FLUID FLOW

Introduction

Fluid flow is an important part of many processes, including transporting materials from one point to another, mixing of materials, and chemical reactions. In this experiment, you will investigate fluid flow in a pipe network and will explore several methods (rotameter, orifice and venturi meters) for measurement of the fluid flow rate. You will also explore effects of the skin friction, pipe network configuration, and pipe fittings (tees, elbows, etc.) on the pressure drop across a pipe. Additionally, you will characterize the behavior of the pump which drives fluid flow throughout the pipe network, and make predictions about the operating point of the system.

The main independent variables in this experiment are:

- Feed flow rate
- Fluid flow network configuration

General Description

The Fluid Flow system uses tap water from the building water supply, held in holding tanks on the first and third floors of the Unit Ops lab. The water is pressurized using a centrifugal pump and flows through the pipe network on the first floor in a closed loop which recirculates back to one of the holding tanks. The water flow rate at the inlet of the pipe network can be adjusted using a globe valve, and is measured using a rotameter. The inlet pressure can be measured by a pressure gauge.

The pipe network contains two Schedule 80 PVC pipes of nominal diameter 0.75" and 1.0". Note that nominal pipe diameters usually differ from their actual diameters. In particular, the actual inner diameters of the 0.75" and 1.0" Schedule 80 pipes are 0.742" and 0.957", respectively\(^1\). Each of the pipes contains a combination of tees, elbows, orifice plates, venturi meters, and valves. A tee is a pipe fitting that joins one pipe run to another that runs in a perpendicular direction to the main run. An elbow is used to change the direction of fluid flow. Venturi meters and orifice plates are flow measurement instruments which use the Bernoulli principle to measure flow rates, as described further below. All throughout the pipe network, there are small metal manometer interfaces, which

are used to measure the pressure differences between any two points in the pipe network using a differential pressure gauge. In addition, there are several pressure gauges built into the network.

**Theory**

For each pipe segment, we can write the mechanical energy balance equation:

$$\frac{1}{2}v_{in}^2 + \frac{p_{in}}{\rho} + z_{in}g = \frac{1}{2}v_{out}^2 + \frac{p_{out}}{\rho} + z_{out}g + W_{loss}$$  (1)

Here,  
- $v_{in}$ = inlet fluid velocity  
- $v_{out}$ = outlet velocity of fluid  
- $z_{in}$ = elevation height of the inlet  
- $z_{out}$ = elevation height of the outlet  
- $p_{in}$ = inlet pressure  
- $p_{out}$ = outlet pressure  
- $W_{loss}$ = energy loss due to friction (per unit mass)  
- $\rho$ = fluid density

Note that Eq. (1) assumes a steady-state flow. This equation simplifies if $v_{in} = v_{out}$ and $z_{in} = z_{out}$:

$$\frac{p_{in} - p_{out}}{\rho} = W_{loss}$$  (2)

If the fluid flow is split between two pipes, the pressure drop is the same in both pipes (since the inlet pressure is the same and the outlet pressure is atmospheric) and the total flow rate $Q$ is

$$Q = Q_1 + Q_2$$  (3)

where $Q_1$ and $Q_2$ are the flow rates through the individual pipes.

**Frictional Losses**

The frictional losses depend on the type of the flow (laminar or turbulent) and pipe elements (valves, elbows, tees, etc.). A common approach to characterization of frictional losses is to use the Fanning friction factor $f$ defined as the friction force per unit surface area divided by the kinetic energy per unit volume ($\rho v^2/2$).

**Frictional Losses in a Circular Tube of Constant Diameter**

$$W_{loss} = 4f \frac{\Delta L v^2}{D}$$  (4)

Here, $\Delta L$ is the pipe length, $D$ is the inside pipe diameter, $v$ is the fluid velocity averaged over the pipe cross-section, and $f$ is the Fanning friction factor.
For a laminar flow one can solve the Navier-Stokes equations analytically and obtain the following expression for the friction factor.

\[ f = \frac{16}{Re} \]  

Here, \( Re = \frac{Dv\rho}{\mu} \) is the Reynolds number (\( \rho \) and \( \mu \) are the fluid density and viscosity, respectively).

For a turbulent flow the friction losses are given by empirical relationships, such as the Colebrook equation or the Moody diagram. These relationships involve new parameter \( \varepsilon \) corresponding to the roughness of the pipe. The roughness depends on multiple factors, including the material from which the pipe is made and degree of corrosion. The flow network in our lab consists of pipes made from PVC.

### Frictional Losses in Fittings

In addition to the pipes, the fluid flow network contains various fittings, including valves, tees, and elbows. The friction losses due to the fittings are described using the loss factor \( K_f \),

\[ W_{\text{loss}} = K_f \frac{v^2}{2} \]  

Empirical values for friction losses due to various fittings are available in the literature.

