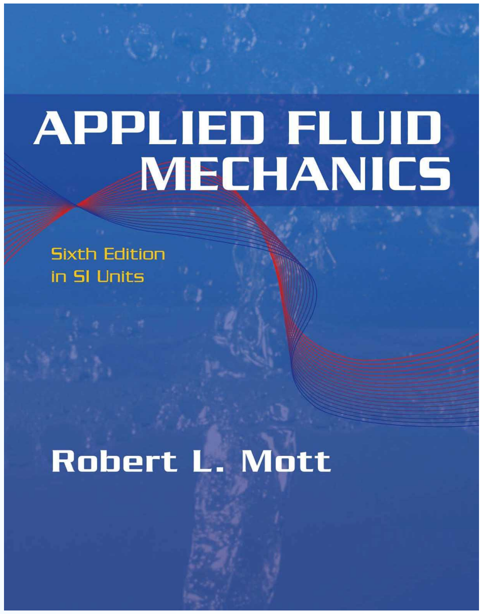
Applied Fluid Mechanics



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2. Viscosity of Fluid
3. Pressure Measurement
4. Forces Due to Static Fluid
5. Buoyancy and Stability
6. Flow of Fluid and Bernoulli's Equation
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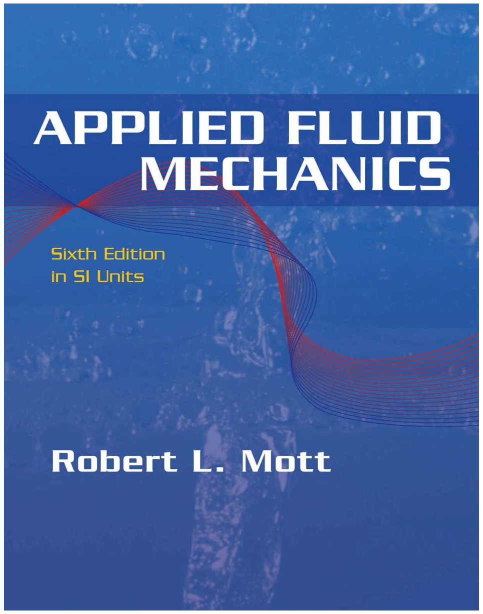
Applied Fluid Mechanics



9. Velocity Profiles for Circular Sections and Flow in Noncircular Sections
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Applied Fluid Mechanics

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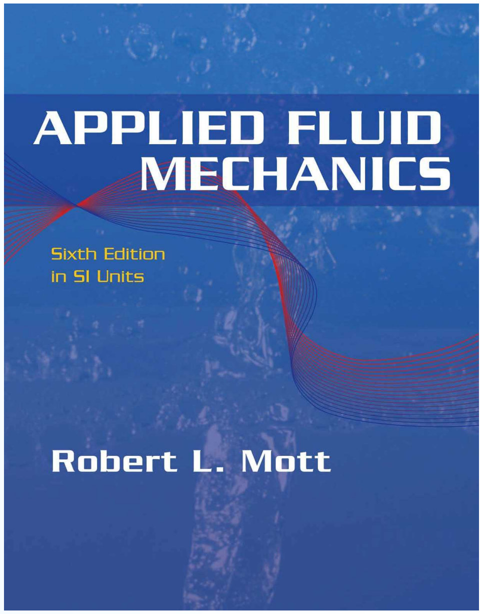


15. Flow Measurement

Chapter Objectives

- Describe six factors that should be considered when specifying a flow measurement system.
- Describe four types of variable-head meters: the *venturi tube*, the *flow nozzle*, the *orifice*, and the *flow tube*.
- Compute the velocity of flow and the volume flow rate for variable-head meters, including the determination of the discharge coefficient.
- Describe the *rotameter variable-area meter*, *turbine flowmeter*, *magnetic flowmeter*, *vortex flowmeter*, and *ultrasonic flowmeter.*

15. Flow Measurement

Chapter Objectives

- Describe two methods of measuring mass flow rate.
- Describe the *pitot-static tube* and compute the velocity of flow using data acquired from such a device.
- Define the term *anemometer* and describe two kinds.
- Describe seven types of level measurement devices.

15. Flow Measurement

Chapter Outline

15. Flow Measurement

Chapter Outline

12. Level Measurement
13. Computer-Based Data Acquistion and Processing

15. Flow Measurement

15.1 Introductory Concepts

- *Flow measurement* is an important function within any organization that employs fluids to carry on its regular operations.
- It refers to the ability to measure the velocity, volume flow rate, or mass flow rate of any liquid or gas.

15.2 Flowmeter Selection Factors

- Many devices are available for measuring flow.
- Some measure volume flow rate directly, whereas others measure an average velocity of flow that can then be converted to volume flow rate by using $Q = vA$.
- Some provide direct primary measurements, whereas others require calibration or the application of a discharge coefficient to the observed output of the device.

15.2.1 Range

- A term often used in flow measurement literature is *turndown*, the ratio of the maximum flow rate the meter can measure to the minimum flow rate that it can measure within the stated accuracy.
- It is a measure of the meter's ability to function under all flow conditions expected in the application.

15.2.2 Accuracy Required

- Virtually any flow-measuring device properly installed and operated can produce an accuracy within 5 percent of the actual flow.
- Most commercial meters are capable of 2-percent accuracy, and several claim accuracy better than 0.5 percent.
- Cost usually becomes an important factor when great accuracy is desired.

15.2.3 Pressure Loss

- Because the construction details of the various meters are quite different, they produce differing amounts of energy loss or pressure loss as the fluid flows through them.
- Except for a few types, fluid meters accomplish the measurement by placing a restriction or a mechanical device in the flow stream, thus causing the energy loss.

15.2.4 Types of Indication

- Factors to consider when choosing the type of flow indication include whether remote sensing or recording is required, whether automatic control is to be actuated by the output, whether an operator needs to monitor the output, and whether severe environmental conditions exist.

15.2.5 Types of Fluid

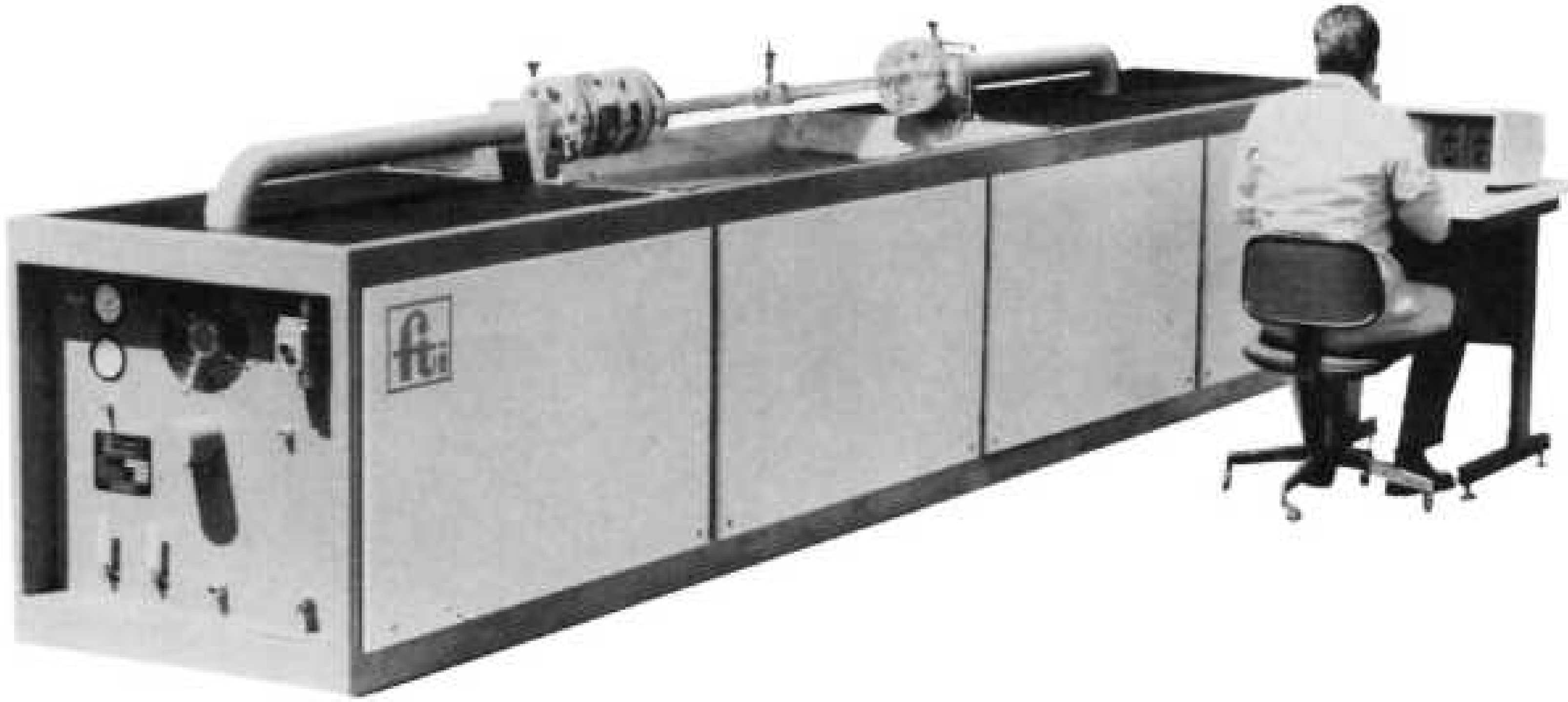
- The performance of some fluid meters is affected by the properties and condition of the fluid.
- A basic consideration is whether the fluid is a liquid or a gas.
- Other factors that may be important are viscosity, temperature, corrosiveness, electrical conductivity, optical clarity, lubricating properties, and homogeneity.
- Slurries and multiphase fluids require special meters.

