Department of Chemical and Biomolecular Engineering
University of California, Irvine

CBE 140A: Fluid Friction Through Pipes and Fittings

1 Introduction

The industrial applications of transport phenomena are ubiquitous: fluids must be transported between unit operations at desired flow rates while minimizing utility cost for pump operation. Fluid flow can be categorized as either laminar, transitional, or turbulent with each regime having unique properties. With this apparatus, flow characteristics of each regime will be investigated.

2 Objective

The flow characteristics of water are to be investigated in: several diameter pipes of varying roughness levels, a wide range of fittings, and through several metering devices. The characteristic relationship between a pump's volumetric output and the pressure of the outlet fluid, often referred to as a pump curve, can also be explored.

3 Theory

Osborne Reynolds was the first to investigate the transition between laminar and turbulent flow in cylindrical pipes in his paper from 1883. [1] Defining a dimensionless group, the Reynolds number, in the following way,

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

$$\begin{aligned} \text{where } \rho &= \text{density}, \\ v &= \text{average velocity}, \\ D &= \text{pipe inner diameter, and} \\ \mu &= \text{dynamic viscosity}, \end{aligned}$$

he discovered that flow was laminar below a Reynolds number of approximately 2,100, underwent a transition period up to values of 4,000, and exhibited turbulent flow at higher values of Reynolds number. Using this dimensionless group, flow can be classified into one of these three regimes based on the fluid physical properties and the geometry and dimensions of the conduit.

The Bernoulli equation [2, 310], applied between two points in space, takes the following form when there are major frictional losses but no pump work:

$$\frac{\Delta v^2}{2g} + \frac{\Delta p}{\rho g} + \Delta z = f_D \left(\frac{L}{D}\right) \frac{v^2}{2g} \tag{2}$$

where g = gravitational acceleration,

Δp = the difference in fluid pressure between the two points,

Δz = the difference in height between the two points,

L = length of pipe, and

f_D = the Darcy friction factor.

The right-hand side's first term, f_D or the Darcy friction factor, is not to be confused with the Fanning friction factor, f_F. Different fields of study and textbooks use one form more often than the other, so be careful not to mix definitions! The Darcy friction factor is equal to four times the Fanning friction factor.

Focusing on laminar flow, the Darcy friction factor is analytically shown to be: [2, 173]

$$f_D = \frac{64}{Re} \tag{3}$$

Substituting this into the Bernoulli equation, ignoring changes in velocity or height, and replacing the Reynolds number with its definition results in the following,

$$\Delta p = \left(\frac{32\mu L}{D^2}\right)v \tag{4}$$

which shows a linear relationship between velocity and pressure drop in a pipe.

The friction factor for completely turbulent flow (referred to here as $f_{C.T.}$) is independent of Reynolds number, but is influenced by the relative roughness of the pipe wall. Empirical correlations exist describing the friction factor as a function of relative roughness. [2, 299] Evaluating for pressure drop from the Bernoulli equation under these conditions,

$$\Delta p = \left(\frac{f_{C.T.}\rho L}{2D}\right)v^2 \tag{5}$$

a quadratic relationship between pressure drop and average fluid velocity emerges.

Finally, considering flow that is neither laminar nor completely turbulent, no analytical solution exists. A number of empirical equations have been suggested relating the friction factor to the Reynolds number and the pipe roughness, such as the Blasius equation, the Prandtl equation, and the Colebrook equation. [2, 300]

The friction factor can be more easily determined (for a given Reynolds number and relative pipe roughness) using the Moody chart, which is found in most fluid dynamics textbooks, and is displayed below in Figure 1. [3]

Returning to the Bernoulli equation to consider minor, as opposed to major, frictional losses (that is, those associated with fittings and valves instead of friction in straight pipe) are commonly modeled with one of two common methods: fitting factors or equivalent length. As a note, when needing to consider major and minor frictional losses, their terms can be summed on the right-hand side of the Bernoulli equation.

