Calibration of Flowmeters

Objective

The objective of this experiment is to calibrate bulk-flow measuring devices that rely on measurements of pressure change, such as Venturi meters and orifice-plate meters, by determining their flow coefficients as functions of the flow rate in terms of the Reynolds number. Experimentally obtained coefficients are then compared with ISO published values for similar devices. In addition, a paddlewheel flowmeter (a type of bulk-flow measuring device that provides an electrical output signal suitable for process monitoring and control) will also be calibrated.

Apparatus

Each apparatus consists of a pipe with two different flowmeters—a hydraulic one and a paddlewheel one—in a pipe mounted in the ceiling in Room 126 Talbot Lab, plus a weighing tank

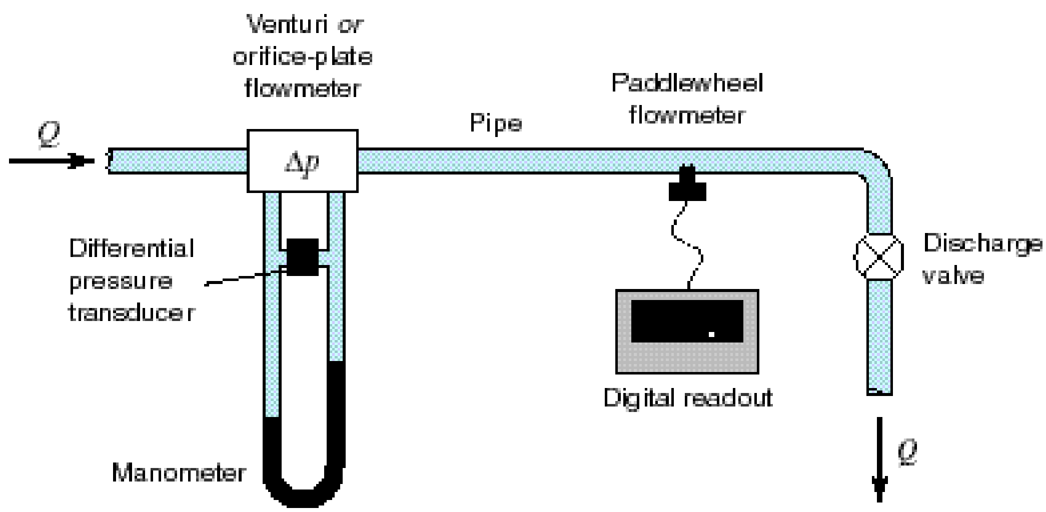


Fig. 1. Arrangement of flowmeters in a section of pipe.

located in the basement. Equipment specifications are given in Table 1 on page 6. As shown in Fig. 1, two types of flowmeter are used to measure the same flow rate Q: a hydraulic flowmeter and a paddlewheel flowmeter. A plan view of the flowmeter locations is given in Fig. 2.

The hydraulic flowmeter is of either the Venturi or orifice-plate type; it is provided with a Validyne pressure transducer and a mercury–water differential manometer to measure differences in pressure, either between the entrance and the throat of the Venturi meter, or between the entrance and the approximate vena contracta of the orifice-plate meter, as shown in Figs. 3 and 4, respectively.

The paddlewheel flowmeter is a Signet 3-8511-P0 "lo-flo" device with a stated operating velocity range of 0.3–20 ft/s. It is connected to a Signet 8511 transmitter that provides a 4–20 mA output current that may be sent through a fixed resistor R to produce a variable voltage output. For example, if $R = 500\ \Omega$, this output voltage should vary between 2 and 10 V. The transmitter senses the number of revolutions of the paddlewheel over a period of approximately 1 s and

