This manual contains all relevant material necessary to complete Florida International University Mechanical and Materials Engineering's Transport Phenomena Lab

EML 3126L

Laboratory Guide

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Laboratory Safety

What YOU should know

You need to develop the habit of asking yourself whether an operation is safe and ensuring that you have the adequate knowledge and training about the equipment/ experiment you are using and safe working practices for that equipment/ experiment. Tidiness and thinking ahead are important aspects of a safe working environment.

For your work in the undergraduate teaching laboratories the following rules apply; but you must use common sense and ask an instructor if you have any doubts about safety or a particular situation.

General Laboratory Safety

1. Students are not permitted to work in the laboratories outside the specified times of laboratory classes unless they have been given specific permission to do so by the Department Lab Manager, who will then supervise the work.

2. Smoking and the consumption of food and drink are not permitted in the laboratories.

3. Apparatuses should be disconnected at the end of a session, unless you have asked for and been given permission by the Department Lab Manager to leave it assembled.

4. All accidents or breakages, however small, should be reported immediately to the Department Lab Manager.

5. Any dangerous incident or anything which is suspected to be an unsafe situation must be reported immediately to the Department Lab Manager or to the MME Department.

6. Bags and other personal items are not allowed to obstruct exits or pathways.

7. Solvents (propanol, acetone etc.) should only be used in a well-ventilated environment. They are highly flammable and should be kept away from ignition sources.

8. Students should be aware of the dangers of loose clothing or long hair when working with machinery or chemicals.

    a. Sandals or open toed shoes are not allowed to be worn in the lab. Doing so, will not allow you entrance to the lab.

Electricity

Electricity is potentially lethal. Under normal circumstances, any voltage over 55V is to be treated as hazardous unless it is incapable of delivering a current in excess of 1mA.

1. Students are not permitted to work with exposed electrical mains or to perform any kind of maintenance work on the electrical mains or any of its circuitry, including plugs. Equipment requiring repair should be brought to the attention of the Department Lab Manager.

2. Before connecting any equipment/ experiment, a check should be made that all instruments and apparatuses are of a suitable rating for the experiment to be performed.

   a. Check also that all wires are of a suitable current capacity.

   b. All supply switches should be in the "**OFF"** position whilst connections are made (during disconnection as well).

   c. All power supplies should be switched off before changing any components.

3. Before switching on check that all connections are correct (if in doubt, ask).

4. Place apparatus so that short circuits cannot occur.

Laboratory Rules:

1. No one is allowed to use the laboratory facilities without permission of the Department Lab Manager.

2. In order to use the laboratory facilities, you must schedule it at least 5 business days prior to the day of intended use.

3. No one is allowed to take out any equipment, devices and/or tools from the MME laboratories without permission of the Department Lab Manager.

4. Written permission or documentation is necessary when borrowing any equipment, devices and/or tools from the MME laboratories. The documentation must include the reason, usage, return date and signature of the Department Lab Manager. Return of the equipment must be punctual and without any damage.

5. Everyone must sign in before using the MME laboratories, and sign out when leaving.

6. No food, drink (except water), or gum is permitted in the laboratory.

7. Everyone must follow the instructions during any experiments.

8. When finishing with the experiments, everyone is responsible for putting back what was used to its original place and for shutting off the power.

9. Everyone is responsible for his or her own safety.

10. Everyone who uses the MME laboratory facilities is responsible to provide experimental documentation (with certain exemptions).

Lab Report Format and Guide

Required Format for Lab Reports

1. All laboratory reports must be done on a computer using a word processing software program.
   a. All mechanical engineering students have access to the computer laboratory, where all the computers have the software required to comply with this requirement.
2. Reports must be in Adobe PDF format.
3. Allow for a one inch margin on each edge of the paper.
4. The major headings in the report should be on the left-hand side and underlined.
5. Number all pages, including plots and appendices, at the bottom right-hand corner of the page.
6. The report (PDF) must be named in the following manner:
   Class_Section_Experiemnt#_Group#_.pdf
7. Remember, laboratory report grades are unduly influenced by the quality of the presentation of the report.

Report Sections

All reports should contain the following sections:

1. **Title Page**
   a. The title page should include the experiment's title, group number, names of the members of your group, and the date of the experiment.
2. **Table of Contents, List of Tables, and List of Figures**
   a. A table of contents should be provided for ease of locating the desired material of the report. The table of contents gives page numbers for easy reference to the individual sections of the report, and provides an outline of the topics to be covered in the report.
   b. All tables in a report should be numbered and titled. The list of tables is the index to all tables in the report.

c. All figures in a report should be numbered and titled. The list of figures is the index to all figures in the report. All graphs and sketches are to be given figure numbers and titles.

3. **Nomenclature**

   a. A list of all mathematical symbols with their respective units and description.

4. **Abstract**

   a. The abstract is the last section that is written and the first section that is read of a technical report. All technical reports should begin with an abstract. The abstract is a summary or synopsis of the experiment written for the reader who wants to know whether or not he/she would be interested in reading the full text of the report. Therefore, the abstract should be self-contained and independent of the rest of the report.

   b. The abstract should **not** exceed a full page in length; **and for the typical length of a lab report, the abstract is generally 3-4 sentences**.

   c. The purpose of the abstract is to inform the reader of the important aspects of the work. Any new equipment or unusual procedures used to perform the work and the significance of the results obtained should be briefly presented in the abstract.

5. **Body of report**

   a. The body of the report will contain eight (8) sub sections:

      i. **Introduction**

      An introduction is not always necessary, but it is usually desirable to spend a few paragraphs describing the background of the project and the reasons for undertaking it. References to previous works of a similar nature are often cited, and the differences between those projects and the current study are presented. Any important notation or mathematical preliminaries can also be briefly given in the introduction.

      ii. **Objective(s)**

      Briefly state the nature and purpose(s) of the experiment in a concise manner.

      iii. **Procedure**

      This section should contain a brief description of the specimen, component, or structure used in the experiment (including its geometrical shape and significant dimensions), the material used in the experiment (including significant material properties, if applicable), and a general description of the equipment used. Then briefly describe the methods employed in obtaining the experimental results.

iv. Data, Results and Analysis

Experimental data and results should be presented in this section in a suitable fashion; i.e., tables and figures, following the outline given in the lab handout. If analytical (theoretical or predicted) values are also being calculated tabulated, and/or plotted, it should be done in this section (but comparison with the experimental results should be made in the discussion section). The original data sheet(s) and sample calculations, however, should be in the Appendices.

v. Discussion

This section presents the theoretical and practical evaluation of the results reported in the previous section. The discussion should include the extent to which the objectives of the experiment have been achieved. The reliability, meaning, evaluation, and application of the results should be considered in this section. Compare the results with those which might be expected in practice, theory, or both. An important consideration when writing the discussion, is that any part of it that could have been written without doing the experiment, is not an evaluation of the work done, nor is it a conclusion drawn from the experiment.

vi. Conclusions and Recommendations

In this section the writer should summarize the findings of the report and draw attention to the significance of these results. Any deviations from accepted theory should be noted and their statistical significance discussed. Conclusions are to be drawn with reference to the previously stated objectives of the project. Each conclusion should be supported by reference to data and results, and should follow directly from the numerical results obtained.

Recommendations are often more important than conclusions. Recommendations should be made in this section on changes in the procedure or instrumentation of the experiment, which could make the experiment more accurate or effective. Few experimental projects are an end in themselves. Either the results are to be used for a purpose, or at least the experimenter sees more work that could be done to adequately accomplish the original project.

vii. References

List any books, reports, etc., cited in the previous sections of the report. The references should be listed according to the order in which they were annotated in the report. References should be formatted according to MLA or IEEE guidelines.

viii. Appendices

All information important to the completeness of the report, but either too detailed or cumbersome to include in the smooth flow of the report should be put in an appendix. This would include information such as original data collected, sample calculations, calibration data, computer programs, etc. For the laboratory reports on the experiments at least the following appendices must be present:

1. Appendix A: Apparatus

   A sketch or schematic of the experimental apparatus showing all instrumentation and control stations should be provided. A schematic diagram is adequate, but it must be neat and complete. Describe the experimental setup and the instruments used including limitations and relative accuracy. Full and accurate identification of all instrumentation should be given, including model and serial numbers or other unique identification.

2. Appendix B: Procedure

   A write-up of how the experiment was conducted should be provided. This write-up should be of sufficient detail that anyone, with the proper equipment and your report, could reconstruct the experiment and achieve the same results. This write-up should be factual, almost a log of the steps you went through in performing the experiment to the point of reporting the errors made, and later discovered, in conducting the study. Changes which you would recommend be made to the experimental procedures should be noted in the conclusions and recommendations section of the report. Preliminary tests, equalizing periods, duration of runs, and frequency of readings, should be recorded. Special precautions for obtaining accuracy and means for controlling conditions should be described. Independent variables and reasons for their selection should be given. This section is in much more detail than that of the “Procedure” section in the body of the report.

3. Appendix C: Calibration Data

   The calibration procedure and the results of the calibration process for all equipment should be included in this appendix section. Calibration plots may often be included in the body of the report to support the results of the experiment, however all the supporting material used to develop those charts or tables should be detailed here.

4. Appendix D: Experimental Data

   Scanned images of the original data sheets from an engineering laboratory notebook or from a plotter should be included. Along with all raw data obtained by other means (i.e. a data acquisition device).

5. Appendix E: Sample Calculations

   Examples of calculations used in the experiment should be included in this appendix section. Mathematical developments of special equations should also be included here.

Introduction to Data Analysis

In the following, “Error”, does not mean mistake but rather refers to the uncertainty in a measurement. All measurements in practice and even in principle have some error associated with them; no measured quantity can be determined with infinite precision.

Statistical Errors (also known as Random Errors)

Most measurements involve reading a scale. The fineness of the scale markings (how close together the markings are) is limited and the width of the scale lines is nonzero. In every case, the final reading must be estimated and is therefore uncertain. This kind of scale-reading error is random; since we expect that half of the time the estimate will be too small, and the other half of the time the estimate will be too large. We expect that random errors should cancel on average, that is, many measurements of the same quantity should produce a more reliable estimate. Statistical errors can be controlled by performing a sufficiently large number of measurements. The error estimate on a single scale reading can be taken as half of the scale width. For example, if you were measuring length with a scale marked in millimeters, you might quote the reading as 17.0 mm ± 0.5 mm. If you measured the same length many times, you would expect the error on the measurement to decrease. This is indeed the case. The best estimate of the measured quantity is the mean or average of all the measurements. Simply add all the individual measurements together and divide by the number of measurements. The best estimate of the error associated with the mean value is called the "error on the mean" and is given by (the error on a single measurement) divided by (the square root of the number of measurements). Obviously, this will decrease as the number of measurements increases. The final reading for a quantity should be quoted as: (mean) ± (error on the mean).

Error Propagation

Addition and Subtraction

If several quantities with associated random errors are given by: $\pm\Delta x$, $y \pm \Delta y$, …, $z \pm \Delta z$, then the sum or difference is given by $q \pm \Delta q$ where $\boldsymbol{q}$ might be

$$q = x + y - z$$

and the error on ***q*** is propagated from the errors on ***x***, ***y***, ... , and ***z*** as follows:

$$\Delta q = \sqrt{(\Delta x)^2 + (\Delta y)^2 + \cdots + (\Delta z)^2}$$

Notice that the errors are added in quadrature, even when the quantities are being subtracted. The error always increases when adding or subtracting quantities.