Modeling minor frictional loss using a fitting factor, K, results in the following Bernoulli equation (when changes in velocity and height are negligible):

$$\frac{\Delta p}{\rho g} = \sum K \frac{v^2}{2g} \tag{6}$$

The summation denotes inclusion of all appropriate fittings for the system under study, and where each fitting has a unique fitting factor, K. Tables of empirical fitting factors can be found in Perry's handbook [4] and many fluid dynamics textbooks. [2, 316]

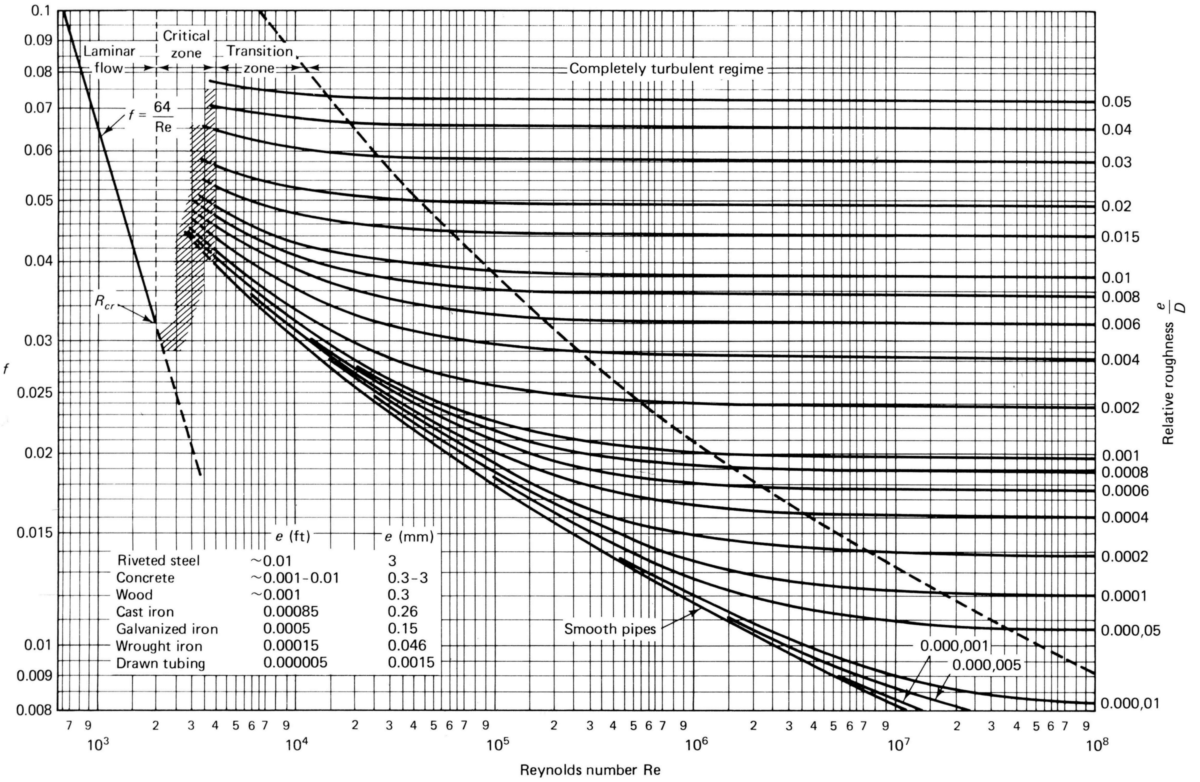

Figure 1: Friction factors for commercial pipes, from [3].