15.2.6 Calibration

- Calibration is required for some types of flowmeters.
- If calibration is required by the user of the device, he or she may use another precision meter as a standard against which the reading of the test device can be compared.
- Alternatively, primary calibration can be performed by adjusting the flow to a constant rate through the meter and then collecting the output during a fixed time interval.
- Figure 15.1 shows a commercially available flow calibrator in which a precision piston moves at a controlled rate to move the test fluid through the flowmeter being calibrated.

15. Flow Measurement

15.2.6 Calibration



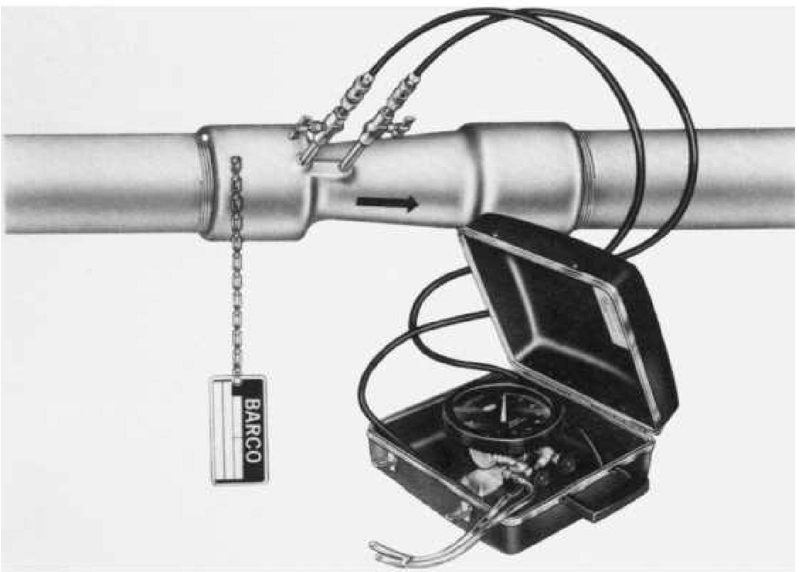
15.3 Variable-Head Meters

- The basic principle on which variable-head meters are based is that when a fluid stream is restricted, its pressure decreases by an amount that is dependent on the rate of flow through the restriction.
- Therefore, the pressure difference between points before and after the restriction can be used to indicate flow rate.
- The most common types of variable-head meters are the venturi tube, the flow nozzle, the orifice, and the flow tube.

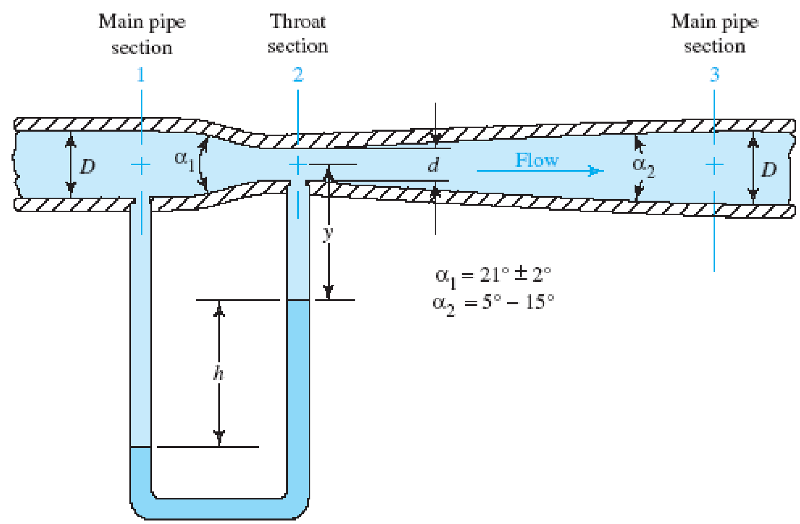
15. Flow Measurement

15.3.1 Venturi Head

- Figure 15.2 shows the basic appearance of a venturi tube.



(a)



(b) Standard details of design

15.3.1 Venturi Head

- The energy equation and the continuity equation can be used to derive the relationship from which we can calculate the flow rate.
- Using sections 1 and 2 in Fig. 15.2 as the reference points, we can write the following equations:

$$\frac{p_1}{\gamma} + z_1 + \frac{v_1^2}{2g} - h_L = \frac{p_2}{\gamma} + z_2 + \frac{v_2^2}{2g} \qquad (15\text{–}1)$$

$$Q = A_1 v_1 = A_2 v_2 \qquad (15\text{–}2)$$

- These equations are valid only for incompressible fluids, that is, liquids.

15.3.1 Venturi Head

- The algebraic reduction of Eqs. (15–1) and (15–2) proceeds as follows:

$$\frac{v_2^2 - v_1^2}{2g} = \frac{p_1 - p_2}{\gamma} + (z_1 - z_2) - h_L$$

$$v_2^2 - v_1^2 = 2g[(p_1 - p_2)/\gamma + (z_1 - z_2) - h_L]$$

- But

$$v_1^2[(A_1/A_2)^2 - 1] = 2g[(p_1 - p_2)/\gamma + (z_1 - z_2) - h_L]$$

$$v_1 = \sqrt{\frac{2g[(p_1 - p_2)/\gamma + (z_1 - z_2) - h_L]}{(A_1/A_2)^2 - 1}} \qquad (15\text{–}3)$$

15.3.1 Venturi Head

- But it is more convenient to modify Eq. (15–3) by dropping h_L and introducing a discharge coefficient *C*:

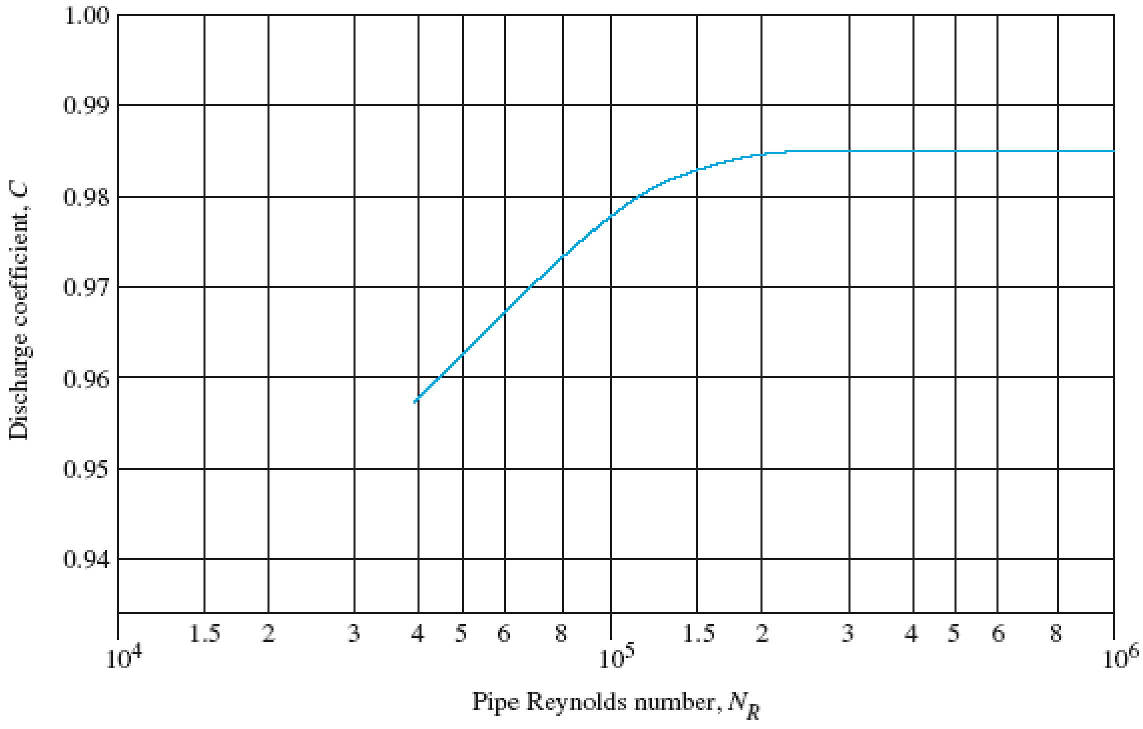
$$v_1 = C\sqrt{\frac{2g(p_1 - p_2)/\gamma}{(A_1/A_2)^2 - 1}} \tag{15–4}$$

- Normally we want to calculate the volume flow rate.

$$Q = CA_1\sqrt{\frac{2g(p_1 - p_2)/\gamma}{(A_1/A_2)^2 - 1}} \tag{15–5}$$

15.3.1 Venturi Head

- Figure 15.3 indicates that the actual value of *C* depends on the Reynolds number for the flow in the main pipe.



15.3.1 Venturi Head

- Below is the procedure for computing the flow rate of a liquid through a venturi, nozzle, or orifice meter.

1. Obtain data for:

a. Pipe inside diameter at the inlet to the venturi, .

b. Diameter of throat of the venturi, .

c. Specific weight and kinematic viscosity of the flowing fluid at the prevailing conditions in the pipe.

d. Measurement of the differential pressure between the pipe and the throat.

i. in pressure units.

ii. indicated by the deflection of a manometer.