Multiplication and Division

If several quantities with associated random errors are given by: $\pm\Delta x$, $y \pm \Delta y$, …, $z \pm \Delta z$, then the product or quotient is given by $q \pm \Delta q$ where ***q*** might be

$$q = \frac{x * y}{z}$$

and the error on ***q*** is propagated from the errors on ***x***, ***y***, ... , and ***z*** as follows:

$$\frac{\Delta q}{q} = \sqrt{\left(\frac{\Delta x}{x}\right)^2 + \left(\frac{\Delta y}{y}\right)^2 + \cdots + \left(\frac{\Delta z}{z}\right)^2}$$

Systematic Errors

These errors are more insidious than statistical errors. Systematic errors are difficult to detect, and the sizes of systematic errors are difficult to estimate. Increasing the number of measurements has no effect on systematic errors because the error is always in the same direction (all measurements too high, or all measurements too low). Careful instrument calibration and an understanding of the measurements being made, aid in prevention of these errors.

For example, suppose that you are using a stopwatch to time runners in the 100-meter dash. You are quite adept at making the measurement; but, unknown to you, the watch runs 5% fast. All times will be 5% too high. There will be no immediately obvious indication of a problem. If you happen to be familiar with the runners' normal times, you might notice that everyone seems to be having a slow day. To prevent such problems, one should calibrate the stopwatch with a known standard such as the Nation Institute of Standards and Technology's standard time service on short wave radio.

The guidelines for data recording are:

1. The error should have one significant figure

2. The number of decimal places in the measurement should be the same as the number of decimal places in the error.

3. Always remember: There is no such thing as "human error".

4. Try to find the deeper cause for any uncertainty or variation in the data.

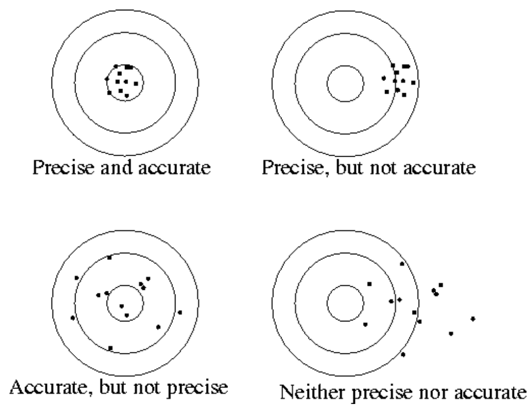

Figure 1: Difference between Precision and Accuracy

Statistics and Error

The second method of estimating error on measured quantities uses statistics as a tool. Now that we have some idea about the types of error found in the lab, random and systematic, we can discuss how statistics are used to describe them. Statistics can only be used to describe random error. All systematic error should have been eliminated from the experimental setup. On the other hand, random errors are made to order for a statistical description. If your balance reading is being influence by air current, sometimes your readings will be high, and sometimes low.

Whether or not the reading is high or low is pretty much a random thing. Statistics excel at describing these kinds of events. So, if you are sure all systematic errors have been eliminated, the rest, the random error, can be estimated statistically.

We make several assumptions in using statistics to describe errors. The main assumption is that the errors are normally distributed. The normal distribution, also called the Gaussian distribution or the bell-shaped curve, is one of the most common probability distributions. A probability distribution tells us about the probability of randomly selecting different values. For instance, if you roll a fair die (singular of dice); the probability that you get a two is 1/6. There are six possible outcomes, all equally likely. The probability that any one of the six faces will be up is 1/6. This type of probability distribution, in the continuous case, is call a uniform distribution and is graphed as a straight flat line. All values are equally likely. If you think about it for a moment, you will realize that all values aren't equally likely when it comes to errors. If your experiment is correctly set up, you should get only small errors. A value near the "correct" value is more likely than a value far from it. This is exactly the type of probability described by the normal distribution.

In Figure 2, one example of the distribution is plotted with values on the x-axis vs. the probability of those values on the y-axis. In the figure, the curve is centered at zero and has a standard deviation of one. Both of these values can be adjusted to be most any value and will depend on the specific system being modeled; zero and one are just a convenient example.

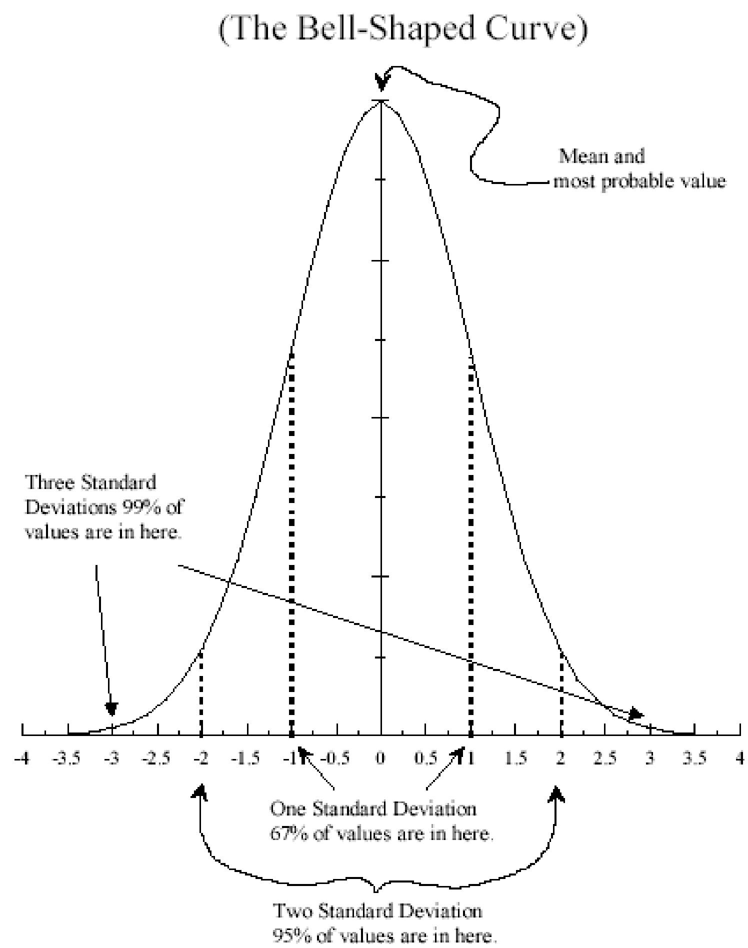

Figure 2: Normal Probability Distribution

The normal distribution has a maximum probability in the middle, where the curve is the highest. This spot corresponds to the mean value of the random variable being measured. Also, we see that the probability drops off quickly away from the mean. How quickly? In other words, just how closely packed in toward the mean are the values. A measure of this is the standard deviation, σ. The standard deviation gives the width of the curve or the probability of finding a value far from the mean. In Figure 2, the standard deviation was selected to be one. For the normal distribution, 67% of randomly selected values will fall within one standard deviation of the mean, which is within -1σ and +1σ. 95% of the randomly selected values will fall between -2 σ and +2 σ and 99% between +3 σ and -3 σ.

For the example distribution shown in Figure 2, 67% of the values will be between +1 and -1 (σ = 1), 95% between +2 and -2, and 99% between +3 and -3.

The formula for the mean is the same as always:

$$\bar{x} = \frac{x_1 + x_2 + \cdots + x_n}{n}$$

(In MS Excel: use function AVERAGE)

As with all measured quantities, we need to associate an error with the mean: The standard deviation can be found by:

$$\sigma_x = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$$

(Excel: use function STDEV)

However, the standard deviation isn't quite right. It tells us about the probability of a given value being a certain distance from the true mean. What we want to know is, given the number of trials, what is the probability that out mean reflects the true mean? Such a quantity is given by the standard error,

$$\sigma_{\bar{x}} = \frac{\sigma_x}{\sqrt{n}}$$

(Excel: use function STEYX or simply $\frac{STDEV}{n^{0.5}}$)

For measured data, the values used in calculations or the estimates in the results are:

Estimated Value = Average ± (factor*standard error)

When using statistics to estimate the error on your measurements; use the average value with the standard error as the uncertainty. The following table gives the factor values with the corresponding confidence level.

Confidence Level	Factor
50 %	0.67
67 %	1.0
95 %	2.0
99 %	2.6

Table 1: Confidence Level and Factor Correlation

Rejection of Data

Many scientists believe that data points should never be rejected since some important scientific discoveries have come from data that initially appeared "strange data". If an experimental result appears to be flawed the experiment should be repeated to check the particular data point(s). However, in a student lab with limited time it may not be practical to repeat an experiment. In this case we can sometimes reject a data point based on a consideration of the mean and standard deviation of the particular quantity being measured. Suppose we measure the acceleration of gravity 10 times, obtaining a mean value of $9.72\frac{m}{s^2}$ with a standard deviation of $0.2\frac{m}{s^2}$. Suppose we have one data point that has a value of $9.32\frac{m}{s^2}$, which is two standard deviations from our mean. The probability of getting a data point this far from the mean (or worse) in a single trial is 5% (making the usual statistical assumptions concerning the data distribution). Therefore, in ten measurements the probability of obtaining at least one data point this bad (or worse) would be ten times 5% or 50%. Chauvenet's Criterion states that if this calculated probability turns out to be less than 50% the data point can be rejected. Without this data point the standard deviation of the remaining points will be much less of course.

For example, let's say we make six measurements of the period of a pendulum and come up with 3.8, 3.5, 3.9, 3.9, 3.4, and 1.8 seconds. The 1.8 looks like it might be bad.

The standard deviation of this set of measurements is 0.8 seconds, and the mean is 3.4 seconds. The 1.8 therefore is two standard deviations away from the mean. The probability of getting a value deviant by 2 σ or more, on a single measurement, is 5% (recall the definition of the 2 σ confidence level). The probability of finding a single value this bad in six measurements, then, is 30%.

This is certainly not inconceivable; it may even seem reasonable to you now that this point should have come up. If this point is bad, however, then the standard deviation we used to calculate the probability has been contaminated. The true standard deviation is likely to be much smaller, and for this reason people commonly set the lower limit of probability to be 50%. If a point comes up to be less than 50%, which is likely to occur using this method, it can be thrown out.

In the example above, the point does indeed get thrown out, leaving us with a set of five measurements. The mean of this set is 3.7, and the standard deviation is 0.2; which is significantly smaller! In other words, the measurement we discarded was approximately 9 σ and the total probability of its occurrence was really astronomically small. Even if it were only 5 σ, the probability would only be about 4 in a million. Of course, to be rigorous you should check each point in your data set using this method, and after throwing out the first round of bad points, start all over again on the new set.

Graphs

Your graph is intended to present your data and results in an easily interpreted manner. The experimental results are contained in the plotted data points. In a sense, the data points are the heart of your graph. They are to contain as much information as possible and still be easily examined. Along with the data you recorded, you can also present the error or uncertainty on the data. These uncertainties are indicated by using error bars on your data points.

