 or 2 mm behind it. This will avoid disturbing the jet, but will minimize errors due to parallax.

- Attach a sheet of paper to the backboard, between the needles and board, and secure it in place with the clamp provided so that its upper edge is horizontal.
- Position the overflow tube to give a high head (e.g., 320 mm). The jet trajectory is obtained by using the needles mounted on the vertical backboard to follow the profile of the jet.
- Release the securing screw for each needle, and move the needle until its point is just immediately above the jet. Re-tighten the screw.
- Mark the location of the top of each needle on the paper. Note the horizontal distance from the plane of the orifice (taken as) to the coordinate point marking the position of the first needle. This first coordinate point should be close enough to the orifice to treat it as having the value of y=0. Thus, y displacements are measured relative to this position.
- The volumetric flowrate through the orifice can be determined by intercepting the jet, using the measuring cylinder and a stopwatch. The measured flow rates will be used in Part B.

- Repeat this test for lower reservoir heads (e.g., 280 mm and 240 mm)

Repeat the above procedure for the second orifice with diameter of 6 mm.

Part B: Determination of coefficient of discharge under constant head

- Position the overflow tube to have a head of 300 mm in the tank. (You may have to adjust the level of the overflow tube to achieve this.)
- Measure the flow rate by timed collection, using the measuring cylinder provided.

- Repeat this procedure for a head of 260 mm.

The procedure should also be repeated for the second orifice.

9. Results and Calculations

Please visit this link for accessing excel workbook for this experiment.

9.1. Results

Use the following tables to record your measurements.

Raw Data Table: Part A

Needle No.	Orifice Diameter (m)	x (m)	Head (m)			y(m)		
			Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3
1	0.003	0.014						
2		0.064						
3		0.114						
4		0.164						
5		0.214						
6		0.264						
7		0.314						
8		0.364						

Needle No.	Orifice Diameter (m)	x (m)	Head (m)			y(m)		
			Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3
1	0.006	0.014						
2		0.064						
3		0.114						
4		0.164						
5		0.214						
6		0.264						
7		0.314						
8		0.364						

Raw Data Table: Part B

Test No.	Orifice Diameter (m)	Head (m)	Volume (L)	Time (s)
1	0.003			
2				
3				
4				
5				
6	0.006			
7				
8				
9				
10				

9.2. Calculations

Calculate the values of $(y.h)^{1/2}$ for Part A and discharge (Q) and ($h^{0.5}$) for Part B. Record your calculations in the following Result Tables.

The following dimensions of the equipment are used in the appropriate calculations. If necessary, these values may be checked as part of the experimental procedure and replaced with your measurements [6].
– Diameter of the small orifice: 0.003 m
– Diameter of the large orifice: 0.006 m
– Pitch of needles: 0.05 m

Result Table- Part A

Needle No.	Orifice Diameter (m)	x (m)	Head (m)			y(m)			$(y.h)^{1/2}$(m)		
			Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3
1	0.003	0.014									
2		0.064									
3		0.114									
4		0.164									
5		0.214									
6		0.264									
7		0.314									
8		0.364									

Needle No.	Orifice Diameter (m)	x (m)	Head (m)			y(m)			$(y.h)^{1/2}$(m)		
			Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3
1	0.006	0.014									
2		0.064									
3		0.114									
4		0.164									
5		0.214									
6		0.264									
7		0.314									
8		0.364									

Result Table- Part B

Test No.	Orifice Diameter (m)	Head (m)	Volume (L)	Time (s)	Volume (m^3)	Q (m^3/sec)	$h^{0.5}$ ($m^{0.5}$)
1	0.003						
2							
3							
4							
5							
6	0.006						
7							
8							
9							

10. Report

Use the template provided to prepare your lab report for this experiment. Your report should include the following:

- Table(s) of raw data
- Table(s) of results
- Graph(s)

Part A: On one chart, plot a graph of x values (y-axis) against $(y.h)^{1/2}$ values (x-axis) for each test. Calculate the slope of these graphs, using the equation of the best-fit for your experimental data and by setting the intercept to zero. Using Equation 11, calculate the coefficient of velocity for each orifice as:

$$C_v = \frac{average\,of\,the\,slopes\,from\,three\,experiments}{2}$$

Part B: Plot Q values (y-axis) against $(h)^{0.5}$ values (x-axis). Determine the slope of this graph, using the equation of the best- fit for your experimental data and by setting the intercept to zero. Based on Equation 12, calculate the coefficient of discharge for each orifice, using the equation of the best-fit for your experimental data and the following relationship:

$$C_d = \frac{slope\,of\,the\,graph}{A_o\sqrt{2g}}$$

- Find the recommended values for C_v and C_d of the orifices utilized in this experiment from reliable sources (e.g., textbooks). Comment on the agreement between the textbook values and experimental results, and give reasons for any differences.
- Comment on the significance of any experimental errors.

7

Experiment #7: Osborne Reynolds' Demonstration

1. Introduction

In nature and in laboratory experiments, flow may occur under two very different regimes: laminar and turbulent. In laminar flows, fluid particles move in layers, sliding over each other, causing a small energy exchange to occur between layers. Laminar flow occurs in fluids with high viscosity, moving at slow velocity. The turbulent flow, on the other hand, is characterized by random movements and intermixing of fluid particles, with a great exchange of energy throughout the fluid. This type of flow occurs in fluids with low viscosity and high velocity. The dimensionless Reynolds number is used to classify the state of flow. The *Reynolds Number Demonstration* is a classic experiment, based on visualizing flow behavior by slowly and steadily injecting dye into a pipe. This experiment was first performed by Osborne Reynolds in the late nineteenth century.

2. Practical Application

The Reynolds number has many practical applications, as it provides engineers with immediate information about the state of flow throughout pipes, streams, and soils, helping them apply the proper relationships to solve the problem at hand. It is also very useful for dimensional analysis and similitude. As an example, if forces acting on a ship need to be studied in the laboratory for design purposes, the Reynolds number of the flow acting on the model in the lab and on the prototype in the field should be the same.

3. Objective

The objective of this lab experiment is to illustrate laminar, transitional, and fully turbulent flows in a pipe, and to determine under which conditions each flow regime occurs.

4. Method

The visualization of flow behavior will be performed by slowly and steadily injecting dye into a pipe. The state of the flow (laminar, transitional, and turbulent) will be visually determined and compared with the results from the calculation of the Reynolds number.

5. Equipment

The following equipment is required to perform the Reynolds number experiment:

- F1-10 hydraulics bench,
- The F1-20 Reynolds demonstration apparatus,
- Cylinder for measuring flow,
- Stopwatch for timing the flow measurement, and
- Thermometer.

6. Equipment Description

The equipment includes a vertical head tank that provides a constant head of water through a bellmouth entry to the flow visualization glass pipe. Stilling media (marbles) are placed inside the tank to tranquilize the flow of water entering the pipe. The discharge through this pipe is regulated by a control valve and can be measured using a measuring cylinder [7]. The flow velocity, therefore, can be determined to calculate Reynolds number. A dye reservoir is mounted on top of the head tank, from which a blue dye can be injected into the water to enable observation of flow conditions (Figure 7.1).

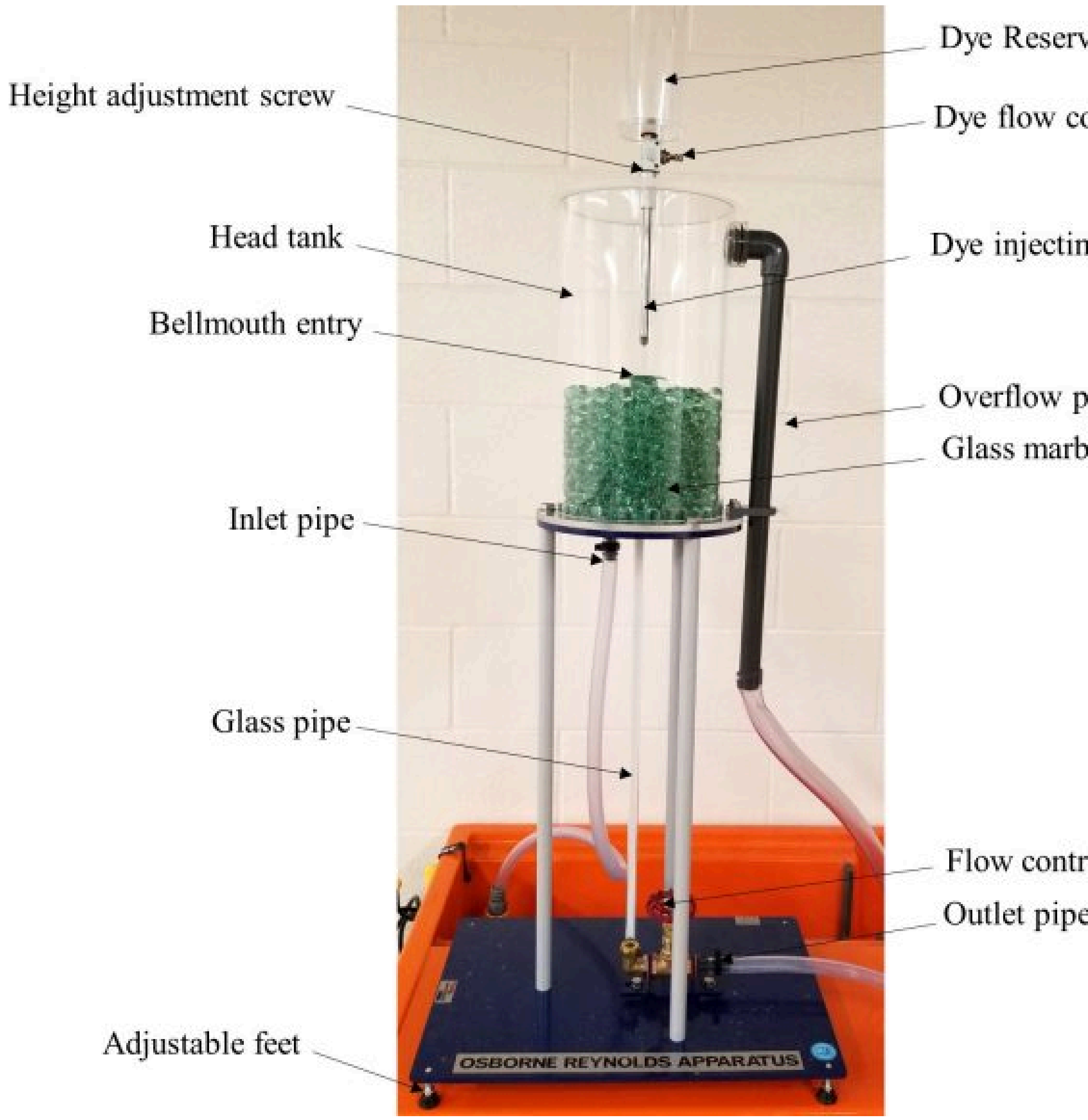


Figure 7.1: Armfield F1-20 Reynolds apparatus [7]

7. Theory

Flow behavior in natural or artificial systems depends on which forces (inertia, viscous, gravity, surface tension, etc.) predominate. In slow-moving laminar flows, viscous forces are dominant, and the fluid behaves as if the layers are sliding over each other. In turbulent flows, the flow behavior is chaotic and changes dramatically, since the inertial forces are more significant than the viscous forces.

In this experiment, the dye injected into a laminar flow will form a clear well-defined line. It will mix with the water only minimally, due to molecular diffusion. When the flow in the pipe is turbulent, the dye will rapidly mix with the water, due to the substantial lateral movement and energy exchange in the flow. There is also a transitional stage between laminar and turbulent flows, in which the dye stream will wander about and show intermittent bursts of mixing, followed by a more laminar behavior.

The Reynolds number (*Re*), provides a useful way of characterizing the flow. It is defined as:

$$Re = \frac{vd}{\nu} \qquad (1)$$

where (ν) is the kinematic viscosity of the water (Figure 7.2), v is the mean flow velocity and d is the diameter of the pipe.

