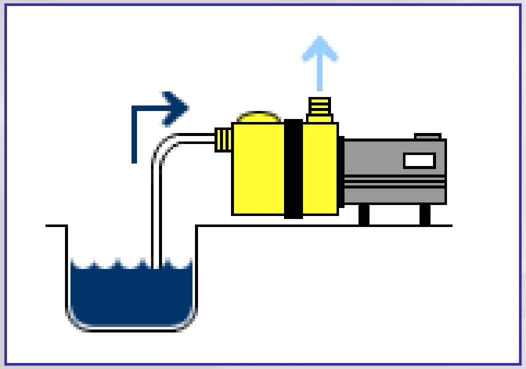
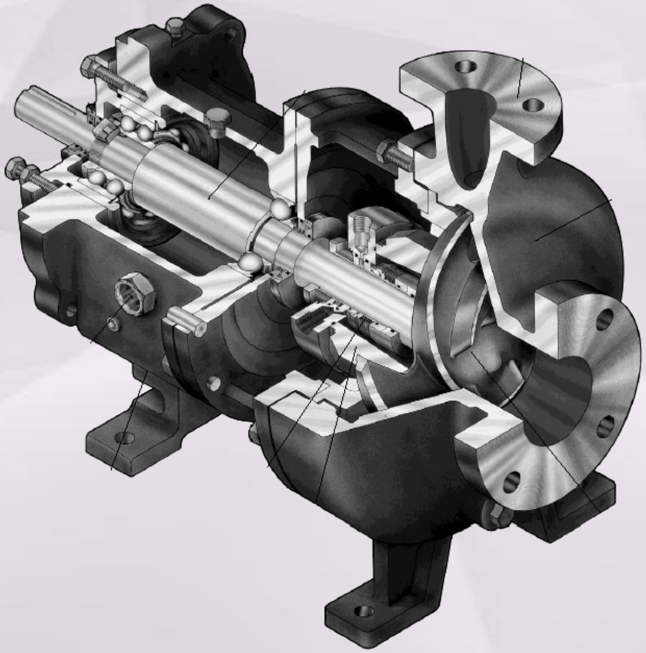
7-6 ■ PUMP SELECTION

- Device used to move/transport liquids through pipes & channels.
- Pump increases the mechanical energy, velocity & pressure of the liquid.
- 2 main forms are the positive displacement type & centrifugal pumps.
- Both of which are commonly used for delivery against high pressures & where nearly constant delivery rates are required.





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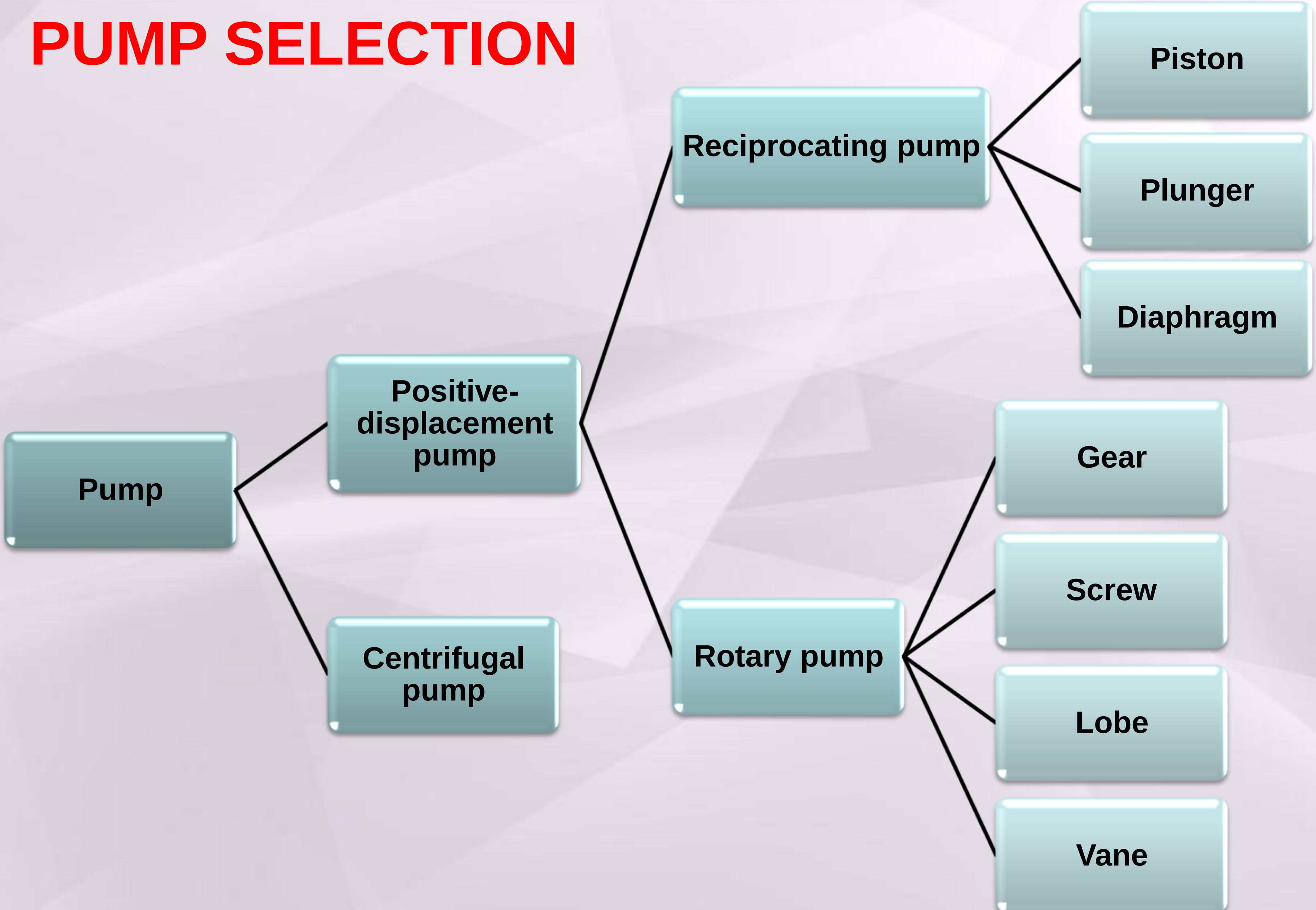
PUMP SELECTION