The equivalent length method models [4, 6-16] the pressure drop across various fittings as the amount of straight pipe required to affect the same decrease in pressure. This effective length to diameter ratio, denoted as $L_e \cdot D^{-1}$, depends on the type and geometry of a fitting and, for laminar flow, the Reynolds number. As before, the summation symbol denotes the inclusion of all fittings in the system being studied.

$$\frac{\Delta p}{\rho g} = f_D \left(\sum \frac{L_e}{D} \right) \frac{v^2}{2g} \tag{7}$$

Venturi and orifice plate flow meters can be treated similarly as both cause a pressure drop from a smooth or sudden constriction, respectively. By manipulating the Bernoulli equation, the following can be shown [2, 334]:

$$Q = C_D A_2 \sqrt{\frac{2\Delta p}{\rho[1 - (\frac{A_2}{A_1})^2]}} \tag{8}$$

where Q = volumetric flow rate,
A_1 = upstream cross-sectional area,
A_2 = cross-sectional area at constriction, and
C_D = discharge coefficient.

The discharge coefficient depends on the metering device, its geometry, and is a weak function of the Reynolds number. For venturi meters, a discharge coefficient of 0.984 is typical at large

Reynolds numbers [4, 10-14]. See, for example, Fig. 10-19 in [4] to predict the discharge coefficient for an orifice meter.

For pitot tubes (see Fig. 10-6 in [4]), a small pipe has a high-pressure line open and in-line with oncoming flow and a low-pressure line open but tangential to the direction of flow. Measuring this pressure differential is identical to the velocity head—rearranging the Bernoulli equation results in [2, 338]:

$$v = C\sqrt{\frac{2\Delta p}{\rho}} \tag{9}$$

where C, an empirically fitted coefficient, is often very close to unity.

Manometers allow for the measurement of a pressure differential between two points. For this apparatus, an inverted differential U tube manometer is employed, where the system fluid (water) contacts air, as shown later in Figure 3. The primary equation governing a manometer is:

$$\Delta p = \rho g \Delta z \tag{10}$$

describing difference in pressure between two heights, $\Delta z = z_2 - z_1$, within one fluid phase of a density denoted by ρ. Given the manometer size and air's density, there are negligible changes in pressure of the gas phase filling the upper section of the manometer. As such, pressure at the water's surface on both sides of the manometer are identical. The pressure differential between the two points connected to the manometer can, therefore, be calculated from height differential between the surfaces of water on either side of the manometer.

The performance of a pump, often characterized in what is referred to as a pump characteristic curve, demonstrates the increase in fluid pressure at a given flow rate. A pump's general behavior is to produce the highest pressure fluid at low flow rates, effecting smaller increases in pressure as the flow increases, eventually imparting no increase in pressure at a critical maximum flow rate. See Figure 10-28 in [4] for an illustration. Pump vendors will often provide the pump curves associated with their products and are generally easily accessible.

4 Experimental Apparatus

A general schematic is given in Figure 2, with parts of interest numbered: A water reservoir contains a submerged pump (24) which, when turned on (23), provides flow for the system that can be controlled by an inlet valve (25) and fine (19) and coarse (20) exit valves. Water can be transported across several pipes (1-4) of varying diameters and internal roughness, through different types of valves (gate (10), globe (11), ball (7)), and through a range of fittings (sudden contraction (5) and expansion (6), strainer (12), 45 (8) and 90° bend (13, 14), T- and Y-connections (15, 9)). Samples of cut sections of pipes (1-4) are available on the apparatus front board. The reservoir's draining tank (21), when plugged, is a volumetric measuring tank with a connected sight gauge (22). The flow meters available are a pitot tube (16), a venturi (17), and an orifice (18) meter—this section of piping has a diameter of 24 mm, with the constriction diameters being 14 mm for the venturi and 20. mm for the orifice plate.

