Viscous Flow

Motivation

Purpose of this experiment is to clarify the idea of viscous flow in pipes. The concepts of pressure head, fluid friction, laminar and turbulent flow, pressure loss mechanism in them, Calculation of pressure drop and friction in pipes would be revised here. Before performing this experiment you must go through

- Friction factor
- Head loss in pipes
- Absolute and relative friction in pipes.
- Moody diagram and its utility
- Reynolds number. Boundary layer
- Laminar and turbulent flow in a pipe. Pressure drop in laminar and turbulent flows

Introduction

The term “fluids” is understood by scientists and engineers to mean both gases and liquids. Gases and liquids have a strong family resemblance which is demonstrated by the fact that gases can be liquefied by reducing temperatures and increasing pressures as liquids can be classified by the converse. Certain fluids (liquids) are considered to be incompressible, although this is not strictly so, since liquids can be compressed very slightly; however, it is substantially true for all practical purposes. There is a considerable range of environmental operating conditions in which common gases, such as air, are considered to be incompressible. For example, the compressibility of air is changed mainly by velocity and temperature. Velocity alone begins to change the performance of aerodynamic bodies at about three quarters the velocity of sound (Mach number = 0.75). Up until recent years the maximum velocity of aircraft was subsonic, well below the velocity of sound, and aerodynamic theory relating to performance, and calculations relating to structural strength did not recognize any influence due to air compression. More recently, in engineering problems associated with aircraft capable of flying near the speed of sound, and other supersonic velocities where a compression wave literally piles up in front of the aircraft, an appropriate mathematical treatment must be employed. The physical laws which control the behavior of fluids, in both compressible and incompressible type flow, are generally the same with certain deviations. In the experimental work in which this manual is used, only incompressible flow needs to be considered.

These experiments serve as an introduction to hydraulic engineering, a vast subject occupied with the transportation and control of fluids, the means for increasing the energy content of fluids, and the ways in which energy either already existing or added may be extracted as power. These processes occur in plants where power is generated by heating water to produce steam and then using the thermal energy to drive engines or turbines to deliver useful mechanical power. Huge hydraulic power plants make use of potential energy of water stored high in lakes behind dams. The water is transported down to large turbines which extract energy converted from potential to kinetic by gravity and finally the turbines drive electric generators to power factories and supply domestic heat, light, and power for cities. Canals and locks have served as highways for shipping from ancient to modern times. The Romans were advanced hydraulic engineers in their time, and today the great works of the St. Lawrence Seaway have no equal in engineering achievement in all world history. Bulk fluids are transported today in ships plying canals, rivers and the oceans. No less important is the network of pipe lines crisscrossing this and other continents through which gas, oil, and powered coal are pumped on their way to consumers, night and day. Pumping machinery, turbines (all kinds), compressors, flotation and buoyancy equipment, the hydrodynamics of ship hulls, the aerodynamics of aircraft, offshore well drilling, the science of cryogenics - all of these are the concern of the fluid dynamics engineer.

Theory

The physical properties of fluids are normally understood to be defined by pressure, temperature, density, and viscosity. Pressure, P, when associated with experimentation of the type of apparatus herein described is usually expressed in inches of water column (which can subsequently be converted to psi, Pa, etc.). Temperature, T, is normally expressed in degrees Fahrenheit. Density, ρ, is expressed in slugs per cubic foot, however, you should be aware that in practice most engineers will use the units of pounds per cubic foot and refer to this as the density when in actuality it is the specific weight. Viscosity of a fluid is the property which causes resistance to flow due to shearing forces within the fluid itself. A characteristic called dynamic (absolute) viscosity, μ, is the ratio of shearing stress to the rate of shear. In general, changes of temperature have a great effect on the viscosity; however, changes in pressure have only a slight effect.

The force required to overcome the shearing resistance between adjacent layers of a fluid moving at different velocities is directly proportional to the absolute viscosity, the area in shear, the relative velocity between adjacent moving fluid layers, and is inversely proportional to the thickness of the moving films. Consider Figure 1 below showing stationary plate (1), and a moving plate (2), in between which is a fluid film (3).