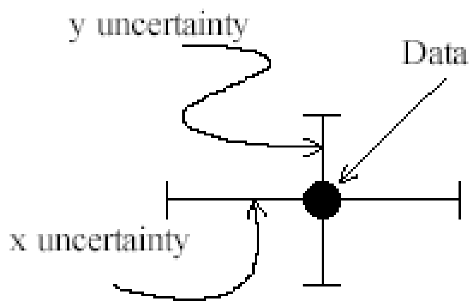

Figure 3: Data Point with X and Y Uncertainties

Curve Fitting: Least Squares Fit (linear regression)

A mathematical technique allows one to 'fit' a straight line to a set of data points. If you suspect that a set of data points lie on a straight line, then you need to be able to fit those points on that line. The equation for a straight line is given by:

$$y = mx + b$$

Where ***m*** is the slope of the straight line and ***b*** is the y-intercept (where the line crosses the y-axis). Given these two quantities the line can be drawn by selecting a set of x-values, inserting them into the equation for the line, and plotting the result. The *least squares method* allows us to find ***m*** and ***b***.

In the laboratory you will have collected a set of data points, (x1, y1), (x2, y2), (x3, y3)… and wish to find the "best" straight line through them. Before we can do anything else, we must decide what is meant by the "best" line. By "best" we could mean the line that passes through the most points; we could also mean the line that clips the most error bars. We need a definition of "best". A simple and sufficient definition turns out to be that the "best" line through the data points is the line that minimizes the sum of the squares of the distances from the data points to the line. Minimization is a straight forward calculus problem. If the procedure is carried out, one finds:

$$m = \frac{\overline{XY} - \bar{X}\bar{Y}}{\overline{X^2} - \bar{X}\bar{X}} \qquad\qquad b = \bar{Y} - m\bar{X}$$

(Excel: uses the function SLOPE for the calculation of ***m*** and the function INTERCEPT for the calculation of ***b***)

Where, the *over-bar* indicates the average of the values. Note that the average of x squared (X X) is not the same as the average of X^2. One difference is that the two averages treat negative values differently. Try calculating X X and X^2 for the two values 1 and -1.

Sample graph:

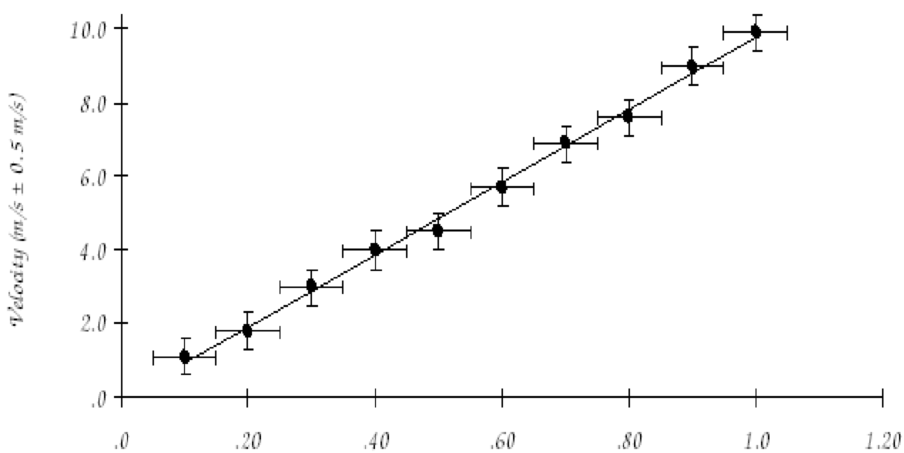

Figure 4: Example of Line Fitting

In case of an exponential relationship (for example, $= ax^n$), the linear least squares method should be applied to the log-log plot of the results. For example, given:

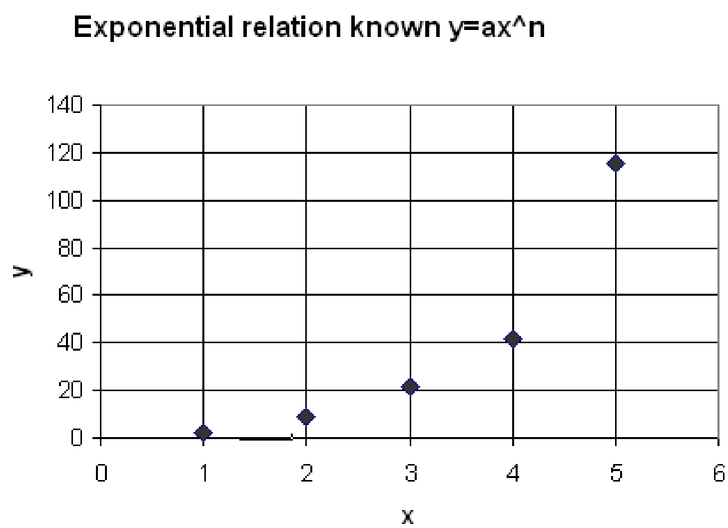

Figure 5: Example Data Points

Then the log-log plot with curve fitting would be:

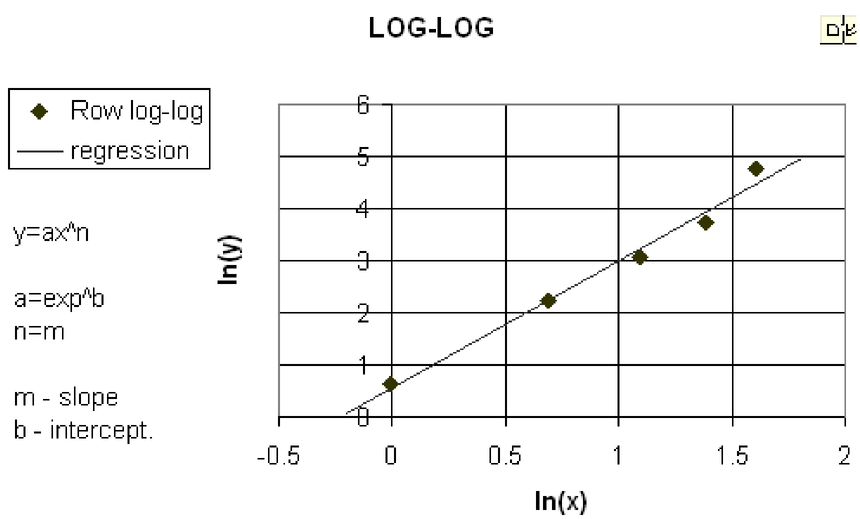

Figure 6: Log-Log Curve Fitting Plot

Experiment 1: Air Speed Measurement in Ducts

Objectives

This laboratory exercise is used to investigate the velocity profile of air flowing through a round duct. The performance of an air handler or an air conditioning unit is largely dependent on the configuration of the ducts, losses in the ducts and the velocity profile within the ducts. The velocity within the duct is not uniform throughout the cross-section of the duct, and hence, it is necessary to determine the velocity profile of the duct. Upon successful completion of the experiment you should be able to:

1. Determine the air velocity at each probed location.
2. Calculate the non-dimensional velocity and each probed location.
3. Calculate the Reynolds Number for the duct and determine whether the flow is laminar or turbulent.

Nomenclature

Symbol	Description	SI Unit
A	Cross-sectional Flow Area	in^2 or ft^2
d or D	Diameter	in^2 or ft^2
g	Gravity	$32.2\ \frac{ft}{s^2}$
Δh	Difference between the Stagnation pressure head and the static pressure head; read from the manometer	in_{H_2O}
l or L	Duct Length	ft or in
P or p	Pressure	in_{H_2O}
ρ	Density	$\frac{lb}{in^3}$
v	Velocity	$\frac{ft}{min}$
z	Elevation above datum	in
P_S	Static Pressure	in_{H_2O}
P_T	Total (stagnation) Pressure	in_{H_2O}
cfm	Volumetric Flow Rate	$\frac{ft^3}{min}$
rpm	Rotational Speed	$\frac{rev.}{min}$
fpm	Velocity	$\frac{ft}{min}$

Introduction

The flow within the duct may be either laminar or turbulent, and the regime of the flow can be determined using the Reynolds number:

$$Re = \frac{\rho V D}{\mu} = \frac{V D}{\nu} \tag{1}$$

Under normal conditions, the transition from laminar to turbulent flow occurs at $Re \approx 2300$. Hence, to determine the Reynolds number, the properties of the fluid, the diameter of the duct, and the velocity (mean) of the flow must be known.

For incompressible flow in a duct, viscous shear stresses will cause the flow to have a non-uniform velocity profile across the duct. Far from the entrance of a duct, viscous shear forces will cause the flow to become fully developed with a particular velocity profile depending on whether the flow is laminar or turbulent. In fully developed velocity profiles, the maximum velocity will be at the centerline of the duct with a symmetrical shape across the duct from the centerline. However, in many practical applications, the flow may be affected by the internal surface of the duct, or may be disturbed by objects protruding into the flow. Additionally, the flow downstream of objects such as the fans, pumps, valves, bends, and contractions, may not be symmetrical about the duct centerline and the flow may have a swirl induced in it.

A simple device called a Pitot-Static Tube can be used to determine airspeed. The probe is named after the French aeronaut, Pitot (pronounced pee-toe), who found that airspeed can be determined by measuring the total (stagnation) and static pressure of a fluid flow simultaneously. The velocity of the air is related to the difference of these two pressures by the Pitot-Static equation:

$$V = \sqrt{\frac{2(P_T - P_S)}{\rho_{air}}} \tag{2}$$

In many cases, pressure is indicated in the equivalent column height of a liquid, (sometimes known as a pressure head) usually water for gas (air) flow, or mercury for liquid (water) flow. The hydrostatic pressure created in a column of any liquid is given by:

$$P = \rho g H \tag{3}$$

Hence, when a pressure is given in terms of liquid height, i.e. inches H_2O or mm Hg, then it can be converted to a pressure using equation (3). This pressure head or liquid height is historically related to the differential height for the two columns of the liquid in a U-Tube manometer.

In this experiment, the pressure difference is measured by a digital manometer with the pressure unit of in_{H_2O} . It should be noted that 1 $in_{H_2O} \approx 249.02\ Pa$. Converting to SI units in this lab is required.

Apparatus Setup and Use

Description of Apparatus

The Technovate Vari-Speed Multi-Fan Air Distribution System consists of a 12.25 inch diameter centrifugal fan with interchangeable wheels. The fan is driven by a 0.5 horsepower electric motor through a variable speed drive; where in, the rotational speed of the fan wheel can be varied. The airflow from the fan goes through a transition fitting into an 8 inch diameter round metal duct provided with a damper and a Pitot-static system.

Instrumentation Calibration

1. With the unit **OFF**, check that all the instruments on the panel have a zero reading.
2. If necessary, adjust the zero position of the meter indicator by adjusting the calibration screw on the front of each instrument. **ADJUST SLOWLY** and **GENTLY**.

Safety Precautions

1. Before turning the unit **ON**, make sure the area beyond the exhaust is clear.
2. **DO NOT OPEN FAN DOOR WHEN OPERATING**.
3. Verify that the fan wheel is securely mounted before turning the unit on.

Apparatus Setup

1. Before turning the unit **ON**, check that the fan wheel door is closed and secured.
2. Attach a single section of 8 inch duct to the end of the unit using a coupler section. Support the duct at its free end and use duct tape at the coupling to minimize leaks.
3. Turn the speed control to the lowest setting (full counter clockwise).
4. Turn the power switch to **ON**.

5. Adjust the speed control to obtain the desired fan wheel speed or air speed.

6. Monitor the current drawn by the motor.

DO NOT EXCEED 11.0 AMPS!