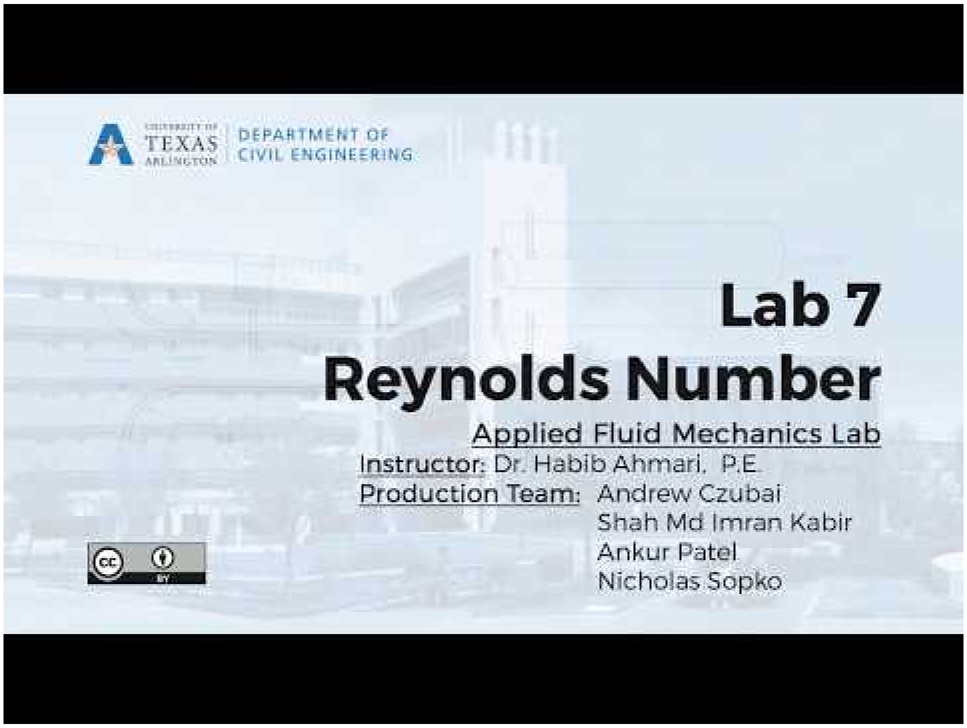
The Reynolds number is a dimensionless parameter that is the ratio of the inertial (destabilizing) force to the viscosity (stabilizing) force. As *Re* increases, the inertial force becomes relatively larger, and the flow destabilizes and becomes fully turbulent.

The Reynolds experiment determines the critical Reynolds number for pipe flow at which laminar flow ($Re<2000$) becomes transitional ($2000<Re<4000$) and the transitional flow becomes turbulent ($Re>4000$). The advantage of using a critical Reynolds number, instead of critical velocity, is that the results of the experiments are applicable to all Newtonian fluid flows in pipes with a circular cross-section.

Temperature (degree C)	Kinematic viscosity v (m^2/s)	Temperature (degree C)	K
0	1.793E-06	25	
1	1.732E-06	26	
2	1.674E-06	27	
3	1.619E-06	28	
4	1.522E-06	29	
5	1.520E-06	30	
6	1.474E-06	31	
7	1.429E-06	32	
8	1.386E-06	33	
9	1.346E-06	34	
10	1.307E-06	35	
11	1.270E-06	36	
12	1.235E-06	37	
13	1.201E-06	38	
14	1.169E-06	39	
15	1.138E-06	40	
16	1.108E-06	45	
17	1.080E-06	50	
18	1.053E-06	55	
19	1.027E-06	60	
20	1.002E-06	65	
21	9.780E-07	70	
22	9.550E-07	75	
23	9.330E-07	80	
24	9.110E-07	85	

Figure 7.2: Kinematic Viscosity of Water at Atmospheric Pressure.

8. Experimental Procedure



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Set up the equipment as follows:

- Position the Reynolds apparatus on a fixed, *vibration-free* surface (not on the hydraulics bench), and ensure that the base is horizontal and the test section is vertical.
- Connect the bench outflow to the head tank inlet pipe.
- Place the head tank overflow tube in the volumetric tank of the hydraulics bench.
- Attach a small tube to the apparatus flow control valve, and clamp it to a fixed position in a sink in the lab, allowing enough space below the end of the tube to insert a measuring cylinder. The outflow should not be returned to the volumetric tank since it contains dye and will taint the flow visualisation.

Note that any movement of the outflow tube during a test will cause changes in the flow rate, since it is driven by the height difference between the head tank surface and the outflow point.

- Start the pump, slightly open the apparatus flow control valve and the bench valve, and allow the head tank to fill with water. Make sure that the flow visualisation pipe is properly filled. Once the water level in the head tank reaches the overflow tube, adjust the bench control valve to produce a low overflow rate.
- Ensuring that the dye control valve is closed, add the blue dye to the dye reservoir until it is about 2/3 full.
- Attach the needle, hold the dye assembly over a lab sink, and open the valve to ensure that there

is a free flow of dye.

- Close the dye control valve, then mount the dye injector on the head tank and lower the injector until the tip of the needle is slightly above the bellmouth and is centered on its axis.
- Adjust the bench valve and flow control valve to return the overflow rate to a small amount, and allow the apparatus to stand for at least five minutes
- Adjust the flow control valve to reach a slow trickle outflow, then adjust the dye control valve until a slow flow with clear dye indication is achieved.
- Measure the flow volumetric rate by timed water collection.
- Observe the flow patterns, take pictures, or make hand sketches as needed to classify the flow regime.
- Increase the flow rate by opening the flow control valve. Repeat the experiment to visualize transitional flow and then, at higher flow rates, turbulent flow, as characterized by continuous and very rapid mixing of the dye. Try to observe each flow regime two or three times, for a total of eight readings.
- As the flow rate increases, adjust the bench valve to keep the water level constant in the head tank.

Note that at intermediate flows, it is possible to have a laminar characteristic in the upper part of the test section, which develops into transitional flow lower down. This upper section behavior is described as an "inlet length flow," which means that the boundary layer has not yet extended across the pipe radius.

- Measure water temperature.
- Return the remaining dye to the storage container. Rinse the dye reservoir thoroughly to ensure that no dye is left in the valve, injector, or needle.

9. Results and Calculations

Please visit this link for accessing excel workbook for this experiment.

The following dimensions of the equipment are used in the appropriate calculations. If required, measure them to make sure that they are accurate [7].

- Diameter of test pipe: $d = 0.010\ m$
- Cross-sectional area of test pipe: $A = 7.854\times10^{-5}\ m^2$

9.1. Results

Use the following table to record your measurements and observations.

Raw Data Table

Observed Flow Regime	Volume (L)	Time (sec)	Temperature ($^\circ C$)

9.2. Calculations

Calculate discharge, flow velocity, and Reynolds number (*Re*). Classify the flow based on the *Re* of each experiment. Record your calculations in the following table.

Result Table

Observed Flow Regime	Discharge $Q(m^3/sec)$	Velocity v(m/ sec)	Kinematic Viscosity $\nu(m^2/s)$	Renolds Number	Flow Regime Classified using Reynolds Number

10. Report

Use the template provided to prepare your lab report for this experiment. Your report should include the following:

- Table(s) of raw data
- Table(s) of results
- A description, with illustrative sketches or photos, of the flow characteristics of each experimental run.
- Discuss your results, focusing on the following:
    - How is the flow pattern of each of the three states of flow (laminar, transitional, and turbulent) different?
    - Does the observed flow condition occur within the expected Reynold's number range for that condition?
- Discuss your observation and any source of error in the calculation of the number.
- Compare the experimental results with any theoretical studies you have undertaken.

8

Experiment #8: Free and Forced Vortices

1. Introduction

Vortices can occur naturally or be produced in a laboratory. There are two types of vortices: free vortices and forced vortices. A free vortex is formed, for example, when water flows out of a vessel through a central hole in the base. No external force is required to rotate the fluid, and the degree of rotation is dependent upon the initial disturbance. Whirlpools in rivers and tornadoes are examples of natural free vortices. A forced vortex, on the other hand, is caused by external forces on the fluid. It can be created by rotating a vessel containing fluid or by paddling in fluid. Rotational flow created by impellers of a pump is an example of a forced vortex in turbomachinery.

2. Practical Application

Studying natural phenomena such as hurricanes, tornadoes, and whirlpools (free vortices) requires a full understanding of vortex behavior. It is also critical for engineers and designers to be able to characterize forced vortices generated in machinery, such as centrifugal pumps or turbines. Vortices often have adverse effects, as have been seen during hurricanes, tornadoes, or scour holes created downstream of a dam outlet; however, understanding vortex behavior has enabled engineers to design turbomachinery and hydraulic structures that take advantage of these phenomena. For example, hydrodynamic separators have been developed, based on vortex behavior (swirling flow), to separate solid materials from liquids. This type of separator is used in water treatment plants.

3. Objective

The objective of this lab experiment is to study and compare the water surface profiles of free and forced vortices.

4. Method

This experiment is performed by measuring the water surface profiles of a number of free and forced vortices, and observing the differences. We will study the profiles of free vortices that are produced when water flows from orifices of different diameters that are installed at the base of a tank. Varying the size of the orifice creates changes in the flow rate, thereby changing the rotational speed and size of the vortex profile. Forced vortices are created due to external forces, so we will increase the rotational speed throughout the experiment to study the theoretical and experimental relationships between the vortex surface profile and angular velocity.

5. Equipment

The following equipment is required to perform the free and forced experiment:

- P6100 hydraulics bench, and
- P6238: Free and forced vortices apparatus.

6. Equipment Description

The free and forced vortices apparatus consists of a transparent cylindrical vessel, 250 mm in diameter and 180 mm deep, with two pairs of diametrically opposed inlet tubes of 9.0 mm and 12.5 mm diameter. The 12.5 diameter inlet tubes are angled at 15° to the diameter in order to create a swirling motion of the water entering the vessel during the free vortex experiment (Figure 8.1a). An outlet is centrally positioned in the base of the vessel, and a set of push-in orifices of 8, 16, and 24 mm diameter (Figure 8.1b) is supplied to reduce the outlet diameter to a suitable value and produce free vortices of different sizes. The vortex surface profile is determined by a measuring caliper (Figure 8.1c) housed on a mounted bridge, that measures the diameter of the vortex at various elevations. This provides the coordinate points that are required for plotting the free vortex profile [8].

The forced vortex is created by positioning a bushed plug in the central hole of the vessel and introducing the flow through 9 mm inlet tubes that are angled at 60° to the diameter. The water inflow from these tubes impinges on a two-blade paddle. The water exits the vessel via the 12.5 mm angled inlet tubes that are used as *entry tubes* for the free vortex experiment. The two-bladed paddle rotates on a vertical shaft supported by the bushed plug. A bridge piece mounted on top of the vessel houses a series of needles (Figure 8.1d) to determine the coordinates of the forced vortex profile [8].

A 3-way valve allows water to be diverted through the 12.5 mm inlet tubes for the free vortex experiment, and 9 mm inlet tubes for the forced vortex experiment.

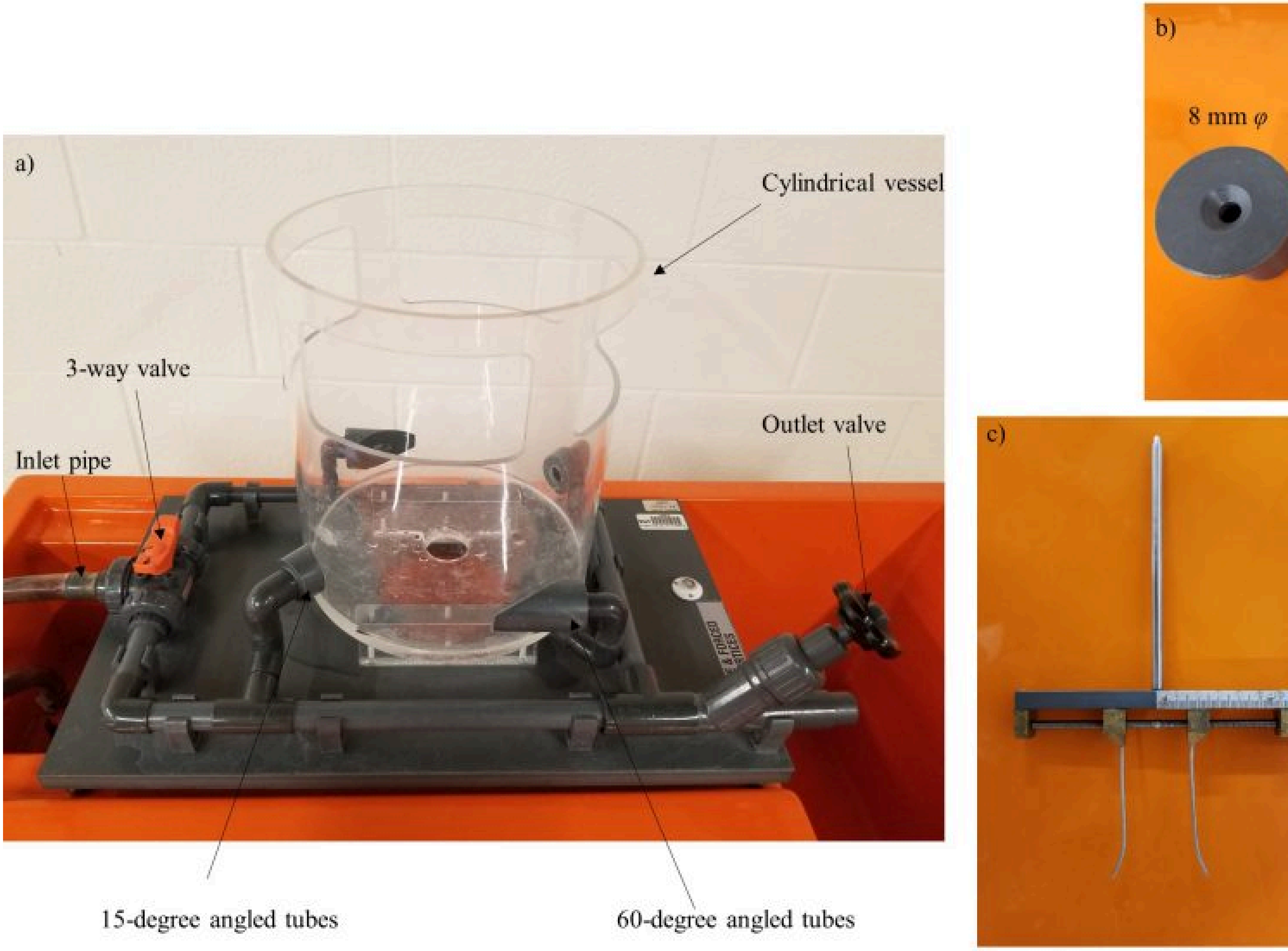


Figure 8.1: a) P6238 CUSSONS free and forced vortex apparatus, b) push-in orifices, c) free vortex measuring calip

7. Theory

Two types of vortices are distinguished in the dynamics of the motion: forced and free vortices. The forced vortex is caused by external forces on the fluid, such as the impeller of a pump, and the free vortex naturally occurs in the flow and can be observed in a drain or in the atmosphere of a tornado.