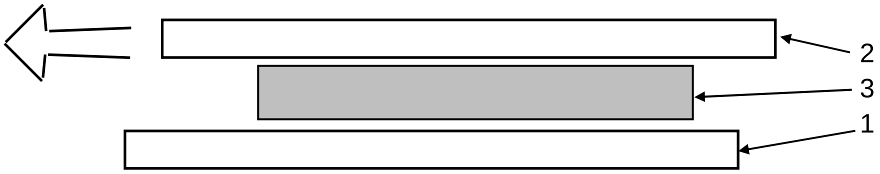

***Figure 1**, Fluid Shear Force*

Assume there is no relative movement between each plate and the molecules of fluid immediately in contact with the plates. There is a shearing displacement of the molecules in the fluid itself across the profile of the fluid. Therefore, the shearing force, F, required to move the upper plate at a velocity, v, is

$$F = \frac{\mu A_s v}{d} \tag{1}$$

$$\mu = \frac{F/A_s}{v/d} \tag{2}$$

As the physical characteristics of a fluid vary, so does the energy content of the fluid. For example if pressure or temperature or both are increased in a fluid, its energy will be increased. When temperature and pressure are reduced, as in the case of the fluid performing work, then the energy is reduced and converted to work. Energy is considered to be one of these three types;

1) ***Potential Energy*** is the energy possessed by a fluid by reason of its height with reference to a datum plane; for example, one pound of a fluid at an elevation of 100 feet above a zero plane would possess potential energy of 100 foot-pounds
2) ***Kinetic Energy*** is the dynamic energy derived from the motion of the fluid and varies as the velocity squared.
3) ***Pressure Energy*** is the energy associated with static pressure, the pressure which would be sensed by an observer moving with the fluid, and the pressure provided by the static pressure taps used in the Model 9009 Fluid System.

Specific Consideration of Incompressible Fluid Flow through Channels, Pipes, and Fittings

In the particular study of incompressible fluid flow it is usually considered that the density, viscosity and temperature do not change and that the specific weight is a constant. For a selected diameter and length of pipe, pressure losses are experienced due to friction effects which are a function of the Reynolds Number, Re. Reynolds Number is a quantity which relates the density of the fluid, viscosity, and the mean velocity of the fluid within the pipe. There are large variations in the resistance as Reynolds Number changes. Reynolds Number is defined as the ratio of the inertia forces in the fluid to viscous forces and is expressed mathematically as

$$\mathrm{Re}_{\mathrm{D}} = \frac{\rho \mathrm{Dv}}{\mu} \tag{3}$$

Whenever fluid flows through a pipe or channel of any kind, or over and around an object, there is always a drag caused by friction between the fluid and the surface of the pipe, channel, or object. This friction accounts for a loss of mechanical energy which appears as a reduction in pressure downstream. Friction and loss of pressure are the result of viscous drag (see Figure 1) and by energy dissipation in eddies and turbulence. When the flow is laminar (very smooth and free from eddies), the energy loss is principally due to viscous drag, but when the flow is turbulent, the losses are principally due to turbulent eddy formations. There is a region of flow between laminar and turbulent called the transition range, which cannot be defined definitely in either category of flow.

The entire spectrum of energy losses from laminar through the turbulent regimes of flow, are expressed as a function of the Reynolds Number. The Moody diagram, Figure 2, represents the relation between Reynolds number and the friction factor, f, a constant of proportionality in the Darcy-Weisbach flow equation, equation (4).

$$h = f \cdot \left(\frac{L}{D}\right) \cdot \frac{v^2}{2g} \tag{4}$$

As observed from the Moody diagram, at low flow-laminar regime, the friction factor is a strong function of Reynolds Number. The exact relationship can be developed from the Hagen-Poisuelle equation for laminar pipe flow as

$$h = \frac{32 \mu L v}{D^2 \rho g} \tag{5}$$

Rearranging equation (5) in the form of equation (4) given above by multiplying and dividing by 2/v yields

$$h = \frac{32\mu}{D\rho} \cdot \frac{2}{v} \cdot \frac{Lv^2}{2Dg} = \frac{64\mu}{D\rho v} \cdot \left(\frac{L}{D}\right) \cdot \frac{v^2}{2g} \tag{6a}$$

