ME332
FLUID MECHANICS LABORATORY
(PART I)

Mihir Sen

Department of Aerospace and Mechanical Engineering
University of Notre Dame
Notre Dame, IN 46556

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Contents

Unit 1: Hydrostatics

(a) Force on vertical wall

The objective is to determine the hydrostatic force on a plane vertical wall and to compare the result with analysis. The experimental apparatus is shown in Fig. 1. The wall is free to articulate about its lower edge. The force on the load cell can be measured as a function of the two water depths h_1 and h_2.

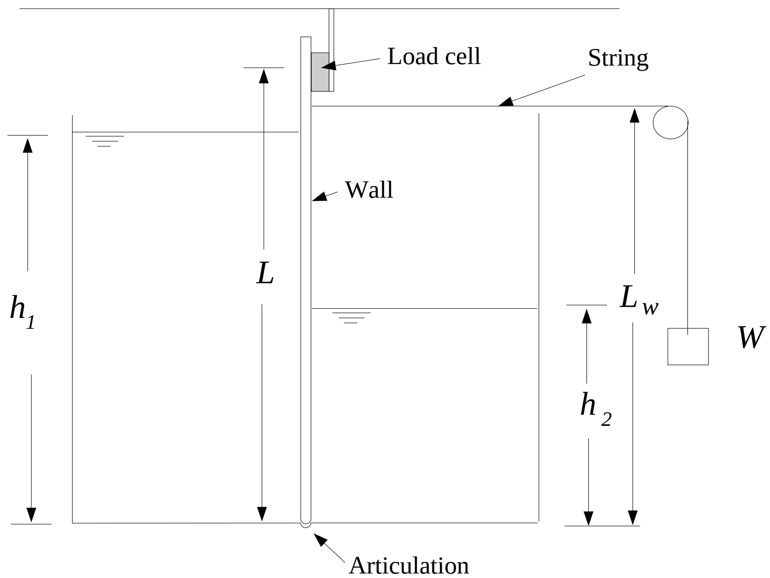

Figure 1: Hydrostatic force on vertical wall.

The theoretical force on the load cell is given by

$$F_t = \frac{1}{6L}\rho g w(h_1^3 - h_2^3) \tag{1}$$

where L is the distance fom the articulation to the location of the load cell, ρ is the fluid density, g is the acceleration due to gravity, and w is the width of wall. The friction at the articulation has been neglected.

The output of the load cell can be calibrated (without water in the chambers) by using known weights W. The distance to the point of application of the force due to the weights is L_w, which is different from L. If F_L is the force on the load cell during calibration, then

$$F_L L = W L_w \tag{2}$$

(b) Free surface under rotation

The objective is to measure the geometry of the free surface of water in solid-body rotation as shown in Fig. 2, and to compare the results with theory. The equation of a free surface under rotation can be shown to be

$$z = \frac{\omega^2 r^2}{2g} \tag{3}$$

where the origin is at the bottom of the paraboloid, z is the vertical coordinate measured upwards, r is the radial coordinate, ω is the radian speed of rotation, and g is the acceleration due to gravity. The geometry of the surface is measured by a traverse that is free to move both horizontally and vertically. For comparison with theory the measured data has to be reduced to (z, r) coordinates. Recommended reading: Section 3-7.