7. When turning the unit **OFF**, reduce the speed control to the lowest setting.

Procedure

1. Set up the fan system as described in the Apparatus Set-Up section.

2. Turn the unit on and adjust the speed control to obtain the desired air speed within the duct.

3. Using the external Pitot-tube to measure the difference between the static pressure (SP) and the stagnation/total pressure (TP) at several locations across the duct using the following procedure:

   a. Record the pressure at several locations across the horizontal and vertical diameters of the duct.

   b. Use at least nine positions across each diameter. Use the same radial positions for both diameters.

   c. Try to obtain readings close to the duct wall and at the center of the duct.

4. Repeat steps (2) and (3) at a second airspeed.

Analysis and Discussion

1. Using the pressure data obtained, calculate the velocity of the air at each probe location. Include a table of data in the appendix.

2. Calculate the non-dimensional velocity $V^* = \frac{V}{V_{max}}$ at each probe location.

3. Calculate the non-dimensional (radial) duct position $r^* = \frac{r}{R_{duct}}$ relative to the centerline of the duct (i.e. r* = 0 at centerline, r* = 1 at one wall and r* = -1 at the opposite wall).

4. Calculate the Reynolds Number for the airflow using the average velocity measured in the experiment. Is the flow laminar or turbulent?

5. Plot the non-dimensional velocity vs. non-dimensional duct location:

   a. Plot both airspeeds and each diameter in a single figure (i.e. five curves).

   b. For location, use the relative measure from the centerline of the duct

   c. Differentiate the two airspeeds by their Reynolds number in the legend.

6. Compare the velocity profiles obtained. Note and discuss any similarities or discrepancies. Is the flow symmetrical? Is the velocity profile characteristic of either laminar or turbulent flow?

Report Requirement

1. The report must follow the lab report format.

2. The report must be submitted electronically (**PDF**) by the due date.

3. The electronic file must have a file name of: EML3126L_section#_Exp#_Group#.pdf

   Example: EML3126L_U01_Exp1_Grp1.pdf

Experiment 2: Losses in Pipe Fittings

Objectives

This laboratory exercise is used to investigate the losses associated with pipe fittings. The performance of any pumping system is largely dependent on the configuration of the system and the number of fittings associated with the system. The determination of pump size is almost entirely dependent on losses found in the system; and a primary source of those losses are found in the pipe fittings. Upon successful completion of the experiment you should be able to determine:

1. The volumetric flow rate
2. The flow velocities in both pipe diameters
3. The Reynolds Number for both pipe diameters.
4. The velocity heads in both pipe diameters
5. The total loss of head for each pipe fitting

Nomenclature

Symbol	Description	SI Unit
A	Cross-sectional Flow Area	m^2
g	Gravity	$9.81\ \frac{m}{s^2}$
Δh	Minor Loss of Pressure Head Across Fittings	m
ΔH	Total Head Loss Across Fitting	m
h_d	Downstream Pressure Head	m
h_u	Upstream Pressure Head	m
V_d	Velocity Down Stream of the Fitting	$\frac{m}{s}$
V_u	Velocity Up Stream of the Fitting	$\frac{m}{s}$
$\frac{V^2}{2g}$	Velocity Head	m

Introduction

All piping systems contain fittings such as bends, changes in diameter, junctions and valves. The constrictions and changes in direction of flow, through such fittings, cause frictional losses; which are additional to those due to friction at the pipe wall. Since the fittings losses usually contribute significantly to the overall losses in the piping system, it is important to have reliable information about them.

Figure 7 depicts a fluid flowing at velocity, V_u , within a pipe of diameter, D_u , through a pipe fitting such as a valve; but for simplicity, depicted as a simple restriction in the cross-section of the pipe. Downstream of the fitting, the water flows within a pipe of smaller diameter, D_d , with the velocity V_d. The figure indicates the variation of pressure head along the pipe, as would be shown by numerous pressure taps along the pipe wall. In the region of undisturbed flow, far upstream of the fitting, the distribution of velocity across the pipe remains unchanged from one cross-section to another; this is the condition referred to as '*fully developed pipe flow*'. Within this region, the piezo-metric head falls, with a uniform, mild gradient; as a result of constant friction at the pipe wall in fully developed pipe flow. Close to the fitting, however, there are sharp and substantial local disturbances to the piezo-metric head, caused by rapid changes in direction and speed as the fluid passes through the fitting. In the downstream region, these disturbances die away, and the line of piezo-metric head returns asymptotically to a slight linear gradient as the velocity distribution gradually returns to the condition of fully developed pipe flow.

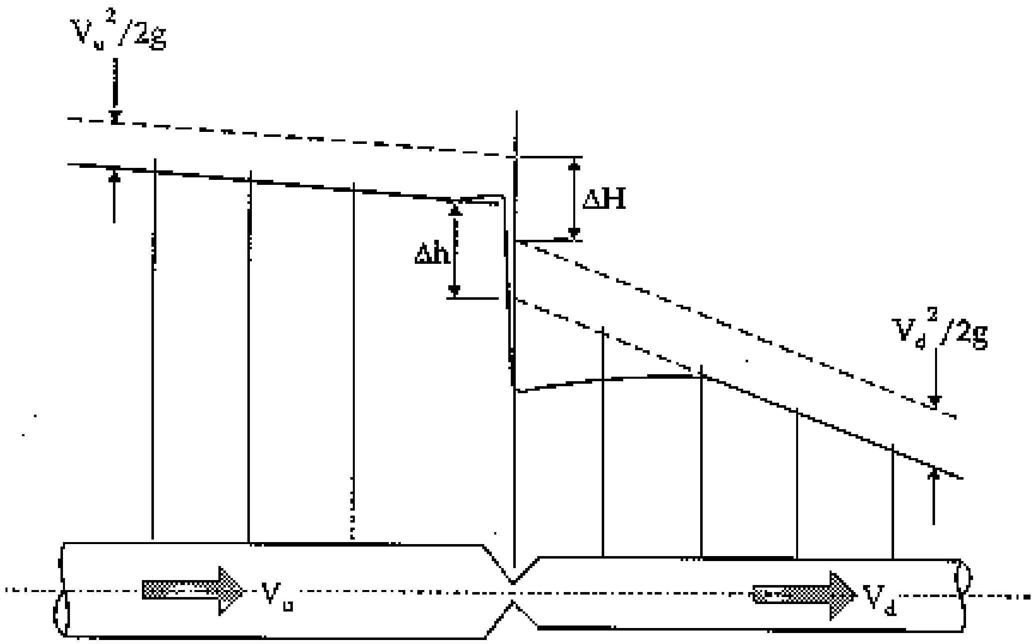

Figure 7: Diagram of Frictional Losses at a Pipe Fitting

If the upstream and downstream lines of linear friction gradient are now extrapolated to the plane of the fitting, a **minor loss of pressure head**, Δh , due to the fitting is found and is defined as:

$$\Delta h = h_u - h_d \quad (1)$$

To establish the corresponding **loss of total head**, ΔH , it is necessary to introduce the velocity heads in the upstream and downstream portions of the piping system. From Figure 7 it is clear that:

$$\Delta H = \Delta h + \frac{V_u^2}{2g} - \frac{V_d^2}{2g} \quad (2)$$

It is convenient to express this as a **dimensionless loss coefficient**, *K*; this is accomplished by dividing through by the velocity head, thus giving

$$K = \frac{\Delta H}{V^2/2g} \quad (3)$$

For the case where, $D_u = D_d$, as for bends and elbows, the flow velocities in the upstream and downstream are identical, so either velocity may be used. However, when an expansion ($D_u < D_d$) or contraction ($D_u > D_d$) is encountered, it is customary to use the larger velocity head (i.e. the side with the higher velocity).

Characteristics of Flow through Bends

Figure 8(a) illustrates flow through a 90° bend that has a constant circular cross-section of diameter *D*. The radius of the bend, *R*, is measured to the centerline. The curvature of the flow as it passes through the bend is caused by a radial gradient of piezo-metric head, so that the piezo-metric head is lower at the inner surface of the pipe than at its outer surface. As the flow exits the bend, these piezo-metric heads start to equalize as the flow loses its curvature, so that the piezo-metric head begins to rise along the inner surface. This rise causes the flow to separate from the pipe wall, generating mixing losses in the subsequent turbulent reattachment process.

Additionally, the radial gradient of pressure head creates a secondary cross-flow in the form of a pair of vortices, having outwardly directed velocity components near the pipe center, and inwardly components near the pipe walls. When superimposed on the general streaming flow, the result is a double spiral motion; which, persists for a considerable distance in the downstream flow, and which generates further losses that are attributable to the bend.

Clearly, the value of the loss coefficient, *K*, will be a function of the geometric ratio R/D ; as this ratio increases, decreasing the sharpness of the bend, the value of *K* decreases. The smaller the value of R/D , 0.5 for example, for which the bend has a sharp inner corner, makes the value of *K* approximately 1.4. As R/D increases, the value of *K* decreases, resulting in values of *K* which may be as low as 0.2. Alternatively, as R/D decreases, the values of *K* can be as large as 2 or 3. There is also a minor dependence on Reynolds Number, *Re*, but for most cases this is small enough to be neglected.