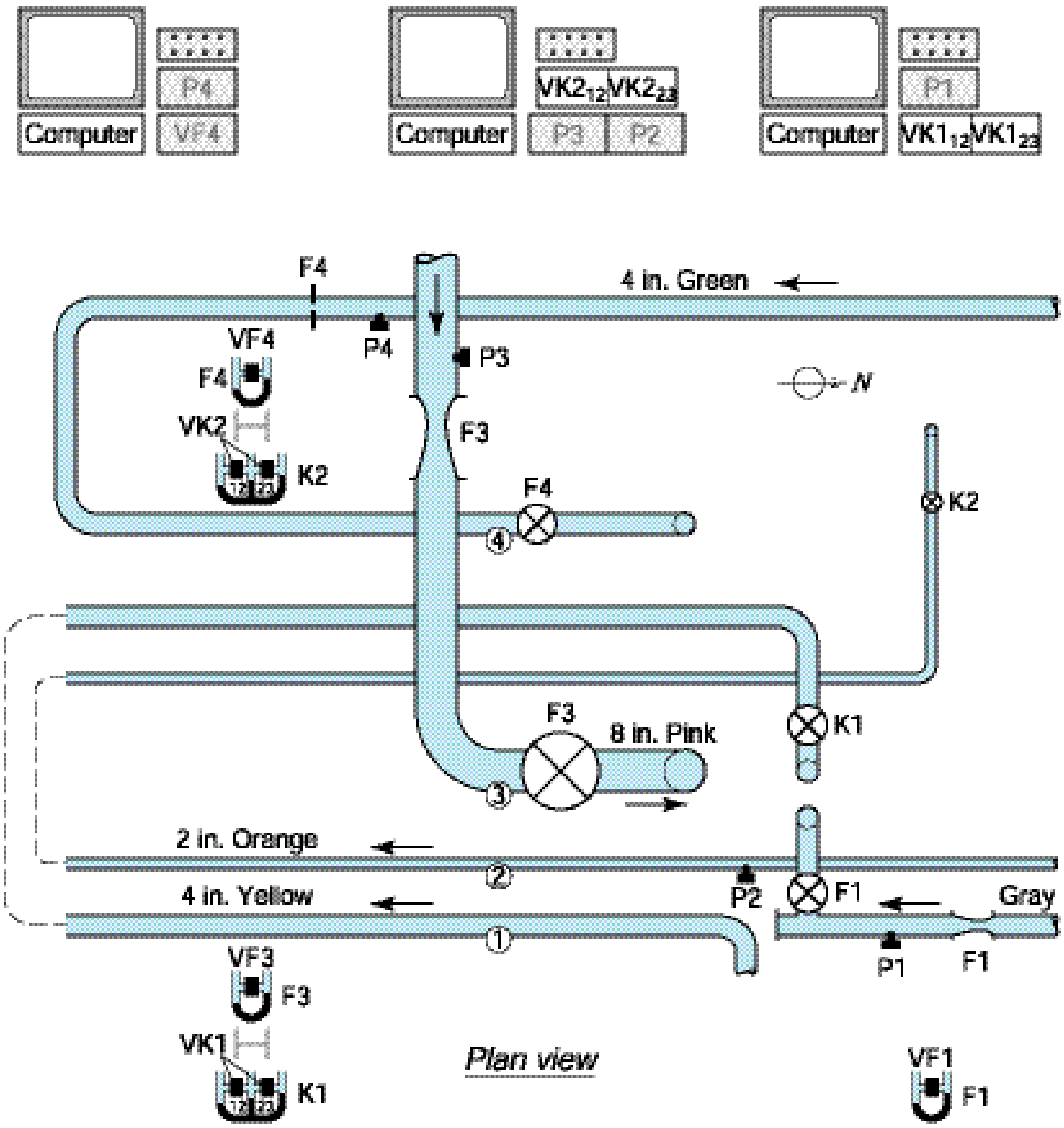


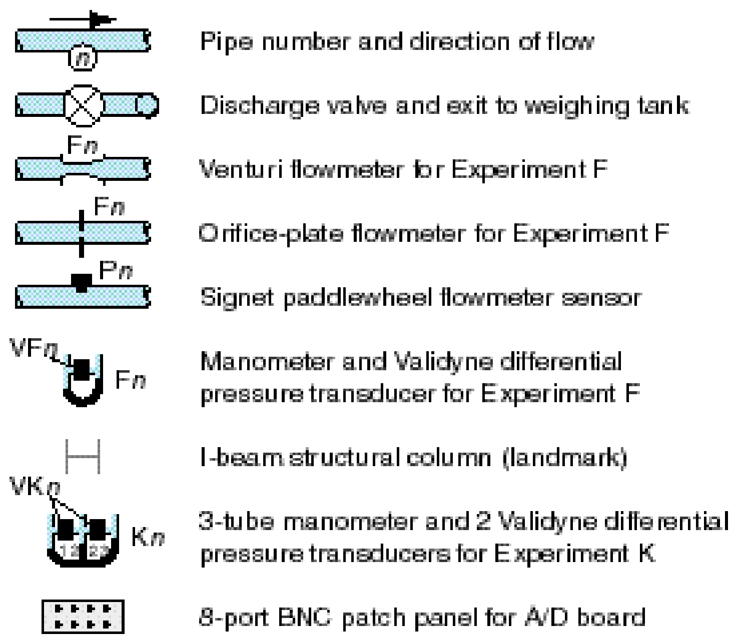
Fig. 2. Plan view of the laboratory, looking west. See key to symbols, opposite page.

