PART IB EXPERIMENTAL ENGINEERING

SUBJECT: FLUID MECHANICS & HEAT TRANSFER EXPERIMENT T2
LOCATION: HYDRAULICS LAB (SHORT)
(Gnd Floor Inglis Bldg)

PIPE FLOW

OBJECTIVES

1) To note the changes in the character of the flow of a fluid down a pipe as the flow rate is increased.

2) To verify using two fluids (air and water) that, for suitable non-dimensional variables, the measured pressure drop due to friction is independent of the fluid used.

3) To compare the measured friction coefficient for low flow rates with that given by the theoretical relationship derived in lectures.

4) To determine an empirical relationship for the friction coefficients for high flow rates.

5) To note the use of an orifice plate as a simple, robust method of measuring flow rate.

INTRODUCTION

When a fluid, such as air or water, flows down a pipe, it loses momentum due to the action of friction between the fluid and the pipe walls. It is shown in lectures (and in Appendix A if you have not yet covered it), that the non-dimensional friction coefficient c_f, is a function only of the non-dimensional flow rate (which is more commonly called the Reynolds number).

$$c_f = f(Re)$$

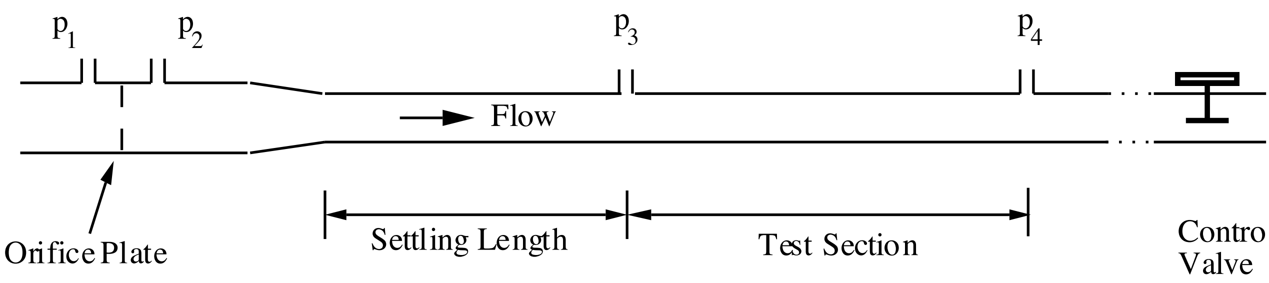
It is assumed in deriving this result that the pipes under consideration have varying diameters and lengths but are otherwise geometrically similar (an example, which is the one considered here, is straight pipes which all have a constant circular cross section and which all have smooth walls). In addition, it is assumed that the pressure drops involved are not sufficient to significantly change the density of the fluid.

The flow of a fluid down a pipe can be almost perfectly steady (laminar flow – found at low Reynolds numbers), or can take place in a highly disturbed manner (turbulent flow – found at high Reynolds numbers). The form of the relationship between friction coefficient and Reynolds number changes considerably in the two flow regimes.

One of the most common ways of moving fluids is through a pipe. A pressure gradient must be applied to restore the momentum lost by the fluid due to friction acting at the pipe walls in order to ensure an adequate flow rate. Pipes may be a few centimetres long (for example an engine lubrication system), a few metres long as in a chemical processing plant, or many hundreds of kilometres as is the case for oil and gas pipelines. The results obtained here (and related ones for rough pipes) are directly applicable to these problems and are thus of immense practical interest.

Good quality results can be obtained for this experiment if care is taken.

EXPERIMENTAL ARRANGEMENT



The fluid enters from the left (the rigs are in mirror image pairs) and flows through an orifice plate. This has been calibrated (see Appendix B) and the flow rate through it can be infered from the pressure drop across it. The fluid then flows through a settling length to ensure that the flow is fully developed in the test section (i.e. it is no longer changing in the downstream direction). The flow rate is controlled by a valve downstream of the test section. The readings to take are thus the pressure drop (p_1 - p_2) across the orifice plate and the pressure drop (p_3 - p_4) across the working section.

For the air test a vacuum cleaner provides the air flow, and the pressures are measured on two inclined-tube alcohol manometers mounted on the same board. You should verify that the first manometer measures the pressure drop across the orifice plate and the second that across the test section.

