

MAAE 2300 Fluid Mechanics I
LABORATORY EXERCISES
(Revised January 2010)

LABORATORY EXERCISES

1 INTRODUCTION

Each student will be required to perform three laboratory experiments. A semi-formal report on each experiment must be submitted one week after performing the experiments, as described in Section 3.0.

There are two main goals for the experiments:

- i. To develop a familiarity with the basic experimental methods for measuring common fluid-flow quantities, such as pressure, velocity and flow rate.
- ii. To examine the validity of a number of the simplifying assumptions commonly used in the engineering analysis of fluid flows.

The latter goal will be achieved by comparing the experimental results with a corresponding simplified analysis for the experimental flow. Your report should specifically discuss the degree to which the simplifying assumptions appear to be supported by the measurements.

The experiments will be performed by groups of about 4-5 students. The data may be recorded by one individual. **The data sheet(s) must be initialled and dated by the Teaching Assistant before the end of the laboratory period.** The original or a photocopy of these data sheets must be included as an appendix to the report submitted by every student.

The report must be prepared according to the specification given in the next section. All reports must be typed although hand calculations are permissible.

2 REPORT REQUIREMENTS

The report should contain, **IN THE ORDER GIVEN BELOW**, the following items:

Title page: Correct title, author and date. **Also note the group number and names of the partners at the bottom of the page.** Authors should include their email address.

Summary: A brief statement of the purpose of the experiment and a very concise summary of the main results and conclusions. This should not exceed about 200 words in length. The goal is to enable a potential reader to see if the report contains material of interest to him/her. See the end of this section for a sample Summary.

Nomenclature (also called List of Symbols): Lists all the symbols, parameters, and variables with their appropriate units.

Flow Analysis: Each of the flows that will be measured can also be analyzed with the methods taught in the course. This section presents, with brief explanatory notes, the equations and derived results which will be compared with the measurements. The outlines of the experiments in this manual indicate specific analyses which must be included. Equations should be numbered where appropriate so that reference can be made to them in the discussion of the results.

Experimental Setup and Procedure: This section must include a neat, fully-labelled schematic drawing of the experimental setup. Apart from this, if the experiment was conducted entirely according to the outline in the manual, a single sentence to that effect is sufficient. Otherwise, record any deviations from the outline (eg. due to problems with the apparatus or instrumentation) with a brief explanation.

Results and Discussion: This section presents and discusses the data acquired during the experiment. Where possible, results should be plotted to facilitate comparisons and assessments. These graphs should be placed within the text. Reference can be made to the Appendix in which the detailed results are tabulated, but the main body of the report must be readable without reference to this Appendix.

The results should be interpreted and assessed for accuracy and credibility. Any discrepancies should be discussed: this includes the major sources of error and plausible magnitudes of these errors, and any particularly interesting or unusual features of the results. Finally, there must be a discussion of the apparent validity of each of the simplifying assumptions used in the analysis, in the light of the comparison between the analysis and the measurements.

Conclusions: This section lists the specific conclusions arrived at on the basis of the work described in the report. Conclusions must be significant, pertinent and valid; they must be substantiated by data and discussion in this report, and they must be appropriate.

References (if appropriate): Citations are to be correctly ordered and should include authors, titles, periodical title or publisher as appropriate, and date of publication. (A reference is incomplete unless a reader can actually locate it.)

Appendices: These should be properly identified as to their content. The signed original data sheet(s) must be attached as an appendix. A second appendix presents the detailed analysis of the measurements, including: sample calculations for all but the most trivial calculations; detailed data tables (e.g. in the form of the output from a spreadsheet program, if used); and listings of any computer programs written to analyze the data.

Semi-formal reports such as the present one might be prepared for internal use in a company. They can omit the detailed discussion of the background, theory and experimental methods which would normally be included in a more formal report, such as one prepared for an outside client. The "Summary" must therefore provide any introductory comments needed to make the report understandable. As an example, the following might be a suitable summary for a semi-formal report which reports a performance test for a centrifugal pump:

"Pressure rise versus flow rate measurements were made for a Model 255 centrifugal pump at rotational speeds of 600, 1200 and 1800 RPM. The non-dimensional head coefficient versus flow coefficient data were found to fall on a single curve. This indicates that the pump performance is not a function of Reynolds number for the range of conditions examined. For each speed, the inlet pressure was also reduced, for constant pressure rise across the pump, until cavitation occurred. The average value of the Suction Specific Speed (a cavitation parameter) was found to be 2.4. This is at the low end of the range typically found for centrifugal pumps. Thus, the present pump has somewhat poor resistance to cavitation."