updates the output current accordingly; thus some time-averaging is inherent in the device. Even so, when the indicated flow rate is changing, the meters should be allowed to settle before reading them; if the readings continue to fluctuate, average values should be recorded.

The standard for calibration in each experiment is the flow rate measured by a weight–time procedure using weighing tanks. The weight ratios for the weighing scales for the three experimental stations (F-1, F-3, and F-4) are 200:1, 10,000:1 and 200:1, respectively.

The data acquisition for this experiment is controlled by LabVIEW software, which requires first the calibration of the pressure transducers used to measure the pressure differential across the hydraulic flowmeters. The LabVIEW software also controls subsequent data acquisition for both the hydraulic and paddlewheel flowmeters, determines the flow coefficients, produces an output spreadsheet, and manages output files.

Key to symbols in Fig. 2



Procedure

To begin the experiment, first check that the discharge valve is closed. Then check the levels of mercury in the mercury–water manometer for the hydraulic flowmeter. If the levels are not equal, then slowly open and close the two manometer drain valves (one of which is labeled "CAL VALVE") to bleed any trapped air in the supply lines. If necessary, adjust the central scale between the two sides of the manometer to give a zero reading for no flow.

Calibration of the manometer differential pressure transducer

The first step is to calibrate the output voltage from the Validyne differential pressure transducer (labeled VF*n* in Fig. 2, where *n* denotes the pipe number) that is used to measure the pressure difference induced by the hydraulic flowmeter. This procedure is carried out statically with no flow in the test section, to avoid fluctuations in measurements, as follows.

First, zero the transducer output on the VF*n* interface box that is located next to the computer. Then, with the discharge valve closed, open the manometer bleed valve labeled "CAL VALVE" to reduce the pressure artificially in one of the manometer lines, and simultaneously take readings of transducer output (in volts) and manometer levels (in cm), using LabVIEW software to record the results. Five data points are generally used, from zero pressure differential to the maximum pressure differential possible with the bleed valve fully open. The maximum output voltage should not exceed 10 V—if it does, ask your instructor for assistance, since the A/D board will not correctly read voltages that exceed 10 V.

The LabVIEW program performs a linear least-squares analysis on the manometer–transducer data as they are collected, and stores the slope and intercept of the resulting line for later use in data acquisition. Close the "CAL VALVE".

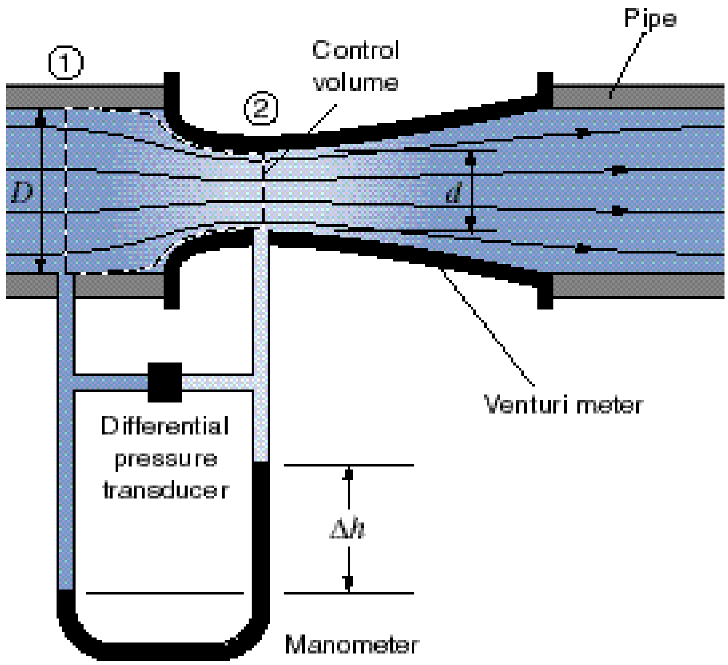


Fig. 3. Venturi meter.