For the water test the flow is provided by an overhead tank and the pressure drops are measured on two identical air-water manometers. The difference between the two limbs for the first manometer measures the pressure drop across the orifice plate and the difference between those of the second measures the pressure drop across the test section.

PROCEDURE

There are six identical experimental rigs. Three of them are set up for air and three for water. The first 45 minutes are spent on one of these rigs (it does not matter which). At the end of this period change over to the one that uses a different fluid. For each case:

a) measure the pressure drop along a smooth straight length of pipe for different flow rates as indicated below.

b) calculate the corresponding values of friction coefficient and Reynolds number, Re, and plot these on the log-log paper provided taking Re as abscissa. (Using different symbols for air and water).

You should change rigs no later than 1 hour after the start of the lab period.

Air Test

1) Read briefly Appendix B and convince yourself that the non-dimensional flow rate and non-dimensional friction coefficient are given by

$$Re = K_{ra}\frac{\sqrt{p_1 - p_2}}{\nu_a} \qquad\qquad c_f = K_{fa}\frac{p_3 - p_4}{p_1 - p_2}$$

where the difference in pressure p_1-p_2 and p_3-p_4 are the manometer readings in **millimetres** of water, ν_a is the kinematic viscosity of air measured in m^2s^{-1}, and $K_{ra}=5.31 \cdot 10^{-3}$ and $K_{fa}=8.25 \cdot 10^{-3}$ are constants.

2) For air, the viscosity depends on pressure and temperature. Measure the air temperature and pressure using the thermometer and barometer alongside the rigs and obtain the value of ν_a from the chart provided.

3) Level the base of the manometers using the spirit level and adjust the reservoirs so that the bottoms of the meniscuses are accurately on zero.

4) Switch on the vacuum cleaner and set the control valve to give a reading of about 1 mm on the orifice-plate upstream manometer (p_1-p_2). Read the two manometers (making your estimates to within 1 mm), calculate c_f and Re and plot them on the log-log paper provided.

5) Repeat the readings for successively higher flow rates. Since the results are plotted on a log-log scale, evenly spread data points will correspond to successive values of p_1-p_2 which represent an increase by a constant multiplicative factor. A value of about 1.5 for the multiplication factor is recommended.

6) Observe the point where the trend in the readings change more rapidly or are unstable, and take additional points around this range. This is the point of transition to turbulence.

Pressure (mmHg)	Temperature (°C)	ν/ν_o (–)	ν (m^2/s)

$p_1 - p_2$ (mm)	Re (-)	$p_3 - p_4$ (mm)	c_f (-)

Water Test

1) Read briefly Appendix B and convince yourself that the non-dimensional flow rate and non-dimensional friction coefficient are given by:

$$Re = K_{rw} \frac{\sqrt{p_1 - p_2}}{\nu} \qquad c_f = K_{fw} \frac{p_3 - p_4}{p_1 - p_2}$$

where the pressures are the manometer readings in **millimetres** and ν is the kinematic viscosity of water measured in m^2/s , and the constants are $K_{rw} = 3.52 \cdot 10^{-4}$ and $K_{fw} = 1.60 \cdot 10^{-2}$.

2) For water, the viscosity depends on temperature. Measure the water temperature using the thermometer which is set into the outlet flow of one of the water rigs and obtain the value of ν from the chart provided.

3) Check for each manometer that, with no flow, the levels are the same in the two limbs.

4) Check that all valves upstream of the working section are open and then set the control valve to give a reading of about 2 mm on the orifice-plate manometer (the difference in the levels) . Read the two manometers (making your estimates to within 1 mm), calculate c_f and Re and plot them on the log-log paper provided.

5) Repeat the readings for successively higher flow rates. Since the results are plotted on a log-log scale, evenly spread data points will correspond to successive values of the pressure difference which represent an increase by a constant multiplicative factor. A value of about 1.5 is recommended for the factor.

Temperature(°C)	ν/ν_o (–)	ν (m^2/s)

p_1 (mm)	p_2 (mm)	$p_1 - p_2$ (mm)	Re (-)	p_3 (mm)	p_4 (mm)	$p_3 - p_4$ (mm)	c_f (-)

DISCUSSION

1. Include on the graph of your results the theoretical relation (which will be derived in lectures)

$$c_f = \frac{16}{Re}$$

and compare it with your results for low flow rates.