7.1. Free Vortex

A free vortex is formed when water flows out of a vessel through a central hole in the base (Figure 8.2). The degree of the rotation depends on the initial disturbance. In a free cylindrical vortex, the velocity varies inversely with the distance from the axis of rotation (Figure 8.3).

$v = \frac{k}{r}$ (1)

The equation governing the surface profile is derived from the Bernoulli's theorem:

$\frac{v^2}{2g} + z = C$ (2)

Substituting Equation (1) into (2) will give a new expression:

$\frac{k^2}{2gr^2} + z = C$ (3)

or:

$C - z = \frac{k^2}{2gr^2}$ (4)

which is the equation of a *hyperbolic curve* of nature $y = \frac{A}{x^2}$ (Figure 8.4)

This curve is asymptotic to the axis of rotation and to the horizontal plane through z=c.

7.2. Forced Vortex

When water is forced to rotate at a constant speed (ω) (Figure 8.2), the velocity will be also constant and equal to:

$v = \omega r$ (5)

The velocity head (or kinetic energy) can be calculated as:

$h_c = \frac{v^2}{2g}$ (6)

Substituting Equation (5) into (6) results in:

$h_c = \frac{r^2\omega^2}{2g}$ (7)

If the horizontal plane passing through the lowest point of the vortex is selected as datum, the total energy is equal to:

$H = h_o + h_c$ (8)

where h_o is the pressure head at the datum. Substituting h_c from Equation (7) into (8) gives:

$H = h_o + \frac{r^2\omega^2}{2g}$ (9)

At $r=0$: $H=0$, therefore, $h_o=0$, and :

$$H = \frac{r^2\omega^2}{2g} \qquad (10)$$

This is the equation of the water surface profile, which is a parabola (Figure 8.4).

Figure 8.2: Free vortex (left) and forced vortex (right) produced in the lab

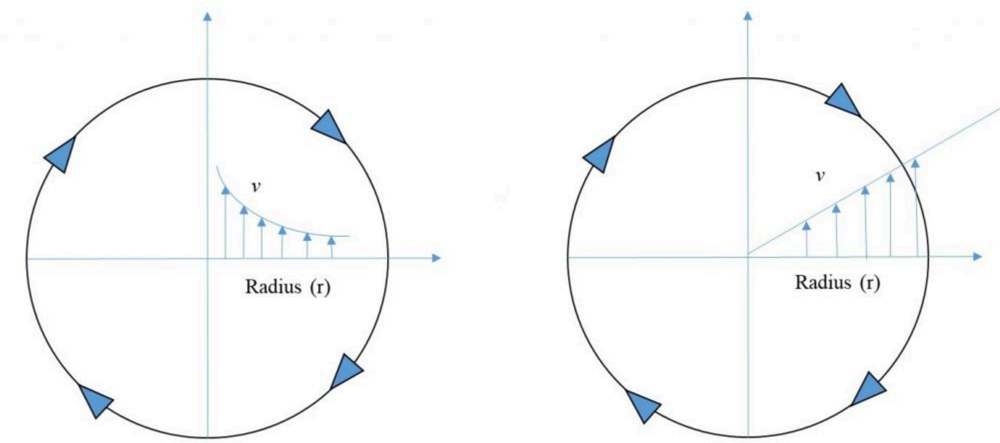


Figure 8.3: Velocity profile of free vortex (left) and forced vortex (right)

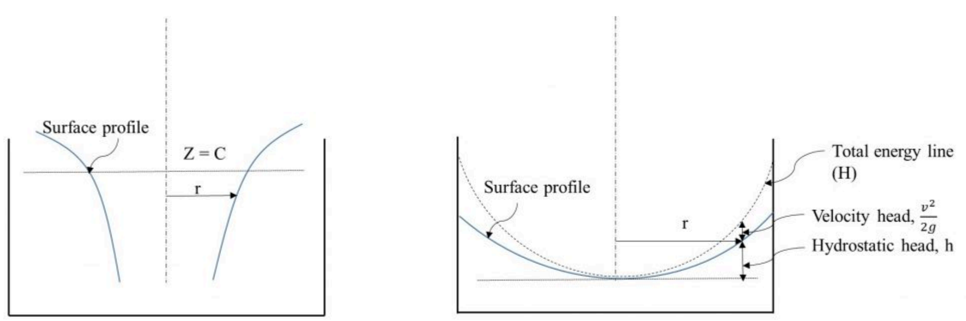
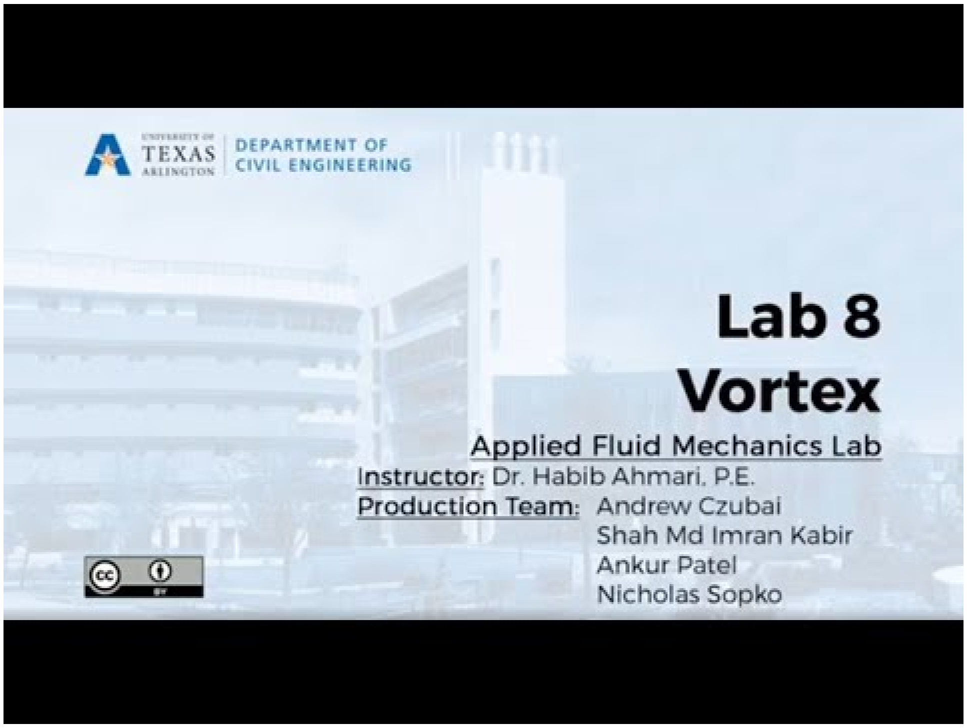


Figure 8.4: Surface profile of a free vortex (left) and a forced vortex (right)

8. Experimental Procedure



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This experiment will be performed in two parts: free vortex and forced vortex.

8.1. Free Vortex

- Position the apparatus on the hydraulics bench so that the central outlet in the base of the vessel is located over the weir trough.
- Adjust the feet to ensure that the apparatus is level.
- Push the 24 mm diameter orifice into the central outlet located in the base of the apparatus.
- Connect the inlet pipe of the apparatus (situated on the 3-way valve) to the hydraulics bench outlet, using the flexible pipe provided.
- Close the apparatus outlet globe valve, and position the 3-way valve so that water flows into the vessel via the 15-degree inlet ports.
- Close the bench outlet valve, and turn on the pump.
- Gradually open the bench valve, and allow the vessel to fill with water until water begins to overflow through the cutouts.
- After the vessel is slightly overflowing, slowly open the outlet valve so that the water level maintains a stable height. Note that you can also adjust the bench valve to maintain a constant water level.
- After a constant water level has been achieved, measure the water surface profile, by adjusting the measuring caliper to a desired radius, and then lower it into the vortex until the needles

evenly touch the walls of the vortex. At this point, record the height indicated by the caliper and repeat the procedure for the remaining radii (Figure 8.5).
- After completing your measurements, close the bench valve, turn off the pump, drain the apparatus, and repeat the process for the remaining two orifices.

Note: The vortex profile tends to wander, so the vortex diameter- measuring gauge arm should be positioned at 90° to the main arm. This allows a meaningful vortex diameter measurement to be made.

8.2. Forced Vortex

- Position the bushed plug into the outlet of the vessel and mount the two-blade paddle wheel on the shaft, ensuring that the tapered edges of the blades angle upward.
- Adjust the 3-way valve so that water flows into the vessel via the 60-degree outlet ports. Turn on the pump, open the bench control valve, and allow the vessel to fill with water until water just begins to overflow through the cutouts. Note that the inlet may need to be adjusted in order to achieve a low-profiled, calm vortex. Water will now flow through these ports and impinge on the paddle wheel before flowing out of the apparatus via the two 15-degree ports.
- After the vessel is filled with water, adjust the outlet valve so that the water level remains stable.

Note: If the water level fluctuates, raise the free end of the outlet tube above the grade line of the water in the vessel, and then lower it again into the bench tank. Doing this will ensure that water discharges at the same rate that it flows in, thereby helping to maintain the water level.

- After the water level is stable, measure the vortex surface profile. This is done by mounting the measuring bridge to the vessel, and then lowering the needles until they are touching the profile of the vortex. Lock them in place, then remove the bridge, and measure the height of each needle. It is recommended that this be done with a graph or engineering paper.
- Record the time that it takes for the paddles to make 10 revolutions in the vessel. You can find the angular velocity of the flow by dividing the number of revolutions by the time.
- Increase the inflow rate to achieve higher angular velocity, and repeat the process so that you have four distinct vortex profiles. Note that as you increase the inflow, you will need to adjust the outlet flow to maintain the water level. As you increase the flow rate, change the count of the revolutions to 20, 40, and 50.