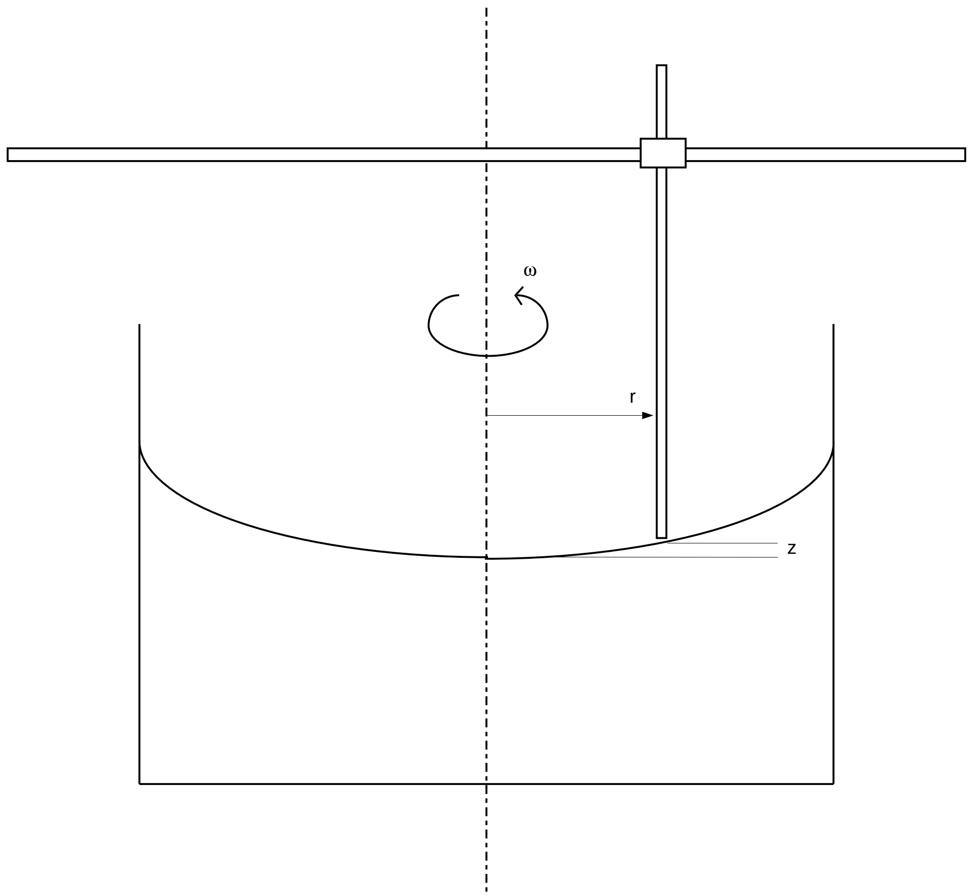

Figure 2: Set-up for free surface in rotating cylinder.

Unit 2: Flow visualization

(a) Water table

The objective is to observe the flow around objects using dye injection, especially the phenomena of separation and vortex shedding. A schematic of the water table is shown in Fig. 3. The velocity of the flow can be measured by inducing a disturbance in the dye stream and clocking its motion downstream. A camera is placed above the test zone where the object is to be placed. The flows can be photographed, downloaded to the laboratory computer, and transferred to an /afs account where Photoshop (Mac or PC) can be used to edit the picture for inclusion in the report. Recommended reading: Sections 2-2.2, 2-6.4.

The two objects to be tested are:
(i) Cylinder (p. 34, p. 322[1], Prob. 7.43, p. 328): Describe the flow patterns at increasing Reynolds numbers; the Reynolds number is usually based on the diameter of the cylinder. In the vortex shedding mode (Karman vortex street, p. 452 footnote) determine the Strouhal number. The Strouhal number is defined as $\nu D/\overline{V}$, where ν is the frequency of vortex shedding, D is the cylinder diameter, and $\overline{V}$ is the free stream velocity. Remember that vortices are shed from both sides of the cylinder, even though only one side may be visible with the dye.
(ii) Flat plate (p. 416, p. 457, Sections 9-1, 9-6, 9-7.2): The angle of attack of the plate with respect to the flow can be varied. Describe the flow patterns at increasing angles of attack; determine the approximate angle at which the flow separates from the plate. For a plate at a certain angle of attack with respect to the flow, the separation, when it happens, will be on the surface facing away from the flow.

(b) Reynolds' experiment

This experiment was originally carried out by Osborne Reynolds (p. 332) to observe the nature of the difference between laminar, transitional and turbulent flows, and to determine the critical Reynolds number for transition. The apparatus is schematically shown in Fig. 4. The flow is visualized by dye injection. The flow rate can be measured by using a graduated flask and stopwatch; the manometer will give the pressure drop between that point and the end of the pipe. (a) Describe your observations in words. Take several readings to estimate the critical Reynolds number. (b) Plot the pressure drop as a function of flow rate; it should be linear for laminar and nonlinear for turbulent flow. Recommended reading: Sections 2-6.2, 2-6.4, 8-1.

[1] The definition of Strouhal number in this page is misleading; the shedding frequency must be in Hz and not in rad/s as implied.