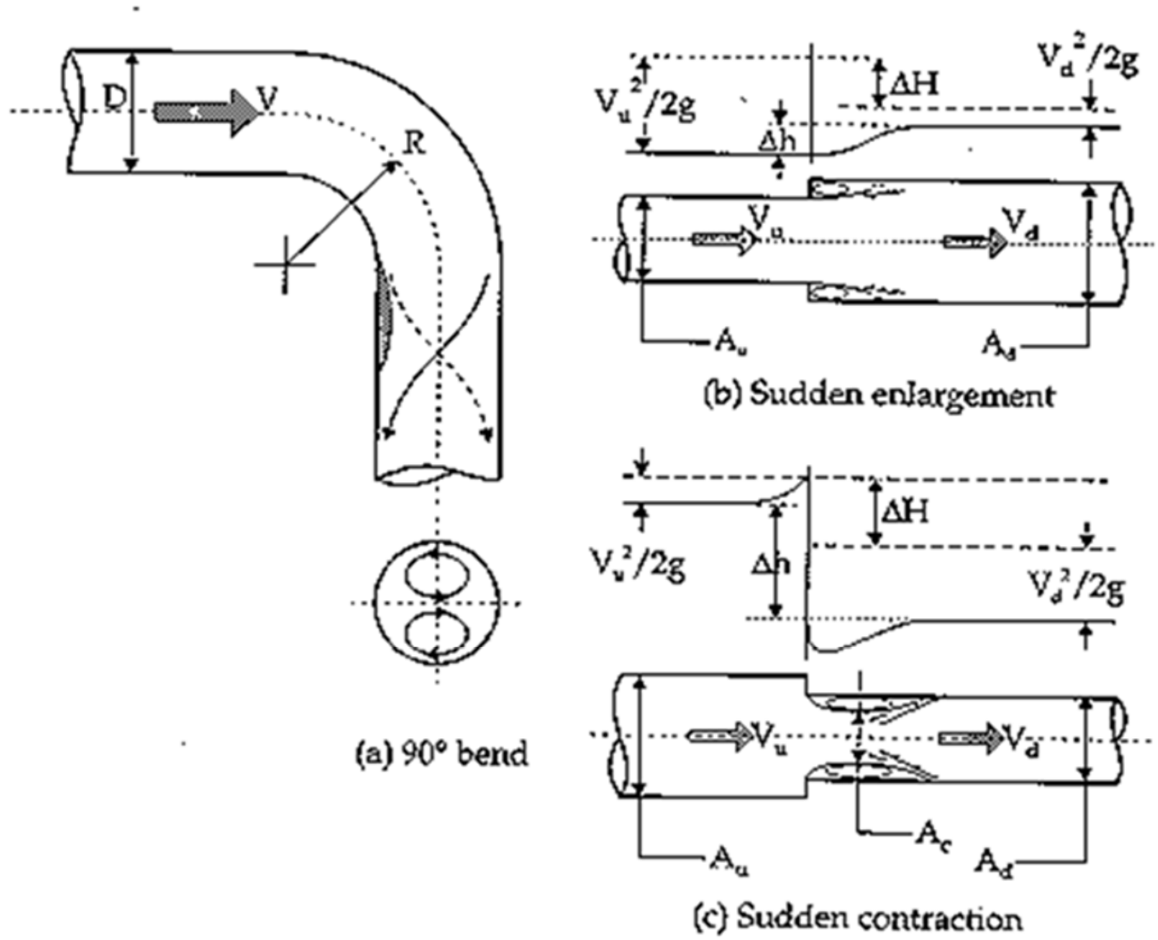

Figure 8: (a) Flow in a Bend; (b) Sudden Enlargement; (c) Sudden Contraction

Characteristics of Flow through Sudden Enlargement

Figure 8(b) shows the flow in a sudden enlargement. The flow separates at the exit from the smaller pipe, forming a jet, which diffuses into the larger bore, and reattaches to the wall some distance downstream. This vigorous turbulent mixing, resulting from the separation and reattachment of the flow, causes a loss of total head. However, the piezo-metric head in the emerging jet starts at the same value as in the pipe immediately upstream, and increases through the mixing region; hence, rising across the enlargement. These changes in total and pressure head, neglecting the small effect of friction gradient, are illustrated in the Figure 8(b).

The theoretical loss coefficient, *K*, in this case, is related to the upstream velocity, V_u , so that:

$$K = \frac{(V_u - V_d)^2 / 2g}{V_u^2 / 2g} = \left[1 - \frac{V_d}{V_u}\right]^2 = \left[1 - \frac{A_u}{A_d}\right]^2 \tag{4}$$

Characteristics of Flow through Sudden Contraction

Consider lastly, the case of the sudden contraction as shown in Figure 8(c). The flow separates from the edge where the face of the contraction leads into the smaller pipe, forming a jet, which converges into the contracted section of the cross-sectional area, A_c. Beyond this contracted section, there is a region of turbulent mixing, in which, the jet diffuses and reattaches to the wall of the downstream pipe. The losses occur almost entirely in the process of turbulent diffusion and reattachment.

The best choice of reference velocity in this case is V_d, regardless of piezo-metric head, the theoretical loss coefficient, *K*, becomes:

$$K = \left(\frac{V_u}{V_d}\right)^2 = \left(\frac{A_d}{A_c}\right)^2 \tag{5}$$

However, since the actual diameter of the contracted section is not known or measurable, during the experiment, the loss coefficient must be empirically determined.

Note: that for the case of the enlargement and of the contraction only, the loss of total head, ΔH , is not equal to the differential pressure reading, Δh .

Description of Apparatus

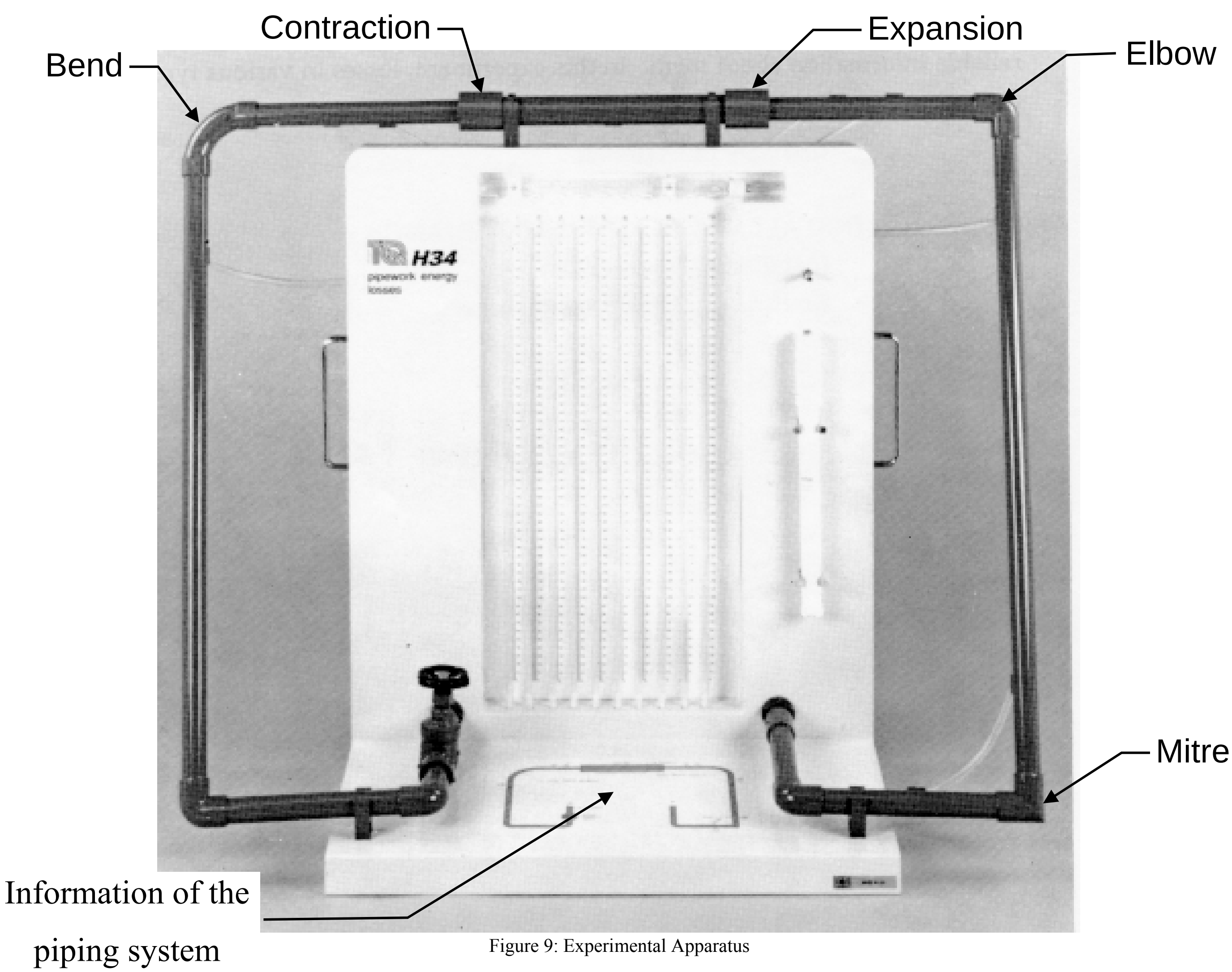

Figure 9: Experimental Apparatus

Procedure

1. Note the diameters of the pipes and fittings around the flow circuit in the apparatus.
2. Close the exit valve on the left side of the flow circuit and then turn on the water source.
3. Slowly open the exit valve on the apparatus, and watch the water levels in the manometer tubes.
4. Release air from the manometer manifold to keep all of the readings within the range of the scale.
5. When the maximum feasible flow rate is achieved:
   a. Determine the flow rate of the liquid by measuring the time it takes to fill a known volume. Perform the time measurement at least three times and average the results.
   b. Record the differential pressure readings across each of the fittings.
6. Repeat Step (5) to obtain data for at least five different flow rates; by adjusting the exit valve or the valve at the source. Additional air pressure may need to be added to the manifold as the flow rate is decreased. Make all flow rate changes slowly.

Note: The flow rates need to cover an adequate range for the analysis. The exit valve will not provide an adequate range of flow rates alone.

Experimental Data to be Collected

- Time to fill a known volume
- All dimensions of pipes and fittings (see chart on apparatus)
- Differential Pressure Head Readings:
  - Mitre (Taps 1-2)
  - Elbow (Taps 3-4)
  - Enlargement (Taps 5-6)
  - Contraction (Taps 7-8)
  - Bend (Taps 9-10)

Analysis and Discussion

1. Calculate and present the following parameters:

   a. The volumetric flow rate, Q

   b. Flow velocities in both pipe diameters, V_u and V_d

   c. Reynolds Number for both pipe diameters.

   d. Velocity heads in both pipe diameters, $\frac{V_u^2}{2g}$ and $\frac{V_d^2}{2g}$

   e. For each fitting, calculate the total loss of head, ΔH

Note: For all fittings other than the sudden contraction, the velocity head in the upstream pipe is used for calculating and plotting the loss coefficient.
For the sudden contraction, the velocity head in the downstream pipe is used.

Deliver the following data:

- Show all experimental and calculated data in a table
- Plot the *Total Head Loss*, ΔH , vs. the *Velocity Head* for all fittings on the same plot:
  - Mitre, Elbow, Bend, Sudden Expansion, and Sudden Contraction
- For each set of data, fit a line through the data points and determine the "slope" of the line, which is the empirical value of the loss coefficient
- Determine the theoretical loss coefficient and compare it to the empirical values found from the data

Note: Make sure the units are consistent so that the loss coefficient is non-dimensional.

Report Requirement

1. The report must follow the lab report format.
2. The report must be submitted electronically (**PDF**) by the due date.
3. The electronic file must have a file name of: EML3126L_section#_Exp#_Group#.pdf

   Example: EML3126L_U01_Exp2_Grp1.pdf

Experiment 3: Pipe Friction

Objectives

This laboratory exercise is used to investigate effect of pipe friction on various flow rates. The condition (laminar or turbulent) of the flow is heavily dependent on wall roughness, pipe inner diameter, and velocity. Determination of the condition of flow can be a critical factor when various parameters of the pumping and/or piping system is being designed; hence, it is necessary to have an effective understanding of how pipe friction effects a flow. Upon successful completion of the experiment you should be able to:

1. Calculate the volumetric flow rate for each case.
2. Determine the average velocity of the fluid.
3. Calculate the hydraulic gradient for laminar and turbulent flows.
4. Determine the critical Reynolds number.
5. Find a linear relationship between the flow hydraulic gradient and velocity for the laminar flow.
6. Calculate the coefficient of viscosity for the laminar flow
7. Calculate the Reynolds number of the tested flows.
8. Calculate the Darcy friction factor for each tested flow rate.