Data acquisition

To acquire data using both the hydraulic flowmeter and the Signet paddlewheel flowmeter, first check that the Gain Adjust control of the paddlewheel flowmeter (labeled P*n* in Fig. 2, where *n* denotes the pipe number) is set to 6.25 turns[1] for P1 and P4, and is set to 3.00 turns[2] for P3. Then use the Zero Adjust control to zero the paddlewheel flowmeter output.

Open the discharge valve *slowly* until either the valve is fully open, or the allowable manometer deflection is reached.[3] Observe carefully both the Validyne differential pressure voltage reading and the Signet paddlewheel voltage reading as the flow is increased, and record *both* readings at the instant when the Signet paddlewheel voltage takes on a significant nonzero value.

At the maximum flow rate, record the manometer readings, record the paddlewheel flowmeter readings, take a weight–time measurement, and, using the LabVIEW software, record the time-averaged[4] pressure-transducer voltages. Make a note of the maximum manometer deflection Δh_{max}. For F1 and F3, acquire data *only* as the flow is going into the weigh tank.

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[1] These paddlewheel transmitters produces an output current that varies from a minimum of 4 mA to a maximum of 20 mA, a range of 16 mA. This output current is passed through a 10-turn 1 kΩ potentiometer set at 625 Ω, or 6.25 turns, so as to produce an output voltage range of (16 mA)(625 Ω) or 10 V.

[2] This paddlewheel transmitter produces an output current that varies from a minimum of 4 mA to a maximum of 20 mA, a range of 16 mA. This output current is passed through a 10-turn 1 kΩ potentiometer set at 300 Ω, or 3.00 turns, so as to produce an output voltage range of (16 mA)(300 Ω) or 4.8 V.

[3] In setup F-1, it is possible to drive the mercury out of the mercury–water manometer even if the maximum flow rate is approached carefully. *Extreme caution is required.*

[4] Although the flow through each flowmeter is approximately steady for each chosen flow rate in the experiment, pressure fluctuations are revealed from the mercury levels in the mercury–water differential manometers, indicating that there is some turbulence in the flow. It is difficult to obtain accurate manometer readings in such cases. With

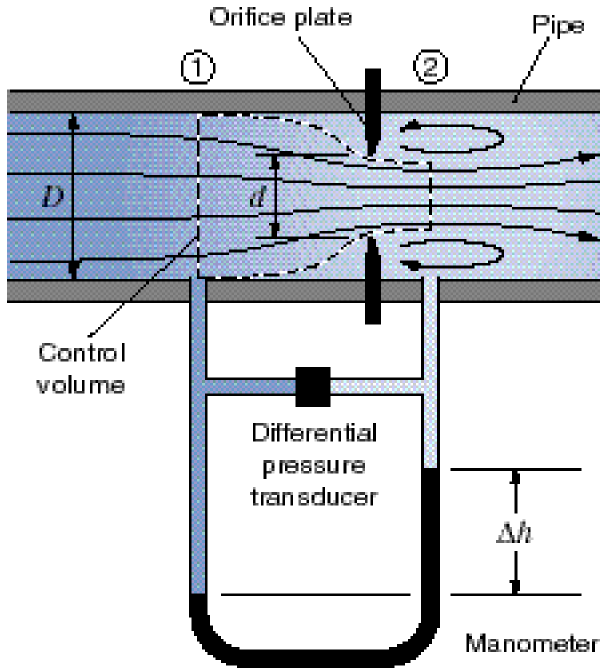

Fig. 4. Orifice-plate flowmeter.

Repeat the procedure at successively slower flow rates set so that the total manometer deflections Δh are approximately $(0.9)^2\,\Delta h_{\max}$, $(0.8)^2\,\Delta h_{\max}$, $(0.7)^2\,\Delta h_{\max}$, $\cdots$, $(0.1)^2\,\Delta h_{\max}$. These manometer settings result in flow rates that are approximately 90%, 80%, 70%, $\cdots$, 10%, of the maximum flow rate, respectively. Observe carefully both the Validyne differential pressure voltage reading and the Signet paddlewheel voltage reading as the flow is decreased, and record *both* readings at the instant when the Signet paddlewheel voltage drops suddenly to zero. For each flow rate, wait until the mercury in the manometer has become reasonably steady before acquiring data.