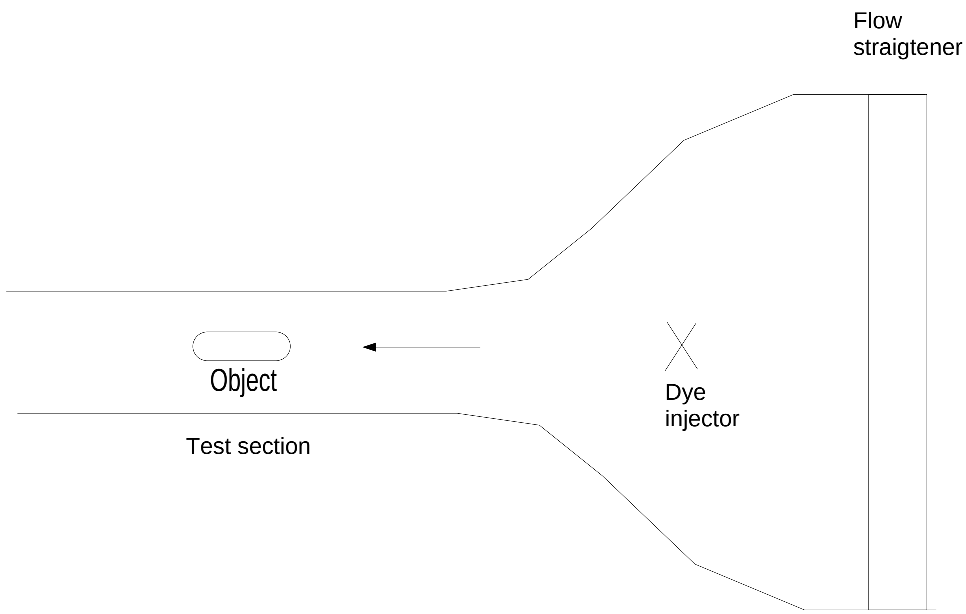

Figure 3: Water table.

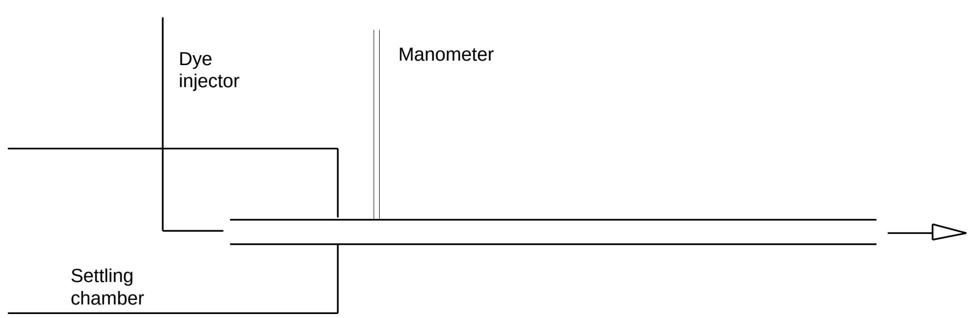

Figure 4: Reynolds experiment.

Unit 3: Flow measurement

(a) Mean velocity

The pumping station on which the flow measurement devices are mounted is shown in Fig. 5. The arrangement of the devices on the mounting frame is shown schematically in Fig. 6; the devices themselves are inside and cannot be seen. For calibration purposes the flow rate is measured using a rotameter (also called a float meter).