Many quick-connection valve ports are installed throughout the apparatus. Connecting tubing between these valves and the manometer allows the pressure differential between two points to be measured, as detailed in Figure 3. To connect, simply push the test probe directly into the connection valve. To disconnect, push in the metal clip on its side while pulling out the probe. The four valves above the water reservoir (21) are either closed, allowing water to flow back to the reservoir, or open, connecting the analog manometer to the system. The range of measurable

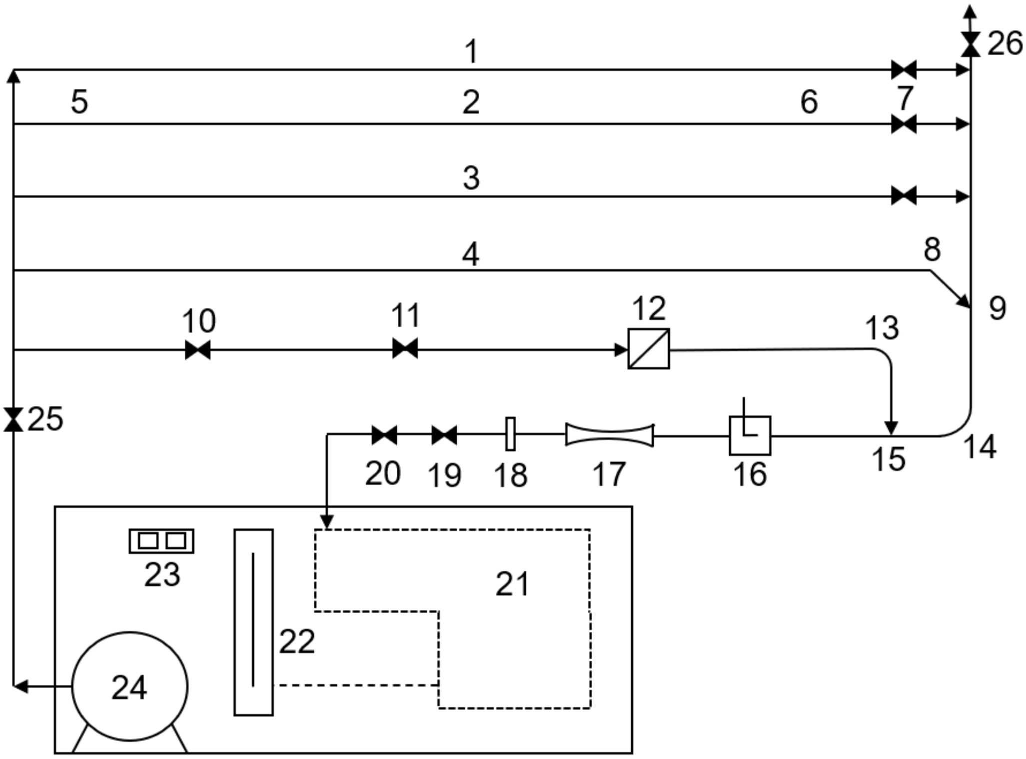

Figure 2: Experiment 1: fluid friction apparatus.

pressure differentials is no more than one meter of water. If the manometer becomes flooded, or needs to be filled, air can be reintroduced into, or bled from, the manometer via the bleed valve at its top, respectively. When the manometer is in operation, the bleed valve should be closed.

5 Safety

The major hazards associated with this experiment are the following: The pump, powered from an electrical outlet, introduces the risk of injury from electric shock. Avoid by ensuring the pump power cord does not become submerged and is not touched when in operation. Through accumulation of biological contaminants in the water, there is also a risk of infection. Contact the instructional staff if you believe the tubing needs cleaned or replaced. If water splashes out of the apparatus, there are risks to clothing damage, slips, and falls. Avoid this by carefully considering the impact of opening or closing of valves prior to acting, and clean spills immediately if they do occur. This list is only a starting point and not intended to be fully comprehensive—please keep the safety of yourself and others in mind throughout the laboratory sessions.

6 Experimental Procedure

First, prime all pipes with water. This is done by turning on the pump and opening valves (25, 7, 10, 11, and 20) in Figure 2. If air is caught in the system, it can be bled from the piping by opening valve (26).