Substituting the Reynolds number yields

$$h = \frac{64}{\mathrm{Re}_D} \cdot \left(\frac{L}{D}\right) \cdot \frac{v^2}{2g} \tag{6b}$$

A comparison of equation (6b) with equation (4) indicates that for laminar flow

$$f = \frac{64}{\mathrm{Re}_D} \tag{7a}$$

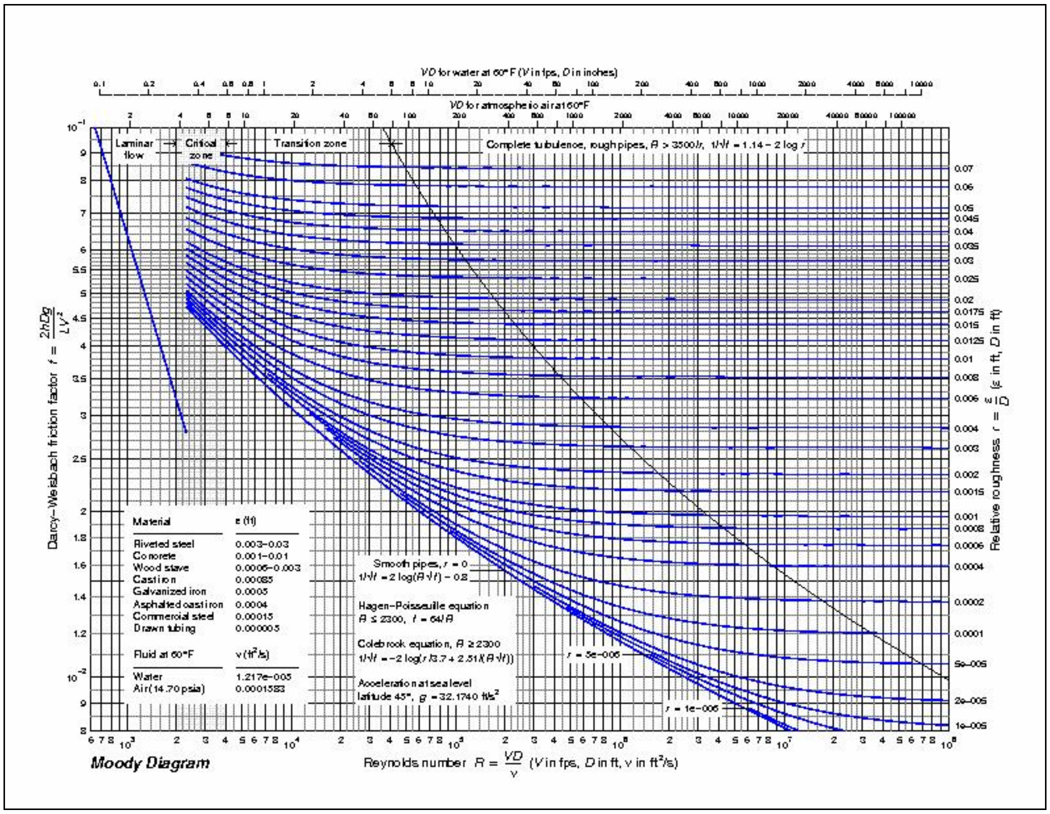

***Figure 2**, Moody diagram*

Equations (6b) and (7a) have been experimentally proven valid up to a critical Reynolds number value of about 2200 as indicated on the graph. An experimental form of the Darcy friction factor which is valid for any Reynolds number is given as

$$f = \Delta P \Big/ \left(\frac{L}{D}\right) \cdot \rho \frac{v^2}{2} \tag{7b}$$