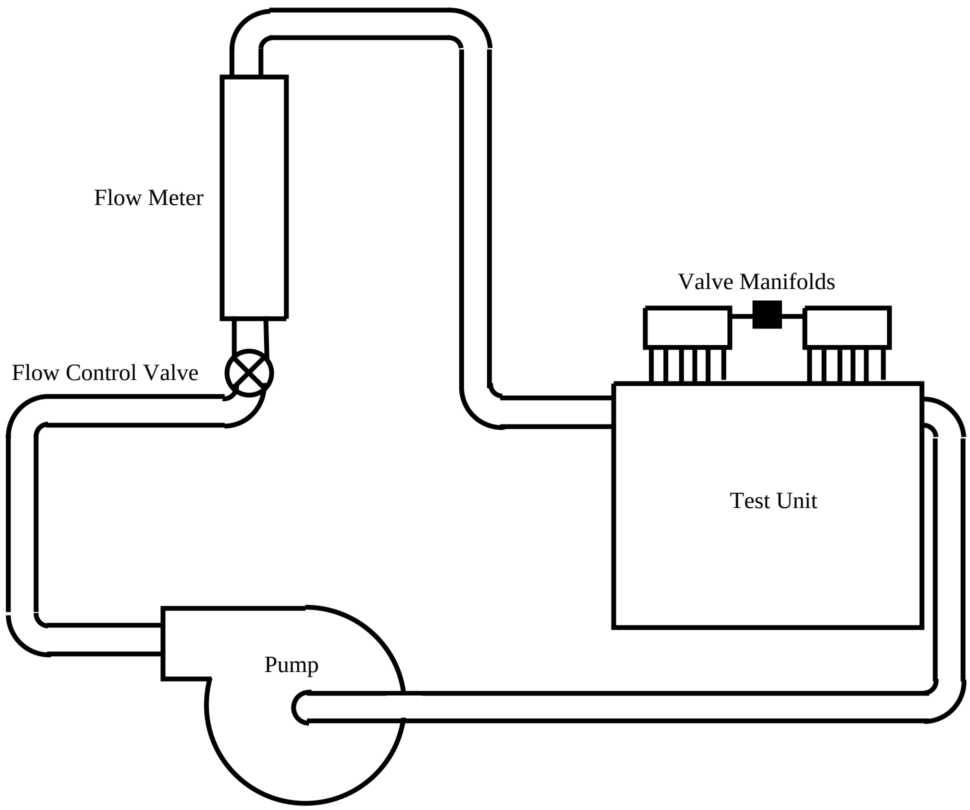

Figure 5: Pumping station.

Venturimeter

The objective is to (i) calibrate the meter (i.e. find the pressure difference versus flow rate curve), (ii) determine the head loss, and (iii) determine the discharge coefficient. Recommended reading: Sections 8-10.3, 8-11.

The volume flow rate in the Venturi shown in Fig. 7 is given by

$$Q = C\sqrt{\frac{2\left(p_1 - p_2\right)}{\rho\left(\frac{1}{A_2^2} - \frac{1}{A_1^2}\right)}} \tag{4}$$

where p_1 and A_1 are the pressure and tube cross-sectional area at location 1, and p_2 and A_2 the values at the throat. C is a discharge coefficient which takes into account frictional losses; $C = 1$ implies no losses.

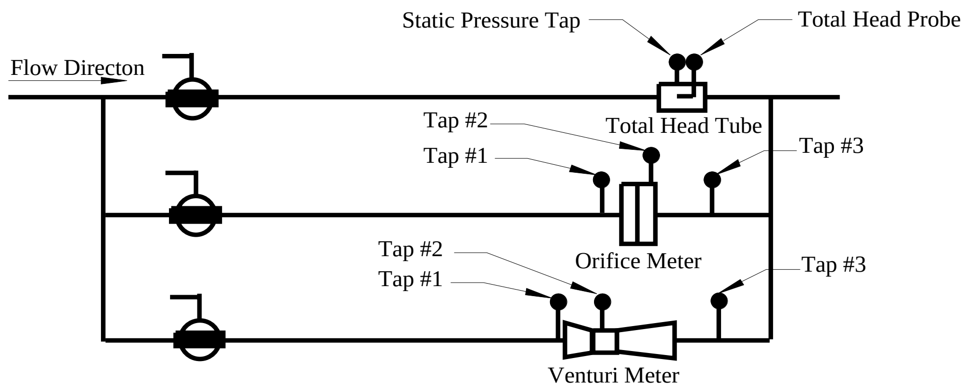

Figure 6: Location of flow measuring devices.

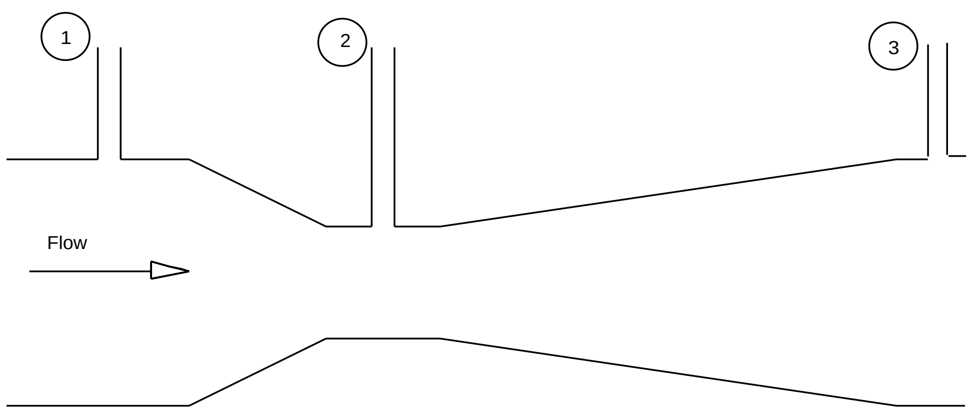

Figure 7: Venturimeter

The head loss due to the Venturi should be determined between the two pressure taps 1 and 3; they have the same cross-sectional areas with centers at the same level.