3 REPORT SUBMISSION

Each member of every laboratory group must submit an individually-written report on each of the experiments. The report on each experiment must be submitted to the appropriate drop box outside the Mechanical & Aerospace Engineering Office (Mackenzie Building Room 3135) one week after the completion of the experiment. Marked reports will be returned at the beginning of the laboratory or PA session one week later. In addition, students must submit an electronic .pdf version of their reports via WebCT for automated scanning as a means for preventing plagiarism.

Do not submit reports to your professor; this results in long delays and late submission penalties.

The late penalty is 10 marks/day (or fraction thereof) out of a maximum possible of 40 marks. One complete report must be submitted for each experiment, even if it is late. Late reports will be marked and annotated as normal before the late penalty is deducted. Incomplete reports will be returned for revision and will incur a late penalty. In line with engineering accreditation requirements, three complete reports must be submitted and an overall passing grade must be obtained for the laboratory portion of the course in order to pass the course as a whole.

4 MARKING SCHEME FOR REPORTS

The reports will be marked out of 40 with the following breakdown:

- i. General Format [10]**
 - General organization (according to the format specified in the manual) and readability
 - Appropriate, fully-labelled graphs
 - No bonus for laser-printed reports; no penalty for hand-written reports (pencil recommended)
- ii. Results [10]**
 - Complete theoretical analysis, as specified in the manual
 - Correctness and completeness of reduced data
 - Complete sample calculation included as an Appendix
- iii. Discussion and Conclusions [20]**
 - Discussion of results (agreement with theoretical analysis and possible sources of discrepancy; sources of experimental error, inaccuracy and scatter; etc.)
 - Brief, specific conclusions

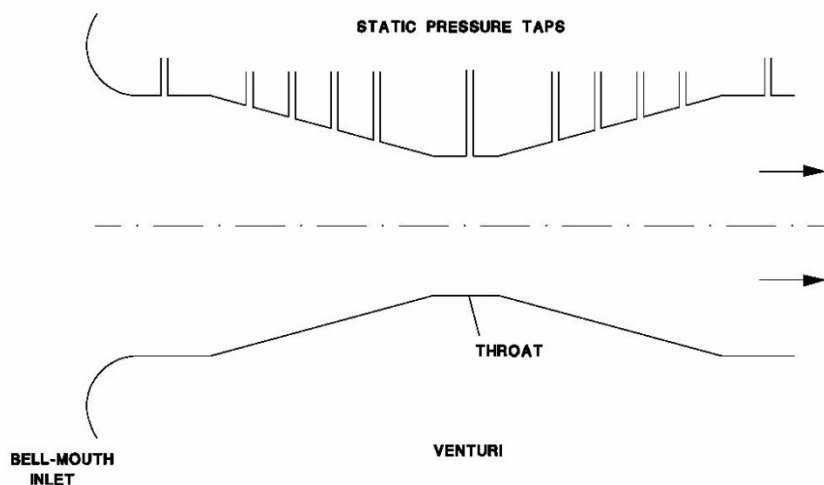
EXPERIMENT 1
Flow Through a Venturi Meter
(Location: 2180 Mackenzie Bldg.)

INTRODUCTION

The aim of this experiment is to provide a better understanding of how to apply Bernoulli's equation in real flows, and of the physical meaning of the terms static pressure, stagnation pressure and dynamic pressure. It will also allow us to compare the ideal, frictionless predictions of Bernoulli's equation to the actual flow through a Venturi.

The Venturi meter is a flow-measurement device consisting of a convergent-divergent length of pipe. The experimental setup consists of a bell-mouth inlet through which air is drawn from the room, followed by the Venturi. The bell-mouth inlet is itself a flow-measurement device and in this experiment the flow rates determined from it will be assumed to be the true values. A vacuum cleaner connected to the downstream end of the Venturi provides suction.

The Venturi is instrumented with static pressure taps at a number of locations. Because of the change in area, the velocity, and therefore the static pressure, changes along the Venturi.