15.3.1 Venturi Head

2. Assume a value for the discharge coefficient *C* for the meter. For the rough-cast venturi of the Herschel type, use C = 0.984, which applies for pipe Reynolds numbers greater than 2 x 10^5.
3. Compute the velocity of flow using Eq. (15–4) or Eq. (15–6).
4. Compute the Reynolds number for the flow in the pipe.
5. Obtain a revised value for the discharge coefficient *C* at the new Reynolds number.
6. If the value for C assumed in Step 5 is significantly different from that in Step 2, repeat Steps 3–5 with the new value for *C* until there is agreement.
7. Compute the volume flow rate from $Q = A_1 v_1$.

Example 15.1

A venturi tube of the Herschel type shown in Fig. 15.2 is being used to measure the flow rate of water at 60°C. The flow enters from the left in a 5-in Schedule 40 steel pipe. The throat diameter *d* is 56 mm. The venturi is rough cast. The manometer fluid is mercury (sg = 13.54) and the deflection *h* is 180 mm. Compute the velocity of flow in the pipe and the volume flow rate.

Example 15.1

First let's document pertinent data and compute some of the basic parameters in Eq. (15–6).

Fluid flowing in the pipe: water at 60°C; $\gamma_w = 9.65\ \text{kN/m}^3$, $\nu = 4.67 \times 10^{-7}\ \text{m}^2/\text{s}$ (from Appendix A)

Manometer fluid: mercury (sg = 13.54);

$$\gamma_m = (13.54)(9.65\ \text{kN/m}^3) = 130.6\ \text{kN/m}^3.$$

Pipe dimensions: $D = 128$ mm, $A_1 = 1.291 \times 10^{-2}\ \text{m}^2$ (from Appendix F)

Throat dimensions: $d = (56\ \text{mm})(1.0\ \text{m}/1000\ \text{mm}) = 0.056\ \text{m}$,

$$A_2 = \pi d^2/4 = 0.0025\ \text{m}^2$$

Example 15.1

Then

$$A_1/A_2 = (1.291 \times 10^{-2}\ \text{m}^2/0.0025\ \text{m}^2) = 5.164$$
$$\beta = d/D = (0.056\ \text{m})/(0.128\ \text{m}) = 0.438$$

Figure 15.3 applies and gives the value of the discharge coefficient *C* for the rough-cast venturi. Let's assume that the Reynolds number for the flow of water in the pipe is greater than 2.0×10^5 and use the value of C = 0.984 as the first estimate. This must be checked later when the Reynolds number is known and adjusted according to Fig. 15.3 if $N_R < 2.0 \times 10^5$.

Example 15.1

Evaluate

$$[(\gamma_m/\gamma_w) - 1] = [(130.66\ \text{kN/m}^3/9.65\ \text{kN/m}^3)\text{-}1] = 12.54$$

Also, let's convert the *h* value to m:

$$h = (180\ \text{mm})(1\ \text{m}/1000\ \text{mm}) = 0.18\ \text{m}$$

Now we can compute from Eq. (15–6):

$$v_B = \sqrt{\frac{2gh[(\gamma_m/\gamma_w)-1]}{(A_1/A_2)^2-1}} = 0.984\sqrt{\frac{2(9.81)(0.18)(12.54)}{(5.164)^2-1}}$$

$$v_1 = 1.294 m/s$$

Example 15.1

Now we must check the Reynolds number for the flow in the pipe using this value:

$$N_r = \frac{v_1 D}{v} = \frac{(1.293)(0.128)}{4.67 \times 10^{-7}} = 3.54 \times 10^5$$

We note that this value is greater than 2 x 10^5 as we initially assumed. Then the value for the discharge coefficient, C = 0.984 is correct and the calculation for v_1 is also correct. If the Reynolds number was less 2 x 10^5, than we would read a new value of *C* from Fig. 15.3 and recompute the velocity.

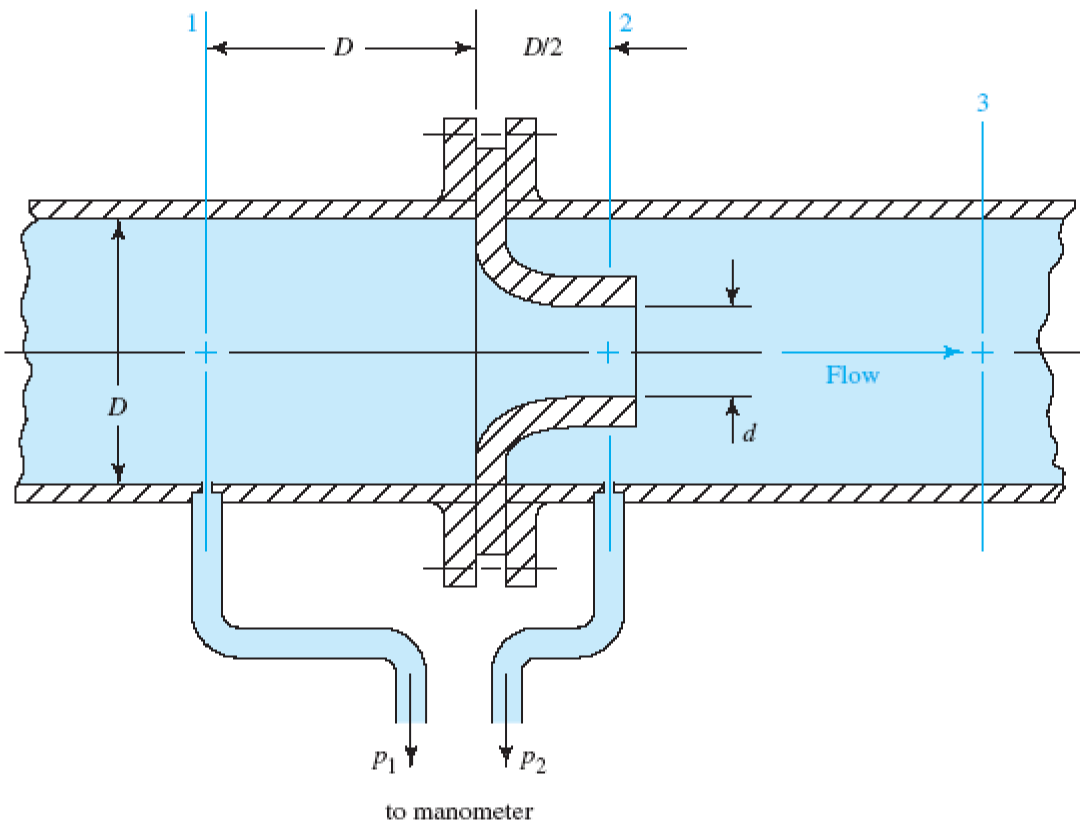
Example 15.1

Now we complete the problem by computing the volume flow rate *Q*:

$$Q = A_1 v_1 = (0.0129\ \text{m}^2)(1.293\ \text{m/s}) = 0.0167\ \text{m}^3/\text{s}$$

15.3.2 Flow Nozzle

- The *flow nozzle* is a gradual contraction of the flow stream followed by a short, straight cylindrical section as illustrated in Fig. 15.4.



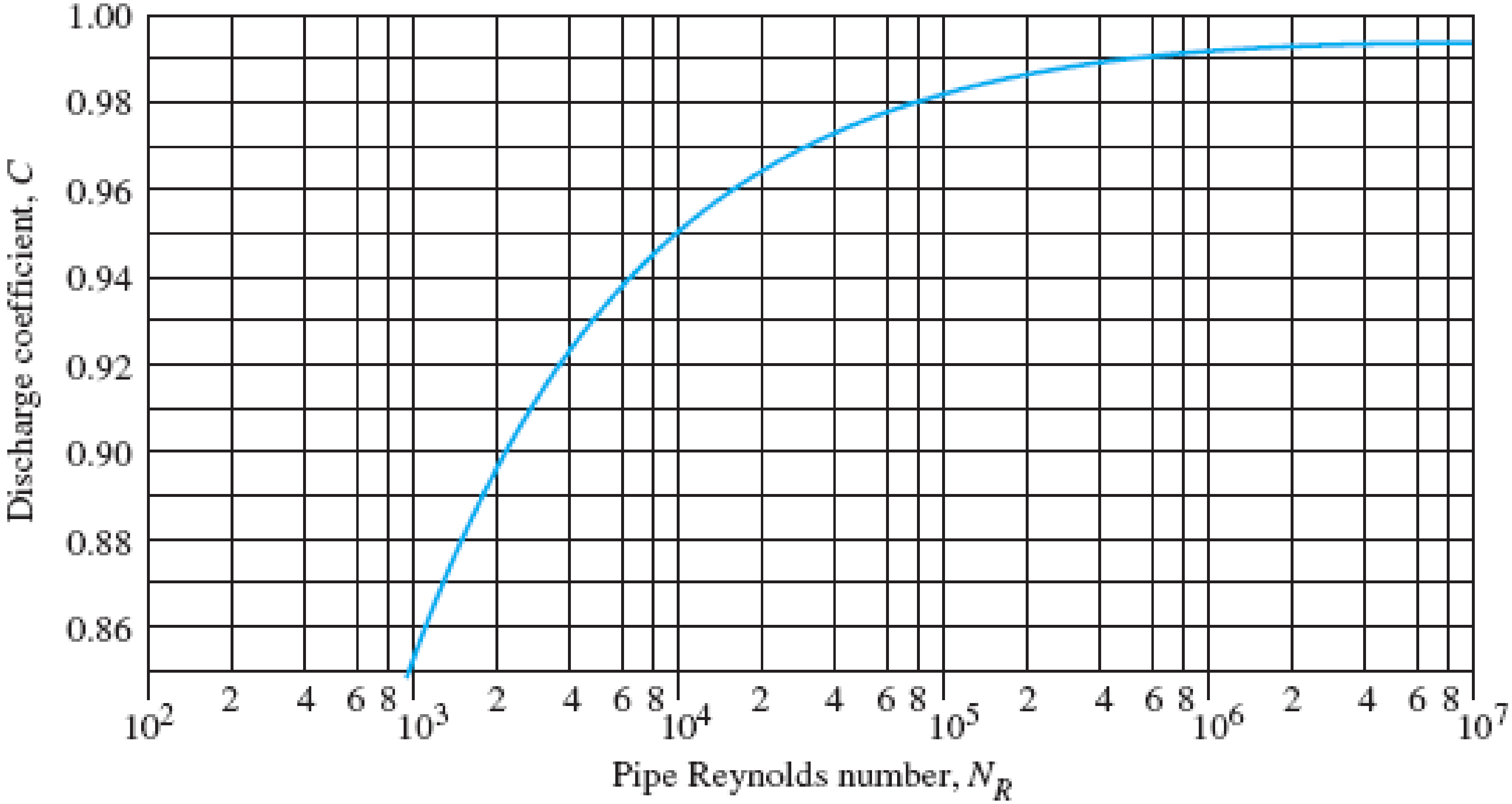
15.3.2 Flow Nozzle

- A typical curve of *C* versus Reynolds number is shown in Fig. 15.5.
- At high Reynolds numbers *C* is above 0.99.
- At lower Reynolds numbers the sudden expansion outside the nozzle throat causes greater energy loss and a lower value for *C*.