Orifice meter

The objective is to (i) calibrate the meter (i.e. find the pressure difference between sections 1 and 2 in Fig. 8 versus flow rate curve), (ii) determine the loss coefficient as a function of flow rate, and (iii) determine the head loss as a function of flow rate. The loss coefficient and head loss are measured between the most separated pressure taps 1 and 3. Recommended reading Sections 8-10.1 and Example 8-11, and Section 8-11.

(b) Total-head tube

The objective is to find the local velocity at a point as a function of the mean velocity. The local velocity is measured by a total-head tube, and the mean velocity is determined from the flow rate measured by the rotameter. Recommended reading: Sections 6-3.3, 8-11.

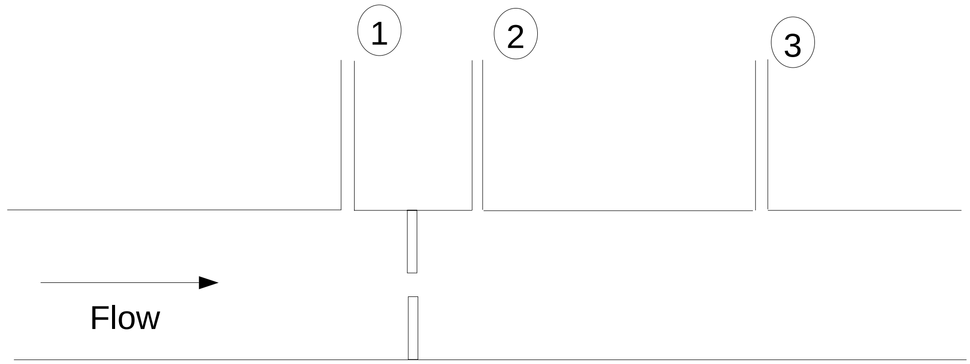

Figure 8: Orifice meter

A total head probe, shown in Fig. 9, is similar to the Pitot tube. The facility is set up to measure the difference between the total and static pressures (i.e. it measures the dynamic pressure). From equation (9), we get

$$V = \sqrt{\frac{2\,(p_0 - p)}{\rho}} \tag{5}$$

The total-head tube measures the local velocity.

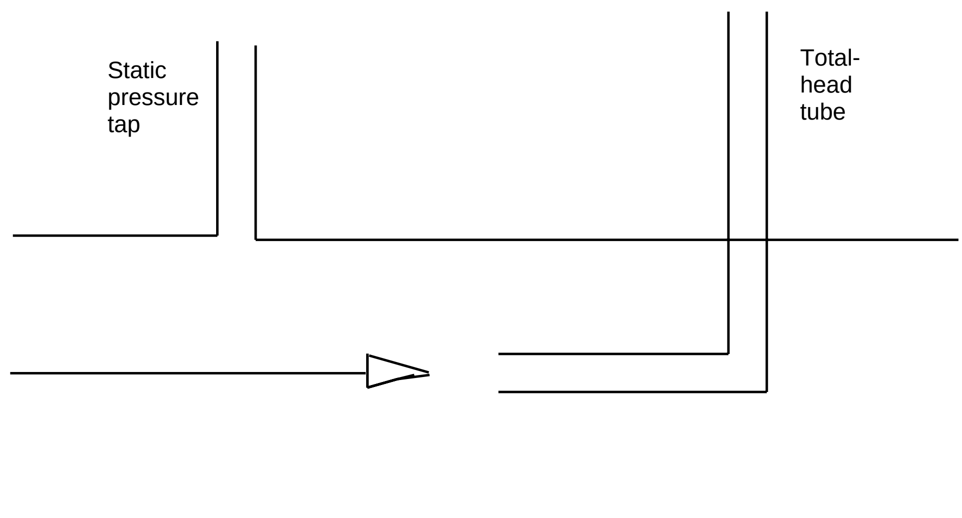

Figure 9: Total head tube.

Unit 4: Pipe flow

(a) Entrance effects and losses

The objective is to determine (i) the pressure distribution in the entrance region with and without the bell-mouth, and (ii) the friction factor in the fully-developed region. The flow of air is induced by a vacuum pump. The flow rate is measured by an orifice meter using a calibration constant and equation (7). There are several pressure taps along the length of the pipe, as shown in Fig. 10. The computer records the pressures and the positions of the pressure tap. The pressures along the pipe (not the orifice plate pressures) are displayed on the screen. Recommended reading: Sections 8-1, 8-6, 8-7.1. The concept of calibration is discussed in Unit 3.