Assuming one-dimensional flow, the continuity equation (conservation of mass) and Bernoulli's equation can be used to calculate the predicted pressure variation along the Venturi. The predicted flow rate can also be expressed as a function of the pressure difference between the Venturi inlet and the throat; this will be referred to as the "ideal flow rate" for the Venturi.

Recall from lectures that Bernoulli's equation is an energy equation which can be applied along a streamline when there is no friction (i.e. no viscous effects), when the flow is both steady and incompressible, **and** when there are no work or heat transfer processes taking place along the streamline between the start and end points of interest. Bernoulli's equation relates two points (1 and 2) along a streamline as

$$P_1 + \frac{1}{2}\rho V_1^2 + \rho g z_1 = P_2 + \frac{1}{2}\rho V_2^2 + \rho g z_2$$

where P is the static pressure, V is the velocity, ρ is the density, g is the acceleration of gravity and z is the elevation of the point. The term $\frac{1}{2}\rho V^2$ is referred to as the “dynamic pressure”. The sum of the static and dynamic pressure terms (i.e. $P + \frac{1}{2}\rho V^2$) are known as the “total pressure” or “stagnation pressure”.

At the walls of the Venturi, viscous effects will slow the velocity of the fluid to zero in accordance with the no-slip condition. This effect spreads farther and farther into the flow with downstream distance. Thus, the actual flow is not one-dimensional. Also, Bernoulli’s equation will only be valid in the core of the flow where viscous effects have not reached. Therefore, the simple analysis described earlier will only approximate the real flow behaviour. The key goals of the experiment are to examine how much the real flow differs from this approximate analysis, and to develop a calibration for the Venturi using the bell-mouth inlet as reference measurement.

PROCEDURE

1. Record which apparatus number you are using and indicate this in your lab report.
2. Operate the experiment for two different flow rates.
3. Measure the static pressures at all of the taps provided. Note the position of each tap along the Venturi and measure the distance from each tap to the tap at the throat of the Venturi.
4. Make sure that at least one of the manometer tubes is open to atmosphere and record the fluid level in this tube along with the others. Note that since the air is drawn from the room, the atmospheric pressure is in fact the total or stagnation pressure for the flow passing through the apparatus.
5. Record the inlet and throat inner diameters and measure the distance from the throat to the start of the taper in both the upstream and downstream directions (assume that the internal profile is a linear taper to the throat). Make sure you record sufficient information to calculate the flow cross-sectional area at the location of each static pressure tap.

ANALYSIS AND DISCUSSION

1. For each flow rate, determine the “actual” volume flow rate, Q_{actual} , from the bell-mouth measurement. This can be determined by applying Bernoulli’s equation along a stream line starting far away from the apparatus and ending at the first pressure tap inside the bell mouth.
2. Calculate the ideal volume flow rate, Q_{ideal} , for the Venturi using Bernoulli’s equation between the Venturi inlet and the throat.
3. Calculate the Venturi coefficient, C_V :

$$C_V = \frac{Q_{actual}}{Q_{ideal}}$$

Note that C_V is a measure of how much the actual flow differs from the idealized flow through the Venturi ($C_V=1$ being a perfect match). It is also effectively the calibration factor for the Venturi. When used as a flow meter in a pipeline, the Venturi would be instrumented with taps at the throat and the maximum area sections. From the measured pressure difference, the ideal flow rate can be calculated. This can then be “corrected” using the known Venturi coefficient to get the true flow rate.

4. For the two flow rates, what is the stagnation pressure on the centerline at the Venturi throat? The static pressure? The dynamic pressure?
5. Plot the static pressure distribution along the Venturi for each of the two flow rates. The pressures may be expressed in terms of head (e.g. inches or mm of water gauge). On the same graphs and to the same scale, plot the static pressure distributions calculated from Bernoulli's equation and continuity, using Q_{actual} to determine the flow velocity at each point.
6. Discuss the flow through the apparatus, explaining why the actual flow differs from the idealized one. Specifically explain the trends in actual and ideal static pressures shown in the graphs in (5). Include a sketch of three approximate velocity profiles for the flow through the apparatus: one at the upstream end of the Venturi, one at the throat and one near the downstream end of the Venturi. An arbitrary scale for velocity can be used, but the profiles must be consistent with the fact that the continuity equation must hold along the Venturi.

