3 Calibration of Flow Meters

Objective:
The objective of this experiment is to measure the flow rate of water by five different methods, to prepare calibration curves for the various flow meters, and to evaluate the methods by comparing their accuracies.

System & Theory:
The means for measuring flow rate are:
(i) a venturi meter
(ii) a sharp-edged orifice meter
(iii) a rotameter,
(iv) a turbine flow meter, and
(v) bucket and stop watch

The meters are mounted in a system of pipes through which water can be circulated. U-tube manometers containing a Meriam oil (the specific gravity is shown on the manometers) are available to measure the pressure drop across the meters. The primary measuring instrument is the bucket and stop watch, which is used to calibrate the meters. The venturi and orifice diameters are 0.625 inches (and they are mounted in a nominal 1 inch, type L, copper tube system). The entrance diameter for the meters is \( D_1 = 1.025 \text{ inches} \). Single pressure taps are located 1.5 pipe diameters upstream of the inlet and at the throat of the venturi meter, as well as at 3/4 pipe diameter upstream and downstream of the orifice plate.

*Meter Equations, Detailed Description of Equipment*

(a) Venturi Meter

Venturi meters are made in a variety of ways depending on the application and precision of the measurement desired. Most commercial venturi meters consist of a casting with flanges, and an insert or liner which provides a relatively sharp contraction followed by a considerably more gradual expansion. In the best meters many pressure taps are located around the circumference of the liner just upstream of the contraction and at the throat. In quality instruments the taps are connected to circumferential rings (called “piezometer ring”) and a differential manometer is attached to the two rings. However, because of the smallness of the equipment used in this study, only single taps at each station are employed. The size of a venturi meter is denoted by its entrance and throat diameters. A schematic of the meter is presented in Figure 1. For steady incompressible flow of an ideal fluid, Bernoulli’s equation, written between stations 1 and 2 in Fig. 1 is

\[
\frac{p_1}{\rho} + \frac{g}{g_e} z_1 + \frac{v_1^2}{2g_e} = \frac{p_2}{\rho} + \frac{g}{g_e} z_2 + \frac{v_2^2}{2g_e},
\]

(1)
where \( p \) is the pressure, \( v \) and \( \rho \) are the fluid velocity and density at the stations identified by the subscripts, respectively, \( g \) is the gravitational constant and \( g_c \) is the conversion factor between mass and force (\( g_c = 1 \) for the SI unit system).

The one-dimensional continuity equation is

\[
Q = v_1 A_1 = v_2 A_2
\]

or, substituting for the areas \( A_1 \) and \( A_2 \),

\[
v_1 D_1^2 = v_2 D_2^2
\]

Combining equations (1), (2) and (3) gives (assuming \( g_c = 1 \))

\[
Q = \frac{A_2}{(1 - (D_2/D_1)^4)^{1/2}} \left[ 2 \left( \frac{p_1 - p_2}{\rho} + g(z_1 - z_2) \right) \right]^{1/2} = Q_{\text{ideal}}
\]

This is, in fact, an ideal relation since frictional effects have been ignored. In order to account for frictional effects in the flow, a discharge coefficient \( C_D \) is defined.

\[
C_D \equiv \frac{\text{actual flow}}{\text{ideal flow}} = \frac{Q}{Q_{\text{ideal}}}
\]
Equation (4) thus becomes

$$Q = C_D \frac{A_2}{(1 - (D_2/D_1)^4)^{1/2}} \left[ 2 \left( \frac{p_1 - p_2}{\rho} + g(z_1 - z_2) \right) \right]^{1/2}$$

(6)

The discharge coefficient, $C_D$, is a function of the meter geometry ($D_2/D_1$) and the Reynolds number, $Re = \rho V_1 D_1/\mu$. Very often the geometrical factor $[1 - (D_2/D_1)^4]^{1/2}$ is called the velocity-of-approach coefficient, $C_A$; a venturi coefficient, $K_V = C_A C_D$, is often introduced. For most work it is desirable to calibrate the meter under the conditions of actual use. The determination of $C_D$ requires simultaneous measurement of the bracketed quantities in equation (6) and the bulk flow rate $Q$. For horizontal installations calibration consists of the measurement of the pressure drop, $(p_1 - p_2)$, and the bulk flow rate, $Q$. $C_D$ usually varies from 0.93 to 0.99 for turbulent pipe flows (c.f. refs. [9], [10]). Note that in our case $C_D = C_D(Re)$ only, since $D_2/D_1$ never changes.