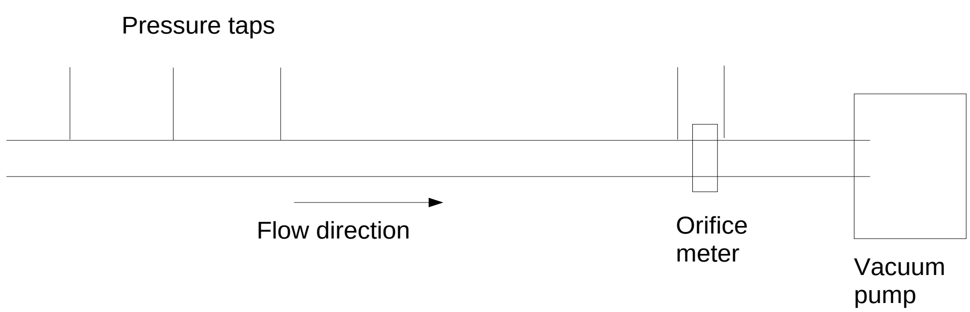

Figure 10: Air flow for entrance effects and friction factor.

The experiment can be done with and without the special bell mouth fitted to the entrance of the pipe. The entrance without the bell mouth exhibits a separation, as shown schematically in Fig. 11, which affects the pressure pattern. On the other hand, the pipe with the bell mouth, as shown in Fig. 12 has a much smoother entrance and does not have the separation region.

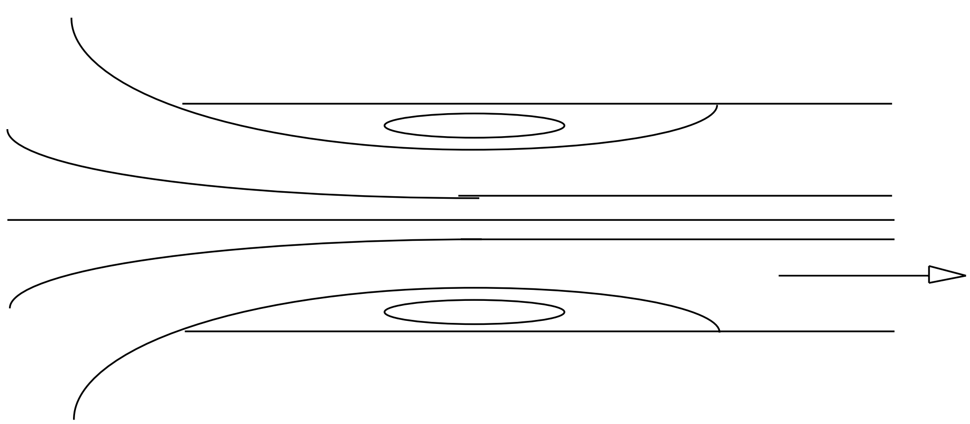

Figure 11: Streamlines at entrance to pipe without bell mouth.

The ports selected by the motorized Scanivalve are in sequence as one moves along the tube from the entrance towards the fan. Note that the first reading comes from a port not connected to the tube since it is used to read the pressure at the entrance,

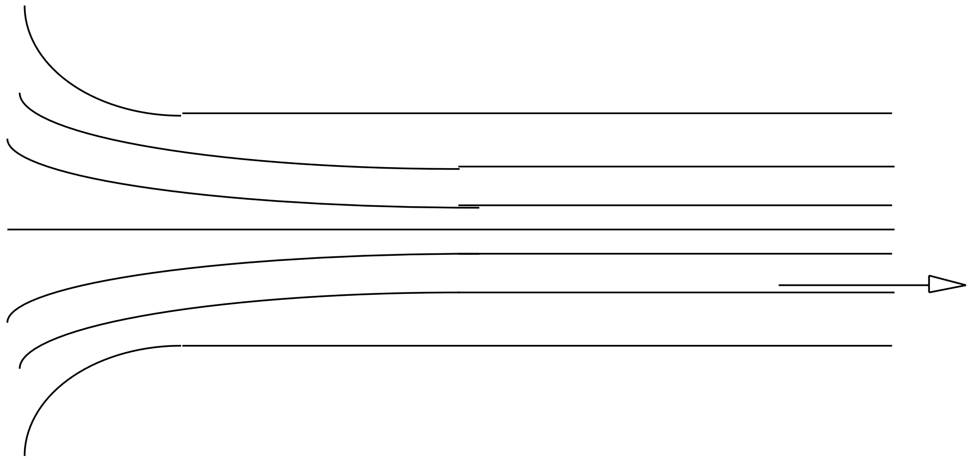

Figure 12: Streamlines at entrance to pipe with bell mouth.

i.e. the atmospheric pressure. The orifice meter has the last two connections. This pressure reading is then used to compute the gage pressures recorded in the data file.