### Venturi and Orifice Flow Meters

The network also contains venturi and orifice flow meters. Both of them rely on measurement of pressure difference between two different points to determine the fluid flow rate.

A venturi meter is a tube of non-constant diameter (see Fig. 1). To minimize disturbances to the flow, the edges of the venturi meter have the same diameter as the pipe into which the meter is inserted. Variation of the tube diameter leads to variation of the fluid pressure inside the meter. There are two pressure taps located at the widest and the narrowest locations of the tube. Therefore, we can determine the flow rate by measuring pressures \( p_1 \) and \( p_2 \) at these locations and substituting them into the Bernoulli equation. For an incompressible fluid, the pressure drop is related to the flow rate by the following formula:

\[ Q = \frac{\pi D_2^2}{4} \frac{C_d}{\sqrt{1 - (D_2/D_1)^4}} \frac{2(p_1 - p_2)}{\rho} \]  

Here, \( D_1 \) and \( D_2 \) are the pipe diameters at the pressure tap locations and \( C_d \) is the discharge coefficient. In the absence of the friction losses, \( C_d =1 \). In most venturi meters, \( C_d \) is very close to 1.
Figure 1. Venturi meter. The figure is taken from documentation by Lambda Square Inc. Complete documentation, including dimensions of the venturi meters, is available on the course website.

**An orifice meter** is a plate with a machined hole in the center (see Fig. 2). The flow rate is determined by measuring the pressure drop as the flow passes through the plate. Eq. (7) still holds for orifice meter with \( D_1 \) and \( D_2 \) being diameters of the pipe and the orifice hole, respectively. The frictional losses in the orifice meter are much larger than in the venturi meter and a typical value of the discharge coefficient \( C_d \) is 0.6. Precise value \( C_d \) should be determined experimentally.

Figure 2. Orifice flow meter (www.wikipedia.org)

Both venturi and orifice flow meters lead to a permanent pressure loss, i.e. pressure downstream from these meters does not fully recover to the pressure \( p_1 \) at their inlets. The permanent pressure loss in a venturi meter is typically about 10%. The permanent pressure loss in an orifice is

\[
p_1 - p_3 = (1 - \beta^2)(p_1 - p_2)
\]

Here, \( p_3 \) is the pressure 4-8 pipe diameters downstream and \( \beta = D_2/D_1 \).
Centrifugal Pumps

Figure 3. Schematic of Centrifugal Pump (www.globalspec.com)

The Fluid Flow system uses a centrifugal pump to achieve the necessary flow rates of water through the pipe network. Centrifugal pumps are designed with a rotating impeller which accelerates fluid from the inlet so that its motion is radially outward, pushing it through the connected pipe network. The operation of the pump therefore results in lower pressure at the pump inlet, which pulls fluid from the supply tank through the system.

Characteristic Curves and Operating Points

Characteristic curves are a useful tool for visualizing the behavior of a device or system over a range of operating conditions. In the case of the Fluid Flow system, characteristic curves will be developed for the pump, valves, and the pipe network, and the operating point will be determined from the intersection of the characteristic curves, as shown below.
A **pump characteristic curve** shows the relationship between the pressure drop across the pump and the flow rate of the fluid exiting the pump. By operating the pump at a range of flow rates (done by adjusting the rotameter at the exit of the pump), experimental values can be recorded. Plotting the pressure drop against the flow rate allows one to create a pump characteristic curve.

A **system characteristic curve** shows the relationship between the pressure drop across the pipe network and the flow rate of water travelling through the network. By operating the system at a range of flow rates (done by adjusting the valve at the inlet to the pipe network), experimental values can be recorded. Plotting the pressure drop across the pipe network against the flow rate allows one to create a system characteristic curve.

**Cavitation**

Cavitation is formation and implosion of small gas bubbles in a liquid. Cavitation may arise in centrifugal pumps due to the pressure decrease in the eye of the impeller. The decrease in pressure leads to a decrease in the boiling temperature, which leads to the bubble formation.

The vapor bubbles collapse as they pass from low to high pressure zones in the pump. When this happens the liquid strikes metal parts at a very high speed. Cavitation sounds like pumping rocks as the implosion of the bubbles results in popping noise. Cavitation decreases the pump efficiency as the energy is lost in expanding the bubbles in the low pressure region and compressing them in the high pressure region inside the pump. Furthermore, cavitation may result in the pump failure. Therefore, pipe networks containing centrifugal pumps must be designed so that the pumps operate away from their shut-off and run-out conditions. Conditions likely to cause cavitation in centrifugal pumps are described below.