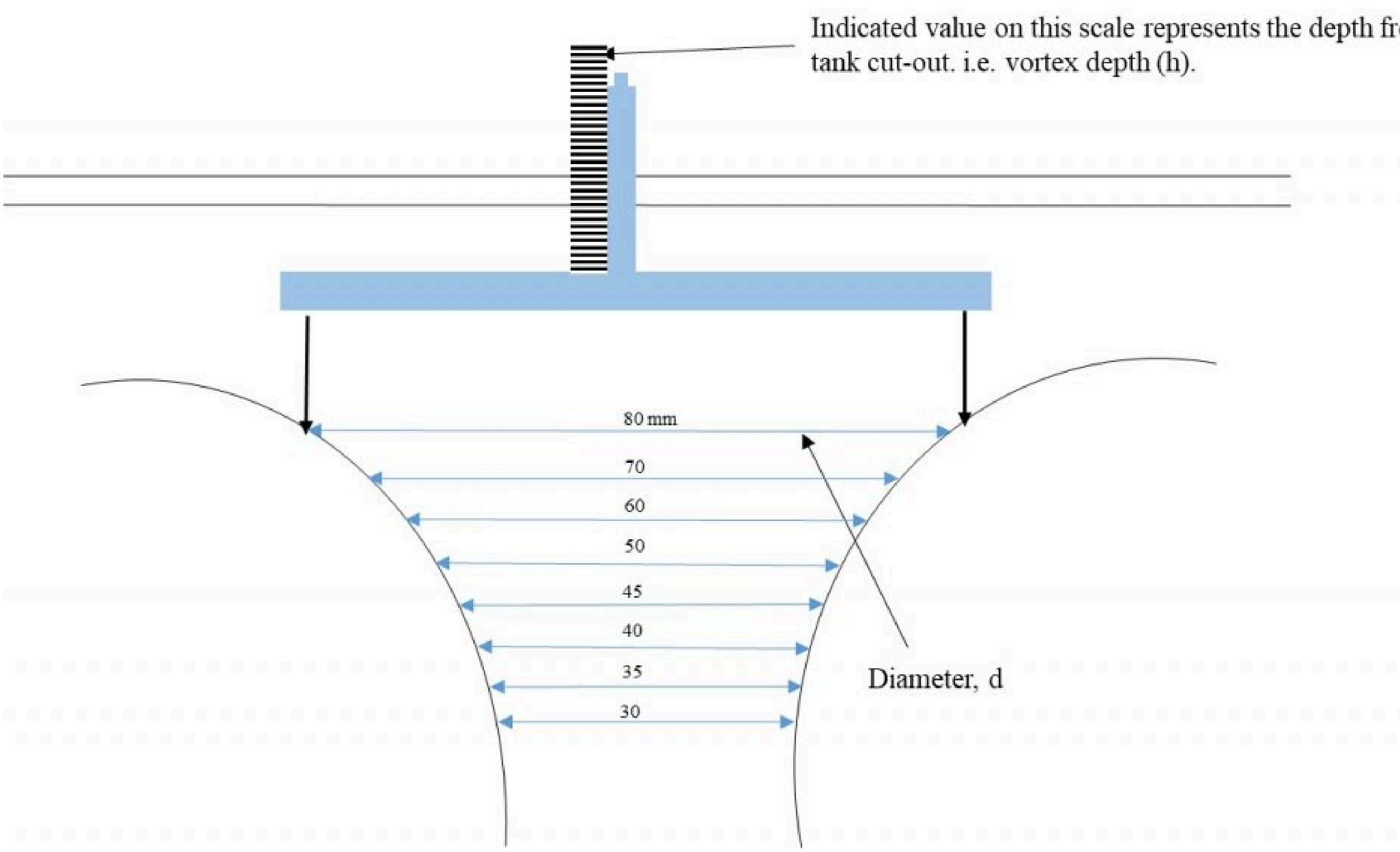


Figure 8.5: Example of water surface profile in free vortex experiment

9. Results and Calculations

Please visit this link for accessing excel workbook for this experiment.

9.1. Results

Use the following tables to record your measurements.

Raw Data Table: Free Vortex

D (mm)	24-mm Orifice	16-mm Orifice	8-mm Orifice
		H (mm)	
80			
70			
60			

50
45
40
35
30

Raw Data Table: Forced Vortex

No. of Revolutions (N)	**T (sec)**	**125 (edge)**	**110**	**90**	**70**	**50**	**30**	**0**
		Distance from center**, r(mm)**						
		Measured height, H(mm)						
10								
20								
40								
50								

9.2. Calculations

a) Free Vortex

Record the coordinate points (D and H) for the three vortex profiles, using Figure 8.5 and the Raw Data Table – Free Vortex.

Result Table: Free Vortex

24-mm orifice		**16-mm orifice**		**8-mm orifice**	
D (mm)	**H (mm)**	**D (mm)**	**H (mm)**	**D (mm)**	**H (mm)**
80		80		80	
70		70		70	
60		60		60	
50		50		50	
45		45		45	
40		40		40	
35		35		35	
30		30		30	

b) Forced Vortex

For all series of experiments with N=10, 20, 40, and 50,

- Calculate angular velocity, ω

$$\omega = 2\pi \frac{No.\,of\ revolution(N)}{t}$$

- Calculate the theoretical water surface profile, using Equation 10.

Result Table – Forced Vortex

Distance from the center, r (mm)	N=10			N = 20			N = 40			N = 50		
	ω (rad/s)	H (mm) cal.	H (mm) meas.	ω (rad/s)	H (mm) cal.	H (mm) meas.	ω (rad/s)	H (mm) cal.	H (mm) meas.	ω (rad/s)	H (mm) cal.	H (mm) meas.
0												
30												
50												
70												
90												
110												
125												

cal.= calculated; meas.= measured.

10. Report

Use the template provided to prepare your lab report for this experiment. Your report should include the following:

- Table(s) of raw data
- Table(s) of results
- Graph(s)
    - Plot all three measured surface profiles of the free vortices on one chart (r as x-axis and H as y-axis). Note that your plots should look like Figure 8.4 (left): as the depth increases, the radius of the vortex decreases.
    - Plot measured and calculated water surface profiles for forced vortices on one chart (r as x-axis and H as y-axis). Note that you need to prepare one chart for each N value (a total of 4 graphs), and the surface profiles should look like Figure 8.4 (right).
- Compare and discuss the calculated and measured surface profiles of forced vortices.
- Discuss briefly the practical applications of free and forced vortices.
- Comment on the possible sources of error (e.g., variance from ideal vortex motion).

Experiment #9: Flow Over Weirs

1. Introduction

A weir is a barrier across the width of a river or stream that alters the characteristics of the flow and usually results in a change in the height of the water level. Several types of weirs are designed for application in natural channels and laboratory flumes. Weirs can be broad-crested, short-crested, or sharp-crested. Sharp-crested weirs, commonly referred to as *notches*, are manufactured from sharp-edged thin plates. The relationship between the flow rate and water depth above the weir can be derived by applying the Bernoulli's equation and by making some assumptions with regard to head loss and pressure distribution of the flow passing over the weir. A coefficient of discharge needs to be determined experimentally for each weir to account for errors in estimating the flow rate that is due to these assumptions.

2. Practical Application

Weirs are commonly used to measure or regulate flow in rivers, streams, irrigation canals, etc. Installing a weir in an open channel system causes critical depth to form over the weir. Since there is a unique relationship between the critical depth and discharge, a weir can be designed as a flow-measuring device. Weirs are also built to raise the water level in a channel to divert the flow to irrigation systems that are located at higher elevations.

3. Objective

The objectives of this experiment are to:

a) determine the characteristics of flow over a rectangular and a triangular weir, and

b) determine the value of the discharge coefficient for both notches.

4. Method

The coefficients of discharge are determined by measuring the height of the water surface above the notch base and the corresponding flow rate. The general features of the flow can be determined by direct observation.

5. Equipment

The following equipment is required to perform the flow over weirs experiment:

- F1-10 hydraulics bench;
- F1-13 rectangular and triangular weirs;
- Vernier height gauge; and
- Stopwatch.

6. Equipment Description

The flow over the weir apparatus includes the following elements that are used in conjunction with the flow channel in the molded bench top of the hydraulics bench (Figure 9.1).

- A combination of a stilling baffle and the inlet nozzle to promote smooth flow conditions in the channel.
- A vernier hook and point gauge, mounted on an instrument carrier, to allow measurement of the depth of flow above the base of the notch.
- The weir notches that are mounted in a carrier at the outlet end of the flow channel [9].

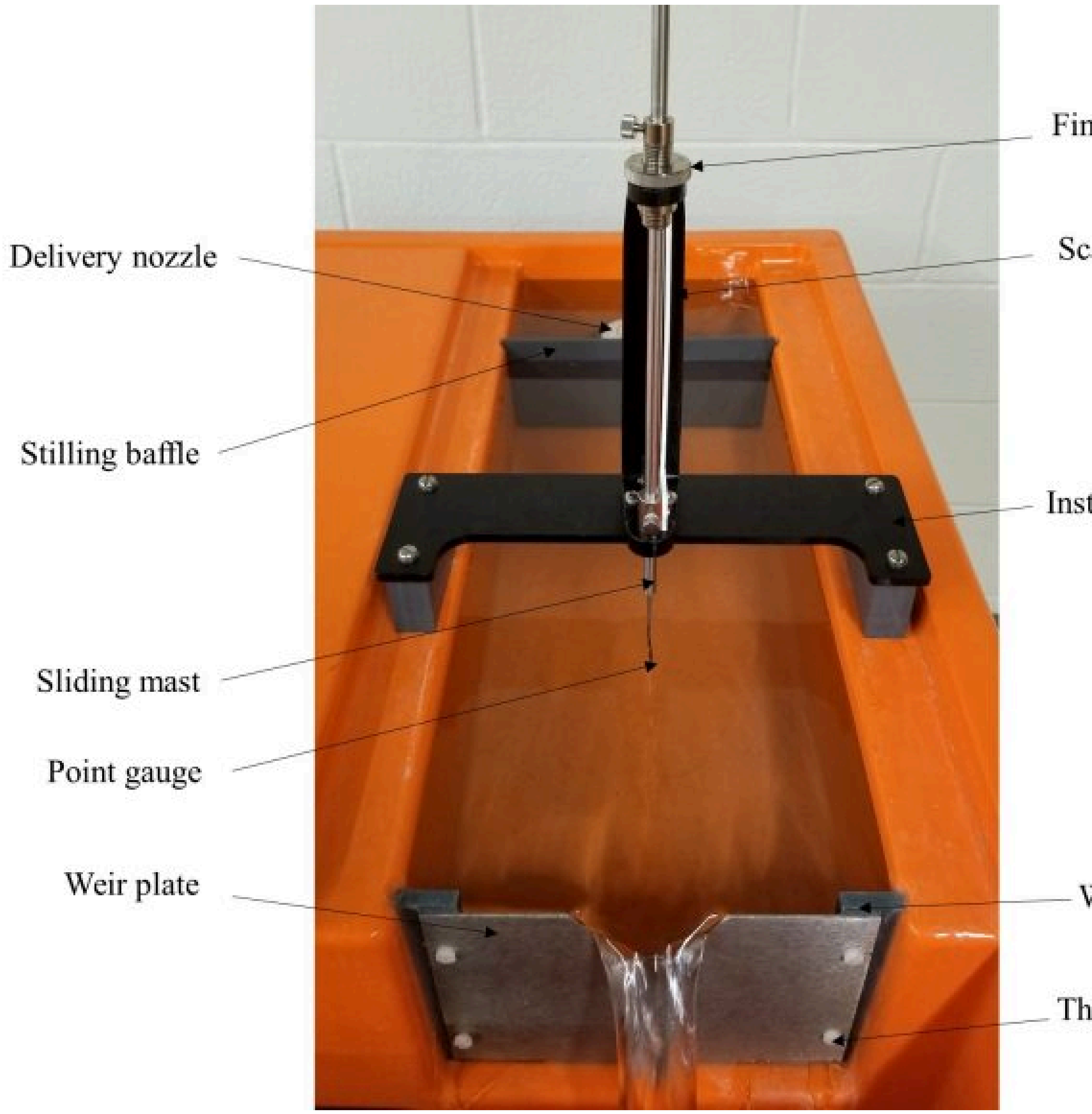


Figure 9.1: Hydraulics bench and weir apparatus

7. Theory

The depth of water above the base of a weir is related to the flow rate through it; therefore, the weir can be used as a flow measuring device. The relationships of flow over weirs can be obtained by applying the energy equation from a point well upstream of the weir to a point just above the weir crest. This approach requires a number of assumptions, and it yields the following results:

- for a triangular weir (Figure 9.2a):

$$Q = C_d \frac{8}{15}\sqrt{2g}\tan\frac{\theta}{2}H^{\frac{5}{2}} \qquad (1)$$

- for a rectangular weir (Figure 9.2b):

$$Q = C_d \frac{2}{3} \sqrt{2g} b H^{\frac{3}{2}} \qquad (2)$$

where:

Q : flow rate;

H : height above the weir base;

b : width of rectangular weir (R-notch);

θ : angle of triangular weir (V-notch);

C_d: discharge coefficient to account for the effects of simplifying assumptions in the theory, which has to be determined by experiment [9].