2. Estimate the values of Reynolds number for which transition from laminar to turbulent flow was found to begin at about Re =

and to be complete at about Re = .

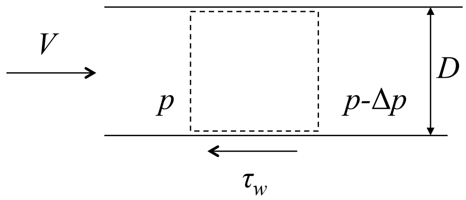
3. Draw the best line through your experimental results for fully turbulent flow and determine an empirical power relation between c_f and Re,

$$c_f = A\ Re^b$$

4. Given your values of c_f, estimate the pressure drop per km along a 2 m diameter storm water drain when the flow rate is 5 m/s.

5. Re-read the objectives of the experiment, and verify that you have met these goals.

APPENDIX A



Consider the flow through the dashed control volume above, along a length Δx. Since the flow is steady (for turbulent flow in the sense that mean quantities do not vary with time), the total mass flow rate and momentum flux entering and leaving the volume is constant. For negligible density changes, therefore, the velocity is unchanged across the volume. Therefore, there is also no momentum change, and the pressure forces across the volume along the direction of flow must be balanced by the viscous forces along the wall:

$$[p - (p + \Delta p)]\frac{\pi D^2}{4} - \tau_w \pi D \Delta x = 0$$

$$\Delta p = \frac{4\Delta x}{D}\tau_w$$

It is convenient (and convention) to non-dimensionalise τ_w for a section of pipe of length L in the form of a friction coefficient:

$$c_f = \frac{\tau_w}{\frac{1}{2}\rho V^2} = \frac{4D}{L}\frac{\Delta p}{\frac{1}{2}\rho V^2}$$

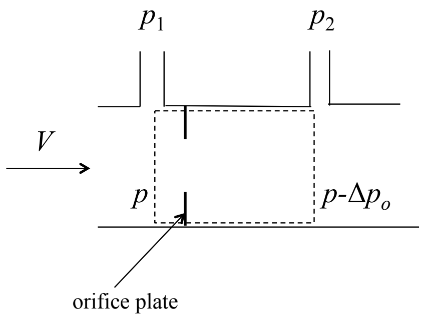
The pressure drop across the length of pipe, $\Delta p = p_3 - p_4$, is measured using manometers, in units of height of a liquid. The velocity is obtained from the relationship between the pressure drop across the orifice plate upstream and the corresponding pressure drop (Appendix B).

We expect the non-dimensional friction coefficient to be a function of the five independent variables V, D, μ and ρ (the pressure drop is a function of these). From dimensional analysis, these can be combined into a single dimensionless group, which is conventionally taken as the Reynolds number:

$$Re = \frac{\rho V D}{\nu} = \frac{VD}{\nu}$$

where $\nu=\mu/\rho$ is the kinematic viscosity. Appendix B explains how the friction coefficient and Reynolds number are obtained from the measurements.

APPENDIX B



An orifice plate is simply a plate with a hole in it, mounted in a pipe as shown. A force balance follows in a very similar manner to that used in Appendix A, where instead of a shear force at the we have in general viscous losses. Here we connect the non-dimensional pressure loss via dimensional analysis, which is also expected to be a function of the Reynolds number.

$$c_{f,o} = \frac{p_1 - p_2}{\frac{1}{2}\rho V^2} = f(\frac{VD}{\nu})$$

Unlike the pressure drop in pipes, the friction coefficient for the orifice is only a weak function of Reynolds number. In this experiment, this variation is neglected. This means that, for the air flow test we can obtain the velocity from a known pressure drop.

$$V = \sqrt{\frac{2}{\rho c_{f,o}}}\sqrt{p_1 - p_2}$$

The Reynolds number can therefore be obtained from the pressure drop across the orifice:

$$Re = \frac{VD}{\nu} = D\sqrt{\frac{2}{\rho c_{f,o}}}\frac{\sqrt{p_1 - p_2}}{\nu}$$

and the friction coefficient for the pipe length derived in Appendix A is:

$$c_f = \frac{D}{2L}\frac{\Delta p}{\rho V^2} = \frac{1}{2c_{f,o}}\frac{D}{L}\frac{p_3 - p_4}{p_1 - p_2}$$

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