KING FAHD
UNIVERSITY OF PETROLEUM & MINERALS

ME 316: Thermofluids Laboratory

Experiment # 1

FLUID FLOW MEASUREMENTS

1) OBJECTIVES

a) To introduce different types of fluid meters.
b) To determine the discharge coefficient for a venturi meter and an orifice meter.
c) To demonstrate the use of a Pitot-tube for flow velocity measurements.

2) INTRODUCTION

The most common flow measurements are pressure, velocity and flow rate. Fluid pressure can be directly and accurately measured by simple devices (such as manometers and pressure gages), however, flow rate measurements require special devices called fluid meters. Fluid meters are either used to determine the quantity of fluid delivered by a certain fluid system or the volumetric flow rate passing through a certain flow passage. Accordingly, fluid meters are classified in two categories, namely, quantity meters and rate meters. A brief description of each type is given below.

a) Quantity Meters

These are the fluid meters in which the fluid passes, more or less, in isolated quantities in spaces of known volumes. Examples of quantity meters are reciprocating and rotary pistons, geared or lobed impellers, sliding-vane meters (see Figure 1) and many others. In all these meters, one stroke of the reciprocating element or one revolution of the rotating element results in a fixed volume of fluid moving through the meter. The number of revolutions (or strokes) is used to determine the volume of fluid moved through the meter. Such meters are equipped with a mechanism for counting the number of revolutions and may be equipped with a digital readout.
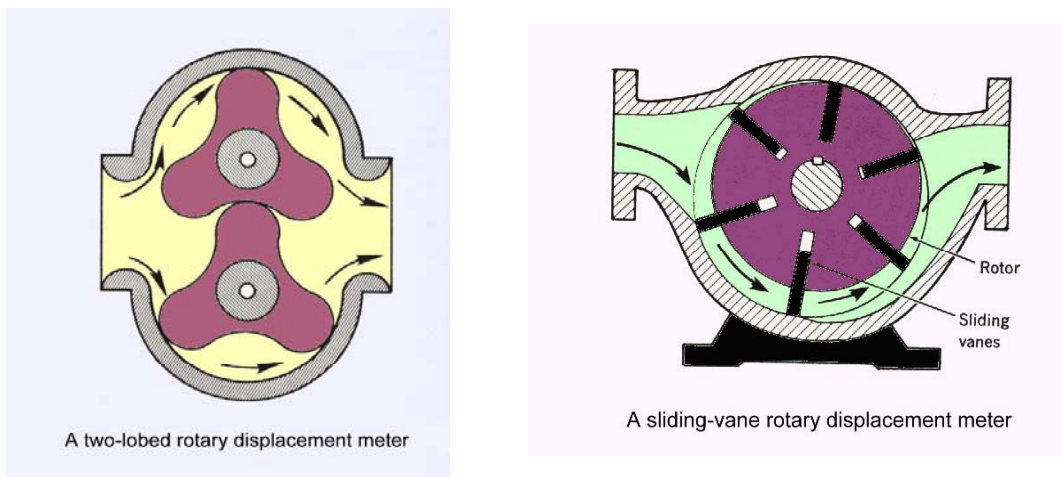

Figure 1. Sectional views of two positive displacement flowmeters

Different types of quantity meters are used for measuring oil flow in pipelines, gasoline meters in gas stations, water in domestic water distribution systems and gas flow in domestic gas distribution systems.

b) Rate Meters

These are the fluid meters in which the fluid passes in a continuous stream. The fluid movement through the primary element of the meter is used to actuate the secondary element. The volume of flow per unit time is derived from the interaction of the fluid stream and the primary element using physical laws supplemented by empirical relations. Examples of rate meters are the differential pressure meters (such as orifice flowmeters, Venturi meters and nozzle flowmeters), rotameters, turbine meters, vortex flowmeters, and many others.
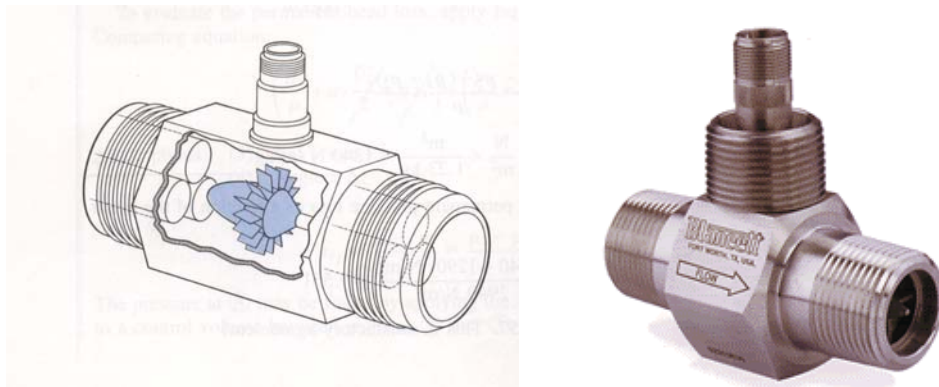

Figure 2. A sectional view and a photograph of a turbine flow meter.