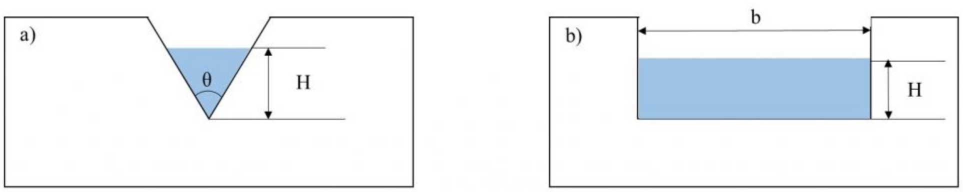


Figure 9.2: (a) Triangular weir, (b) Rectangular weir

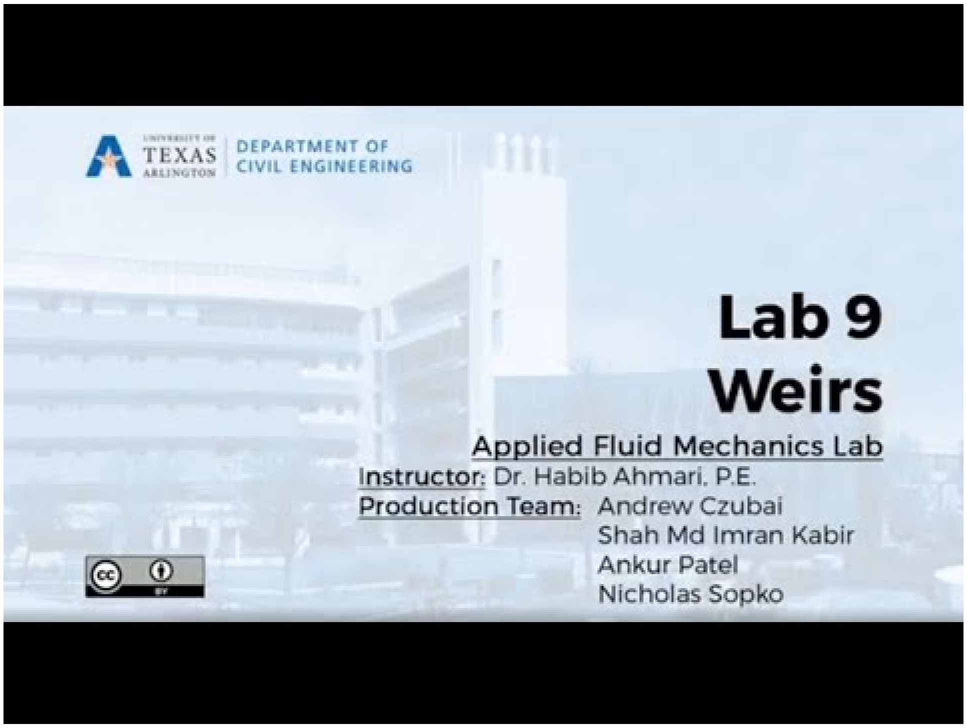
- for a V-notch

$$C_d = \frac{15Q}{2\sqrt{2g}\tan(\frac{\theta}{2})H^{\frac{5}{2}}} \qquad (3)$$

- for a R-notch:

$$C_d = \frac{3Q}{2\sqrt{2g}bH^{\frac{3}{2}}} \qquad (4)$$

8. Experimental Procedure



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This experiment will be performed by taking the following steps:

- Ensure that the hydraulics bench is positioned so that its surface is horizontal. This is necessary because the flow over the notch is driven by gravity.
- Mount the rectangular notch plate onto the flow channel, and position the stilling baffle as shown in Figure 9.3.
- Turn on the pump, and slightly adjust the flow control to fill the channel upstream of the weir with water.
- Turn off the pump when the water starts to flow over the weir.
- Wait a few minutes to allow the water to settle.
- Level the point gauge with the water level in the channel. Record the reading as h_o.

Note: To measure the datum height of the base of the notch (h_o), position the instrument carrier as shown in Figure 9.3. Then carefully lower the gauge until the point is just above the notch base, and lock the coarse adjustment screw. Then, using the fine adjustment, adjust the gauge until the point just touches the water surface and take a reading, being careful not to damage the notch.

- Adjust the point gauge to read 10 mm greater than the datum.
- Record the reading as h.
- Turn on the pump, and slightly adjust the flow until the water level coincides with the point gauge. Check that the level has stabilized before taking readings.

- Measure the flow rate using the volumetric tank.
- Observe the shape of the nappe and take pictures of it.

Note*:* The surface of the water will fall as it approaches the weir. This is particularly noticeable at high flow rates by high heads. To obtain an accurate measurement of the undisturbed water level above the crest of the weir, it is necessary to place the measuring gauge at a distance of at least three times the head above the weir.

- Increase the flow by opening the bench regulating valve to set the heads above the datum level in 10 mm increments until the regulating valve is fully open. Take care not to allow spillage to occur over the plate top that is adjacent to the notch. At each condition, measure the flow rate and observe the shape of the nappe.

Note: To obtain a sufficiently accurate result, collect around 25 liters of water each time, or collect the water for at least 120 seconds.

- Close the regulating valve, stop the pump, and then replace the weir with the V-notch.
- Repeat the experiment with the V-notch weir plate, but with 5 mm increments in water surface elevation.
- Collect seven head and discharge readings for each weir.

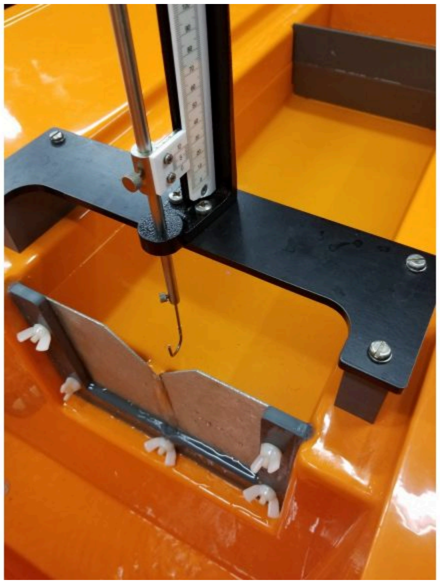


Figure 9.3: Position of the notch and Vernier height gauge to set the datum.

9. Results and Calculations

Please visit this link for accessing excel workbook for this experiment.

9.1. Result

Use the following tables to record your measurements. Record any observations of the shape and the type of nappe, paying particular attention to whether the nappe was clinging or sprung clear, and of the end contraction and general change in shape. (See Figure 9.4 to classify the nappe).

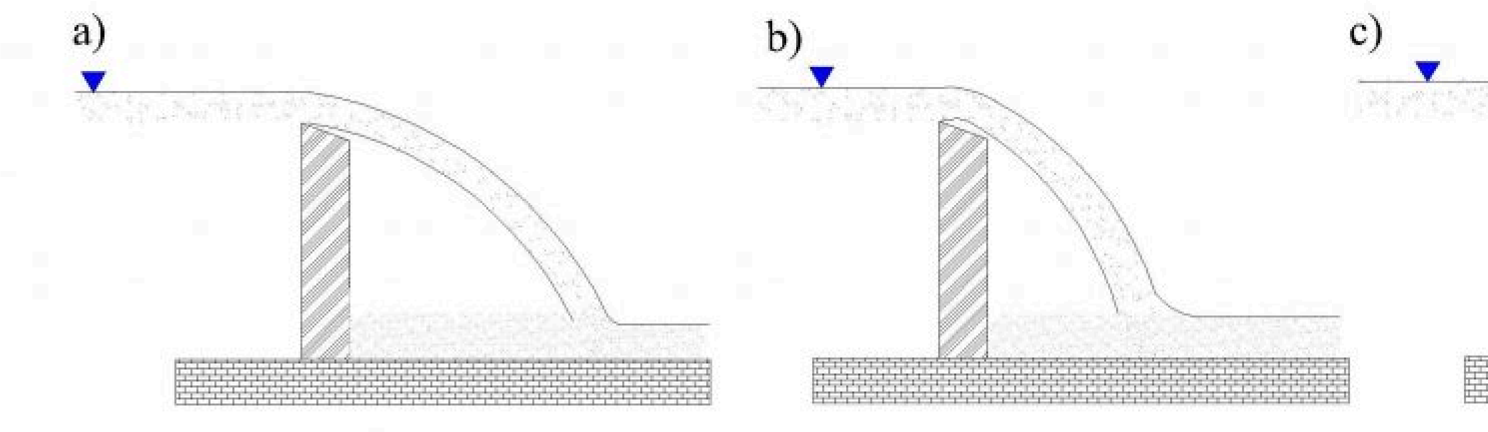


Figure 9.4: Types of nappe: a) Springing clear nappe, b) Depressed Nappe, and c) Clinging Nappe

Raw Data Table: R-notch

Test No.	Datum Height h_0 (m)	Water Surface Elev. h(m)	Volume Collected (L)	Time for Collection (s)
1				
2				
3				
4				
5				
6				
7				

Raw Data Table: V-notch

Test No.	Datum Height h_0 (m)	Water Surface Elev. h(m)	Volume Collected (L)	Time for Collection (s)
1				
2				
3				
4				
5				
6				
7				

9.2. Calculations

The following dimensions from the equipment can be used in the appropriate calculations:

– width of rectangular notch (b) = 0.03 m

– angle of V-notch (θ) = 90°

- Calculate discharge (Q) and head (h) for each experiment, and record them in the Result Tables. For calculation purposes, the depth of the water above the weir is the difference between each water level reading and the datum reading, i.e., $H = h\text{-}h_o$
- Calculate $H^{5/2}$and $H^{3/2}$ for the triangular and rectangular notches, respectively.
- For each measurement, calculate the experimental values of for the triangular and rectangular notches, using Equations 3 and 4, respectively.
- Record your calculations in the Results Tables.

Result Table: R-notch

No.	H (m)	Volume Collected (m^3)	Flow Rate (m^3/s)	$H^{3/2}$	Experimental C_d	Theoretical C_d	%Error
1							
2							
3							
4							
5							
6							
7							

Result Table: V-notch

No.	H (m)	Volume Collected (m^3)	Flow Rate (m^3/s)	$H^{3/2}$	Experimental C_d	Theoretical C_d	%Error
1							
2							
3							
4							
5							
6							
7							

10. Report

Use the template provided to prepare your lab report for this experiment. Your report should include the following:

- Table(s) of raw data

- Table(s) of results
- Graph(s)
    - Schematic drawings or photos of the nappes observed during each experiment, with an indication of their type.
    - Plot a graph of Q (y-axis) against $H^{3/2}$(x-axis) for the rectangular weir and Q against $H^{5/2}$ for the triangular weir. Use a linear function to plot the best fit, and express the relationship between Q and H^n and in the form of: $Q = mH^n$ in which the exponent value n is 1.5 for the rectangular weir and 2.5 for the triangular weir. Calculate the coefficients of discharge C_d (theoretical method) using Equations 5 and 6. Record C_d values calculated from the theoretical method in the Result Tables.

- for a rectangular notch:

$$C_d = \frac{m}{\frac{2}{3}\sqrt{2gb}} \qquad (5)$$

- for a triangular notch:

$$C_d = \frac{m}{\frac{8}{15}\sqrt{2g}\tan\frac{\theta}{2}} \qquad (6)$$

- Compare the experimental results to the theory by calculating the percentage of error.
- What are the limitations of the theory?
- Why would you expect wider variation of C_d values at lower flow rates?
- Compare the results for C_d of the weirs utilized in this experiment with those you may find in a reliable source (e.g., textbooks). Include in your report a copy of the tables or graphs you have used for textbook values of C_d.
- Discuss your observations and any source of errors in calculation of C_d.

10

Experiment #10: Pumps

1. Introduction

In waterworks and wastewater systems, pumps are commonly installed at the source to raise the water level and at intermediate points to boost the water pressure. The components and design of a pumping station are vital to its effectiveness. Centrifugal pumps are most often used in water and wastewater systems, making it important to learn how they work and how to design them. Centrifugal pumps have several advantages over other types of pumps, including:

- Simplicity of construction – no valves, no piston rings, etc.;
- High efficiency;
- Ability to operate against a variable head;
- Suitable for being driven from high-speed prime movers such as turbines, electric motors,

internal combustion engines etc.; and

- Continuous discharge.

A centrifugal pump consists of a rotating shaft that is connected to an impeller, which is usually comprised of curved blades. The impeller rotates within its casing and sucks the fluid through the eye of the casing (point 1 in Figure 10.1). The fluid's kinetic energy increases due to the energy added by the impeller and enters the discharge end of the casing that has an expanding area (point 2 in Figure 10.1). The pressure within the fluid increases accordingly.

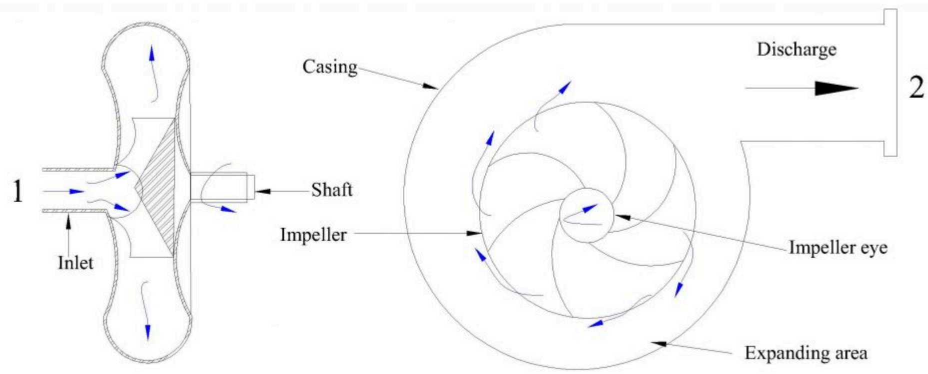


Figure 10.1: Schematic of a typical centrifugal pump

The performance of a centrifugal pump is presented as characteristic curves in Figure 10.2, and is comprised of the following:

- Pumping head versus discharge,
- Brake horsepower (input power) versus discharge, and
- Efficiency versus discharge.