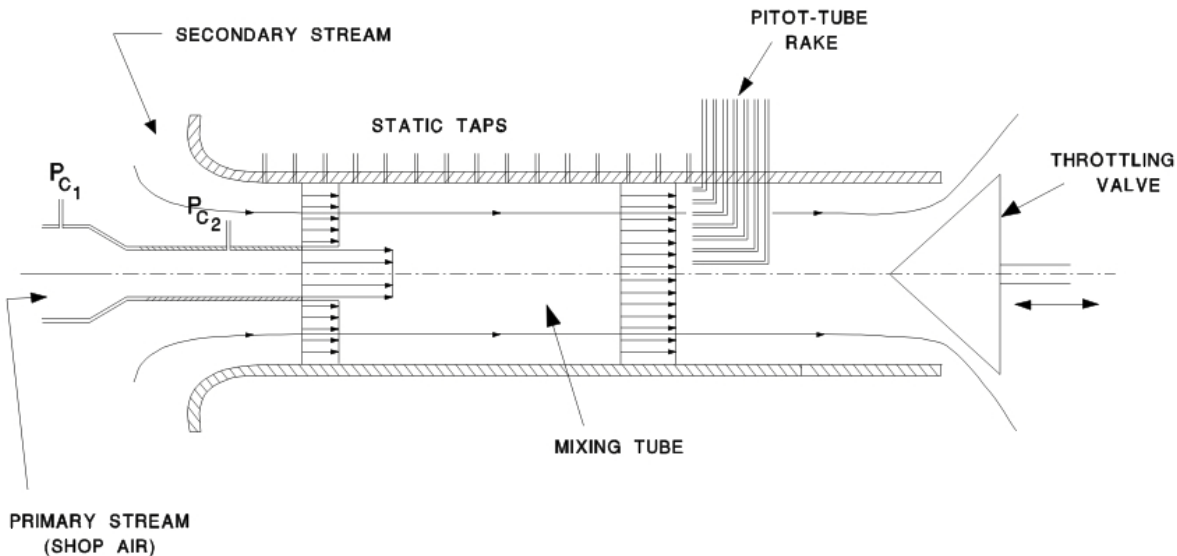
EXPERIMENT 2 Jet Pump

(Location: 2180 Mackenzie Bldg.)

INTRODUCTION

A jet pump is a simple pumping device which has no moving parts. A high velocity, primary stream is injected into the fluid to be pumped (the secondary stream) in a tube. Through mixing, the secondary stream is accelerated and has its pressure raised. While not very efficient, jet pumps are useful for pumping slurries and corrosive or abrasive fluids which might damage conventional pumps. An example of a small, commercial jet pump is shown in cutaway in the laboratory.

The experiment is performed in a simple, large-scale jet pump in which high-pressure shop air is used to pump (compress) air drawn from the room. The geometry of the device is simple enough that, with some suitable simplifying assumptions, it is possible to analyze its performance using the methods you are learning in this course. One objective of the experiment is to compare the performance of the apparatus with a corresponding theoretical analysis of the flow. For the theoretical analysis, review Problem 3.4 in the course manual.



SCHEMATIC OF JET PUMP

The injector (primary) nozzle is instrumented with two static taps, one near the nozzle outlet (with the corresponding pressure designated P_{C2}) and one further upstream (with the pressure designated P_{C1}) where the pipe has a larger diameter. The pressure difference between these two taps is directly related to the flow rate since the contracting pipe behaves like a venturi (if you have not yet performed Experiment 1, read the outline for it to learn about the use of venturis and bell-mouth inlets as flow measuring devices). The relationship between the pressures at these two taps and the static and dynamic pressures of the primary stream as it leaves the nozzle has been measured. These data are expressed as non-dimensional coefficients.

The dynamic pressure coefficient is defined as:
$$C_q = \frac{q}{P_{C1} - P_{C2}}$$

and the static pressure coefficient as:

$$C_p = \frac{P_p - P_{C2}}{P_{C1} - P_{C2}}$$

where $q = \frac{1}{2} \rho V_p^2$ is the dynamic pressure of the primary stream (V_p is the velocity of the primary stream) and P_p is the static pressure of the primary stream at the nozzle outlet. Values of C_q and C_p will be supplied in the laboratory.