The turbine meter shown in Figure 2 is widely used in oil and gas pipelines and consists of a freely rotating propeller installed in a casing and equipped with a magnetic pulse pickup to measure its speed of rotation. The rate of rotation is approximately proportional to the volume flow rate in the pipe. Turbine flowmeters can also be used as quantity meters with the number of propeller rotations calibrated to indicate the volume of fluid. On the other hand, the vortex flowmeter shown in Figure 3 utilizes the phenomenon of vortex shedding from a bluff body. Based of experimental measurements, a bluff body placed in a uniform stream sheds alternating vortices at a frequency proportional to the flow velocity [$f = const. (U/L)$], where U is the flow velocity, f is the frequency of vortex shedding and L is a characteristic length. In this flow meter, a shedding element is introduced in the pipe and a piezoelectric frequency sensor is used to measure the shedding frequency. Turbine and vortex flowmeters are accurate to $\pm1\%$.
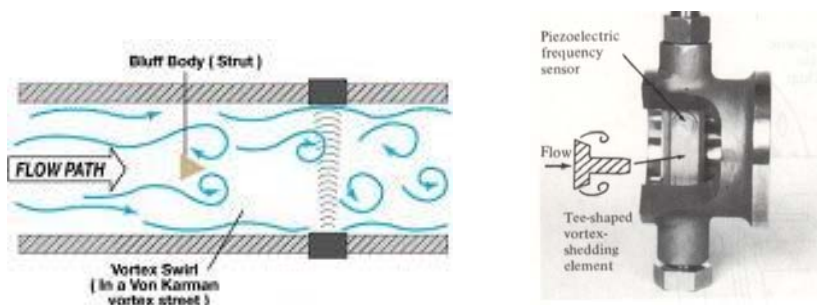

Figure 3. The operation principle and a photograph of a vortex flow meter.

3) <u>THEORETICAL BACKGROUND FOR DIFFERENTIAL PRESSURE METERS</u>

The differential pressure meters are mainly "flow obstruction devices" that operate based on Bernoulli's equation. In these devices, the change of cross-sectional area causes a change of flow velocity that creates a change of pressure. Consider steady incompressible flow in the flow passage shown below and assume that the flow to be inviscid and one-dimensional. The application of the continuity and Bernoulli's equation between sections 1 and 2 yields
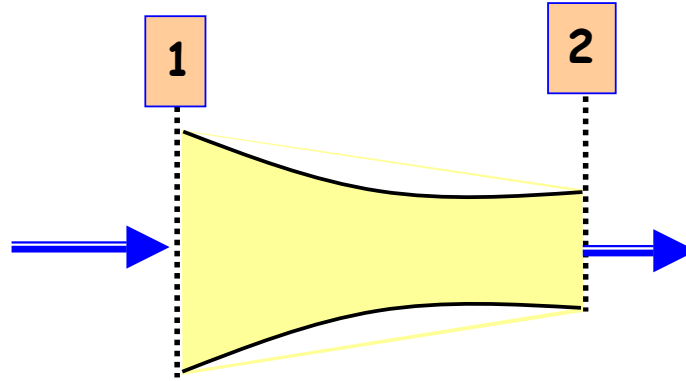
$$A_1 V_1 = A_2 V_2 \tag{1}$$

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + Z_1 = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + Z_2 \tag{2}$$

where V is the flow velocity and p is the static pressure. Solving the above two equations yields

$$V_2 = \frac{1}{\sqrt{1 - (A_2 / A_1)^2}} \sqrt{2g \left[\frac{p_1 - p_2}{\gamma} + (Z_1 - Z_2) \right]} \tag{3}$$

The term $\frac{p_1 - p_2}{\gamma} + (Z_1 - Z_2)$ represents the difference in piezometric head (Δh) between the two sections 1 and 2. The above expression for V_2 is obtained based on the assumption of one-dimensional frictionless flow. Hence the ideal flow rate can be expressed as

$$Q_{ideal} = A_2 V_2 = \frac{A_2}{\sqrt{1 - (A_2 / A_1)^2}} \sqrt{2g (\Delta h)} \tag{4}$$

Because of the above assumptions, the actual flow rate, $Q_{act.}$, differs from Q_{ideal} and the ratio between them is called the discharge coefficient, C_d, which can be written as

$$C_d = Q_{act.} / Q_{ideal} \tag{5}$$

The value of C_d differs from one flowmeter to the other depending on the flowmeter geometry and the

flow Reynolds number. The discharge coefficient is always less than unity due to various losses (friction losses, area contraction, etc.).