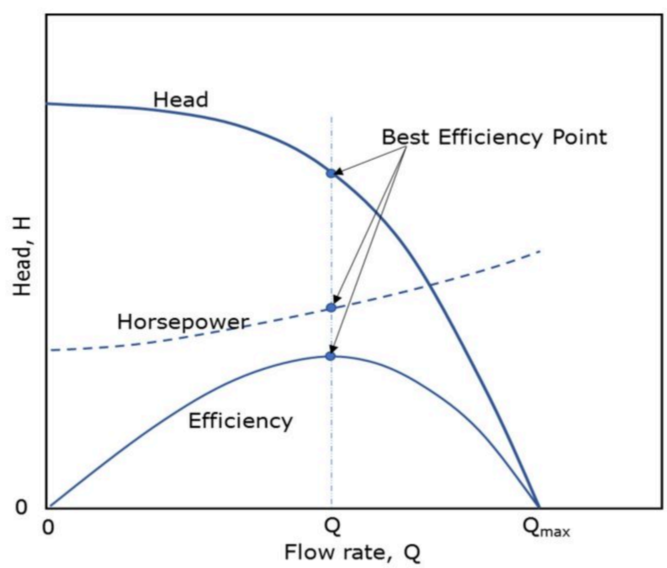


Figure 10.2: Typical centrifugal pump performance curves at constant impeller rotation speed. The units for H and Q are arbitrary.

The characteristic curves of commercial pumps are provided by manufacturers. Otherwise, a pump should be tested in the laboratory, under various discharge and head conditions, to produce such curves. If a single pump is incapable of delivering the design flow rate and pressure, additional pumps, in series or parallel with the original pump, can be considered. The characteristic curves of pumps in series or parallel should be constructed since this information helps engineers select the types of pumps needed and how they should be configured.

2. Practical Application

Many pumps are in use around the world to handle liquids, gases, or liquid-solid mixtures. There are pumps in cars, swimming pools, boats, water treatment facilities, water wells, etc. Centrifugal pumps are commonly used in water, sewage, petroleum, and petrochemical pumping. It is important to select the pump that will best serve the project’s needs.

3. Objective

The objective of this experiment is to determine the operational characteristics of two centrifugal pumps when they are configured as a single pump, two pumps in series, and two pumps in parallel.

4. Method

Each configuration (single pump, two pumps in series, and two pumps in parallel) will be tested at pump speeds of 60, 70, and 80 rev/sec. For each speed, the bench regulating valve will be set to fully closed, 25%, 50%, 75%, and 100% open. Timed water collections will be performed to determine flow rates for each test, and the head, hydraulic power, and overall efficiency ratings will be obtained.

5. Equipment

The following equipment is required to perform the pumps experiment:

- P6100 hydraulics bench, and
- Stopwatch.

6. Equipment Description

The hydraulics bench is fitted with a single centrifugal pump that is driven by a single-phase A.C. motor and controlled by a speed control unit. An auxiliary pump and the speed control unit are supplied to enhance the output of the bench so that experiments can be conducted with the pumps connected either in series or in parallel. Pressure gauges are installed at the inlet and outlet of the pumps to measure the pressure head before and after each pump. A watt-meter unit is used to measure the pumps’ input electrical power [10].

7. Theory

7.1. General Pump Theory

Consider the pump shown in Figure 10.3. The work done by the pump, per unit mass of fluid, will result in increases in the pressure head, velocity head, and potential head of the fluid between points 1 and 2. Therefore:

- work done by pump per unit mass = W/M
- increase in pressure head per unit mass $= \frac{P_2 - P_1}{\rho}$
- increase in velocity head per unit mass $= \frac{v_2^2 - v_1^2}{2}$
- increase in potential head per unit mass $= g(z_2 - z_1)$

in which:

W: work

M: mass

P: pressure

ρ: density

v: flow velocity

g: acceleration due to gravity

z: elevation

Applying Bernoulli's equation between points 1 and 2 in Figure 10.3 results in:

$$\frac{W}{M} = \frac{P_2 - P_1}{\rho} + \frac{v_2^2 - v_1^2}{2} + g(z_2 - z_1) \qquad (1)$$

Since the difference between elevations and velocities at points 1 and 2 are negligible, the equation becomes:

$$\frac{W}{M} = \frac{P_2 - P_1}{\rho} \qquad (2)$$

Dividing both sides of this equation by gives:

$$\frac{W}{Mg} = \frac{P_2 - P_1}{\rho g} \qquad (3)$$

The right side of this equation is the manometric pressure head, H_m, therefore:

$\frac{W}{Mg} = H_m \qquad (4)$

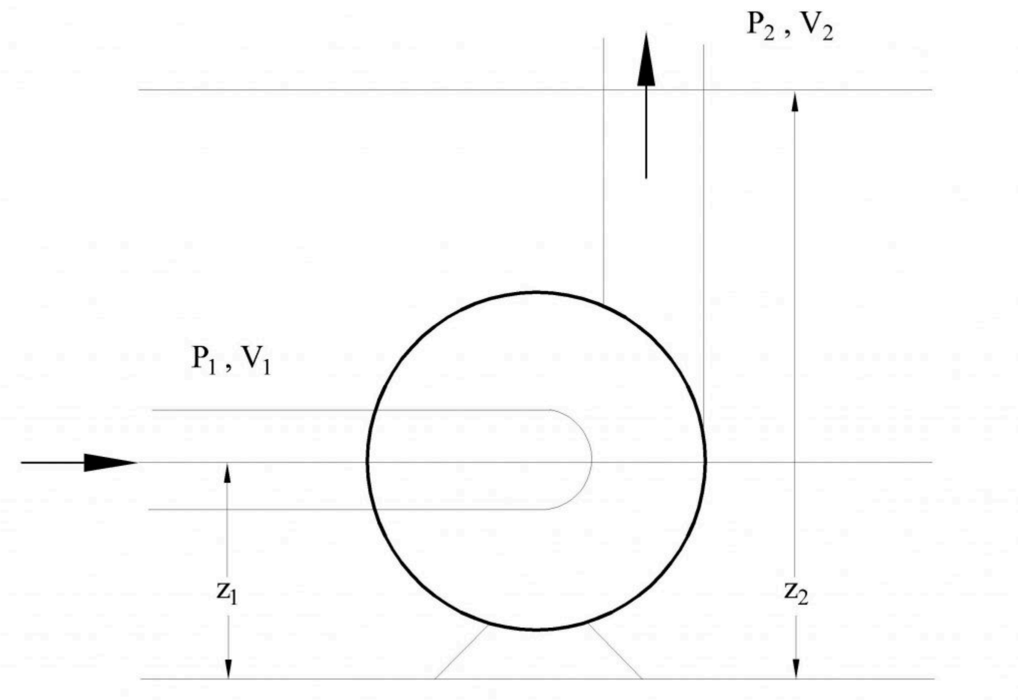


Figure 10.3: Schematic pump–pipe system

7.2. Power and Efficiency

The hydraulic power (W_h) supplied to the fluid by the pump is the product of the pressure increase and the flow rate:

$W_h = (P_2 - P_1)Q \qquad (5)$

The pressure increase produced by the pump can be expressed in terms of the manometric head,

$H_m = \frac{P_2 - P_1}{\rho g}$

Therefore:

$W_h = \rho g H_m Q = \gamma H_m Q \qquad (6)$

The overall efficiency (η) of the pump-motor unit can be determined by dividing the hydraulic power (W_h) by the input electrical power (W_i), i.e.:

$\eta = \frac{W_h}{W_i} 100(\%) \qquad (7)$

7.3. Single Pump – Pipe System performance

While pumping fluid, the pump has to overcome the pressure loss that is caused by friction in any valves, pipes, and fittings in the pipe system. This frictional head loss is approximately proportional to the square of the flow rate. The total system head that the pump has to overcome is the sum of the total static head and the frictional head. The total static head is the sum of the static suction lift and the static discharge head, which is equal to the difference between the water levels of the discharge and the source tank (Figure 10.4). A plot of the total head-discharge for a pipe system is called a *system curve*; it is superimposed onto a pump characteristic curve in Figure 10.5. The operating point for the pump-pipe system combination occurs where the two graphs intercept [10].

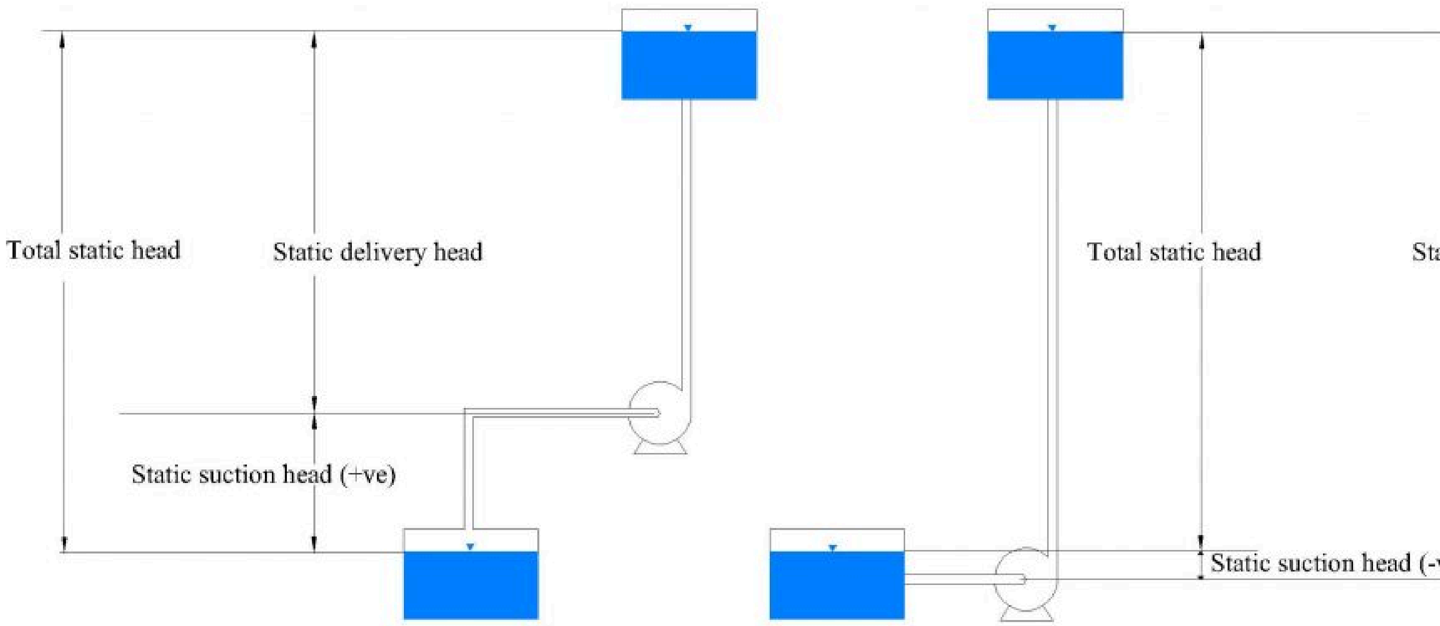


Figure 10.4: Pump and pipe system showing static and total heads: lift pump (left), pump with flooded suction (right

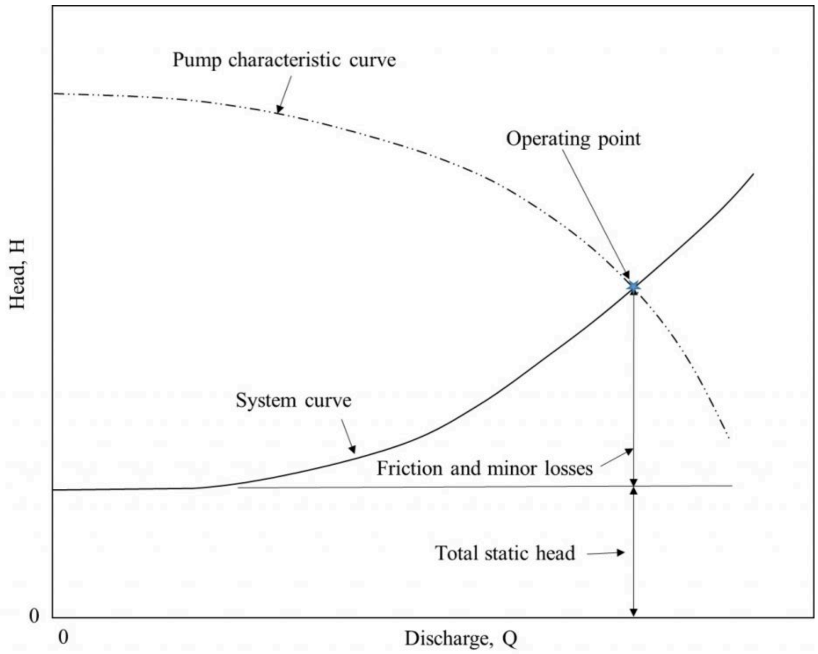


Figure 10.5: Pump-pipe system operating point

7.4. Pumps in Series

Pumps are used in series in a system where substantial head changes take place without any appreciable difference in discharge. When two or more pumps are configured in series, the flow rate throughout the pumps remains the same; however, each pump contributes to the increase in the head so that the overall head is equal to the sum of the contributions of each pump [10]. For n pumps in series:

$$Q = Q_1 = Q_2 ... = Q_n \qquad (7a)$$

$$H_m = H_{m1} + H_{m2} + H_{m3} ... + H_{mn} = \sum_{j=1}^{n} H_m \qquad (7b)$$

The composite characteristic curve of pumps in series can be prepared by adding the ordinates (heads) of all of the pumps for the same values of discharge. The intersection point of the composite head characteristic curve and the system curve provides the operating conditions (performance point) of the pumps (Figure 10.6).