The velocity of the secondary stream as it enters the mixing tube can be determined from Bernoulli's equation along a streamline starting far from the apparatus and ending at the first pressure tap just inside the bell-mouth inlet (again, see Experiment 1).

PROCEDURE

N.B. This apparatus is somewhat noisy. Ear plugs should be used by all occupants of the laboratory.

1. The figure shows a schematic drawing of the experimental apparatus. Record all dimensions of the apparatus.
2. Collect complete sets of data for two operating points corresponding to two significantly different settings of the outlet throttling valve. The pipe to the injector nozzle includes a shut-off valve, a filter/water trap and a pressure regulator. After opening the shut-off valve, use mainly the regulator to adjust the injector flow rate. Note that the regulator turns counter-clockwise to shut off the flow. Operate all valves gradually, watching the fluid levels in the manometers to avoid spillage of manometer fluid.

Among other things, you will be using your measurements to obtain velocities and flow rates for the primary and secondary streams and for the mixed outlet flow. If you are in any doubt about how to obtain such information from your measured data, discuss this with your TA before leaving the laboratory. Since you are not able to measure the temperatures of the streams, it is not possible to determine the fluid densities exactly. For purposes of your analysis, assume $\rho = 1.2 \text{ kg/m}^3$ for air.

ANALYSIS AND DISCUSSION

The goals of your analysis are to compare the measured and predicted performance of the device and to examine critically the validity of the simplifying assumptions used in the predictions. Perform the following specific analyses:

1. Develop a simplified analysis for the mixing process in the mixing tube by applying the continuity and momentum equations to a control volume that extends from the inlet to the outlet of the mixing tube. That is, determine expressions for the velocity and static pressure at the outlet of the mixing section, knowing the velocities and pressures for the primary and secondary streams. Use the same simplifying assumptions as in Problem 3.4: assume uniform velocity for any stream of interest and neglect friction on the walls of the mixing tube. Then, using the measured values of velocity, flow rate and static pressure at the mixing-tube inlet plane, calculate the predicted velocity and static pressure at the mixing-tube outlet (that is, at the plane of the Pitot-tube rake).
2. Plot the static pressure changes along the mixing tube relative to the inlet values, on a single graph for the two cases. Also, for comparison mark the predicted outlet pressures relative to the inlet values. Do the wall-pressure measurements suggest that the mixing process was complete by the end of the mixing tube: that is, is the mixing tube long enough? How well is the pressure rise

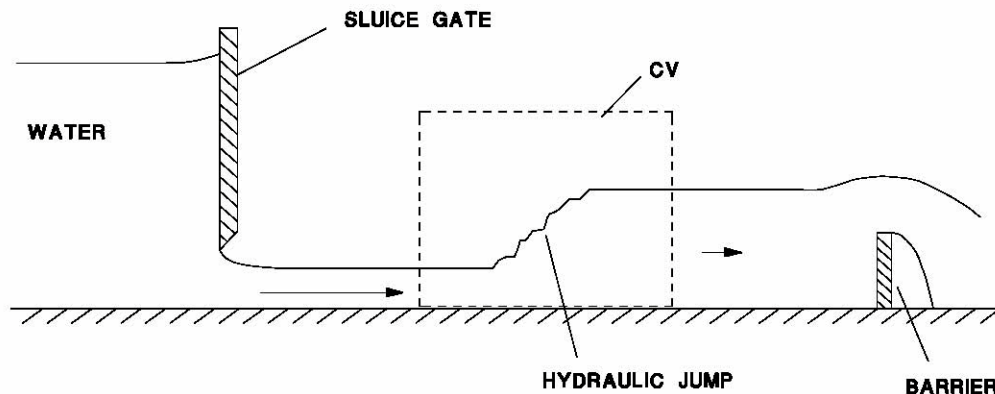
predicted? Does the agreement vary with the flow rate? Would you expect the validity of any of the simplifying assumptions to depend on the flow rate? What about the frictional force at the walls of the mixing tube, for example?