(b) The Orifice Meter

A sharp-edged orifice meter causes a contraction of the flowing stream downstream from the orifice opening as shown in figure 2. Flow "separation" occurs downstream of the orifice and the narrowest portion of the forward flow regime is called the "vena contracta." When the downstream pressure tap is located at this point, the taps are referred to as "vena contracta" taps. Equation (6) describes

Figure 2: Schematic Drawing of an Orifice Meter

the flow between stations 1 and 2 for an orifice meter just as it does for a Venturi meter. However, unlike for the Venturi meter the size and location of the "vena contracta" are unknown because the extent of the recirculation zone is unknown and, in fact, depend somewhat on the Reynolds number. For this reason "3/4 taps" are used in this study. Since the flow cross section, $A_2$, is unknown at the downstream pressure tap, a contraction coefficient $C_c = A_2/A_o = (D_2/D_o)^2$, where $A_o$ is the
orifice area, is introduced. Equation (6) for an orifice meter in a horizontal pipe then becomes
\[ Q = C_e C_D \frac{A_o}{\left(1 - C_e^2 (D_o/D_1)^4\right)^{1/2}} \left(\frac{2g_e(p_1 - p_2)}{\rho}\right)^{1/2}. \]  

For SI units, \( g_e = 1 \). Since \( C_e \) is slightly dependent on Reynolds number, the orifice equation is always written in terms of an overall orifice coefficient \( K_o \) such that equation (7) simplifies to
\[ Q = K_o A_o \left(\frac{2g_e(p_1 - p_2)}{\rho}\right)^{1/2}. \]

Calibration thus consists of the determination of \( K_o \) which usually varies from 0.6 to 0.8 for turbulent flows (c.f. Ref 2). Note that one does not need to know \( C_D \) in order to determine \( K_o \), if equation (8) is used. In our case, \( K_o = K_o(Re) \) only.

(c) The Flow Nozzle

The flow nozzle is not used in this experiment but is mentioned here for completeness. It combines the desirable features of the venturi and orifice meters. It consists only of the contraction portion of the venturi meter and is mounted in a manner similar to the orifice meter. Thus, replacement of

![Figure 3: Schematic Drawing of a Flow Nozzle Meter](image)

a section of the piping system is not required for installation. An equation similar to equation (8) is used with \( K_o \) replaced by a flow nozzle coefficient, \( K_f \), where \( K_f = C_A C_D \). (Since \( C_D \) values for the flow nozzle are high and only a few percent less than those for a venturi meter, and since \( C_A \) is by definition always greater than unity, \( K_f \) values usually vary from about 0.95 to 1.10). The flow nozzle has the advantages of good pressure recovery characteristics, small size and small cost. A disadvantage is that the calibration is very sensitive to alignment and that for many uses the flow nozzle needs to be re-calibrated at frequent intervals. A sketch of a flow nozzle is presented in Figure 3.
(d) Rotameter

The rotameter is a variable area-ratio meter in contrast to the variable pressure, fixed area-ratio of the venturi, orifice and flow nozzle meters. The rotameter consists basically of a "float" contained in a slightly tapered tube. The tube is always oriented vertically and is contained in a casing (not shown) which is mounted in a piping system. The gap between the float and the tube is very small. The float rises higher in the tube as the flow rate of the fluid increases. Thus, the position of the float is an indication of the volumetric flow rate. The forces which act on the float are shown in Fig. 4. (Note: the drag force, $D$, and the buoyancy force, $F_b$, are surface forces, not body forces.) When the float is stationary its weight $W$ is balanced by the drag force $D$ and the buoyancy force $F_b$. Thus,

$$W = D + F_b$$  \hspace{1cm} (9)

which in terms of the float and fluid densities ($\rho_f$ and $\rho$, respectively) and float volume, $V_f$, becomes

$$D = V_f (\rho_f - \rho) g \gamma_c$$  \hspace{1cm} (10)

Note that $D$ does not depend on the position of the float. A loss coefficient, $C_f^2$, can be defined as the ratio of the drag forces to the forces due to the pressure drop across the float

$$D = C_f^2 (p_2 - p_1) A_f$$  \hspace{1cm} (11)

where $A_f$ is the major cross section of the float in a direction transverse to the flow and $p$ is the pressure at stations 1 and 2. The flow between points 1 and 2 is still governed by Bernoulli's equation so the result is again equation (6). Combining equations (6), (10) and (11) gives

$$Q = C_D \frac{A_2}{\left(\frac{p_2}{p_1} - 1\right)^{1/2}} \left(\frac{2g}{C_f^2 A_f} \frac{V_f}{\rho} \frac{\rho_f - \rho}{\rho}\right)^{1/2}, \text{term (}z_1 - z_2\text{) neglected}$$  \hspace{1cm} (12)
Since the tube is only slightly tapered \( D_2 \approx D_1 \), thus \( A_1 \approx A_2 = A \).

Defining \( C_R = \frac{C_D}{C_f} \left[ (D_2/D_1)^4 - 1 \right]^{1/4} \), equation (12) ultimately simplifies to

\[
Q = C_R A \left[ 2g \frac{V}{A_f} \frac{\rho_f - \rho}{\rho} \right]^{1/2}
\]

or

\[
Q = C_R Q_{ROT} = Q(z) \tag{14}
\]

Note that in our case, \( C_R = C_R(Re) \) only. The variables in this equation are not easily determined. However, for a given meter and fluid the parameters in the bracket are constant and the flow depends only on the cross-sectional area (of the tube), which usually varies linearly with height, \( z \). Thus, a well-designed variable area meter has a linear calibration, \( Q \propto z \). However, the advantage of the linear calibration for the rotameter is offset by higher costs, especially when compared to the orifice meter. It should be noted that the float can have many shapes; in fact, spherical floats are seldom used in large flow meters. One reason for using different shapes is to obtain stability in the float position. Students are urged to read the literature relating to this and other problems associated with flow measuring devices (c.f. Refs. [10], [9], [16], [24]).