where

$$\Delta P = \rho \cdot g \cdot \Delta h \tag{7c}$$

$$v = \frac{V}{A_p \cdot t} \tag{8}$$

A microscopic examination of the interior wall of any tube or pipe will show that its surface is quite rough and irregular, although to the naked eye or by sense of touch it may appear to be smooth. This is a natural consequence of the manufacturing techniques for commercially produced pipe. Because such methods of fabrication have been standardized for almost every type of pipe and tube, a measure of this roughness effect has been evaluated for each. The roughness is expressed as the average length of the microscopic protuberances from the tube wall and is generally given the symbol, ε. Values of ε range from .000005 ft. for seamless tubing to about 0.01 ft. for riveted steel pipe. As was explained previously, fluid particles move at different velocities at various pipe radii. This relative motion, ranging from zero at the wall to a maximum at the center-line, is due to the momentum interchange and subsequent shear that occurs between adjacent fluid layers. For laminar flow, the velocity profile across a pipe diameter assumes a parabolic shape as shown in Figure 3.

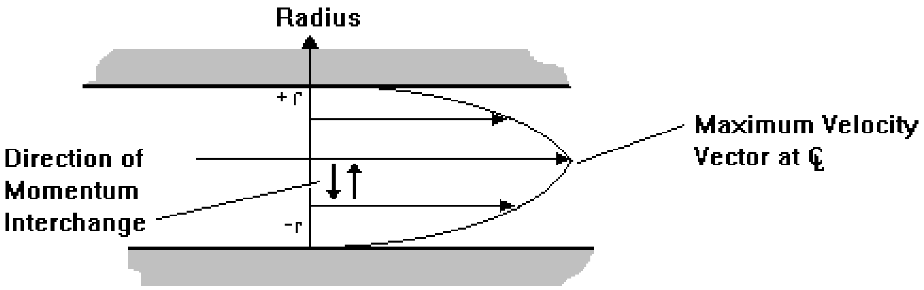

***Figure 3**, Laminar Velocity Profile*

As the Reynolds Number increases significantly beyond it's critical value ($Re_{D,C}$ = 2200) the momentum interchange between fluid layers becomes greater and greater, changing gradually from a micro scale under laminar conditions to a macro scale at fully turbulent flow. Such motion tends to flatten the velocity profile (Figure 4).

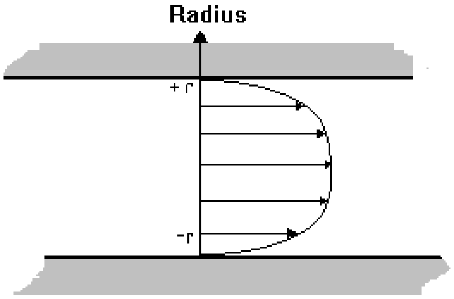

***Figure 4**, Turbulent Velocity Profile*

From the Moody diagram, it is immediately clear that at high flow rates the friction factor becomes totally independent of the Reynolds Number, whereas in the laminar regime, the functional relationship has been previously developed as equation (7a). This apparently anomalous behavior can best be explained by a closer examination of the flow phenomena in the vicinity of the tube wall. In this region the velocity change is most rapid between adjacent fluid layers and therefore the energy dissipation is greatest. Because the fluid velocity at the wall is zero, the flow closest to the solid boundary is laminar and this region is commonly termed the boundary layer. For the conditions shown in Figure 3 where the entire flow field is laminar, the boundary layer builds up until it actually reaches the pipe center-line, hence the parabolic type velocity profile and the dependence of friction factor on Reynolds Number. On the other hand, however, for the case described by Figure 4 the boundary layer remains quite thin. It is, in fact, often considered to be composed of two regions: a laminar sub-layer closest to the wall and a thicker turbulent boundary layer where momentum interchange occurs primarily by relative macro fluid motion. This phenomena is illustrated in Figure 5. As is observed in the sketch, the thickness of the sub layer is of the same order of magnitude as the rough protuberances from the bounding wall. It is precisely these projections into the turbulent flow field that provide the main contribution to the frictional energy loss measured by the pressure drop along the fluid direction.