$$C = 0.9975 - 6.53\sqrt{\beta/N_R} \quad (15\text{–}7)$$

where β = d/D

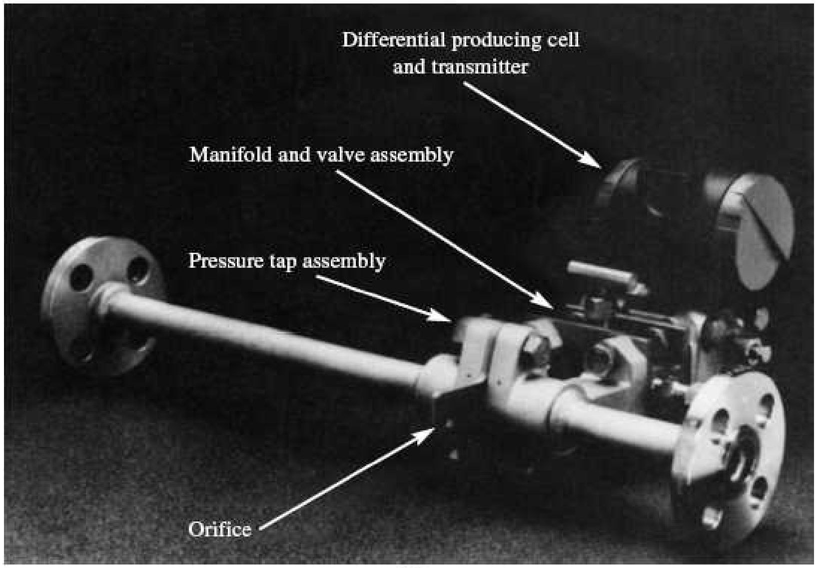
15.3.2 Flow Nozzle



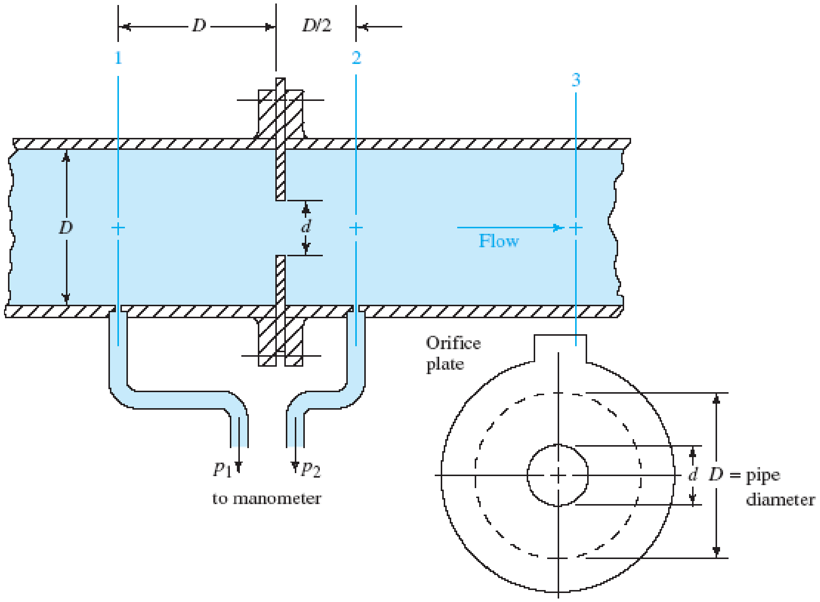
15. Flow Measurement

15.3.3 Orifice

- A flat plate with an accurately machined, sharp-edged hole is referred to as an *orifice*.
- Fig 15.6 shows the square-edged orifice with pressure taps at *D and D/2.*



(a)



(b) Sketch of orifice installation

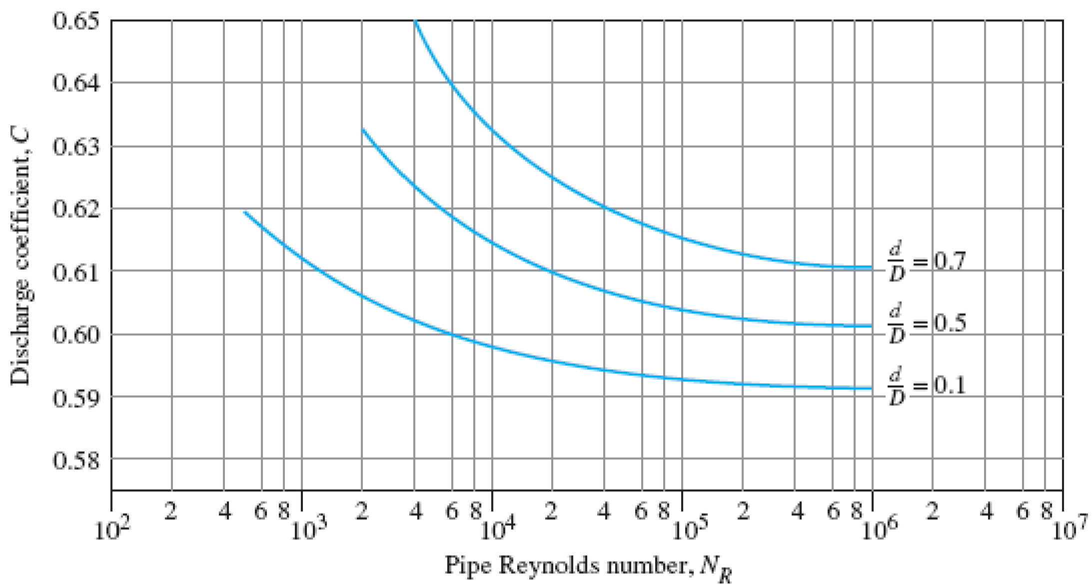
15.3.3 Orifice

- The actual value of the discharge coefficient *C* depends on the location of the pressure taps.
- Three possible locations are listed in Table 15.1.

	Inlet Pressure Tap, p_1	Output Pressure Tap, p_2
1	One pipe diameter upstream from plate	One-half pipe diameter downstream from inlet face of plate
2	One pipe diameter upstream from plate	At vena contracta (see Reference 5)
3	In flange, 1 in upstream from plate	In flange, 1 in downstream from outlet face of plate

15.3.3 Orifice

- The value of *C* also is affected by small variations in the geometry of the edge of the orifice.
- Typical curves for sharp-edged orifices are shown in Fig. 15.7, where *D* is the pipe diameter and *d* is the orifice diameter.



15.3.4 Flow Tubes

- Several proprietary designs for modified variable-head flow meters called flow tubes are available.
- These can be used for applications similar to those for which the venturi, nozzle, or orifice meters are used, but flow tubes have somewhat lower pressure loss (higher pressure recovery).
- Figure 15.8 is a photograph of one manufacturer's flow tube.

15.3.5 Overall Pressure Loss

- The difference in pressure can be evaluated by considering the energy equation:

$$\frac{p_1}{\gamma} + z_1 + \frac{v_1^2}{2g} - h_L = \frac{p_3}{\gamma} + z_3 + \frac{v_3^2}{2g}$$

- Because the pipe sizes are the same at both sections, $v_1 = v_2$.
- We may also assume $z_1 = z_2$. Then,