(e) Turbine Flow meter

When a turbine wheel is placed in a pipe containing a flowing fluid, its rotational speed depends on the flow rate of the fluid. By reducing bearing friction and keeping other losses to a minimum, turbines can be designed such that the rotational speed varies linearly (approximately) with the flow rate. The turbines’s rotational speed can be measured simply and accurately by counting the

![Figure 5: Illustration of Turbine Flow meter](image)

rate at which the turbine blades pass a given point. This is usually accomplished with a magnetic proximity pickup (also known as a pickoff) which produces voltage pulses. By connecting the output signal from the pickoff to an electronic frequency counter (pulse-rate meter), the flow rate can be
measured. The total flow can be obtained by accumulating the total number of pulses during a timed interval. Figure 5 shows a typical turbine flow meter system.

**Calibration:** The rotational speed of a turbine flow meter depends upon fluid properties as well as upon the volumetric flow rate. The most significant fluid properties include viscosity of liquids and density of gases. As liquid viscosity increases, turbine rotor slip caused by viscous drag increases; the rotational speed and, hence, the output frequency is decreased. As gas density decreases, the energy available to turn the rotor is decreased, and retarding torques due to bearing friction and pickoff drag cause the rotor speed to decrease. Thus, high liquid viscosity and low gas density are conditions which cause reductions in output for a given volumetric flow rate and therefore erroneous flow rate indications. Because of these effects, it is essential that the viscosity or density expected in service use be duplicated as closely as possible during calibration. The flow meter was calibrated from the factory using a fluid with a specific gravity of 0.75 (note: not water!) and a viscosity of 1.1 centiStokes. Table 1 shows the calibration data obtained from the manufacturer of the turbine flow meter.

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Table 1: Manufacturer's Calibration Data for the Turbine Flow Meter

Establish the bypass valve settings such that all the flow passing through the rotameter and collected in the bucket also passes through the turbine meter. Note that all fluid passing through the rotameter must pass through the venturi and orifice meters.

**Error Analysis**

c.f. appendix B
Your Experiment:

Establish the proper flow in the piping system. All the fluid passing through the rotameter and collected in the bucket must pass through the venturi and orifice meters. The manometers must be correctly connected to the meters and all lines must be free of bubbles of air before any measurements are made. Finally, be sure to collect data for the full range of flow rates available. For your report, prepare the following figures:

1. A graph showing the variation of the flow rate with the meter scale reading for each of the four meters. These are called "calibration curves." For the turbine flow meter, compare your calibration data to that provided by the manufacturer (Table 1). (i.e., $\Delta P_v$ vs. $Q_{\text{bucket}}$, $\Delta P_0$ vs. $Q_{\text{bucket}}$, $z_{\text{rot}}$ vs. $Q_{\text{bucket}}$, frequency vs. $Q_{\text{bucket}}$)

2. A graph which linearizes the results of (1.) above for the orifice and venturi meters. From the slope of these lines compute an average value for the meter coefficients. (i.e. $\Delta P_v$ vs. $Q_{\text{bucket}}^2$, $\Delta P_0$ vs. $Q_{\text{bucket}}^2$)

3. A graph of the meter coefficients computed from the flow data vs. the Reynolds number of the flow. Note that the velocity to be used in the Reynolds number expression is determined from the relation between velocity and flow rate, $Q = V A$, where $A$ is the inside cross-sectional area ($A = \pi D^2/4$) of the pipe. (i.e., $C_D$ vs. $Re$, $K_o$ vs. $Re$. Note: You don’t have enough information about the float and geometry to calculate $C_R$ vs. $Re$.)

Cautions:

- Make sure all the air is out of the system before you close the turbine bypass and open the turbine flowmeter or tighten the clamps of the manometer bypasses.

- Tighten the clamps of the manometer bypasses carefully before taking data.

- Adjust the flowrate-setting valve and the tank valve so that the water level in the tank (supplying the pump) stays constant.

Questions to be addressed:

1. Evaluation of accuracy and precision of data! (c.f. appendix B) Are the results more affected by uncertainties at low flowrates, or at high flow rates?

2. Any differences between the calibration curves (i.e., are they all linear, nonlinear, or what?). How well does your turbine flow meter calibration agree with the manufacturer’s data?

3. How useful are the various flow metering devices? Are they more convenient, or less convenient, to use than the bucket and stopwatch?

References: [7], [10], [9], [24], [16], [42], [43], [44], [45]