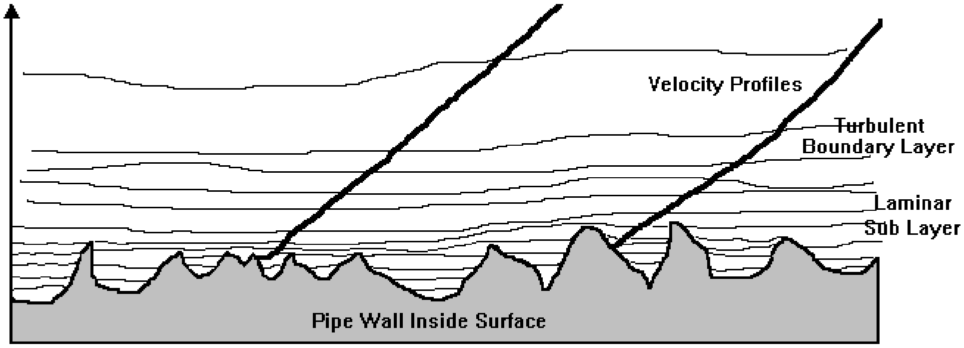

***Figure 5**, Turbulent Flow Boundary Layer*

In summary, one can now simply explain the observed friction factor - Reynolds Number - roughness ratio relationship over the entire continuum flow regime. Under laminar flow conditions, the boundary layer extends throughout the flow field. The roughness projections, because they are so small relative to the thickness of the boundary layer, are not “sensed” or “felt” by the main core of flowing fluid and thus contribute a negligible amount to such frictional losses. As the fluid throughput increases, however, the boundary layer becomes much thinner and the roughness effect becomes more pronounced. At extremely high rates of flow, these projections are the primary cause of pressure loss and so the friction factor is not dependent upon Reynolds Number, but rather, it is a function of the relative roughness, ε/D, only. Between these two extremes exists a gradual transition region from laminar to turbulent flow where the energy loss is accounted for by contributions from both of these sources.

Apparatus

The fluid Circuit System --Model 9009 - is shown in Figure 6. This equipment is designed to provide you with experience through laboratory experiments in which measurements are taken and in connection with which mathematical analyses are made concerning the characteristics of fluid flow in piping networks. It is intended to provide a series of experiments which will enable you to gain an understanding of the pressure changes which occur in fluids in motion and the characteristics of pressure and flow measurements. In general, the characteristics of fluids in the type of circuits exemplified in this particular piece of apparatus will exhibit pressure changes through the system in response to changes in input pressure, rates of flow and resistance to flow. In practical applications, one is usually interested in pressure losses. The past proposed methods used in the preparation and the conduction of experiments do not provide the development of the basic theory of flow in pipes. Experience has shown that a better approach is found when one begins to experiment immediately, then during the course of such experimentation and at the conclusion of your tests you will work out the fundamental relationships which are involved in the behavior of fluids using your own data. This plan appears to result in an improvement in interest and motivation as well as better retention of the fundamental relationships.

This equipment consist of four pipes designated 1 through 4, a pump and motor set (5), a supply tank (6), associated valves and fittings, means for making flow measurements (7, 8, and 9), points for sensing pressures (22-33) and (34-41), and means for making pressure measurements (42, 42). The piping network and fittings are manufactured from copper and brass and the tank is epoxy lined so that little or no difficulty should be experienced from corrosion.

The main tank should not be filled to a greater capacity than is indicated on the tank scale, nor should it be emptied (during an experiment) to less than the scale marking for zero. When the pump is turned on after a period of idleness, some water from the tank is required to fill the pipe system. It is for this reason that a timed or flow rate test be started, not when the pump is turned on, but five to ten seconds thereafter. Similarly, at the conclusion of a test, water may continue to flow temporarily due to capillary effects, or inertia, or water from the system may drain back into the tank. For this reason, the final reading on the tank scale should be taken just before or at the time the pump is turned off.