Nomenclature

Symbol	Description	SI Unit
A	Cross-sectional Flow Area	m^2 or mm^2
d or D	Nominal Diameter of the Pipe	m^2 or mm^2
g	Gravity	$9.81\ \frac{m}{s^2}$
h	Height of Liquid in Manometer	mm
h_f	Hydraulic Gradient	-
h_1	Height of Water or Mercury in Downstream Manometer Tube	m or mm
h_2	Height of Water or Mercury in Upstream Manometer Tube	m or mm
l or L	Length of Pipe between two Piezo-meter Taps	m
$\dot{Q}$	Volumetric Flow Rate	$\frac{m^3}{s}$
Re	Reynolds Number	-
Re_c	Critical Reynolds Number	-
V	Velocity	$\frac{ft}{min}$
ρ	Density	$\frac{kg}{m^3}$
μ	Absolute Viscosity	$\frac{(N \cdot s)}{m^2}$

Experimental Parameters and Constants	
Specific Gravity of Mercury $(SG_{mercury})$	13.6
Length of Pipe between Pressure Taps (L)	524 mm
Nominal Diameter of the Pipe (D)	3 mm

Introduction

The frictional resistance a fluid is subjected to as it flows in a pipe results in a continuous loss of energy, or total head of the fluid. In 1883, Osborne Reynolds performed experiments on fluid flow to determine the laws of frictional resistance. He found that flows in pipes of different diameters and different fluids could be related to each other using the dimensionless parameter (now known as the Reynolds Number):

$$Re = \frac{\rho V D}{\mu} = \frac{V D}{\nu} \tag{1}$$

Reynolds found that as the velocity of the flow increased, the characteristics of the flow had two primary regimes, *laminar* and *turbulent*, which were separated from each other by a small *transitional* regime. Laminar flow is characterized by smooth and steady flow, whereas, turbulent flow is characterized by fluctuations and agitation in the flow. Reynolds determined that the point where the flow switched from laminar to turbulent always occurred at approximately the same value of the Reynolds Number. This transition point is called the *critical Reynolds Number*, and for circular pipes:

$$Re_c \approx 2000 - 2300$$

Different laws of fluid resistance apply to laminar and to turbulent flow. For a given fluid flowing in a pipe, experiments show that for laminar flow, the hydraulic gradient, h_f (friction losses per unit length), is proportional to the velocity of the flow, whereas for turbulent flow, a power law relation is more appropriate:

$$h_f \propto V \qquad \text{Laminar Flow}$$

$$h_f \propto V^n \qquad \text{Turbulent Flow } (n = 1.7 \; to \; 2.0)$$

The hydraulic gradient for flow in a pipe can be determined from the Darcy-Weisbach equation, which is valid for duct flows of any cross section and laminar or turbulent flow:

$$h_f = f \frac{1}{D} \frac{V^2}{2g} \qquad \text{Darcy-Weisbach Equation} \tag{2}$$

The dimensionless parameter, f, is called the **Darcy Friction Factor**, and is a function of the Reynolds Number of the flow and the roughness of the pipe walls. It can be shown that for laminar flow with a Hagen-Poiseuille velocity distribution, the Darcy Friction Factor can be shown to be:

$$f = \frac{64}{Re} \qquad \text{Laminar Flow} \qquad (3)$$

Hence, Equation (2) for laminar flow can be rewritten as:

$$h_{f,lam} = \frac{64}{Re}\left(\frac{1}{D}\right)\frac{V^2}{2g} = \frac{32\mu V}{\rho g D^2} \qquad \text{Laminar Flow} \qquad (4)$$

From which it can be seen that for a pipe of a specific diameter, the total head loss is a linear relationship with the velocity of the flow.

Now for turbulent flow, there is no simple relationship for the Darcy Friction Factor, which is an experimentally determined value that varies with the Reynolds Number, or the flow, and the roughness of the pipe. It is customary to use the Moody Chart to determine the value of the Darcy Friction Factor. However, for smooth walled pipes, some analytical approximations are available:

$$f_{turbulent\,,smooth} \approx 0.316 Re_D^{-0.25} \qquad 4000 < Re < 100{,}000 \qquad (5)$$

In this experiment, a water manometer and a mercury manometer are used to measure the pressure head (liquid height) through the pipe, respectively. The hydraulic gradients for laminar and turbulent flows, i.e., friction losses per unit length (non-dimensional parameter), are defined as:

$$h_{f,exp} = \frac{h_1 - h_2}{L} \qquad \text{Water Manometer} \qquad (6)$$

$$h_{f,exp} = \frac{(h_1 - h_2)(SG_{mercury} - 1)}{L} \qquad \text{Mercury Manometer} \qquad (7)$$

The measured h_f values will be compared with the values calculated by the Darcy Weibach Equation shown in Equation (2).

Apparatus Setup and Use

Description of Apparatus

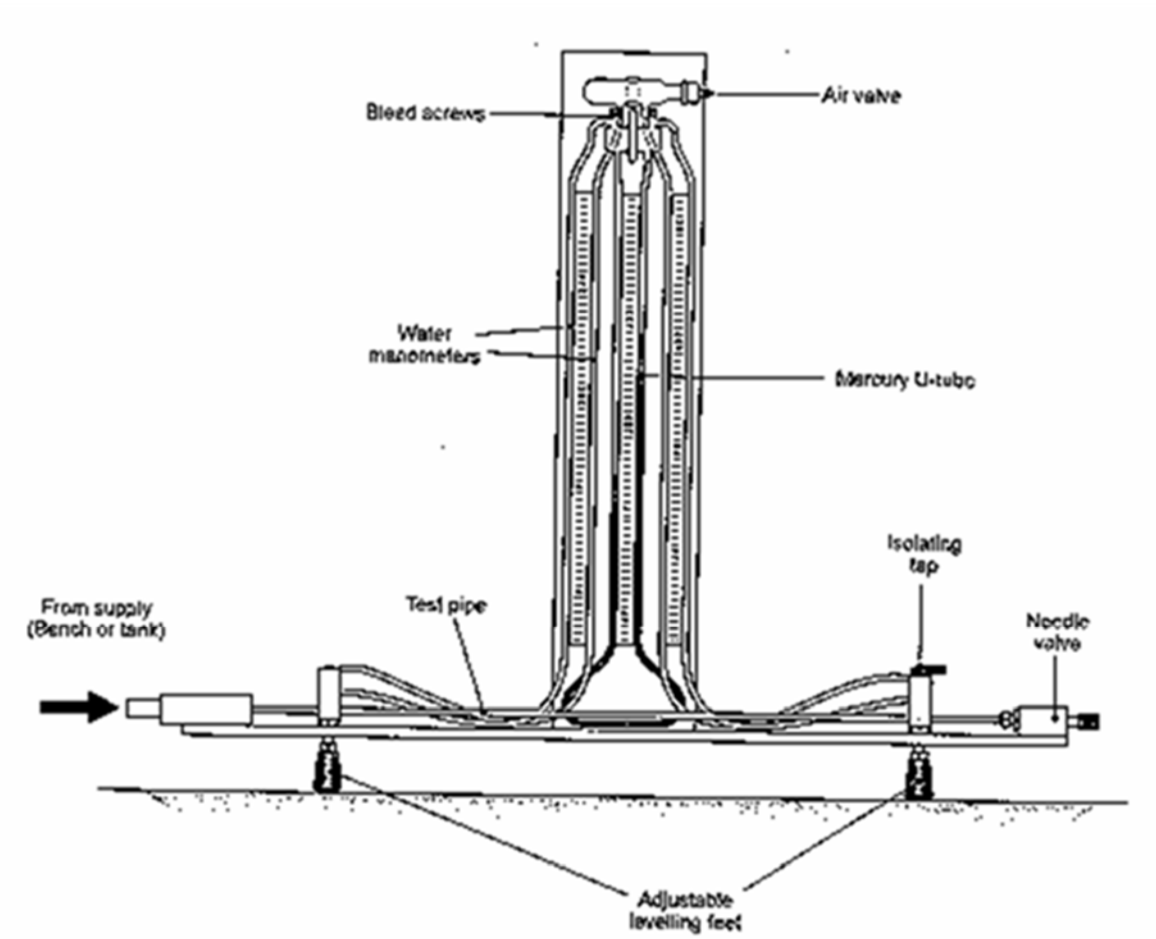

Figure 10: Schematic Diagram of the H7 Pipe Friction Apparatus

The Tecquipment Pipe Friction (H7) apparatus allows for the measurement of friction loss in a small bore horizontal pipe. It allows for measurements to be taken in both the laminar and turbulent regimes. Hence, it can be used to measure the changing of the laws of fluid resistance from laminar to turbulent flow, and therefore, the critical Reynolds Number can be determined. Figure 10 shows the arrangement of the apparatus and its main components. Along the base of the apparatus is a high length to bore ratio pipe across which the frictional loss can be measured. Static pressure taps at each end of the test length are permanently attached and connected by plastic tubes to an inverted water manometer and a mercury U-tube manometer. The water or mercury manometers are isolated from each other using an isolating tap (valve) on the right side of the apparatus.

Note: The water manometer is used for all laminar flows up to and just beyond the critical point, and the mercury manometer for all subsequent turbulent flows.

The pressure taps are located sufficiently far away from the entrance and exits of the horizontal pipe to avoid effects of the entrance or exit. The upstream pressure tap is located approximately 45 diameters away from the pipe entrance and the downstream pressure tap is approximately 40 diameters away from the pipe exit. A downstream needle valve is used to accurately control the flow which comes from a constant head tank mounted above the apparatus. However, to obtain a range of results in the turbulent region, it is necessary to connect the water directly from the main supply.

Procedure

1. **Water Manometer Readings – Laminar Flow**

   a. Turn the switches to the laminar flow testing position. Close the needle valve.

   b. Open the water tap to fill the Header tank until it is full. Open the needle valve a little, turn off the water source and wait for the tank to stop filling.

Warning: Too high a flow rate will cause the header tank to overflow.

   c. Check that the isolating valve is selected for the water manometer.

   d. Open the needle valve fully to obtain a differential head of at least 400 mm. Adjust the air in the manifold at the top of the manometers to get the lower height reading to be at least 400 mm from the bottom of the of the manometer.

   e. Measure the flow rate by timing the water flow into a known volume. Make at least **three** time measurements and average the results to determine the volumetric flow rate.

   f. Measure the water manometer heights, h_1 and h_2 , so as to obtain the differential pressure head across the horizontal pipe section.

   g. Repeat steps (5) and (6) for lower flow rates by slowly adjusting the needle valve to reduce the flow speed. Try to obtain at least **five** data points spread across the available flow range.

2. **Mercury Manometer Readings – Turbulent Flow**

WARNING: ADJUST THE WATER SUPPLY CAREFULLY TO AVOID DAMAGE TO THE APPARATUS

   a. Isolate the water manometer by turning the isolating valve on the right side of the apparatus.

   b. Ensure that the water supply is connected directly to the horizontal pipe.

   c. With the needle valve partially open, tap the manometer lines to dislodge any air bubbles up to the bleed valves at the top of the apparatus. Bleed any air out of the system, there should be a continuous water connection from the pressure taps on the horizontal pipe to the surface of the mercury.

   d. Close the needle valve and ensure that the level of the mercury on both sides of the manometer are equal.

e. Slowly open the needle valve until it is fully open, monitoring the height of the mercury to ensure that it does not overflow out of the U-tube portion of the manometer.

f. Measure the flow rate by timing the water flow into a known volume. Make at least **three** time measurements and average the results to determine the volumetric flow rate.

g. Measure both manometer heights, h_1 and h_2, as shown in the figure above.

h. Repeat step (7) at lower flow rates by adjusting the needle valve to reduce the flow. Take at least **five** measurements and use the software to plot the data to ensure that sufficient data points have been taken across the entire flow range to adequately characterize the curved nature of the response.

