

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.

The main independent variables in this experiment are:

- Feed flow rate
- Fluid flow network configuration

General Description

The Fluid Flow system uses tap water supplied from a large holding tank on the third floor of the Unit Ops lab. The pressurized water flows down under gravity to the pipe network on the first floor. The water flow rate at the inlet of the network can be measured by a rotameter. The inlet pressure can be measured by a pressure gauge.

The pipe network contains two pipes of nominal diameter 0.75" and 0.5". The corresponding actual diameters for pipes of Schedule 40 are 0.824" and 0.622", respectively¹. Each of the pipes contains 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. A venturi meter is a flow measurement instrument which uses the Bernoulli principle to measure the flow rate. It contains a converging section which gives an increase in the flow velocity and a corresponding pressure drop. An orifice plate is a thin plate with a hole in the middle. When the fluid reaches the orifice plate, the fluid is forced to converge to go through the small hole. As it does so, the velocity and the pressure changes. The difference in fluid pressure between the normal pipe section and the hole measured with a manometer can be used to estimate the flow rate. 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 digital manometer. In addition, there are several pressure gauges in the network.

¹ Appendix A5 of C. J. Geankoplis, "Transport Processes and Separation Process Principles (4th ed., 2003)

Theory

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

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

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)
 ρ = fluid density

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

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

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

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

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

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

Here, ΔL 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.

$$f = \frac{16}{Re} \quad (5)$$

Here, $Re = Dv\rho/\mu$ is the Reynolds number (ρ and μ 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 ϵ 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 plastic and galvanized steel.

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 ,

$$W_{loss} = K_f \frac{v^2}{2} \quad (6)$$

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:

$$Q = \frac{\pi D_2^2}{4} \frac{C_d}{\sqrt{(1 - (D_2/D_1)^4)}} \sqrt{\frac{2(p_1 - p_2)}{\rho}} \quad (7)$$

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.

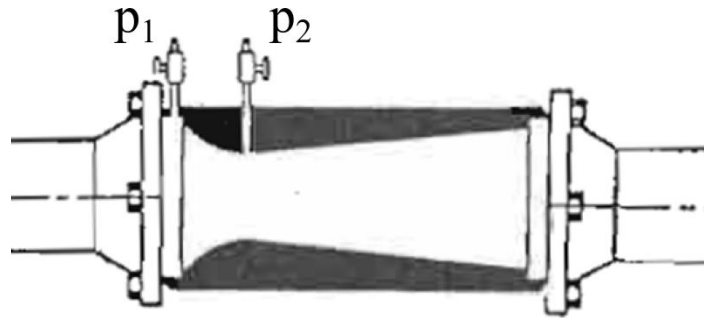


Figure 1. Venturi meter. The figure is taken from documentation by Lambda Square Inc. Complete documentation, including dimensions of the venturi meters, is available on the course website.

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.

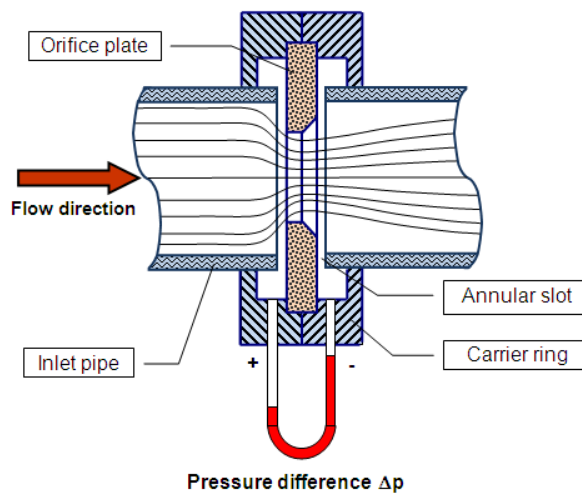


Figure 2. Orifice flow meter (www.wikipedia.org)

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 about 10%. The permanent pressure loss in an orifice is

$$p_1 - p_3 = (1 - \beta^2)(p_1 - p_2) \quad (9)$$

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

Objectives

1. Application and validation of the mechanical balance equation (1) to various pipe segments.
2. Determination of friction factors for pipes and pipe fittings such as tees, elbows, and valves.
3. Prediction of the pressure losses and flow rates in a simple piping network and comparison of prediction with the experiments.
4. Prediction at multiple flow rates of flow splitting through each piping network ($\frac{1}{2}$ " and $\frac{3}{4}$ ") when both lines are simultaneously open; comparison of prediction with actual results
5. Determination of friction factors for pipes and pipe fittings such as tees, elbows, and valves.
6. Comparison of the different methods of flow measurement (rotameter, orifice plates, venturi meter, bucket-and-stopwatch method) in terms of accuracy, sensitivity, etc.