**Shut-off Conditions:** A pump can elevate liquid in a vertical tube up to a point where the weight of the liquid and gravity permit no more elevation. At this point the flow rate of the liquid is zero. The maximum liquid elevation achievable by the pump is referred to as the shut-off head and
the corresponding pressure is the shut-off pressure. If the pump is operated near the shut-off point, the pump will vibrate and the liquid will heat up resulting in cavitation, which in turn is likely to damage the pump.

**Run-out Conditions:** When the flow-rate of the liquid is too high, the liquid may leave the pump faster than it enters the pump. This creates a very low pressure in the pump resulting in vaporization cavitation. Pump run-out is the maximum flow-rate that can be developed by a pump without damaging the pump. The run-out conditions correspond to a very small pump pressure. Decreasing pressure below the run-out point may overload the pump motor.

**Low Net Positive Suction Head (NPSH):** NPSH is the head corresponding to the pressure at the pump’s suction port. It is critical that the NPSH is at all times higher than the minimum suction port pressure, which is the minimum pressure required to avoid cavitation. Cavitation occurs when the pressure at the pump inlet drops below the vapor pressure of the liquid traveling through the pump. Vapor bubbles form at the pump inlet and collapse as they are discharged from the pump, which can cause damage to the pump and also limit pump capacity. In other words, without sufficient NPSH, the system cannot operate at desired flow rates. Therefore, it is critical that the system is configured to achieve the necessary NPSH. One way to achieve this, for instance, is to increase the height of the supply tank above the pump.

**Valve Types & Characteristic Curves**

The term “valve” can refer to one of many devices designed to manipulate the flow of a fluid through a pipe. Common valve varieties include needle valves, gate valves, plug valves, and many more. The Fluid Flow system incorporates a globe valve and ball valves.

![Globe valve and ball valve](https://www.wikipedia.org)

**Figure 5.** Cutaway view of (a) globe valve and (b) ball valve (www.wikipedia.org).

**Globe valves** operate using a movable plug which can descend into its seat in order to close the valve. The height of the plug is manipulated manually using the handwheel. The valve is open when the plug is fully raised, allowing fluid to flow beneath it, and closed when the plug is fully descended into its seat. The design of the globe valve allows for gradual adjustment of flow, therefore making it ideal for applications involving throttling.

**Ball valves** operate using a hollow, perforated ball which rotates to control the flow through it. The orientation of the ball is manipulated using the quarter-turn handle. The valve is open when the perforation in the ball aligns with the direction of the pipe, and the valve is closed when the
perforation sits perpendicular to the pipe. This ball is designed primarily for on/off manipulation, and is therefore not ideal to gradually throttle the fluid flow.

A **valve characteristic curve** shows the dependence of the valve resistance on the amount that the valve has been opened. By adjusting the amount that the valve is open (i.e., 50%) and recording the corresponding differential pressure across the valve, experimental values can be recorded. Plotting the resistance against the percentage opening of the valve results in a valve characteristic curve.

![Valve Characteristic Curves](www.flowserveperformance.com)

Figure 6. Valve characteristic curves. (www.flowserveperformance.com)

Figure 6 displays characteristic curves for three common categories of valves. Quick open valves are designed, as the name implies, to achieve a high flow rate when the valve has only been opened a small amount. Linear valves operate such that the flow (given as a percentage of the maximum flow) corresponds to the percentage opening of the valve. Equal percent valves are designed such that the slope increases as the valve is opened.

During this experiment, characteristic curves will be developed experimentally for globe valves and ball valves. Characteristic curves can be used in unison to make predictions about the system. For example, using the valve and pump characteristic curves together, one can predict the flow rate which will correspond to a given opening of the valve.

**Objectives**

1. Application and validation of the mechanical balance equation (1) to various pipe segments.

2. Experimental determination of friction factors for:
   a. Pipes (i.e., skin friction)
   b. Pipe fittings such as tees, elbows, and valves
3. Verification of flow measurement methods (rotameter, orifice plates, venturi meter) by measuring the change in tank level over a given period of time; comparison of the methods in terms of accuracy and precision.

4. Prediction of the pressure losses and flow rates through a simple piping network; comparison of predicted values with experimental results.

5. Prediction of how flow will be divided between the upper and lower pipes when both lines are simultaneously open; comparison of predicted values with experimental results.
   a. Multiple inlet flow rates should be explored.
   b. Multiple configurations of the flow split should be explored (there are several vertical pipes and therefore multiple locations to split the flow).

6. Development of a pump characteristic curve based on experimental values, as well as system characteristic curves for various system configurations (top only, bottom only, full network); prediction of operating points and experimental validation of these predictions.

7. Development of valve characteristic curves based on experimental values; prediction of how the valve-pump pair will operate (i.e., flow rate achieved for given valve opening) and experimental validation of predictions.