Analysis and Discussion

1. Calculate the volumetric flow rate, $\dot{Q}$, for each case.
2. Determine the average velocity of the fluid, *V*.
3. Using Equations (6) and (7), calculate the hydraulic gradient, h_f, for laminar and turbulent flows, respectively.
4. Plot a graph of hydraulic gradient (*y* axis) vs. velocity (*x* axis), i.e., h_f vs. *V*. Plot the results for laminar flow and turbulent flow on the same graph. From the graph, determine the critical Reynolds number.
5. Find a linear relationship between the flow hydraulic gradient and velocity for the laminar flow; fit a power law curve (i.e. $y = x^n$) through the data of the turbulent flow and determine the index *n*.
6. Calculate the coefficient of viscosity for the laminar flow by using the Eq. (4).
7. Calculate the Reynolds number of the testing flows.
8. Applying the measured value of the hydraulic gradient, $h_{f,exp}$, calculate the Darcy friction factor for each tested flow rate by using the Eq. (2).
9. Plot the Darcy friction factor versus Reynolds number on a log graph, [i.e. Log (*f*), (*y* axis), vs. Log (*Re*), (*x* axis)] for laminar flow and turbulent flow on two separate graphs. Determine the **constant** referred to by Equation (3) for laminar flow and the value of the power referred to by Equation (5).
10. Compare the experimental results with the theoretical equations and discuss the difference.

Report Requirement

1. The report must follow the lab report format.
2. The report must be submitted electronically (**PDF**) by the due date.
3. The electronic file must have a file name of: EML3126L_section#_Exp#_Group#.pdf

   Example: EML3126L_U01_Exp3_Grp1.pdf

Experiment 4: Impact of a Jet

Objectives

This laboratory exercise is used to investigate the effects of a water jet on different boundary shapes. The performance of a water turbine is largely dependent on the configuration of the vanes and how effectively the water impacts those vanes. This experiment simulates basic concepts associated with how a water turbine operates; making it necessary to understand how different boundary shapes effect the jet and its momentum. Upon successful completion of the experiment you should be able to:

1. Determine the volumetric flow rate and Jockey weight position for different vanes.
2. Calculate the rate of momentum delivery and force on the vane.
3. Make a plot of force on the vane vs. rate of momentum delivery.
4. Compare the experimental results with the theoretical values.

Nomenclature

Symbol	Description	SI Unit
A	Cross-sectional Area of the Nozzle	m^2
F	Force	N
g	Gravity	$9.81\ \frac{m}{s^2}$
m	Mass	kg
$\dot{m}$	Mass Flow Rate	$\frac{kg}{s}$
u	Speed of Water from Jet	$\frac{m}{s}$
$\dot{Q}$	Volumetric Flow Rate	$\frac{m^3}{s}$
β	Inclination of Jet Relative to Entry	*degrees*
x	Jockey Weight Position	*m*

Experimental Constants

Symbol	Description	SI Unit
ρ_w	Density of Water	$10^3\ \frac{kg}{m^3}$
d_n	Diameter of Nozzle	$10\ mm$
A_n	Cross-sectional Area of the Nozzle	$78.5\ mm^2$
m_j	Mass of Jockey Weight	$0.6\ kg$
	Distance from Center of Vane to Pivot of Weigh Beam	$0.15\ m$
s	Height of Vane Above Tip of Nozzle	$35\ mm$

Introduction

One way of producing mechanical work from a fluid under pressure is to use the pressure to accelerate the fluid to a high velocity as in a jet. One way that this is implemented, is when the jet is directed on to the vanes of a turbine wheel, which causes them to rotate by the force employed on the vanes due to the momentum change or impulse; this is the result of the jet striking the vanes. Water turbines working on this impulse principle have been constructed with outputs of the order of 100,000 kW and with efficiencies greater than 90%.

The Jet Impact Apparatus measures the force generated by a jet of water as it strikes various boundary shapes. The apparatus provides the following boundaries: flat plate, hemispherical cup, conical plate, and a 30° angled plate.

Background Theory

Consider a vane symmetrical about the x-axis as shown in Figure 11. A jet of fluid flowing at the rate of $\dot{m}$ along the x-axis with a velocity of u_0, strikes the vane and is deflected by it through an angle; the fluid leaves the vane with a velocity of u_1, inclined at an angle, β, to the x-axis. Changes in elevation and in piezo-metric pressure in the jet, from striking the vane until leaving it, are neglected.

Momentum enters the system in the *x* direction at a rate of:

$$\dot{m}u_0$$

Momentum leaves the system in the same direction at the rate of:

$$\dot{m}u_1 cos(\beta)$$

The force on the vane in the x direction is equal to the rate of change in momentum. Therefore:

$$F = \dot{m}\left(u_0 - u_1 cos(\beta)\right)$$

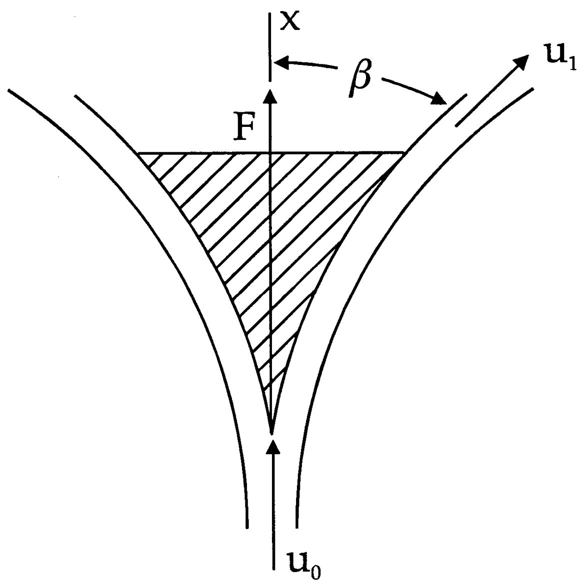

Figure 11: Vane Symmetrical about the x-axis

Ideally, jets are at constant velocity inferring that $u_0 = u_1$. Therefore:

$$F \approx \dot{m}u_0\big(1 - cos(\beta)\big)$$

For the various boundaries provided in the jet impact apparatus; the jet inclination angle β is known, hence, letting the $K = \big(1 - cos(\beta)\big)$ the force can be expresses as:

$$F \approx K\dot{m}u_0$$

where *K* can be found in Table 2.

Table 2: Jet Inclination Angle and Resultant Impact Factor, *K*

Shape	**β**	***K***
Flat Plate	90°	1.0
Conical	120°	1.5
Hemispherical Cup	180°	2.0
30° Angled Plate	30°	0.87

Apparatus Setup and Use

Description of Apparatus

Figure 12 shows the arrangement of the impact of a jet apparatus. From the figure, it can be seen how the water supply is connected to a vertical pipe terminating at a tapered nozzle. This produces a jet of water, which impinges on the chosen vane; either a Flat Plate, Hemispherical Cup, Conical Plate or a 30° Angled Plate. The nozzle and vane are contained within a transparent cylinder, at the base of the cylinder there is an outlet by which the flow may be directed to the weighing tank.

As depicted in Figure 12, the vane is supported by a cantilever beam, which supports the jockey weight and is balanced by a light spring. The cantilever beam may be balanced (as indicated by the tally suspended from its end) by positioning the jockey weight at the zero position and then adjusting the knurled nut above the spring. The force generated by the impact of the jet on the vane can be measured by moving the jockey weight along the beam until the tally shows that the beam has been restored to a balanced position.

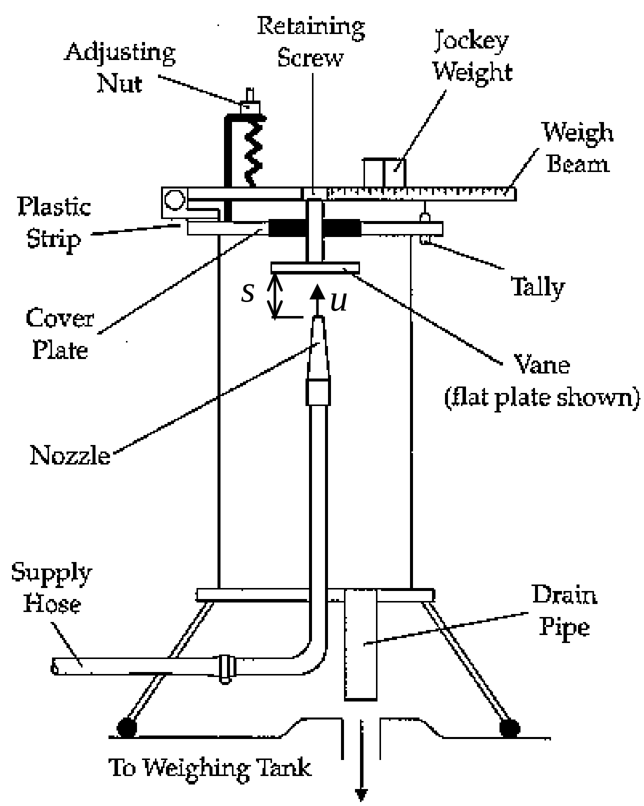

Figure 12: Schematic of the Impact of a Jet Apparatus

Apparatus Set-Up

1. Connect the supply water line and the drain tube to the apparatus. DO NOT TURN THE WATER ON YET!

2. Insert the Flat Plate vane (jet deflecting boundary) through the opening in the cover plate of the apparatus.

3. Fasten the vane to the weigh beam with the retaining screw.

4. Rest the jockey mass on the zero mark of the weight beam and level the beam by adjusting the balance spring. When level, the grooves on the tally should be equally spaced on either side of the top plate hole. Adjust the length of the tally suspension if necessary.

5. Align the axes of the test vane and nozzle, if necessary, by adjusting the three fixing screws in the cover plate bracket.

6. Turn the water on slowly and check for leaks or loose parts. If the alignment is correct, the water should splash symmetrically about the nozzle (for the flat plate vane).

Procedure

1. With the water supply OFF, level the weight beam with the jockey weight set at the zero position.

2. Turn the water supply ON to its maximum flow rate. Adjust the position of the jockey weight until the weigh beam is balanced. Record the position of the jockey weight and the mass of the jockey weight.

3. Using a stopwatch, record the time it takes to fill a known volume of water flowing from the drain hose. It is recommended to collect a large enough volume of water so that the time span to collect the water is between 5 to 20 seconds.

4. Repeat steps 1 through 3 for various flow rates; in order to obtain at least 3 force readings that are taken equidistantly along the weigh beam.