After the 10 data sets have been acquired, the flow coefficient C_d is displayed in the LabVIEW software as a function of the flow rate expressed in terms of the Reynolds number Re, and the paddlewheel flowmeter readings are recorded in a spreadsheet with the flow rate Q measured by the weight–time method.

Analysis and Discussion

Theoretical flowmeter relations

From a one-dimensional analysis of the control volume chosen for the region of the flowmeter between the two manometer connections, it is possible to obtain an analytical expression for the flow coefficient in terms of the flow rate Q, the pressure difference $p_1 - p_2$ across the flowmeter, and the geometrical parameters of the flowmeter. Consider the fixed control

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the aid of LabVIEW software to control data acquisition, however, it is possible to determine more reliable manometer readings by obtaining the average in a prescribed time interval for a large number of readings from the Validyne pressure transducers, which operate in parallel with the mercury–water manometers.

Table 1. Equipment description and dimensions

Apparatus		F-1	F-3	F-4
Pipe color		Gray/Yellow	Pink	Gray
Pipe diameter (nominal)		4 in.	8 in.	4 in.
Hydraulic flowmeter	Type	Venturi	Venturi	Orifice plate
	Nominal dimensions	4 in. x 1.25 in.	8 in. x 3.50 in.	4 in. x 2 in.
	Orientation	Horizontal		
	Entrance diameter *D*	102.3 mm	203.9 mm	102.3 mm
	Throat or orifice diameter *d*	31.8 mm	88.9 mm	50.8 mm
	Pressure sensors	Mercury–water manometer *and* Validyne CD101 pressure transducer		
Electrical flowmeter	Type	Paddlewheel		
	Model	Signet 3-8511-P0 (0.3–20 ft^3/s)		
	Transmitter	Signet 8511 (4–20 mA output)		

volumes shown in Figs. 3 and 4. With the approximation of steady flow in the control volume, the conservation-of-mass equation for flow through the meter can be written as

$$A_1 V_1 = A_2 V_2, \tag{1}$$

which can be simplified to

$$V_1 = \left(\frac{d_2}{D}\right)^2 V_2. \tag{2}$$

The flow through the control volume is regarded as steady flow with no energy losses, in which case Bernoulli's equation for flow from position 1 to position 2 can be written as

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2, \tag{3}$$

where $z_1 = z_2$ because all the pipes are horizontal.

From Eqns. (2) and (3), the pressure difference $p_1 - p_2$ between position 1 and position 2 can be written as

$$p_1 - p_2 = \frac{\rho_w}{2} V_2^2 \left[1 - \left(\frac{d_2}{D}\right)^4\right]. \tag{4}$$

Alternatively, from the differential mercury manometer measurement Δh, the pressure difference $p_1 - p_2$ can be determined experimentally as

$$p_1 - p_2 = \Delta h(\gamma_{\text{Hg}} - \gamma_w) = \Delta h(S_{\text{Hg}} - 1)\rho_w g. \tag{5}$$

Eliminating $p_1 - p_2$ between Eqns. (4) and (5) gives an expression for the velocity V_2, from which the flow rate Q can be written as

$$Q = V_2 A_2 = \frac{1}{\sqrt{1-(d_2/D)^4}} \frac{\pi d_2^2}{4} \sqrt{2g\Delta h(S_{\text{Hg}} - 1)}. \tag{6}$$

For the Venturi flowmeter, the diameter d_2 is the throat diameter d, so the flow rate Q can be expressed as

$$Q = \frac{C_d}{\sqrt{1-\beta^4}} \frac{\pi d^2}{4} \sqrt{2g\Delta h(S_{\mathrm{Hg}}-1)}, \tag{7}$$

where β is the contraction ratio d/D. In Eqn. (7), a discharge coefficient C_d is introduced; theoretically, this discharge coefficient has the value

$$C_d = 1, \tag{8}$$

but in practice the value of C_d is found to be slightly less than unity (Fig. 5).