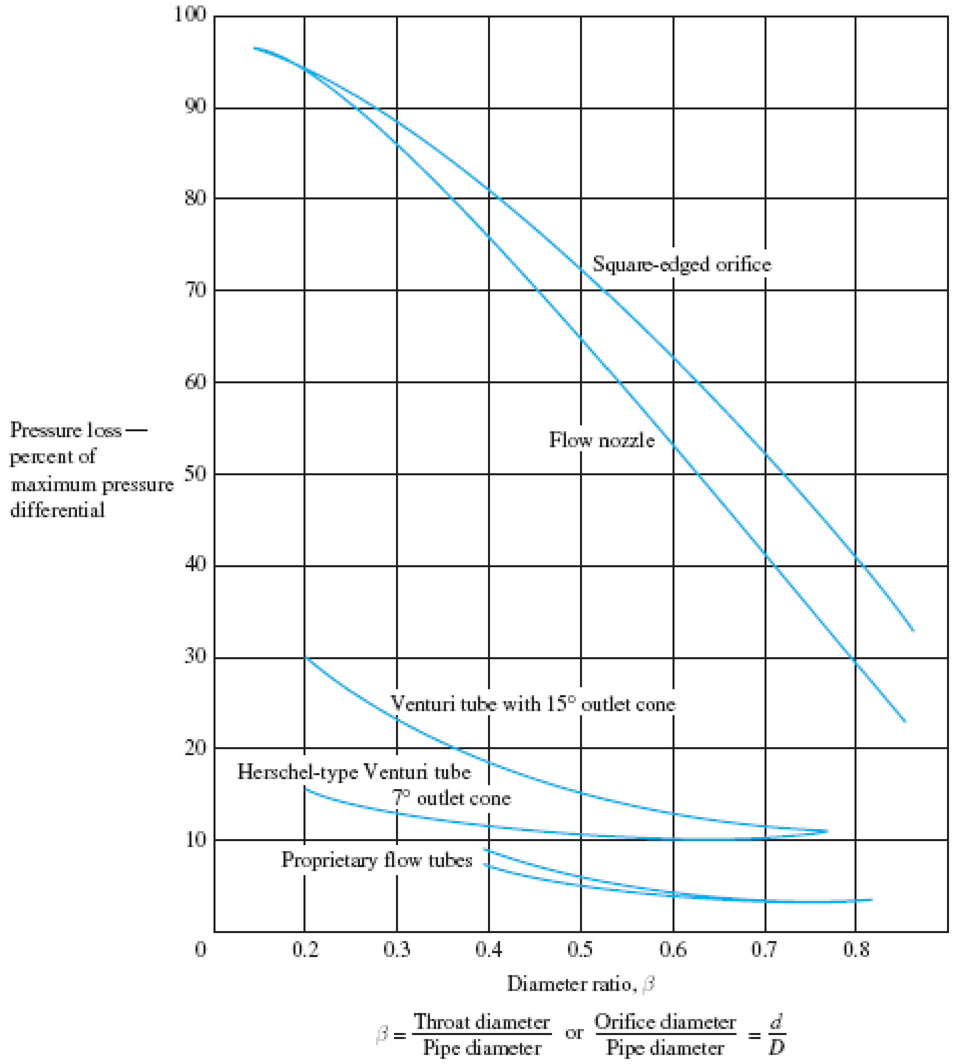
$$p_1 - p_3 = \gamma h_L$$

- The pressure drop is proportional to the energy loss.

15.4 Variable-Area Meters

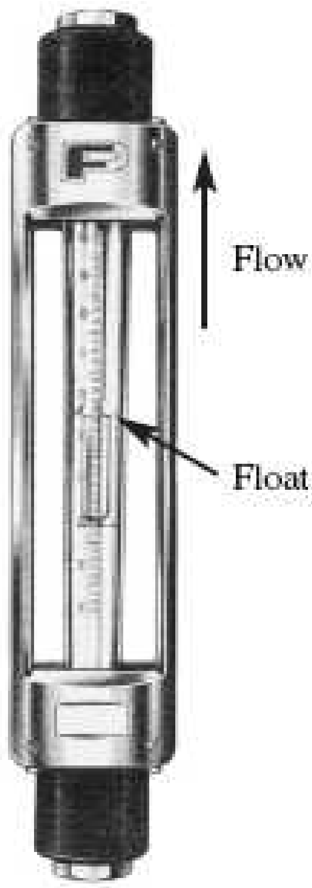
- The *rotameter* is a common type of variable area meter.
- Figure 15.9 shows a typical geometry.
- The position of the float is sensed from outside the tube by an electromagnetic means and the flow rate is indicated on a gage.
- Use of the type of rotameter shown in Fig. 15.10 requires that the fluid be transparent because the operator must visually see the position of the float.

15.4 Variable-Area Meters



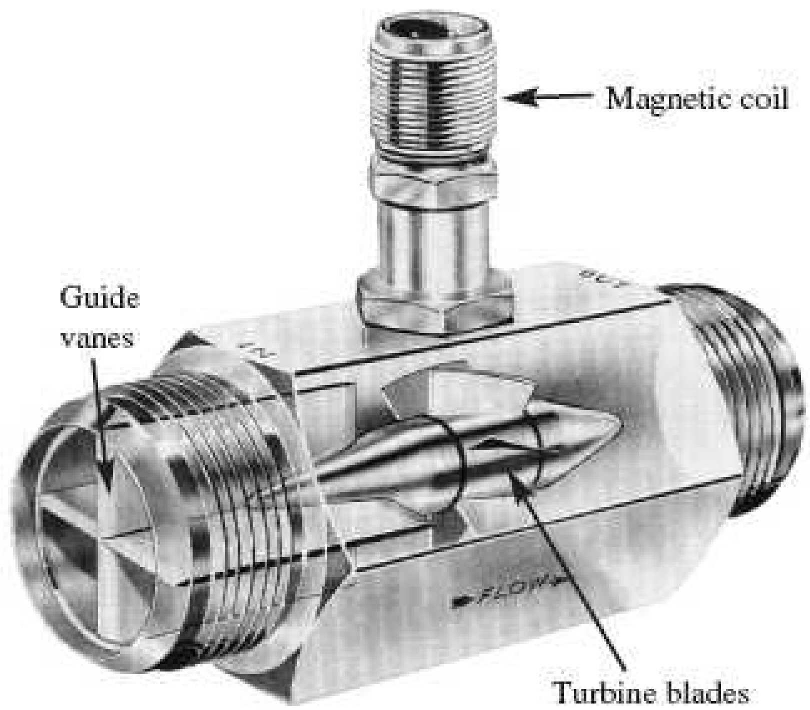
15. Flow Measurement

15.4 Variable-Area Meters



15.5 Turbine Flowmeter

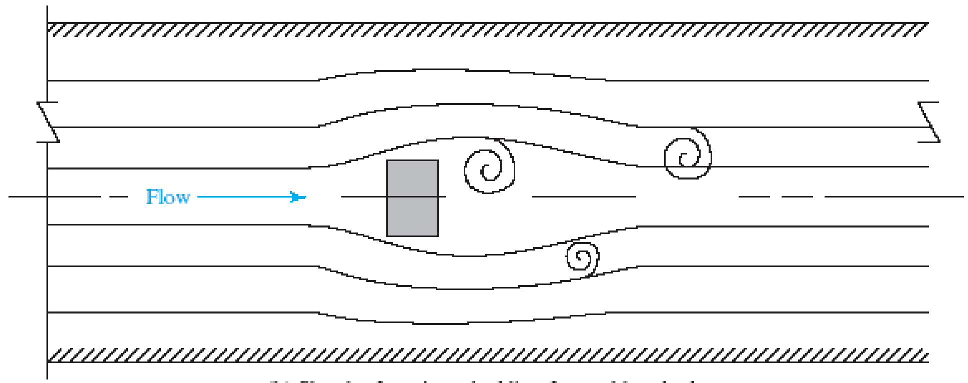
- Figure 15.11 shows a turbine flowmeter in which the fluid causes the turbine rotor to rotate at a speed dependent on the flow rate.



15.6 Vortex Flowmeter

- Figure 15.12 show a *vortex-flowmeter*, in which a blunt obstruction placed in the flow stream causes vortices to be created and shed from the body at a frequency that is proportional to the flow velocity.

(a) Photograph of a vortex flowmeter



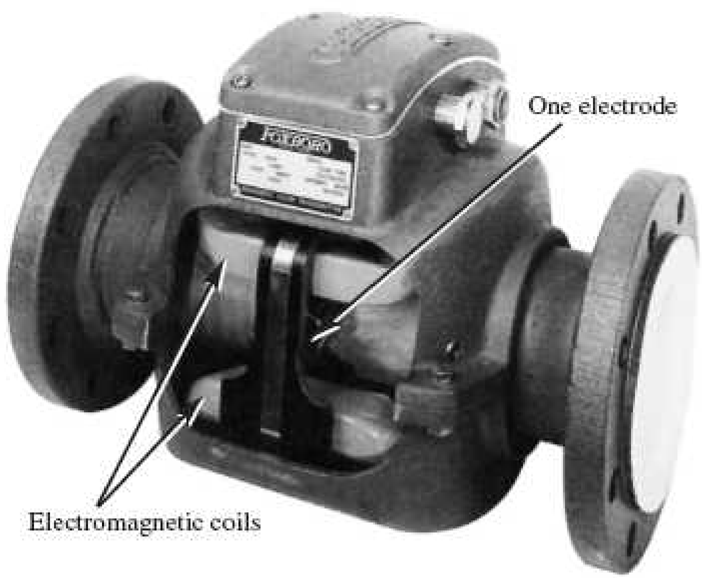
(b) Sketch of vortices shedding from a blunt body

15.6 Vortex Flowmeter

- The difference in velocity causes shear layers to form that eventually break down into vortices alternately on the two sides of the shedding element.
- The frequency of the vortices created is directly proportional to the flow velocity and, therefore, to the volume flow rate.
- Sensors in the meter detect the pressure variations around the vortices and generate a voltage signal that alternates at the same frequency as the vortex-shedding frequency.

15.7 Magnetic Flowmeter

- Totally unobstructed flow is one of the advantages of a magnetic flowmeter like that shown in Fig. 15.13.
- The fluid must be slightly conducting because the meter operates on the principle that when a moving conductor cuts across a magnetic field, a voltage is induced.



15.8 Ultrasonic Flowmeter

- A major advantage of an ultrasonic flowmeter is that it is not necessary to penetrate the pipe in any way.
- An ultrasonic generator is strapped to the outside of the pipe and a high-frequency signal is transmitted through the wall of the pipe and across the flow stream, typically at an acute angle with respect to the axis of the pipe.
- A second type of meter, called the *Doppler-type meter*, is preferred for dirty fluids, slurries, and other fluids that may inhibit the transmission of the ultrasonic signal.
- The ultrasonic pressure wave does not traverse completely to the opposite wall of the pipe.
- Rather, it is reflected from the particles in the fluid itself and back to the receiver.