The Venturi Meter

The commonly used differential pressure flowmeters are the venturi-meter, the orifice-meter and the flow nozzle. The venturi-meter shown in Figure 4 consists of a smooth converging section, a short cylindrical throat and a smooth diverging section. The flow velocity increases in the converging section and then decreases in the diverging section while the pressure does the opposite (following the continuity and Bernoulli's equations). The diverging section may have a conical shape with an angle between 5° and 7° for better pressure recovery. Although the venturi-meter is more expensive than the orifice and nozzle flowmeters, it creates less friction head loss and is self-cleaning. Experimental data have shown that C_d for venturi maters range from 0.98 and 0.995 in the high Reynolds number range (Re > 2×10^5).
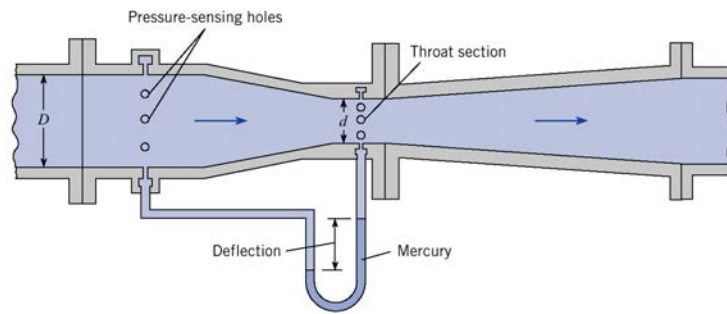

Figure 4. Typical venturi meter.

The Orifice Meter

The orifice meter shown in Figure 5 consists of a concentric hole in a thin plate that may be clamped between the pipe flanges. While the main advantage of the orifice meter is its low cost, its primary disadvantage is the high head loss due to the uncontrolled expansion following the orifice plate. Due to the formation of **vena contracta** the minimum cross-sectional area of the stream tube occurs downstream of the orifice. In general, the discharge coefficient for the orifice meter depends on the diameter ratio (d/D) as well as the Reynolds number. However, at high Reynolds numbers, C_d becomes a function of the diameter ratio only.

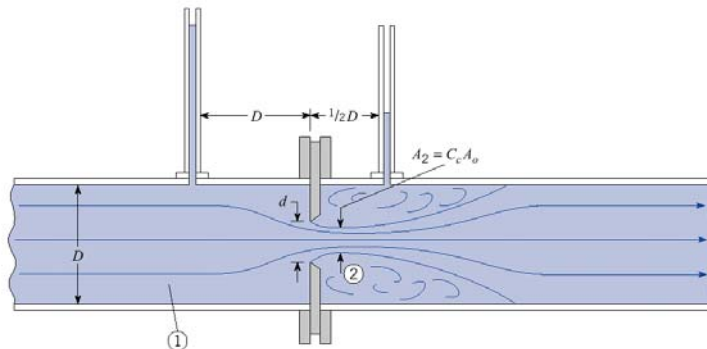
Figure 5. Typical orifice meter.

4) APPARATUS

The apparatus shown in Figure 6 consists of three flow meters, namely, a venturi meter, an orifice meter and a rotameter. Piezometer tubes are used to measure the pressure head difference in the venturi and orifice meters as shown in the figure. The apparatus is connected to the hydraulic bench for actual flow rate measurements.
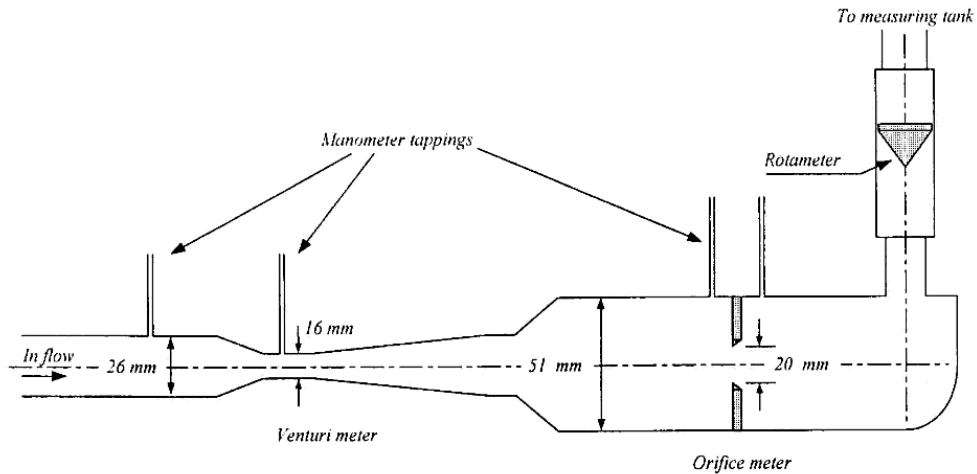