3. You assumed uniform flow at the end of the mixing tube. Plot the measured outlet velocity distributions as a function of radius for the two cases. Show also the predicted outlet velocities for each case. How well was the assumption of uniform flow satisfied? Was the validity of the assumption a function of the flow rate?
4. Where possible, one should always check experimental data for internal consistency. The primary and secondary flow rates are determined from measurements at or upstream of the inlet plane of the mixing tube. The Pitot rake at the outlet of the mixing tube implicitly gives the flow rate of the combined stream. As a check on the internal consistency of the data, integrate the velocity distribution from the rake to obtain the outlet flow rate and compare this with the sum of the inlet flow rates. How well do the flow rates agree? Discuss the possible sources of any discrepancies observed.

EXPERIMENT 3
Flow Through a Sluice Gate and Hydraulic Jump
(Location: 2268 Mackenzie Bldg.)

INTRODUCTION

The drawing shows schematically the flow of water under a sluice gate and the stationary hydraulic jump which can be made to form downstream by suitably adjusting the barrier.



Observe that the waves made by disturbing the flow are swept downstream in the region between the sluice gate and the jump. At this point the flow velocity is greater than the wave speed and the flow is known as supercritical flow. Similarly, observe that waves propagate both upstream and downstream when they are introduced downstream of the hydraulic jump. The flow here is known as subcritical. There is a direct analogy between these flow situations and the supersonic and subsonic flows which can occur in gas flows. In supersonic flows, pressure (sound) waves cannot propagate upstream because the wave speed (the speed of sound) is less than the flow speed. In subsonic flow the sound waves can propagate both upstream and downstream. The hydraulic jump is then analogous to the shock wave which separates regions of supersonic and subsonic gas flows.

Supercritical flow can occur in a variety of hydraulic flows, such flow under a sluice gate (as used here), over a weir, and in the spillway of dams. The high velocity in supercritical flow can cause serious erosion of flow channels and river beds. Therefore, barriers are often used to induce a hydraulic jump and thus cause the flow switch to subcritical conditions.

The purpose of this experiment is to measure the behaviour of a water flow passing through a hydraulic jump and to examine how well the flow can be predicted using the techniques developed in this course. See problems 4.5 and 5.2 for further background on the analysis.

PROCEDURE

1. Note the width of the flow channel. You will need it for your analysis.

For two different flow rates:

2. Observe the occurrence of the hydraulic jump and measure the depths: upstream of the sluice gate; downstream of the sluice gate; and downstream of the hydraulic jump. Make certain that conditions are steady before taking readings.

- Using a Pitot tube with a tubular glass stem, measure the total head in the flow at the same three locations.
- Measure the flow rate in the channel using the V-notch weir at the downstream end of the flume. Calibration measurements have shown that the volume flow rate over a 90° V-notch is related to the height of water in the tank upstream as follows:

$$Q = 2.5H^{2.5}$$

for Q in ft³/sec and H in ft., where H is the water level in the tank as measured from the level at zero flow (you will therefore need to record the level of water in the tank when there is no flow). For Q in m³/s and H in m, the constant coefficient in the above equation is 1.38 instead of 2.5 (but the exponent remains the same).

ANALYSIS AND DISCUSSION

- Apply Bernoulli's equation across the sluice gate to determine the velocity downstream of the gate (Hint: The velocity upstream of the gate may not be zero. However, with appropriate assumptions you can use continuity equation and measured height data in combination with the Bernoulli equation to solve). Compare this downstream velocity with velocity determined from your measurements of the volume flow rate at the V-notch.
- The total head at a particular point in a flow is

$$H_{tot} = \frac{P}{\rho g} + \frac{V^2}{2g} + z$$

where P is the static pressure at that point, V is the velocity and z is the elevation. The total head is an alternative way of expressing the mechanical energy content of a moving fluid. Compare the total heads measured upstream and downstream of the sluice gate. Discuss this comparison.

- The hydraulic jump can be analyzed using the control volume shown in the drawing and applying the continuity and momentum equations. Derive an expression for the depth downstream of the hydraulic jump as a function of upstream depth and the flow rate. Compare the measured and predicted depths downstream of the jump for the two cases. Discuss the possible sources of any discrepancies, making specific reference to the simplified assumptions used in the analysis.
- Mechanical energy (or total head) is not conserved across a hydraulic jump. Calculate the total head change across the jump which is predicted by the control volume analysis. Determine the total head change across the hydraulic jump as given by the measurements. Compare the two and discuss this comparison.