15.9 Positive-Displacement Meters

- Fluid entering a positive-displacement meter fills up a chamber that is moved from the input to the output side of the meter.
- The meter records or indicates the cumulative volume of fluid that has passed through the meter.
- Typical uses for positive-displacement meters are water delivered from the municipal system to a home or business, natural gas delivered to a customer, and gasoline delivered at a service station.

15.10 Mass Flow Measurement

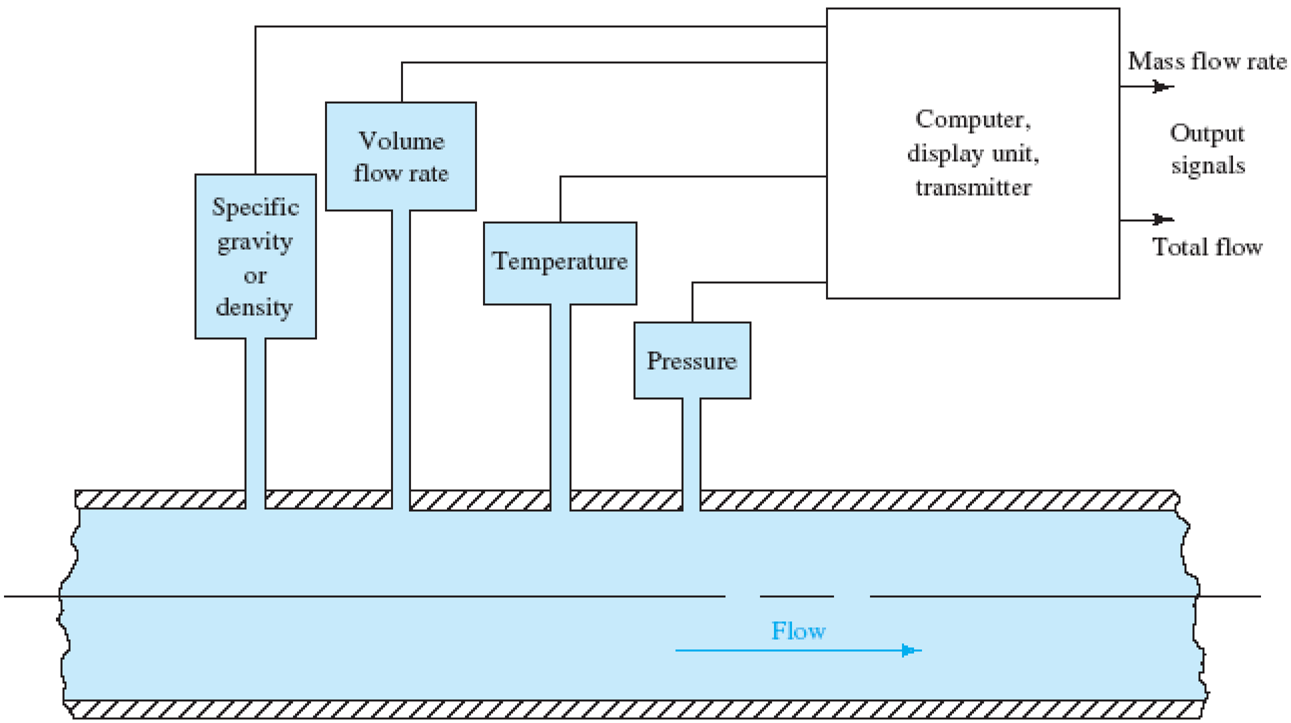
- The flowmeters discussed thus far in this chapter are designed to produce an output signal that is proportional to the average velocity of flow or the volume flow rate.
- This is satisfactory when only the *volume* delivered through the meter is needed.
- The mass flow rate would be

$$M = \rho Q$$

- Density can be measured directly for some fluids with a *densitometer*.

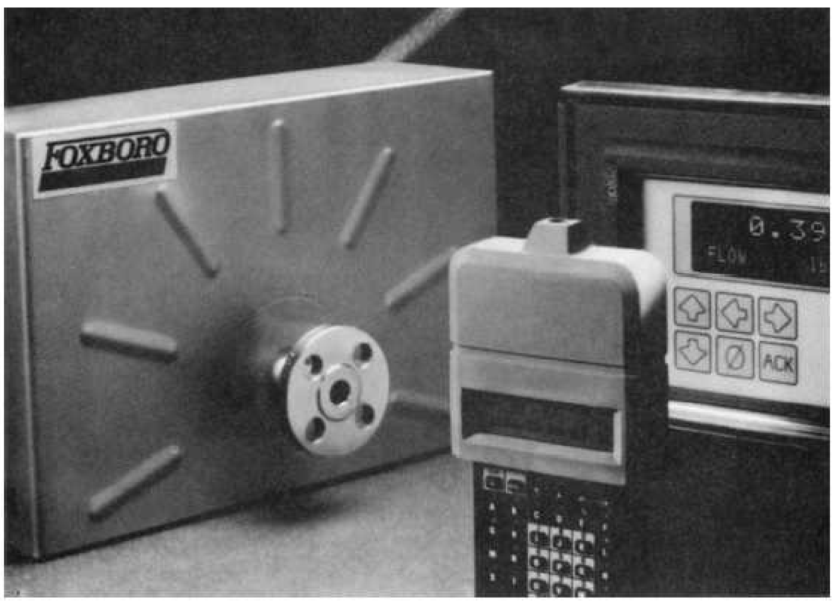
15.10 Mass Flow Measurement

- Fig 15.14 shows the schematic representation of mass flow measurement using multiple sensors.

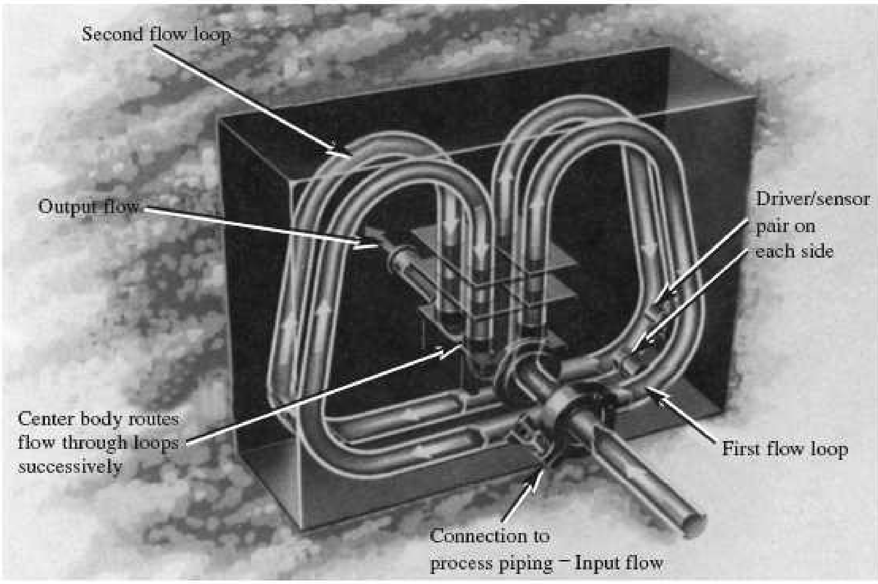


15.10 Mass Flow Measurement

- True mass flowmeters avoid the problems discussed above by generating a signal proportional to the mass flow rate directly.
- One such mass flowmeter is called the *Coriolis mass flowtube*, shown in Fig. 15.15.



(a) External view with programmer and indicator



(b) Internal view

15.10 Mass Flow Measurement

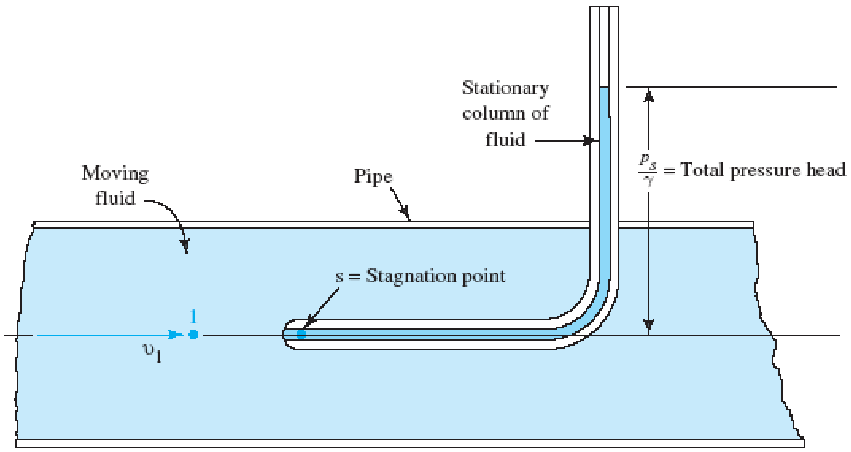
- Density of the fluid can also be measured with the Coriolis mass flowtube because the driving frequency of the tubes is dependent on the density of the fluid flowing through the tubes.
- A temperature probe is also included in the system, completing a comprehensive set of fluid properties and mass flow rate data.
- Another form of mass flowmeter uses a thermal technique in which two probes, called *resistance temperature detectors* (RTDs), are inserted into the flow.

15.11 Velocity Probes

- Several devices are available that measure the velocity of flow at a specific location rather than an average velocity.
- These are referred to as *velocity probes*.