Figure 6. Schematic diagram of flow measuring devices.

The rotameter, which is sometimes called gap meter, consists of a variable-area transparent tube that has a rotor equipped with small vanes (for details see Figure 7). Under the action of the flow, the active element (rotor) rises in the vertical tube and reaches an equilibrium position for any given flow rate. In that equilibrium position, the drag force on the rotor balances its weight. A calibrated scale on the transparent tube indicates the flow rate. The rotameter is simple and gives direct measurements of the flow rate, however, it is less accurate than the venturi and orifice meters (approximately $\pm 5\%$).

Figure 7. A sectional view of a rotameter.

5
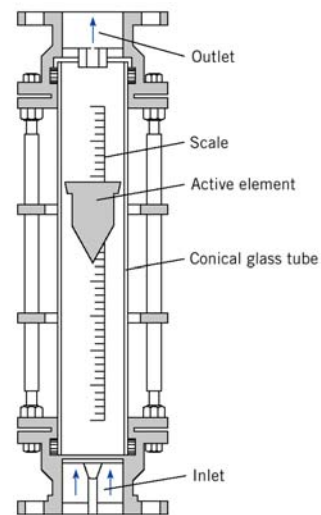
5) TEST PROCEDURE

1. Adjust the apparatus to the maximum flow rate (may utilize the rotameter as a flow rate indicator) and use the measuring tank to determine the actual flow rate, Q_{actual}.

2. Measure the difference in pressure head (Δh) for the venturi and orifice meters.

3. Record the rotameter reading.

4. Use the calibration curve given in Figure 8 to determine the rotameter flow rate.

5. Calculate the ideal flow rate, Q_{ideal}, for each meter using equation (4).

6. Calculate the discharge coefficient, C_d, for each meter.

7. Repeat the above procedure for five other flow rates.

6) IDEAS FOR DISCUSSION

1. Why is the value of C_d for an orifice meter lower than that for a venturi meter?
2. Does the value of C_d depend on the flow rate?
3. What does the friction head loss depend on?
4. What is the accuracy of the rotameter?
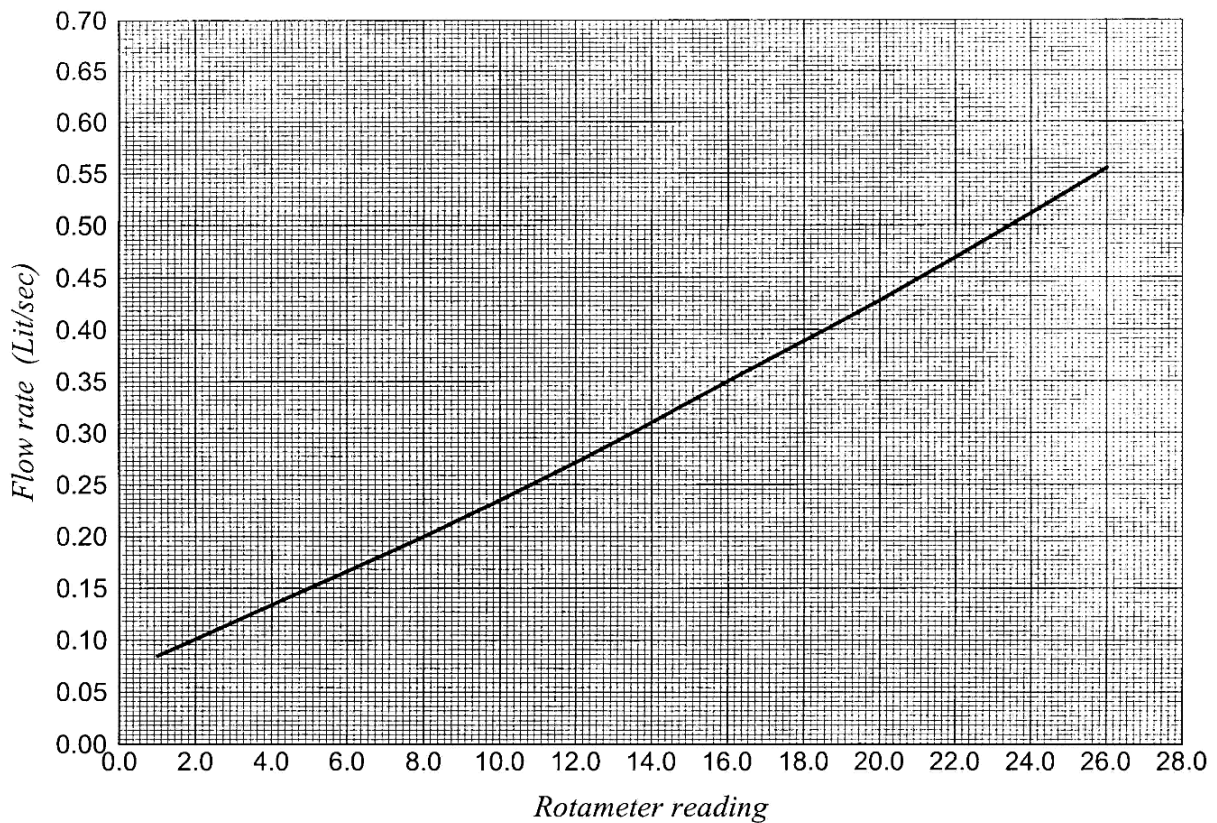5. Is it possible to design a flow meter that is 100% accurate?