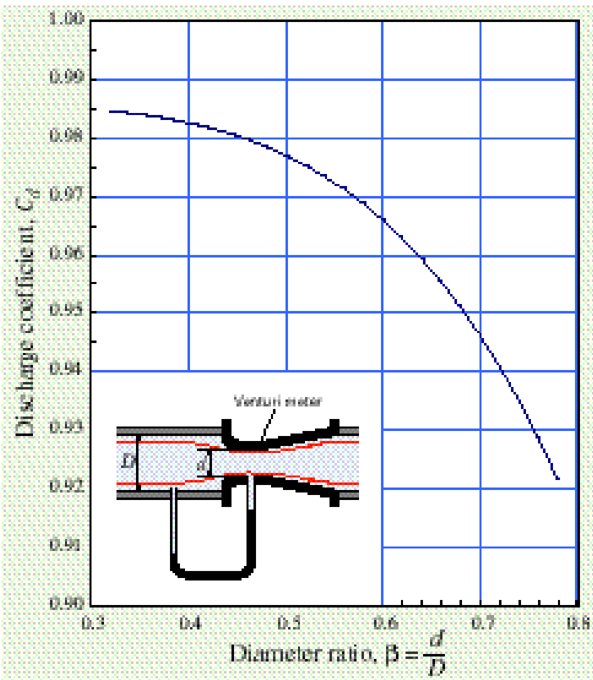

Fig. 5. ISO discharge coefficient curve for a Venturi-type flowmeter. After White (1994).

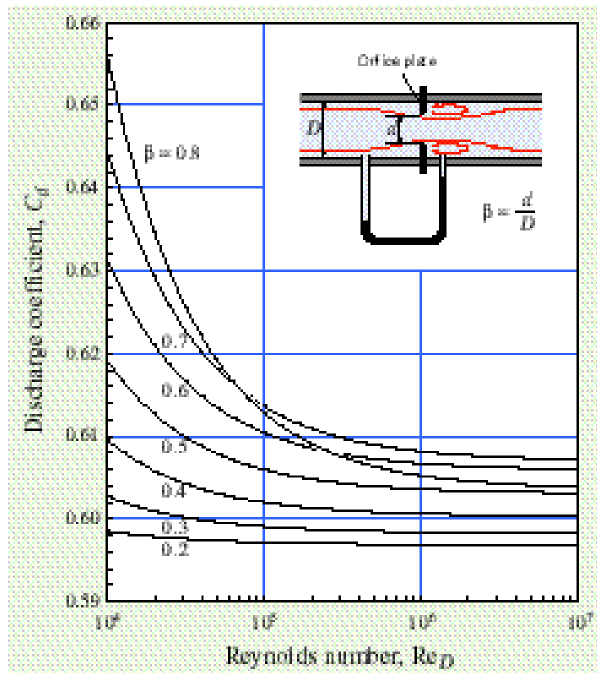

Fig. 6. ISO discharge coefficient curves for an orifice-plate flowmeter. After White (1994).

For the orifice-plate meter shown in Fig. 4, the diameter d_2 is not the orifice diameter d, but rather the unknown diameter of the vena contracta, where the flow has a minimum cross-sectional area. Even so, by taking $\beta = d/D$, where d is taken to be the orifice diameter, Eqn. (7) applies approximately for the orifice-plate meter, as shown in the Appendix. The value of the discharge coefficient C_d for an orifice-plate meter, however, is found experimentally to be significantly less than unity (Fig. 6).

Lab Report

To determine whether a given device is a useful flowmeter, one must determine if a simple, reliable, monotonic relation exists between the flow magnitude and the device's output.

Hydraulic flowmeter

In the case of the hydraulic flowmeters—the Venturi and orifice-plate meters—the theoretical relation, Eqn. (7), between Q and Δh is a nonlinear one, namely,

$$Q = C_d B\sqrt{\Delta h}, \qquad (9)$$

where C_d is the dimensionless discharge coefficient, and B is a derivable constant that depends only on the geometry of the flowmeter and some other fixed parameters. Ideally, C_d should also a constant or, at least, fairly insensitive to flow conditions.