15.11.1 Pitot Tube

- When a moving fluid is caused to stop because it encounters a stationary object, a pressure is created that is greater than the pressure of the fluid stream.
- The magnitude of this increased pressure is related to the velocity of the moving fluid.
- The *pitot tube* uses this principle to indicate velocity, as illustrated in Fig. 15.16.



15.11.1 Pitot Tube

- We can use the energy equation to relate the pressure at the stagnation point to the fluid velocity.

$$\frac{p_1}{\gamma} + z_1 + \frac{v_1^2}{2g} - h_L = \frac{p_s}{\gamma} + z_s + \frac{v_s^2}{2g} \qquad (15\text{–}8)$$

- Observe that $v_s = 0$, $z_1 = z_2$ or very nearly so, and $h_L = 0$ or very nearly so. Then we have

$$\frac{p_1}{\gamma} + \frac{v_1^2}{2g} = \frac{p_s}{\gamma} \qquad (15\text{–}9)$$

15.11.1 Pitot Tube

- The names given to the terms in Eq. (15–9) are as follows:

$$p_1 = \text{Static pressure in the main fluid stream}$$
$$p_1/\gamma = \text{Static pressure head}$$
$$p_s = \text{Stagnation pressure or total pressure}$$
$$p_s/\gamma = \text{Total pressure head}$$
$$v_1^2/2g = \text{Velocity pressure head}$$

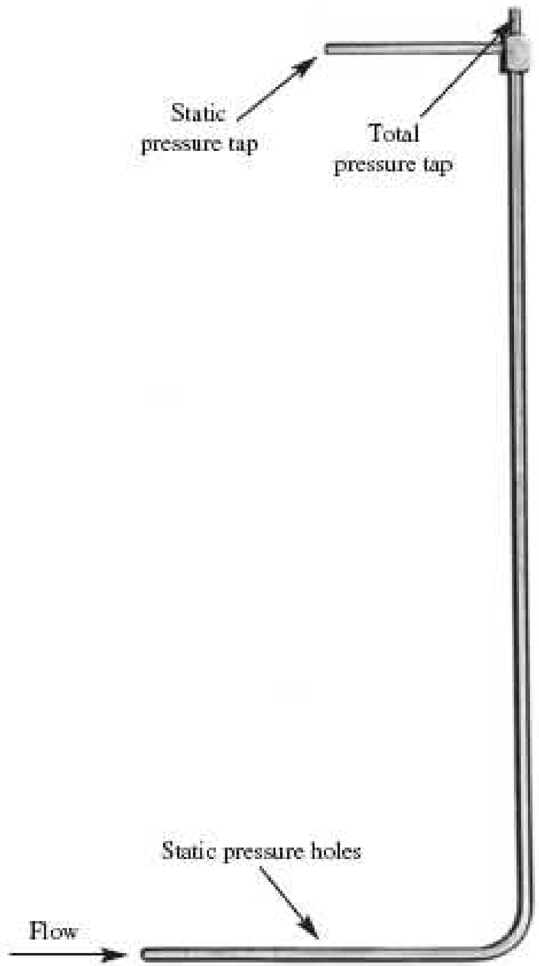
- The total pressure head is equal to the sum of the static pressure head and the velocity pressure head. Solving Eq. (15–9) for the velocity gives

$$v_1 = \sqrt{2g(p_s - p_1)/\gamma} \qquad (15\text{–}10)$$

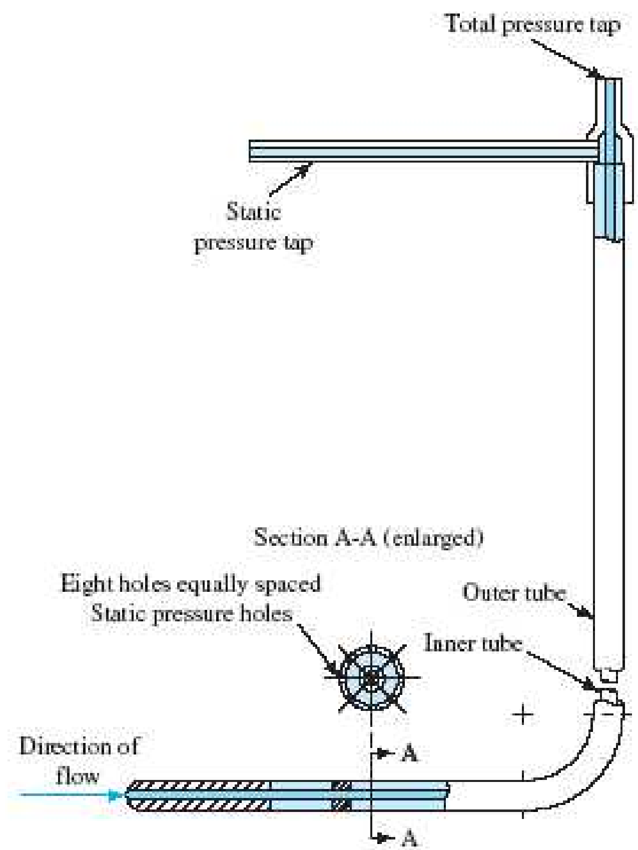
15.11.1 Pitot Tube

- The device shown in Fig. 15.17 facilitates the measurement of both the static pressure and the stagnation pressure simultaneously and so it is sometimes called a *pitot-static* tube.
- Its construction shown in part (b) is actually a tube within a tube.
- If a differential manometer is used as shown in Fig. 15.18, the manometer deflection h can be related directly to the velocity.

15.11.1 Pitot Tube



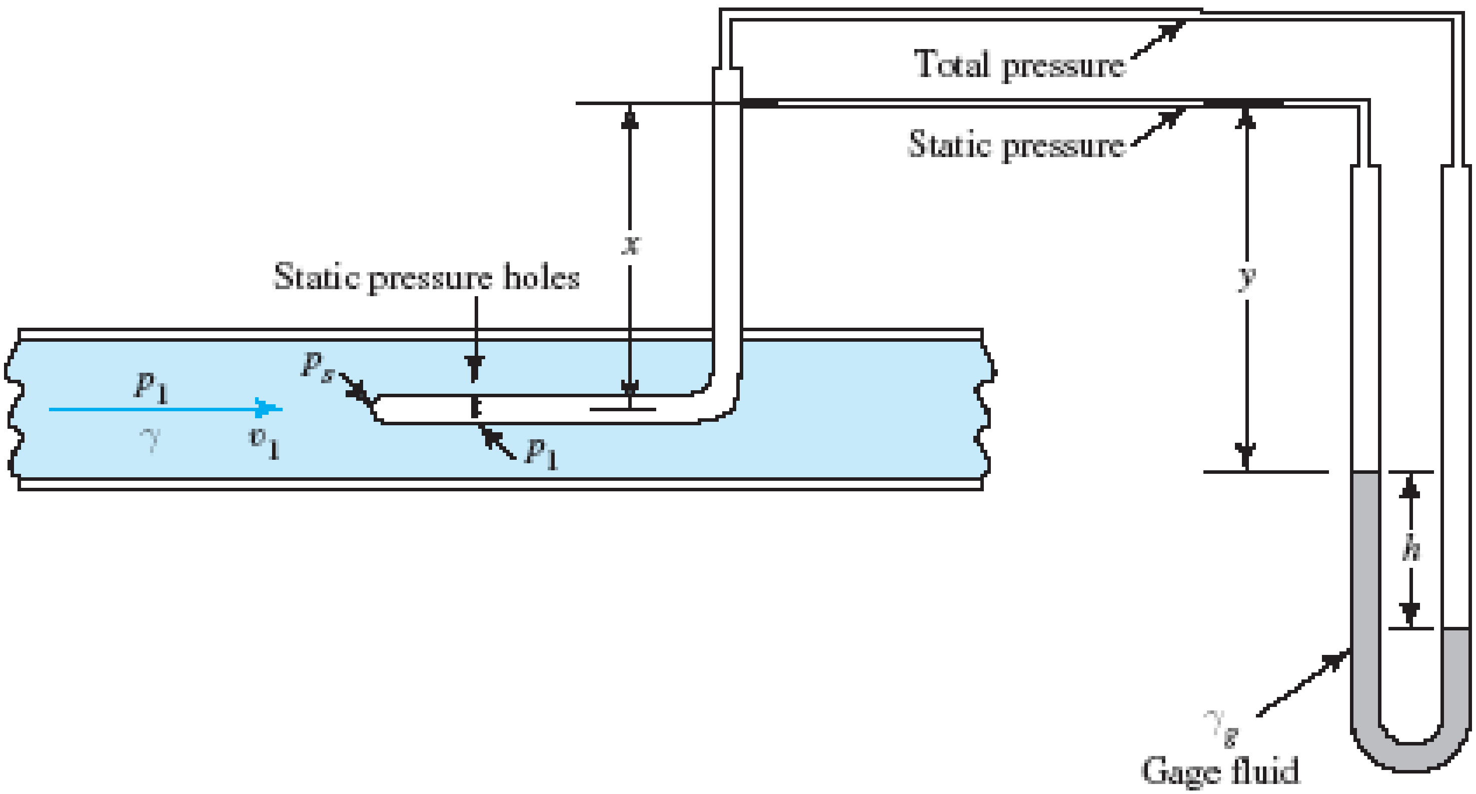
(a) Photograph of commercially available Pitot-static tube



(b) Drawing of the construction of a Pilot-static tube

15. Flow Measurement

15.11.1 Pitot Tube



15.11.1 Pitot Tube

- We can write the equation describing the difference between p_s and p_1 by starting at the static pressure holes in the side of the tube, proceeding through the manometer, and ending at the open tip of the tube at point *s*:

$$p_1 - \gamma x + \gamma y + \gamma_g h - \gamma h - \gamma y + \gamma x = p_s$$