Figure 8. Rotameter calibration curve.

7) Demonstration of Using the Pitot-tube for Flow Velocity Measurements

The Pitot-tube shown in the figure below is designed for measuring the velocity of a fluid stream. The difference between the stagnation pressure p_o and the static pressure p is used to calculate the velocity of the approaching stream. Based on the material studied in ME 311, we know that

$$p_o = p + \frac{1}{2}\rho V^2 \quad \Rightarrow \quad V = \sqrt{2\Delta p / \rho} \tag{6}$$

where $\Delta p = p_o - p$ is the pressure difference to be measured by a differential manometer. The experimental setup shown in Figure 9 represents an axial flow blower delivering air to a duct of circular cross section. The pressure difference Δp is measured using the shown inclined water manometer. The density of air may be obtained from Table A4 at room temperature.
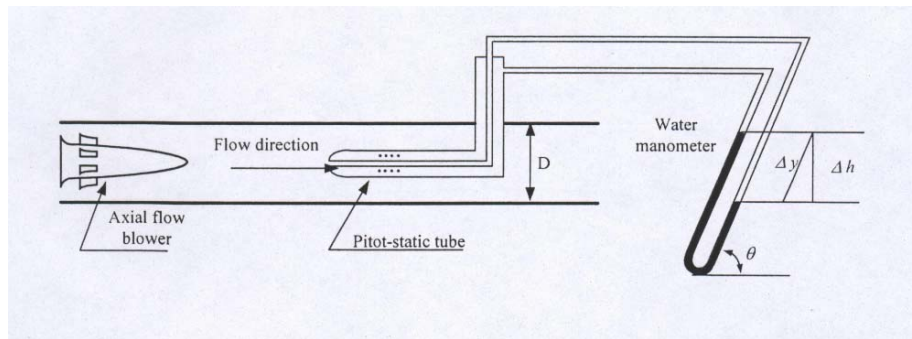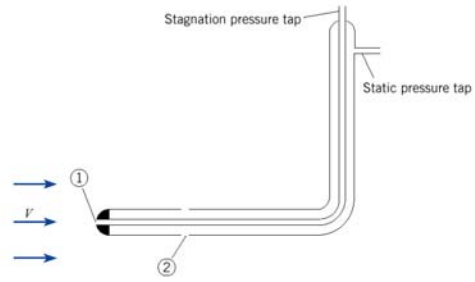

Figure 9. Flow velocity measurement using the Pitot-tube

8) *Possible Additional Work (20% extra credit)*

It is required to use the Pitot-tube for measuring the mass flow rate delivered by the axial flow blower shown in Figure 8 knowing that the velocity distribution in the duct is not uniform. You are required to propose an experimental procedure and write all details. Conduct an error analysis for this experiment.