The experimental test fixture has the following characteristics:

Piping

Type L Drawn Copper Water Tubing

Dimensions:

Pipe #	Nominal Size (in)	O.D. (in)	I.D. (in)
4	1	1.125	1.025
3	3/4 (0.75)	0.875	0.785
2	1/2 (0.5)	0.626	0.545
1	3/8 (0.375)	0.500	0.430

Pressure tap locations: 0” and 60”

Maximum Reynolds Number in pipes is approximately 35,000

Orifice: Orifice Diameter: 0.625”

Venturi: Venturi entrance diameter: 1.025” and Venturi throat diameter: 0.625”

Storage Tank: Capacity: 14 gallon, Inside diameter: 12", Tank is vented to lab

Pipe Length: 60”

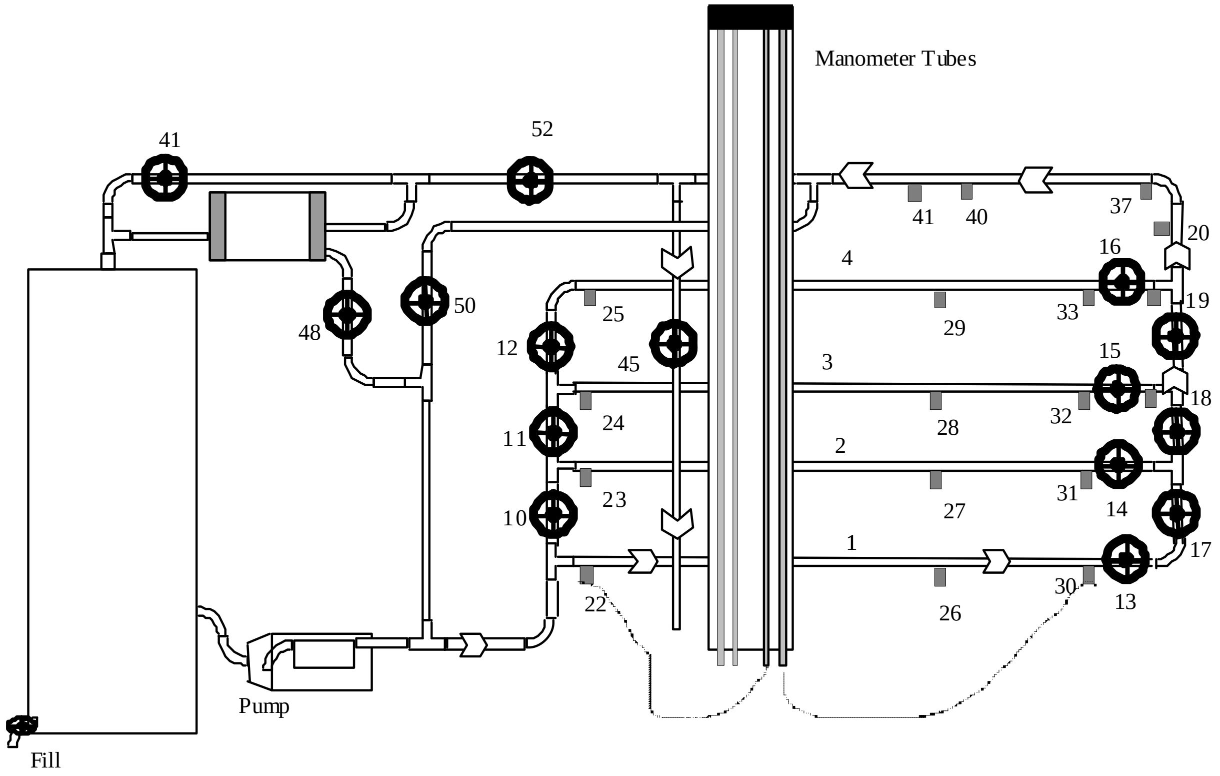

Figure 6, *Fluid Circuit System (Model 9009)*

Objective

To calculate the relative roughness of the 3/8” (pipe #1) and the 1” (pipe #4) pipes in an effort to find their corrected diameters.