(b) LFE and velocity profile

An LFE (laminar flow element) is a device that is often used to measure the flow rate in a pipe. The objective is to (i) determine the velocity profile in a pipe and (ii) to calibrate the LFE (i.e. find the pressure difference versus flow rate curve). An LFE and total-head rake are mounted on the same circuit as shown in Fig. 13. The rake provides the velocity profile from which the flow rate can be calculated. Recommended reading: Sections 6-3.3, 8-10.4.

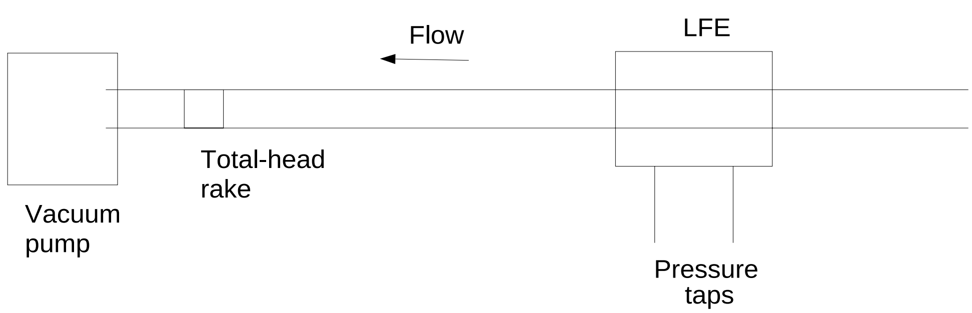

Figure 13: Set-up for calibration of LFE and velocity profile measurement.

A schematic of the LFE is shown in Fig. 14. The pressure difference across it is a measure of the flow rate through it.

The rake of total head tubes consists of 20 tubes that are 0.1 in. apart. The rake is symmetrically placed in the duct. The density of the air can be calculated from the ideal gas law at the measured temperature and static pressure. The inputs to the manual Scanivalve are from the pressure transducer. Therefore, when switch position 1 is chosen, the connected pressure source is output to the transducer. The

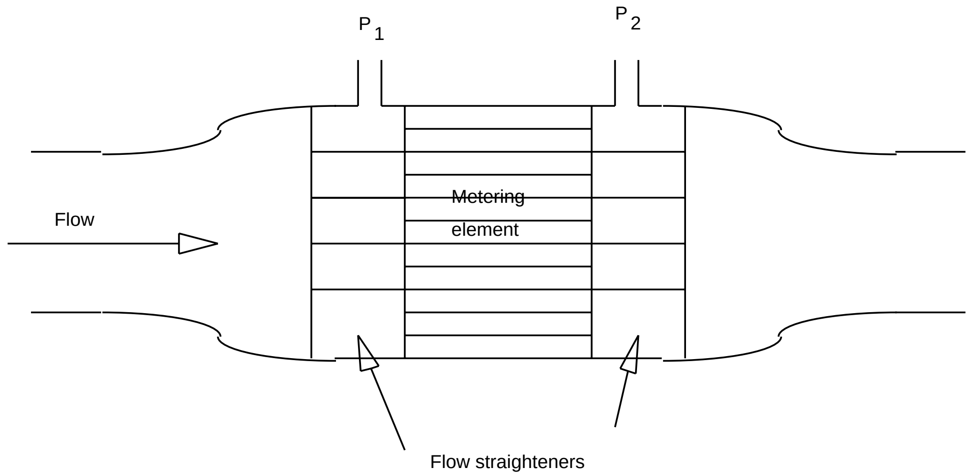

Figure 14: LFE.

twenty tubes of the total head rake have been connected in sequence. For each position on the switch the port directly behind is connected. Each total head tube thus measures the local velocity at a different location. After calculating the local velocities, the velocity profile in the duct can be graphed. Remember that the velocity at the wall is zero. Turbulent flows have a flattened velocity profile compared to laminar flows.

The volume flow rate, Q, may be numerically determined from the local velocity measurements made by the total head tubes, $V(r)$, using equation (16). The volume flow rate measured by the LFE and the total head rake should be the same. This enables the LFE to be calibrated.

Appendix

Major losses

The friction factor f in fully developed flow of an incompressible fluid in a horizontal pipe of constant cross-sectional area is defined by

$$h_f = f\ \frac{L}{D}\ \left(\frac{\overline{V}^2}{2g}\right) \tag{6}$$

where $p_1 - p_2$ is the pressure drop along a length L of the pipe, and D is the inner diameter of the pipe. Section 1 is upstream of 2.