- The terms involving the unknown distances *x* and *y* drop out. Then, solving for the pressure difference, we get

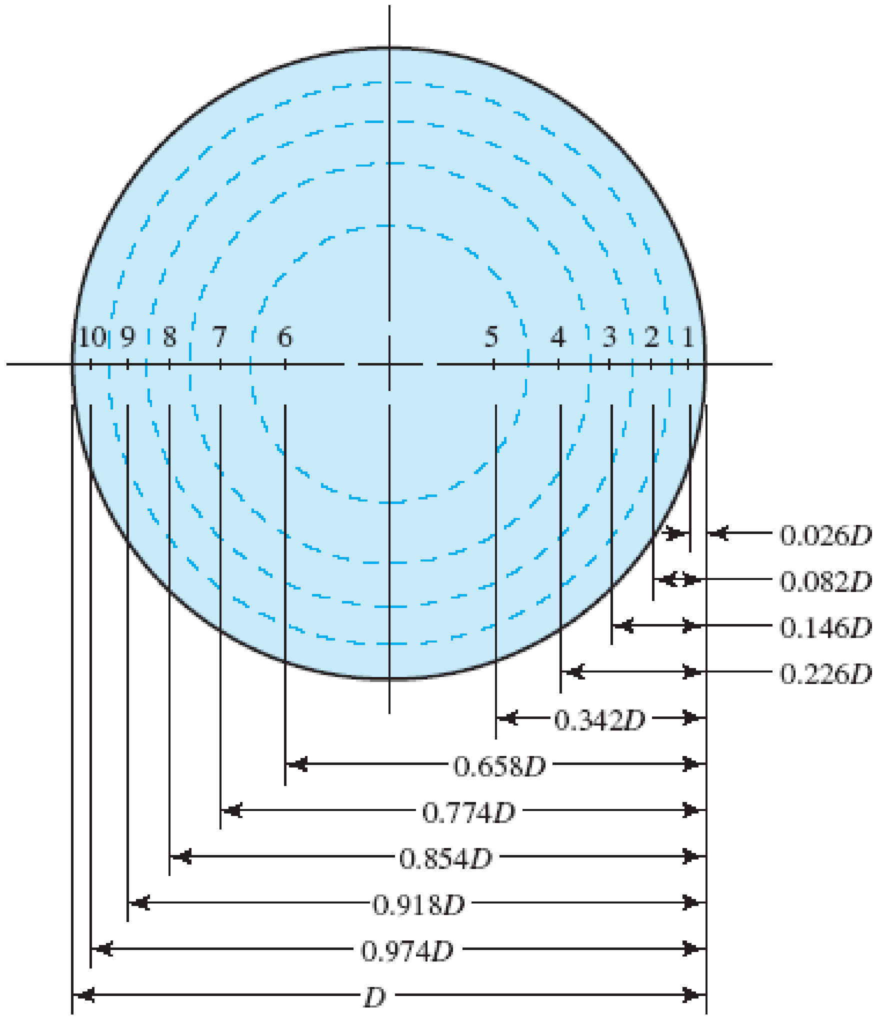
$$p_s - p_1 = \gamma_g h - \gamma h = h(\gamma_g - \gamma) \qquad (15\text{–}11)$$

$$v_1 = \sqrt{2gh(\gamma_g - \gamma)/\gamma} \qquad (15\text{–}12)$$

15.11.1.1 Pipe Traverse to Obtain Average Velovity

- The velocity calculated by either Eq. (15–10) or Eq. (15–12) is the loscal velocity at the particular location of the tip of the tube.
- Therefore, if the average velocity of flow is desired, a traverse of the pipe should be made with the tip of the tube placed at the specific ten points indicated in Fig. 15.19.

15.11.1.1 Pipe Traverse to Obtain Average Velovity



15.11.1.2 Traverse of a Rectangular Duct

- To obtain the average velocity for a rectangular duct, it is recommended that the area be divided into 16–64 equal rectangular areas, taking velocity measurements at the center of each of these areas, and then averaging all the readings.
- The pressure differential created by a pitot tube can also be read by an electronic device such as that shown in Fig. 15.20.

15.11.1.2 Traverse of a Rectangular Duct

Example 15.2

For the apparatus shown in Fig. 15.18, the fluid in the pipe is water at 60°C and the manometer fluid is mercury with a specific gravity of 13.54. If the manometer deflection *h* is 264 mm, calculate the velocity of the water.

Equation (15–12) will be used:

$$v_1 = \sqrt{2gh(\gamma_g - \gamma)/\gamma}$$

$$\gamma = 9.65 \text{ kN/m}^3 \qquad \text{(water at 60°C)}$$

$$\gamma_g = (13.54)(9.81 \text{ kN/m}^3) = 132.8 \text{ kN/m}^3 \qquad \text{(mercury)}$$

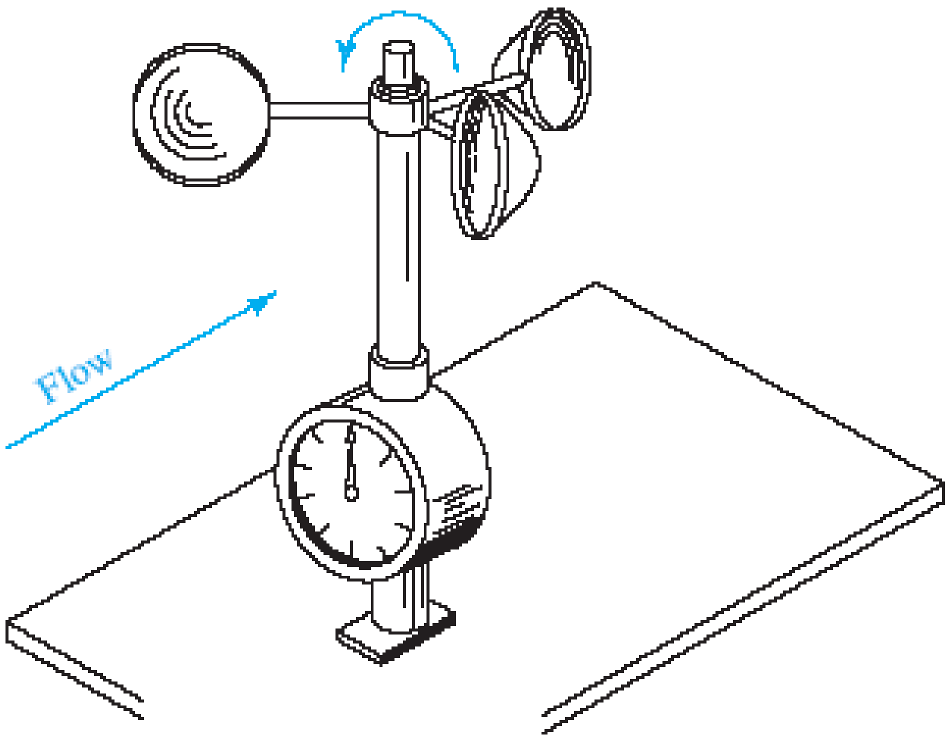
$$h = 264 \text{ mm} = 0.264 \text{ m}$$

$$v_1 = \sqrt{\frac{(2)(9.81)(0.264)(132.8 - 9.65)}{9.65}}$$

$$= 8.13 \text{ m/s}$$

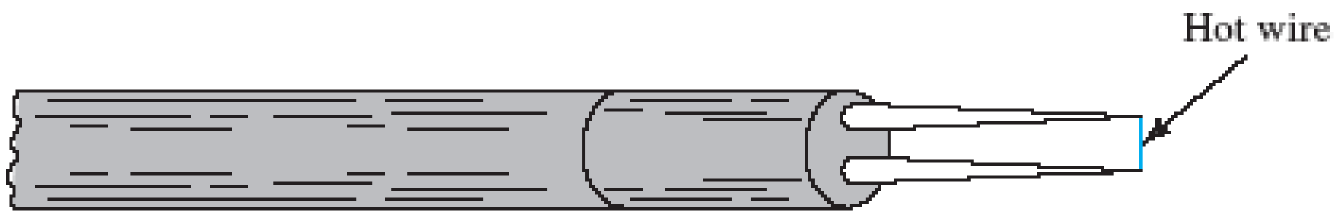
15.11.2 Cup Anemometer

- Air velocity is often measured with a *cup anemometer* such as that shown in Fig. 15.21.



15.11.3 Hot wire Anemometer

- This type of velocity probe employs a very thin wire, about 12 μm in diameter, through which an electrical current is passed.
- The wire is suspended on two supports as shown in Fig. 15.22 and inserted into the fluid stream.



15.11.4 Flow Imaging

- Various techniques are available for creating visual images of flow patterns that represent velocity distribution and flow direction for complex fluid flow systems.

15.12 Flow Measurement

- Bulk storage tanks are integral parts of many fluid flow systems, and it is often necessary to monitor the level of fluid in such tanks.
- Some of the measurement types are float type, pressure sensing, capacitance probe, vibration type, ultrasonic, radar and guided radar

15.13 Computer-based Data Acquisition and Processing

- Microcomputers, programmable controllers, and other microprocessor-based electronic instrumentation greatly simplify the acquisition, processing, and recording of flow measurement data.
- The computers can total the fluid flow rate over time to determine the total quantity of fluid transferred to a given location.
- A comprehensive measurement and control system can consist of pressure, temperature, level, and flow measurement devices; automatic process controllers; interface units; operator control stations; and large host computers.