Requirements

Assuming pipe diameter given is correct

1) Calculate the Reynolds Number and friction factor for each pressure drop. Use equation (7b), not equation (7a), to calculate the friction factor.
2) Using the Colebrook equation, find values of ε/D for each pressure drop (the Colebrook equation can be found from the internet or a typical fluids book). Find the mean value and values for +/- one standard deviation. Note that the Colebrook equation cannot be used for the laminar or transition region.
3) Using the spreadsheet given by the instructor (called moody.xls and can be found on the class website) create a log-log plot (moody diagram) of: (a) expected value ε/D (b) mean value ε/D from 2), (c) plus one standard deviation value ε/D from 2) and (d) minus one standard deviation value ε/D from 2).

Estimating the corrected pipe diameter

1) Using a parametric modeling process use a spreadsheet (moody.xls) that allows for all calculations to be based upon the single parameter "D", the diameter of the pipe and create another Moody diagram. Change the value of "D" until the data points follow the trends existing in the Moody (minimize the standard deviation).
2) Record the corrected value of "D" found and the corresponding value of ε/D.
3) Perform uncertainly analysis using one set of reading from the data sheet.

Note: For your Moody diagram, make the chart as large as possible and don’t use the default gray backing. Make trend lines appear as constant lines and data points appear as singular points.

Procedure

Preparation for 3/8” pipe

1) Close all valves except 13, 17, 18, and 19.
2) Ensure that the storage tank is filled to about 40th division and subsequently stays there during testing. In other words, filling of the tank is necessary after every iteration of testing. Failing to do this will give results that are wrong. Adjust by opening the fill tank valve located at the bottom of the fill tank on the lower left of the test apparatus.

Experiment

1) Weigh bucket. Place outlet hose in bucket and turn the pump on. Open valve 45 to start the fluid flow. While monitoring the flow meter, fill the bucket with 1 gallon of water (One full revolution of the flow meter). Measure the water temperature to find the water properties needed in the equations. Weigh the full bucket and verify that the meter is measuring one gallon of water. Most likely, there will be more than one gallon in the bucket. The results can be normalized before using them in the equations described earlier in the report. Also, there is no need to weigh the bucket every time. Close the valve.
2) Reposition the outlet hose over the floor drain. Use valve 45 to regulate the pressure drop as needed. Measuring the differential pressure can be done by reading the pressures from the two columns of

the monometer and taking the difference. Adjust the fill hose valves to maintain the water level in the tank.

3) Use the flow meter to find the flow rate of water (One complete revolution of flow meter is equivalent to one gallon of fluid per unit time).
4) Repeat steps 2 and 3 for the remaining pressure drops.
5) Close valve 45, 13, 17, 18, 19, 22 and 30 (note: valves 22 and 30 are small and delicate). Turn off the pump. Turn off valve at bottom of tank.

Preparation for 1" pipe

1) After ensuring all valves are closed, open valves 10, 11, 12, 16, 25 and 33 (note: valves 25 and 33 are small and delicate).
2) Ensure that the storage tank is filled to about 40th division and subsequently stays there during testing. In other words, filling of the tank is necessary after every iteration of testing. Failing to do this will give results that are wrong. Adjust by opening the fill tank valve located at the bottom of the fill tank on the lower left of the test apparatus.

Experiment

1) Use valve 45 to regulate the pressure drop as needed. Measuring the differential pressure can be done by reading the pressures from the two columns of the monometer and taking the difference. Adjust the fill hose valves to maintain the water level in the tank.\
2) Use the flow meter to find the flow rate of water (One complete revolution of flow meter is equivalent to one gallon of fluid per unit time).
3) Repeat steps 2 and 3 for the remaining pressure drops.
4) Close valve 45. Turn off the pump. Turn off valve at bottom of tank. Turn off the valve at wall.