5. Repeat step 4 for each remaining boundary vane: Hemispherical Cup, Cone, and 30° Angled Plate.

Analysis and Discussion

Sample Calculations

Using the data provided in the nomenclature, the following sample calculations were performed. The weight of the jockey weight is found by using $W = mg$. Taking moments about the weigh beam pivot gives:

$$F(0.15) = 0.6g(x + 0.15)$$

Where g is the acceleration due to gravity and x is the location of the jockey weight relative to its zero position. Thus,

$$F = 4g(x + 0.15)$$

Since, the speed of the jet at exit from the nozzle is equal to:

$$u = \frac{\dot{Q}}{A}$$

The velocity of the jet when it reaches the vane surface is decelerated due to gravity over the distance it travels from the jet exit to the vane surface. The velocity at the vane surface is found by using:

$$u_0^2 = u^2 - 2gs$$

Or

$$u_0 = \sqrt{u^2 - 2gs}$$

Where, s, is the distance from the nozzle exit to the surface of the vane. Then the rate of momentum delivered to the system can be calculated by:

$$\dot{m}u_0 = \rho\dot{Q}\sqrt{u^2 - 2gs}$$

Data Collection and Analysis

5. Collect the following data: Volumetric Flow Rate (m3/s) and Jockey weight position *x* (m); for different vanes by following the experimental procedures.
6. Calculate the Rate of Momentum Delivery (N) and Force on the Vane *F* (N) using the aforementioned equations.
7. Tabulate the calculated parameters.
8. Make a plot of Force on the Vane (Y axis) vs. Rate of Momentum Delivery (X axis) using the data from all of the vanes tested; with a linear interpolation line for each vane.
9. Compare the experimental results of K with the theoretical values shown in Table 2 and discuss the results.

Report Requirement

4. The report must follow the lab report format.
5. The report must be submitted electronically (**PDF**) by the due date.
6. The electronic file must have a file name of: EML3126L_section#_Exp#_Group#.pdf

   Example: EML3126L_U01_Exp4_Grp1.pdf

Experiment 5: Centrifugal Pump

Objectives

This laboratory exercise is used to investigate the performance characteristics of a centrifugal pump. To select a pump that is appropriate for a given application, the engineer ordinarily looks at its published performance curves. These include plots of total pressure or "head" rise (ΔP) against volume flow rate (Q) at constant speed (n). The manufacturer will usually furnish such curves to the potential user for each pump it builds. The goal of this experiment is to generate performance curves for a pump in the ME lab. At the conclusion of this experiment you should have acquired physical insight into:

1. Methods for measuring pressure and fluid flow
2. The performance of centrifugal pumps.
3. The efficiency of centrifugal pumps.

Nomenclature

Symbol	Description	SI Unit
A	Cross-sectional Flow Area	m^2 or mm^2
d or D	Nominal Diameter of the Pipe	m^2 or mm^2
g	Gravity	$9.81\ \frac{m}{s^2}$
h	Height of Liquid in Manometer	mm
h_f	Hydraulic Gradient	-
h_1	Height of Water or Mercury in Downstream Manometer Tube	m or mm
h_2	Height of Water or Mercury in Upstream Manometer Tube	m or mm
l or L	Length of Pipe between two Piezo-meter Taps	m
$\dot{Q}$	Volumetric Flow Rate	$\frac{m^3}{s}$
Re	Reynolds Number	-
Re_c	Critical Reynolds Number	-
V	Velocity	$\frac{ft}{min}$
ρ	Density	$\frac{kg}{m^3}$
μ	Absolute Viscosity	$\frac{(N \cdot s)}{m^2}$

Experimental Parameters and Constants	
Specific Gravity of Mercury $(SG_{mercury})$	13.6
Length of Pipe between Pressure Taps (L)	524 mm
Nominal Diameter of the Pipe (D)	3 mm

Introduction

Developing piping systems and selecting pumps for them is an important industrial problem. In this lab you will be introduced to the procedures for quantifying pipe flow losses for a given piping network, and correspondingly, selecting an appropriate pump to perform the desired task. In a previous experiment, pressure loss data for several network components such as elbows and straight lengths of pipe were obtained. In this experiment, the efficiency of a particular pump and its pump curves will be determined.

The apparatus for these tests is a Plint model TE47 centrifugal pump test bench. It is essentially a flow loop containing:

- The pump
- Instrumentation to measure pump operating parameters
- Valves to vary "load" on pump

The pump is driven by a variable speed D.C. dynamometer motor, which is mounted on bearings and fitted with a spring balance for measurement of torque, and a tachometer for measurement of speed. The pump is mounted on a cart which carries the water reservoir. Water is drawn from this reservoir by way of a foot valve and strainer, and pump discharge is taken through a venturi flow meter back to the reservoir. Valves are located on the suction (inlet) and delivery (discharge) sides of the pump to control the suction and delivery pressures, which are indicated by the gages.

Procedure

To begin the test, open the discharge valve wide and turn on the pump. Open the inlet valve to obtain a reading of about 0.4 bars on the suction gage and adjust its speed (n) to 2400 rpm using the tachometer on the panel behind the pump. Make sure that the pump is primed, if it isn't, have the T.A. or a technician show you how to do so. Once the loop has reached a steady operating condition, record the following data:

- Pump Speed (n), in rpm
- Inlet and discharge pressure $(P_1 \; and \; P_2)$, in bars
- Venturi meter manometer readings (h), in mm Hg
- Force (F) on spring balance, in N, after adjusting level of spring balance so that point on torque arm coincides with fixed pointer.

Now close the valve on the discharge side enough so that a measurable change in manometer pressure occurs and allow the system to reach a new steady state. Make sure that n remains as 2400 rpm. Again record the values of n. P_1, P_2, h, and F. Repeat this procedure until you have reduced the pump flow to almost zero, or until pump "surge" begins to occur. Obtain at least five data points at n = 2400 rpm.

Now set the pump for a lower speed (n = 2000 rpm) and use the same methods to again obtain at least five data points. This concludes data acquisition for the centrifugal pump, the remainder of your work will consist of analyzing this raw data.

To begin, you should calculate volume flow rate, Q (liters/sec), and the pump pressure rise, ΔP (bars), for each test condition. The flow is determined by application of Bernoulli's equation to the venturi manometer system. It is shown here that the result is:

$$Q = C_D \frac{\pi}{4} d_2^2 \sqrt{\frac{2gh}{1-\left(\frac{d_2}{d_1}\right)^4} * \frac{\rho_{Hg}-\rho_w}{\rho_w}}$$

where d1 and d2 are the venturi nozzle diameters at its two pressure taps. The density of mercury, ρ_{Hg} is 13,350 kg/m3, and the density of water is 1000 kg/m3. The discharge coefficient (C_D) of the meter must, in general, be determined by calibration. In this case, you may determine Q from the following simplified relationship:

$$Q = 0.103\sqrt{h}$$

In the previous equation, h must be in mm and Q will be in liters/ sec. Finally, the pump pressure rise is given by:

$$\Delta P = P_2 - P_1$$

where you must remember that P1 is below the atmospheric pressure for this experiment, that is, it is a negative gage pressure.

Plot ΔP (bars) vs. Q (liters/s). Put your two performance curves (n = 2400 rpm, n = 2000 rpm) on the same graph.

The performance of a centrifugal pump may be analyzed on the basis of the steady flow energy equation for an incompressible fluid:

$$Q * \Delta P = W_S - W_L$$

This equation states that the rate of work done by the pump on the fluid, (Q*ΔP), ignoring kinetic energy and the difference in the level between the pump inlet and outlet, is equal to the shaft power in put to the pump (W_S) less frictional losses (W_L). The shaft power is the product of the shaft torque and its angular velocity; the torque is, of course, the spring balance force multiplied by the moment arm (which is 189 mm for this apparatus). Finally, the efficiency, (η), of the pump is given by:

$$\eta = \frac{Q * \Delta P}{W_S}$$

Calculating the pumping power (Q*ΔP), the shaft power, and the efficiency for each test point.

Plot efficiency vs. Q for the two values of n on the same graph.

As you remember from your fluids course, it is convenient to express pump flow and pressure rise in terms of dimensionless variables called the flow coefficient (Q*) and the head coefficient (ΔP*), These are defined as:

$$Q^* = \frac{Q}{nD^3}$$

$$\Delta P^* = \frac{\Delta P}{\rho n^2 D^2}$$

where n is the pump speed and D is some characteristic length associated with the pump,. The choice of D is somewhat arbitrary; for the sake of consistency we shall use the diameter of the pump impeller, which is 100.4 mm. You have to be careful of the units in the above equations: n should be in rpm's, ρ in kg/m3, Q in m3/s, D in m, and ΔP in N/m2. For geometrically similar pumps (of varying size D and varying speed n) all performance data should collapse onto a single performance curve if expressed in these new variables. This lets you represent many data by a single curve. Convert your Q ΔP data (for the two values of n) to Q* ΔP* values and plot the two performance curves (with Q* on the horizontal axis) on the same graph. Use different symbols to represent data at the two pump speeds. Does your data fall onto one curve?

The performance curves may be used to determine the conditions at which a given pump will run when operating against a known load. Suppose that the pump you have just tested is to be used to pump water through 150 m of 38 mm i.d. galvanized pipe with an average roughness ε = 0.15 mm, with the pipe inlet and discharge at the same elevation. This pipe represents a resistance to flow, and the frictional pressure drop (ΔP_f) between its ends is given by:

$$\Delta P_f = constant * Q^2$$

Use your knowledge of pipe friction to find the value of the constant and plot the resulting load curve (ΔP_f vs. Q) on the graph with your pump curves. The operating points will be those points where the pump and load curves intersect. Read the operating points from the graph to determine the flows that the pump will actually deliver through the flow system at the two operating speeds. Include these values in your report.

In addition, use these performance curves to determine the conditions at which this pump will run when operating with the known load that you obtained in part 1 of this experiment.

Attach to your report pages showing all raw data, calculations, and graphs. Be sure to include the relevant uncertainty analysis for the measured quantities (see notes in lab manual).

Report Requirement

1. The report must follow the lab report format.
2. The report must be submitted electronically (**PDF**) by the due date.
3. The electronic file must have a file name of: EML3126L_section#_Exp#_Group#.pdf
   Example: EML3126L_U01_Exp5_Grp1.pdf

Appendix

Air Speed Calculation Using a Pitot Tube

In many cases, pressure is indicated in the equivalent column height of a liquid, (sometimes known as a *pressure head*) usually water for gas (air) flow, or mercury for liquid (water) flow. The hydrostatic pressure created in a column of any liquid is given by:

$$P = \rho g H \qquad (1)$$

Hence, when a pressure is given in terms of height, [e.g. **inches H_2O** or **mm Hg**], then it can be converted to a pressure using equation (1). This pressure head or liquid height is historically related to the differential height for the two columns of the liquid in a U-Tube manometer.
A *Pitot Tube* measures both the *total* (or *stagnation*) pressure and the *static* pressure in an air flow. The velocity of the air is related to the difference of these two pressures by:

$$V = \sqrt{\frac{2(P_{Total} - P_{Static})}{\rho_{air}}} \qquad (2)$$

The pressure in equation (2) is in terms of force over area, so a pressure measured in liquid column height must be converted. For example, if the pressure is given in terms of **inches H_2O** then using equation (1) in equation (2) gives:

$$V = \sqrt{\frac{2(H_{Total} - H_{Static})\rho_{water} g}{\rho_{air}}} \qquad (3)$$

To obtain the density of ambient air, use the ambient pressure and temperature and the Ideal Gas Law:

$$V = \sqrt{\frac{2(H_{Total} - H_{Static})\rho_{water} g}{\frac{P_{ambient}}{R_g T_{ambient}}}} \qquad (4)$$

where R_g is the Universal Gas Constant and equal to:

$$R_g = 287\,\frac{J}{kg\cdot K} \qquad \text{(for air only!)}$$

Warning: CHECK YOUR UNITS! Pressure heads may need to be converted to standard length dimensions and temperature will need to be converted to Rankine or Kelvin.