7.5. Pumps in Parallel

Parallel pumps are useful for systems with considerable discharge variations and with no appreciable head change. In parallel, each pump has the same head. However, each pump contributes to the discharge so that the total discharge is equal to the sum of the contributions of each pump [10]. Thus for pumps:

$$Q = Q_1 + Q_2 + Q_3 ... + Q_n = \sum_{j=1}^{n} Q \qquad (8a)$$

$$H_m = H_{m1} = H_{m2} ... = H_{mn} \qquad (8b)$$

The composite head characteristic curve is obtained by summing up the discharge of all pumps for the same values of head. A typical pipe system curve and performance point of the pumps are shown in Figure 10.7.

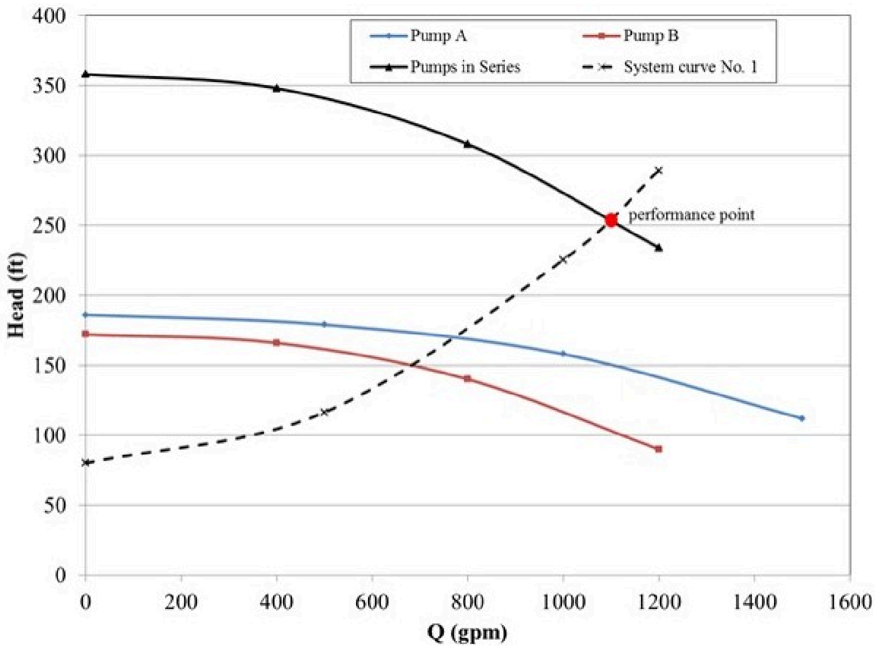


Figure 10.6: Characteristics of two pumps in series

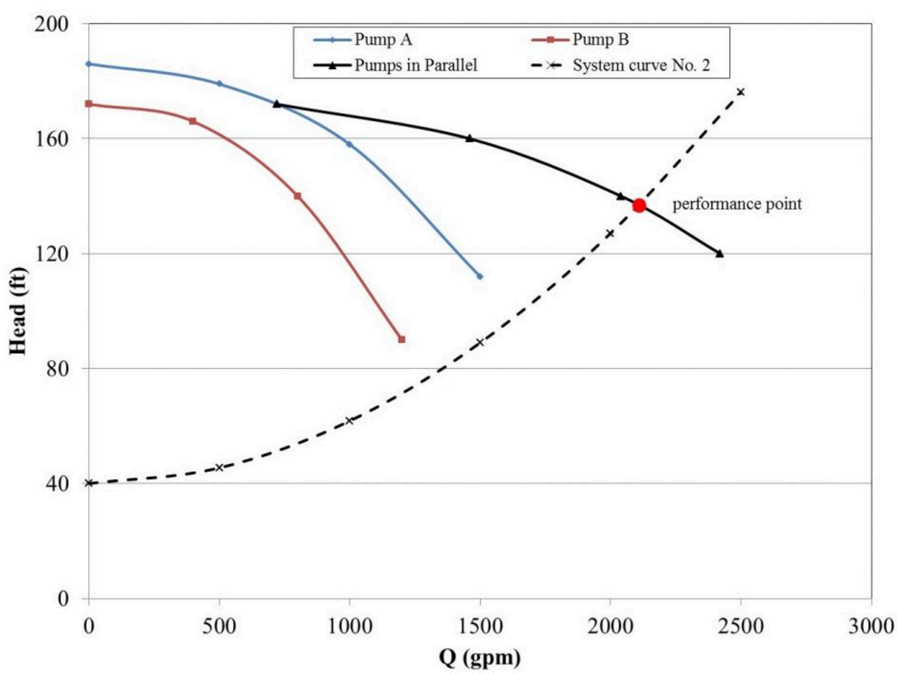
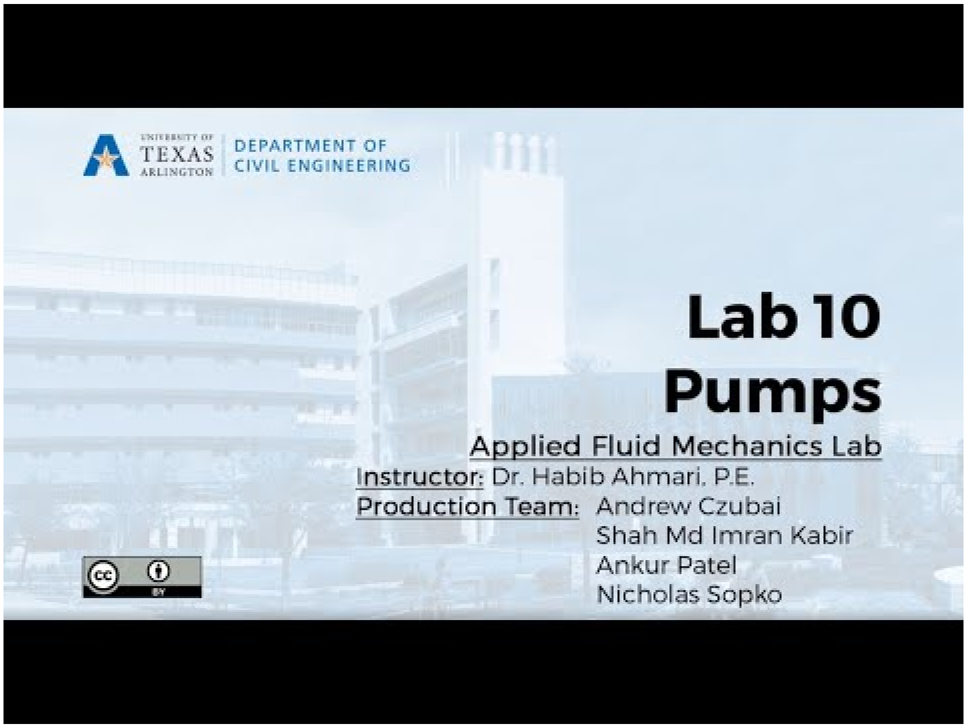


Figure 10.7: Characteristics of two pumps in parallel

8. Experimental Procedure



A YouTube element has been excluded from this version of the text. You can view it online here: https://uta.pressbooks.pub/appliedfluidmechanics/?p=243

8.1. Experiment 1: Characteristics of a Single Pump

a) Set up the hydraulics bench valves, as shown in Figure 10.8, to perform the single pump test.

b) Start pump 1, and increase the speed until the pump is operating at 60 rev/sec.

c) Turn the bench regulating valve to the fully closed position.

d) Record the pump 1 inlet pressure (P_1) and outlet pressure (P_2). Record the input power from the watt-meter (Wi). (With the regulating valve fully closed, discharge will be zero.)

e) Repeat steps (c) and (d) by setting the bench regulating valve to 25%, 50%, 75%, and 100% open.

f) For each control valve position, measure the flow rate by either collecting a suitable volume of water (a minimum of 10 liters) in the measuring tank, or by using the rotameter.

g) Increase the speed until the pump is operating at 70 rev/sec and 80 rev/sec, and repeat steps (c) to (f) for each speed.

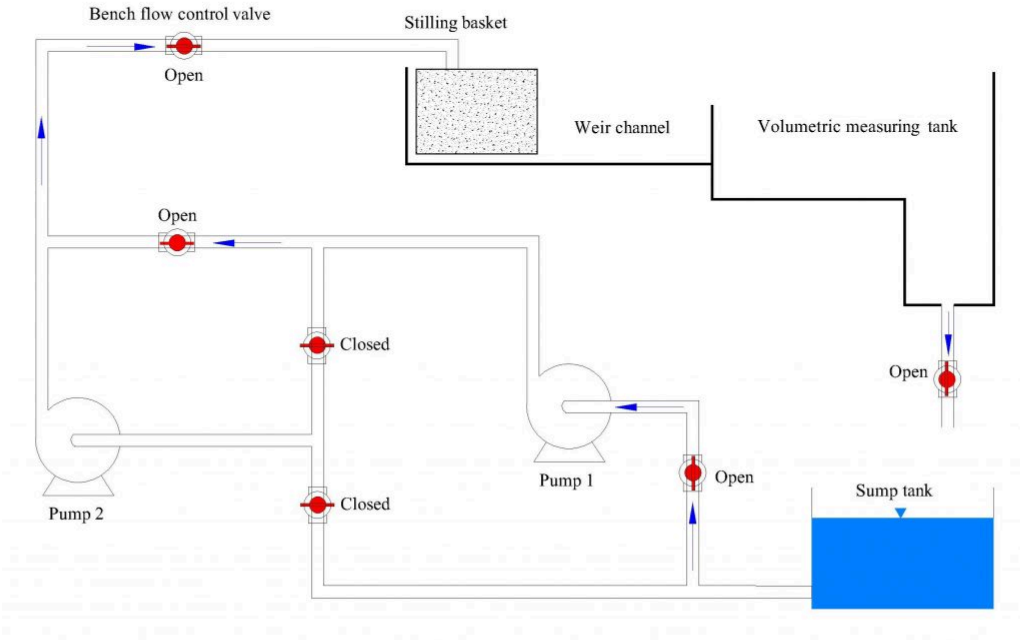


Figure 10.8: Configuration of hydraulics bench valves for the single pump test.

8.2. Experiment 2: Characteristics of Two Pumps in Series

a) Set up the hydraulics bench valves, as shown in Figure 10.9, to perform the two pumps in series test.

b) Start pumps 1 and 2, and increase the speed until the pumps are operating at 60 rev/sec.

c) Turn the bench regulating valve to the fully closed position.

d) Record the pump 1 and 2 inlet pressure (P_1) and outlet pressure (P_2). Record the input power for pump 1 from the wattmeter (Wi). (With the regulating valve fully closed, discharge will be zero.)

e) Repeat steps (c) and (d) by setting the bench regulating valve to 25%, 50%, 75%, and 100% open.

f) For each control valve position, measure the flow rate by either collecting a suitable volume of water (a minimum of 10 liters) in the measuring tank, or by using the rotameter.

g) Increase the speed until the pump is operating at 70 rev/sec and 80 rev/sec, and repeat steps (c) to (f) for each speed.

Note: Wattmeter readings should be recorded for both pumps, assuming that both pumps have the same input power.