1. Using linear scales, plot the data points for measured flow rate Q as a function of the manometer deflection Δh for the Venturi meter or the orifice-plate meter. Pass a smooth curve (not necessarily a straight line) through the data. This curve becomes the calibration curve for the flowmeter under analysis.
2. Using logarithmic scales, plot the data points for measured flow rate Q as a function of the manometer deflection Δh. Pass a smooth curve (not necessarily a straight line) through the data. This curve can be regarded as an alternate calibration curve for the flowmeter. Do the data appear to fall along a straight line, indicating that a power-law relation of the type $Q = K(\Delta h)^m$ might apply?
3. From Eqn. (7) or Eqn. (9), show that, on logarithmic scales, the theoretical curve should be a straight line with slope m equal to 1/2, provided C_d is constant.
4. Investigate the extent to which your data fit a power-law relation, and if so, what the apparent value of the exponent m is. You may use either (or both) of the following methods:
   - Using the power-law "trendline" feature of your spreadsheet program, determine the best-fit value of the exponent m for your linearly plotted data.
   - Using linear regression analysis on the *logarithms* of the data, obtain the slope m of the best-fit *straight* line through your (logarithmic) data.
5. Using values from your calibration curve, plot the discharge coefficient C_d as a function of the Reynolds number Re on linear–log scales. You may wish to use the reproduced versions of Figs. 5 and 6 on page F-11 for this purpose. Include this figure with your report. Note that the Reynolds number is calculated using the *full* pipe diameter D and the velocity in the pipe V_1:

   $$\mathrm{Re}_D = \frac{V_1 D}{\nu}. \qquad (10)$$

   (The viscosity ν is calculated within the LabVIEW software using the temperature of water as an input variable.)

Paddlewheel flowmeter

The paddlewheel flowmeter is supposed to produce a voltage that is proportional to the fluid velocity in the pipe.

6. Present a calibration curve (with linear scales) for the paddlewheel flowmeter, showing the voltage output versus the actual discharge rate Q (in m^3/s) calculated using weight–time measurements. Be careful to indicate the rising and falling cutoff flow rates, if any, below

which the paddlewheel appears to be motionless. Calculate the corresponding cutoff fluid velocities, as well as the maximum fluid velocity achieved in your experiment.

7. Discuss the relative merits of the two flowmeters tested, noting any experimental difficulties and non-ideal behavior.

Questions

1. Do your experimental results from your three graphs agree well with theoretical predictions (where appropriate)?
2. Is the discharge coefficient C_d essentially constant over the range of Reynolds numbers tested? Are the experimentally measured values for C_d close to the ideal value of unity derived theoretically? What corrections might need to be made to the theory to obtain more realistic values for C_d?
3. Can either the Venturi or orifice-plate flowmeter be used reliably to measure flow rates, using the "optimum" value of C_d determined in Step 4 of the lab write-up? Considering all the manometer data available, determine the largest relative error in measuring Q using this value of C_d.
4. How reliable is the paddlewheel flowmeter? Was the reading more accurate at high or low flow rates?
5. Suppose your local gas station uses paddlewheel flowmeters in its gas pumps. Is there a way you could fill your gas tank for free?
6. The specifications on the Signet flowmeters state that the device provides a linear voltage output over a range of fluid velocities from 0.3 to 20 ft/s (0.09 to 6.0 m/s). Does the product meet specifications, according to your data?

Partial Report

If you have not selected this laboratory exercise for preparation of a full report, then you will write a partial report in the form of an Instructable. The audience for your Instructable is a yet-to-be-hired new engineer. You are to assume the role of an experienced engineer who has recently been promoted to a new job in your company (congratulations!). Unfortunately, you must start this new job sooner than your company can hire your replacement, so that person will only have your Instructable to use for training. Make a series of easy-to-follow steps for the engineer to use. Be sure that your Instructable addresses the assigned questions above, which are posted on the TAM 335 Compass site.

References

Munson, B. R., D. F. Young, and T. H. Okiishi. 2004. *Fundamentals of Fluid Mechanics*, 4th ed. New York: Wiley, Section 8.6.1.

Shames, I. H. 1992. *Mechanics of Fluids*, 3rd ed. New York: McGraw-Hill, A-5–A-10.

Street, R. L., G. Z. Watters, and J. K. Vennard. 1996. *Elementary Fluid Mechanics*, 7th ed. New York: Wiley, Sections 14.12, 14.14.

White, F. M. 2003. *Fluid Mechanics*, 5th ed. New York: McGraw-Hill, Section 6.12.