Minor losses

The loss coefficient, K, in a fitting is defined by

$$h_f = K\frac{\overline{V}^2}{2g} \tag{7}$$

where K is the loss coefficient and $\overline{V}$ is the mean velocity. There is no confusion if $\overline{V}$ is the same on either side of the fitting. If, however, it is different, as in a contraction, it should be specified which side $\overline{V}$ corresponds to.

The length of straight pipe that would have the same pressure drop is given by

$$L_{eq} = \frac{K}{f}D \tag{8}$$

where L_{eq} is the equivalent length, f is the friction factor and D is the diameter of the straight pipe.

Total pressure

The total (or stagnation) pressure in an incompressible fluid is

$$p_0 = p + \frac{1}{2}\rho V^2 \tag{9}$$

where p_0, p and $\rho V^2/2$ are the total, static and dynamic pressures, respectively.

Differential pressure transducer

A differential pressure transducer gives a voltage corresponding to the difference between two pressures. There is an offset, i.e. the output is not zero even when the two pressures are the same.

Calibration

Calibration is a concept that is frequently used in relation to measuring instruments, and it is worthwhile discussing it in further detail. Consider an instrument which has an input x and output y. Taking the example of a pressure transducer, x may be a pressure difference, and y may be the voltage. In general, the output will obey some law of the form

$$y = f(x) \tag{10}$$

The calibration then is this curve. For every instrument, one needs the calibration curve to convert the output y into the input x.

Many instruments have strongly nonlinear calibration curves which must be reported as a graph or table. Sometimes, however, the curve is simple like, for example, a straight line. Thus, we may have

$$y = ax + b \tag{11}$$

Here a is a calibration (or sensitivity) constant being the slope of the y vs. x curve, and b is an offset. If this is the case, it is sufficient to provide the value of the two constants. Sometimes the same information is given in another form: the user is told that x psi gives a reading of y volts. Also since the offset is the reading of y for zero x, it is easily measured.

Scanivalves

A manual Scanivalve is analogous to a manual selector switch on an electronic device. It has several inputs that may be selected for connection to a single output. The motorized Scanivalve is a motorized version and operates on the same principle as the manual Scanivalve.

Load cell

The load cells used in this laboratory are Model LCL made by Omega. More information can be found in their Webpage:

http://www.omega.com/toc_asp/subsection.asp?subsection=F07&book=Pressure

Volume flow rate from velocity profile

The mean velocity at a given section of a duct, $\overline{V}$, is defined by

$$\overline{V} = \frac{Q}{A} \tag{12}$$

where Q is the volume flow rate, and A is the cross-sectional area.

The volume flow rate, Q, can be determined from local velocity measurements by numerical integration since it is related to the local velocity, $V(r)$ by

$$Q = 2\pi \int_0^R rV(r)\ dr \tag{13}$$

where R is the radius of the pipe. From Q we can calculate the mean velocity

$$\overline{V} = \frac{Q}{\pi R^2}$$

from equation (12).

To perform the integration from experimental data, we first divide the circular flow area along a diameter perpendicular to the measurement diameter to get two semi-circles. We find the flow rate in each semi-circle and then add them to get the total flow rate. We have $V(r)$ measurements at specific radial points on each semi-circle. Writing $V(r_1) = V_1$ and $V(r_2) = V_2$, we will assume that the velocity profile between the two points is linear, so that

$$V(r) = V_1 + \frac{V_2 - V_1}{r_2 - r_1}\,(r - r_1) \text{ for } r_1 \leq r \leq r_2 \tag{14}$$

The flow rate through a semi-circular strip between r_1 and r_2 is

$$\Delta Q = \pi \int_{r_1}^{r_2} rV(r)\;dr \tag{15}$$

Substituting for $V(r)$ and integrating, we get

$$\Delta Q = \pi \left[\left\{ V_1 - r_1 \frac{V_2 - V_1}{r_2 - r_1} \right\} \frac{r_2^2 - r_1^2}{2} + \frac{V_2 - V_1}{r_2 - r_1} \frac{r_2^3 - r_1^3}{3} \right] \tag{16}$$

This gives the flow rate in one semi-circular strip. Similarly, find the flow rates for all the other such strips and add to get the flow rate in the semi-circle. Remember that the fluid velocity at the wall is zero. Determine the flow rate in both semi-circles and add them to get the flow rate across the entire cross section.