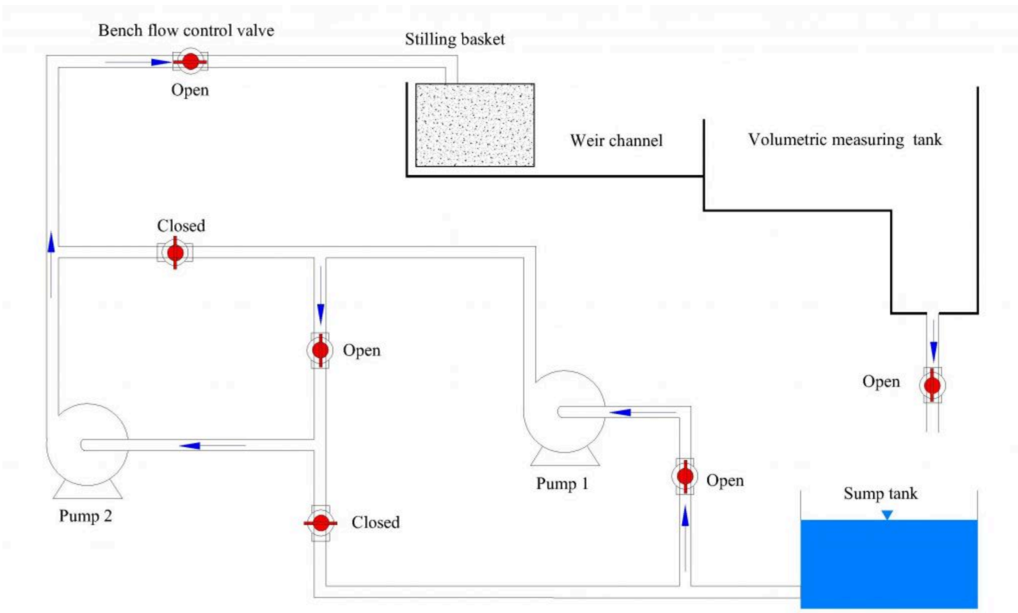


Figure 10.9: Configuration of hydraulics bench valves for pumps in series test.

8.3. Experiment 3: Characteristics of Two Pumps in Parallel

a) Configure the hydraulic bench, as shown in Figure 10.10, to conduct the test for pumps in parallel.

b) Repeat steps (b) to (g) in Experiment 2.

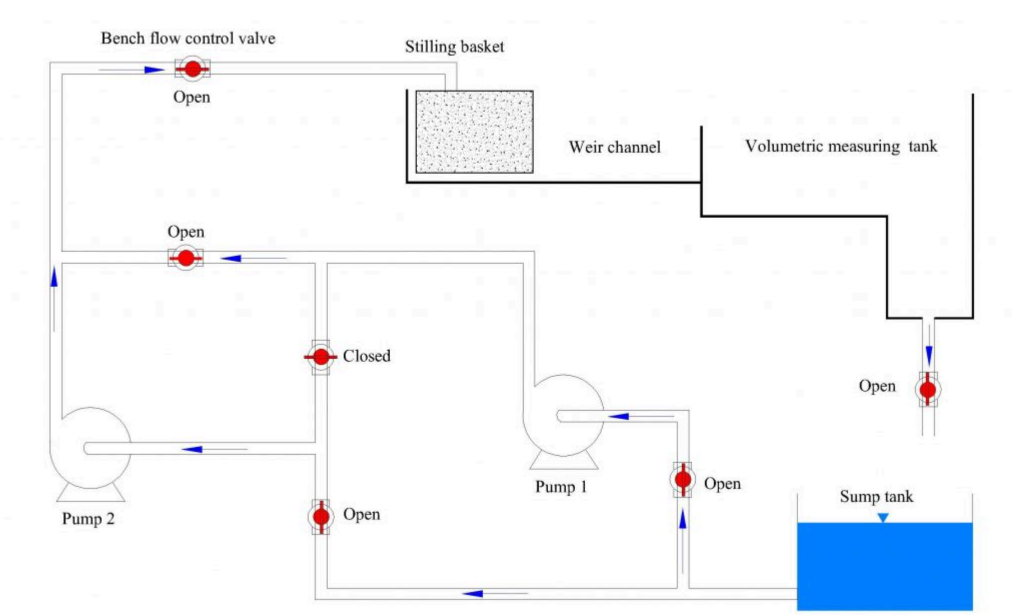


Figure 10.10: Configuration of hydraulic bench valves for pumps in parallel

9. Results and Calculations

Please visit this link for accessing excel workbook of this manual.

9.1. Result

Record your measurements for Experiments 1 to 3 in the Raw Data Tables.

Raw Data Table

Single Pump: 60 rev/s					
Valve Open Position	**0%**	**25%**	**50%**	**75%**	**100%**
Volume (L)					
Time (s)					
Pump 1 Inlet Pressure, P_1 (bar)					
Pump 1 Outlet Pressure, P_2 (bar)					
Pump 1 Electrical Input Power (Wi)					

Single Pump: 70 rev/s					
Valve Open Position	**0%**	**25%**	**50%**	**75%**	**100%**
Volume (L)					
Time (s)					
Pump 1 Inlet Pressure, P_1 (bar)					
Pump 1 Outlet Pressure, P_2 (bar)					
Pump 1 Electrical Input Power (Wi)					

Single Pump: 80 rev/s					
Valve Open Position	**0%**	**25%**	**50%**	**75%**	**100%**
Volume (L)					
Time (s)					
Pump 1 Inlet Pressure, P_1 (bar)					
Pump 1 Outlet Pressure, P_2 (bar)					
Pump 1 Electrical Input					

Power (Wi)

Two Pumps in Series: 60 rev/s					
Valve Open Position	0%	25%	50%	75%	100%
Volume (L)					
Time (s)					
Pump 1 Inlet Pressure, P_1 (bar)					
Pump 1 Outlet Pressure, P_2 (bar)					
Pump 1 Electrical Input Power (Wi)					
Pump 2 Inlet Pressure, P_1 (bar)					
Pump 2 Outlet Pressure, P_2 (bar)					
Pump 2 Electrical Input Power (Wi)					

Two Pumps in Series: 70 rev/s					
Valve Open Position	0%	25%	50%	75%	100%
Volume (L)					
Time (s)					
Pump 1 Inlet Pressure, P_1 (bar)					
Pump 1 Outlet Pressure, P_2 (bar)					
Pump 1 Electrical Input Power (Wi)					
Pump 2 Inlet Pressure, P_1 (bar)					
Pump 2 Outlet Pressure, P_2 (bar)					
Pump 2 Electrical Input Power (Wi)					

Two Pumps in Series: 80 rev/s					
Valve Open Position	0%	25%	50%	75%	100%
Volume (L)					
Time (s)					
Pump 1 Inlet Pressure, P_1					

(bar)					
Pump 1 Outlet Pressure, P_2 (bar)					
Pump 1 Electrical Input Power (Wi)					
Pump 2 Inlet Pressure, P_1 (bar)					
Pump 2 Outlet Pressure, P_2 (bar)					
Pump 2 Electrical Input Power (Wi)					

Two Pumps in Parallel: 60 rev/s

Valve Open Position	0%	25%	50%	75%	100%
Volume (L)					
Time (s)					
Pump 1 Inlet Pressure, P_1 (bar)					
Pump 1 Outlet Pressure, P_2 (bar)					
Pump 1 Electrical Input Power (Wi)					
Pump 2 Inlet Pressure, P_1 (bar)					
Pump 2 Outlet Pressure, P_2 (bar)					
Pump 2 Electrical Input Power (Wi)					

Two Pumps in Parallel: 70 rev/s

Valve Open Position	0%	25%	50%	75%	100%
Volume (L)					
Time (s)					
Pump 1 Inlet Pressure, P_1 (bar)					
Pump 1 Outlet Pressure, P_2 (bar)					
Pump 1 Electrical Input Power (Wi)					
Pump 2 Inlet Pressure, P_1					

(bar)					
Pump 2 Outlet Pressure, P_2 (bar)					
Pump 2 Electrical Input Power (Wi)					

	Two Pumps in Parallel: 80 rev/s				
Valve Open Position	**0%**	**25%**	**50%**	**75%**	**100%**
Volume (L)					
Time (s)					
Pump 1 Inlet Pressure, P_1 (bar)					
Pump 1 Outlet Pressure, P_2 (bar)					
Pump 1 Electrical Input Power (Wi)					
Pump 2 Inlet Pressure, P_1 (bar)					
Pump 2 Outlet Pressure, P_2 (bar)					
Pump 2 Electrical Input Power (Wi)					

9.2. Calculations

- If the volumetric measuring tank was used, then calculate the flow rate from:

$$Q = \frac{V}{t}$$

- Correct the pressure rise measurement (outlet pressure) across the pump by adding a 0.07 bar to allow for the difference of 0.714 m in height between the measurement point for the pump outlet pressure and the actual pump outlet connection.
- Convert the pressure readings from bar to N/m^2 (1 Bar=10^5 N/m^2), then calculate the manometric head from:

$$H_m = \frac{P_2 - P_1}{\rho g}$$

- Calculate the hydraulic power (in watts) from Equation 6 where Q is in m^3/s, ρ in kg/m^3, g in m/s^2, and H_m in meter.
- Calculate the overall efficiency from Equation 7.

Note:

– Overall head for pumps in series is calculated using Equation 8b.
– Overall head for pumps in parallel is calculated using Equation 9b.
– Overall electrical input power for pumps in series and in parallel combination is equal to $(Wi)_{pump1}+(Wi)_{pump2}$.

- Summarize your calculations in the Results Tables.

Result Tables

Single Pump: N (rev/s)

Valve Open Position	**0%**	**25%**	**50%**	**75%**	**100%**
Flow Rate, Q (L/min)					
Flow Rate, Q (m^3/s)					
Pump 1 Inlet Pressure, P_1 (N/m^2)					
Pump 1 Outlet Corrected Pressure, P_2 (N/m^2)					
Pump 1 Electrical Input Power (Watts)					
Pump 1 Head, Hm (m)					
Pump 1 Hydraulic Power, W_h (Watts)					
Pump 1 Overall Efficiency, η_0 (%)					

Two Pumps in Series: N (rev/s)

Valve Open Position	**0%**	**25%**	**50%**	**75%**	**100%**
Flow Rate, Q (L/min)					
Flow Rate, Q (m^3/s)					
Pump 1 Inlet Pressure, P_1 (N/m^2)					
Pump 1 Outlet Corrected Pressure, P_2 (N/m^2)					
Pump 1 Electrical Input Power (Watts)					
Pump 2 Inlet Pressure, P1 (N/m2)					
Pump 2 Outlet Corrected Pressure, P2 (N/m2)					
Pump 2 Electrical Input Power (Watts)					
Pump 1 Head, Hm (m)					
Pump 1 Hydraulic Power, Wh (Watts)					
Pump 2 Head, Hm (m)					
Pump 2 Hydraulic Power, Wh (Watts)					
Overall Head, Hm (m)					
Overall Hydraulic Power, Wh (Watts)					
Overall Electrical Input Power, Wi (Watts)					
Both Pumps Overall Efficiency, η_0 (%)					

Two Pumps in Parallel: N (rev/s)					
Valve Open Position	**0%**	**25%**	**50%**	**75%**	**100%**
Flow Rate, Q (L/min)					
Flow Rate, Q (m^3/s)					
Pump 1 Inlet Pressure, P_1 (N/m^2)					
Pump 1 Outlet Corrected Pressure, P_2 (N/m^2)					
Pump 1 Electrical Input Power (Watts)					
Pump 2 Inlet Pressure, P1 (N/m2)					
Pump 2 Outlet Corrected Pressure, P2 (N/m2)					
Pump 2 Electrical Input Power (Watts)					
Pump 1 Head, Hm (m)					
Pump 1 Hydraulic Power, Wh (Watts)					
Pump 2 Head, Hm (m)					
Pump 2 Hydraulic Power, Wh (Watts)					
Overall Head, Hm (m)					
Overall Hydraulic Power, Wh (Watts)					
Overall Electrical Input Power, Wi (Watts)					
Both Pumps Overall Efficiency, η_0 (%)					

10. Report

Use the template provided to prepare your lab report for this experiment. Your report should include the following:

- Table(s) of raw data
- Table(s) of results
- Graph(s)
  - Plot head in meters as y-axis against volumetric flow, in liters/min as x-axis.
  - Plot hydraulic power in watts as y-axis against volumetric flow, in liters/min as x-axis.
  - Plot efficiency in % as y-axis against volumetric flow, in liters/min as x-axis on your graphs.

In each of above graphs, show the results for single pump, two pumps in series, and two pumps in parallel – a total of three graphs. Do not connect the experimental data points, and use best fit to plot the graphs

- Discuss your observations and any sources of error in preparation of pump characteristics.

1

References

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Experiment #4: ENERGY LOSS IN PIPES

Figure 4.1: "Moody diagram. Lines created using Swami and Jaine formula." Plot created on Matlab. By S Beck and R Collins, University of Sheffield, 2008. Wiki Commons. (https://commons.wikimedia.org/wiki/File:Moody_diagram.jpg)