Removing trapped air from the system (Optional - Ask the instructor before performing this procedure)

When this unit is first placed in operation, and thereafter when the apparatus has been standing for sometime, air will become trapped in the pipes and in the water columns of the manometer tubes, which is difficult to remove unless a prescribed procedure is followed. Also, there are some experiments which, by their nature, require moving the rubber tubes, leading from the manometer to various pressure taps in the system, while numerous functional conditions exist. This may result in air bubbles forming in the manometer and manometer tubes. There is no way to avoid these air bubbles all of the time, but the problem can be minimized.

1) Fill the tank (6) in excess of 8 gallons with clean, clear water.
2) Turn the pump "off" if you had it "on" during filling.
3) Close valves 44, 45, 48, 50. Open all others (when using the system as a discharge circuit, substitute valve (45) for (52) in this and following procedures).
4) Attach the four rubber hoses from the manometer to any four pressure taps in the system. Open the four valves. Close all others.
5) Close the two finger vent-screws at the top of the manometer.
6) Turn the pump on. The water and air entrapped in the system will be pumped through the visual observation tank and it will be observed that air bubbles are coming out of the inlet pipe to this tank. Continue until the discharge into the tank appears to be free of air. Close valve (52). At this point of the procedure, it will be observed that the water remaining in the visual observation tank (47) will gradually flow into the main tank, replacing air in the main tank. The air will bubble back through the discharge line into the visual observation tank, filling this tank with air. During this process any slight pressure differential existing in the two tanks will be eliminated because of the air vent at the top of

the main tank. The piping system is now full of water excepting for the air spaces in the two tanks, and other possible air pockets which will be eliminated as follows

7) Have ready a cup or container to collect water
8) Close one of the valves mentioned in step 4 and remove the manometer tube from this pressure point. A good method is to crimp the rubber tube as illustrated.
9) Release the pinched tube while holding it over your container to permit water and any air bubbles to be forced through and out of the manometer into the container.
10) Pinch the tube again and connect to a pressure point on the pipe system. Open the associated valve.
11) Note that one side of the manometer is clear of bubbles. Repeat steps 7, 8, 9, and 10 for the other side.
12) Shut off the pump.
13) Very slowly open the two vent screws, one at a time, at the top of the manometer. Air will enter from the top of each pair of tubes and slowly permit the two water columns to drop (the levels being the same) until they reach about midway on the scale. Close the vent screw.
14) If a few bubbles are present after step 13, either of the two processes will eliminate them.
    a) Double the appropriate rubber tube connected to the manometer and squeeze several times rapidly to eliminate any residual bubbles that may be trapped in the clear plastic tube.
    b) Turn the pump on, then off again. Repeat.
15) Close the four valves
16) At this time the bubbles should have been completely eliminated, and the level of the water in either pair of the manometer tubes should be equal. All four levels do not need to be the same, only each pair.
17) The entire system is now ready for operation.

Nomenclature

A = area
d = film thickness
D = hydraulic diameter (normally inside diameter)
F = shearing force
g = acceleration due to gravity
h = frictional energy (head) loss due to flow
L = length of pipe
P = pressure
Re = Reynolds number
t = time
v = velocity
V = volume
f = Darcy friction factor
ε = roughness
μ = absolute viscosity
ρ = density

Subscripts

c = critical
s = shear
p = pipe (internal)

References

Munson, B. R., Young, D. F., and Okiishi, T. H., *Fundamentals of Fluid Mechanics*, John Wiley and Sons, New York, 1990.

Data Sheet (3/8” pipe)

(Check with the GTA for which pipe to use)

Pressure Drop (in. H_2O)	Flow Rate of Water (Gallons Per Minute)
1/2	
3/4	
1	
2	
4	
8	
16	
32	
60 (or close to it)	

Temperature of Water

Student Names:

Date:

Instructor's Initials

Data Sheet (1” pipe)

(Check with the GTA for which pipe to use)

Pressure Drop (in. H_2O)	Flow Rate of Water (Gallons Per Minute)
1/2	
3/4	
1	
2	
4	
8	
16	
32 (or close to it)	

Temperature of Water

Student Names:

Date:

Instructor's Initials