Appendix—Orifice-plate Analysis

For the orifice-plate meter, the downstream pressure manometer is located approximately at the vena contracta, where the flow diameter is minimal. Because the diameter d_2 there is not the same as the orifice diameter d, the above analysis is modified by an area contraction coefficient C_c, the ratio of the orifice area to that at position 2, namely

$$A_2 = C_c \frac{\pi d^2}{4}. \tag{A.1}$$

Hence, the theoretical flow rate Q for the orifice-plate meter from Eqn. (6) is given by

$$Q = V_2 A_2 = \frac{1}{\sqrt{1 - C_c^2 (d/D)^4}} C_c \frac{\pi d^2}{4} \sqrt{2g\Delta h (S_{\mathrm{Hg}} - 1)}. \tag{A.2}$$

In practice, for the orifice-plate meter, there is considerable loss of energy due to turbulence and flow separation, and a velocity coefficient C_V relating the actual mean velocity through the orifice to the theoretical mean velocity through the orifice is introduced, so that the formula for Q becomes

$$Q = \frac{C_V}{\sqrt{1 - C_c^2 (d/D)^4}} C_c \frac{\pi d^2}{4} \sqrt{2g\Delta h (S_{\mathrm{Hg}} - 1)}. \tag{A.3}$$

Unfortunately, it is difficult to determine C_V and C_c separately by experiment, and therefore the coefficient in Eqn. (A.3) is often written in the form

$$\frac{C_V C_c}{\sqrt{1 - C_c^2 (d/D)^4}} \cong \frac{C_d}{\sqrt{1 - (d/D)^4}}. \tag{A.4}$$

This approximation leads to the same form as Eqn. (7). Note that d is the known diameter of the orifice, and *not* the unknown diameter of the vena contracta. Experimentally measured values for C_d are given in various references, such as Section 8.6 of Munson, Young, and Okiishi (2004) and Section 6.12 of White (2003).

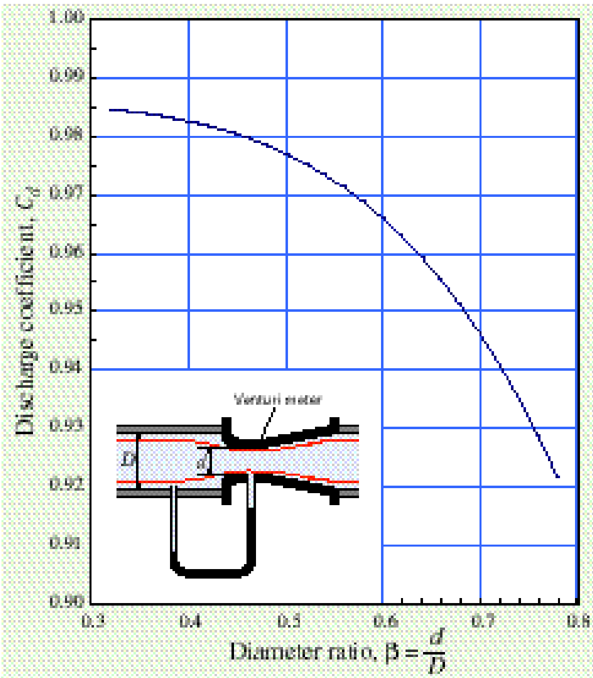

Fig. __. Comparison of lab data with ISO discharge coefficient curve for a Venturi-type flowmeter. After White (2003).

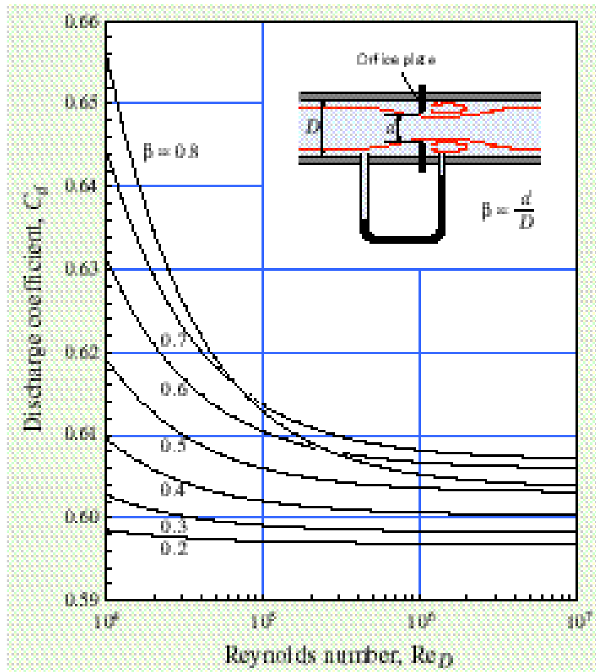

Fig. __. Comparison of lab data with ISO discharge coefficient curves for an orifice-plate flowmeter. After White (2003).

Notes