Large flow rates can be measured using the volumetric tank (21, 22) and timing with a stop-

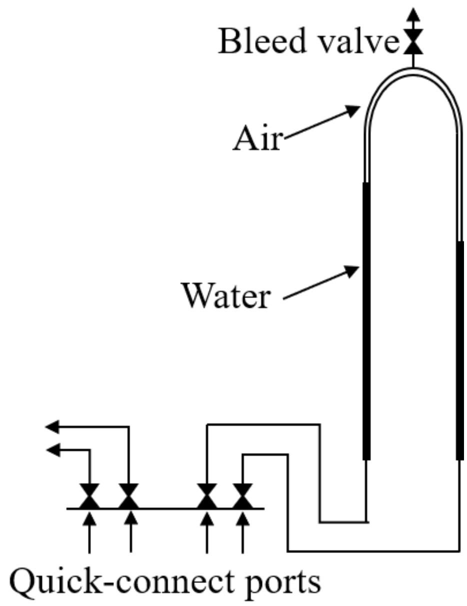

Figure 3: Connection diagram for analog manometer.

watch. Record both the volume and timespan in which the measured amount of water fills the tank. Flow rates are best controlled with valve 20 for large flows, or valve 19 for small flow rates, e.g., for achieving laminar flow (with valve 20 closed). When using valve 19 to reach low flow rates, measure accumulated volume with a graduated cylinder instead of the volumetric tank. Pressure differentials across points of interest can be measured using the manometer. A caliper is available for measuring the diameter of sample pipe pieces and estimating the pipe roughness. When measuring flow rate through a particular pipe, make sure all other pipes are closed, otherwise the observed volumetric flow rate will be inaccurate.

Collect pressure differentials across the four straight pipes (1-4) for a variety of flow rates. Control the flow rates to obtain results in the laminar, transitional, and turbulent regimes.

Collect pressure differentials across the many fittings and valves in the apparatus for a variety of flow rates. For valves, collect readings for different stem positions (from fully open to closed). As accurately as possible, quantify how open or closed each valve is.

Measure the pressure differentials across the three flow meters (venturi, pitot tube, orifice) for a variety of flow rates.

Collect the gauge pressure at the pump outlet for a variety of flow rates.

7 Data Analysis

Calculate pressure differentials and fluid velocities for the straight pipes 1-4, and plot the pressure drops as a function of velocity. Does the relationship vary between these variables when in the laminar or turbulent regime? Estimate the upper and lower Reynolds numbers associated with the transitional regime. Does it match your predictions? Why or why not?

Plot calculated friction factors as a function of Reynolds number for the major frictional losses measured for pipes 1-4. Compare with predicted friction factors from the Moody chart or the appropriate equation. Do these agree? Why or why not? For the rough pipe, does the measured roughness agree with the roughness obtained from the Moody chart? Why or why not?

Are calculated fitting factors independent of flow rate for the same fitting or valve position? Do they agree with literature values for this type of fitting? Plot and comment on the relationship between a fitting factor for a given valve and the stem position of that valve. Alternatively, what are the equivalent lengths associated with each fitting? Do they agree with literature? Why or why not?

Plot calculated flow rates, based on flow meter readings, as a function of measured flow rate. Find the discharge coefficient from your data and compare to an expected value. Are they in agreement? Why or why not? What can be done to calibrate the flow meters so they accurately predict actual flow rates? Do so, if needed.

Generate a pump performance curve, plotting pump head generated as a function of fluid flow rate. Comment on the curve shape and compare to an expected pump curve. Describe plausible causes of differences between the two curves.

References

[1] Osborne Reynolds. An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous, and of the law of resistance in parallel channels. *Philosophical Transactions of the Royal Society of London*, 174:935–982, 1883.

[2] Stephen Whitaker. *Introduction to fluid mechanics*. Krieger Publishing Company, 1968.

[3] L. F. Moody. Friction factors for pipe flow. *Trans. ASME*, 66:671, 1944.

[4] Don W. Green, editor. *Perry's chemical engineers' handbook*. McGraw-Hill, eighth edition, 2008.