POSITIVE DISPLACEMENT PUMP (PDP)

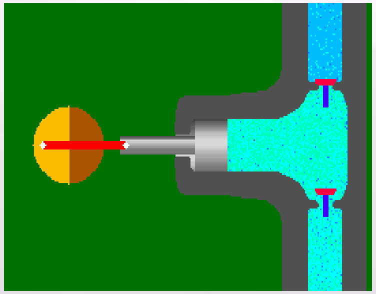
- Force the liquid by changing volume.
- It delivers a pulsating/periodic flow as the cavity volume opens, traps & squeezes the fluid.
- Advantage: deliver any fluid regardless of viscosity.
- Can operate up to 300 atm (high pressure) but only produces very low flowrate (100 gal/min).
- At constant rotation speed, it produces nearly constant flowrate.

- Flowrate cannot be varied except by changing the displacement/speed.
- Mechanical efficiency varies from 40-50% for small pumps & 70-90% for large pumps.
- PDP are classified into two general categories:
  - (a) Reciprocating Pump (piston pump, plunger pump, diaphragm pump)
  - (b) Rotary Pump (single rotor, multiple rotors – gear, lobe, multiple screw)

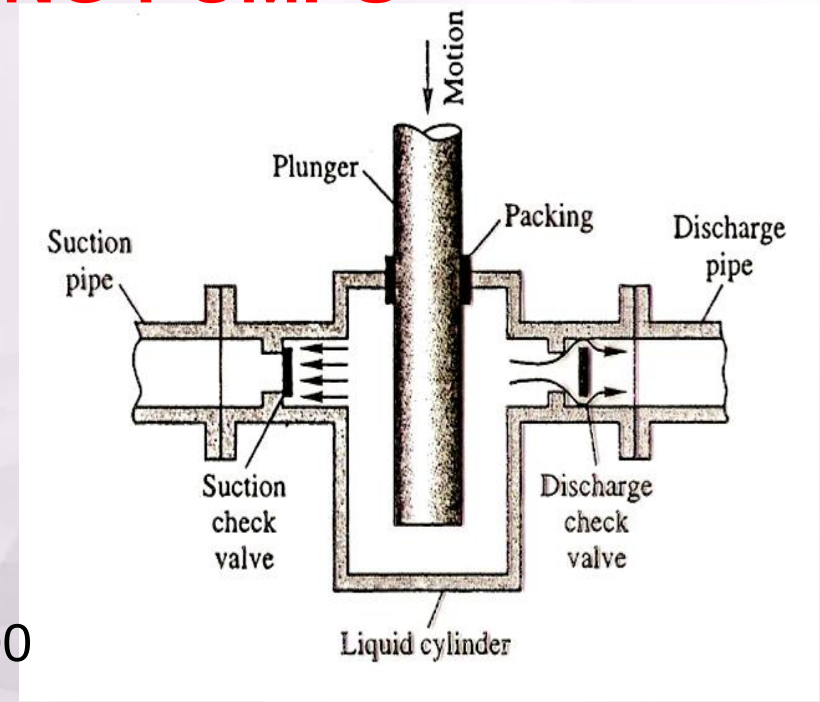
(A)-RECIPROCATING PUMPS

(i) Piston pump:

- Liquid is drawn through an inlet check valve into the cylinder by withdrawing of piston & forced out through discharge check valve on return stroke.
- Piston may be motor driven through reducing gears.
- Max. discharge for piston pumps ~ 50 atm.



(A)-RECIPROCATING PUMPS



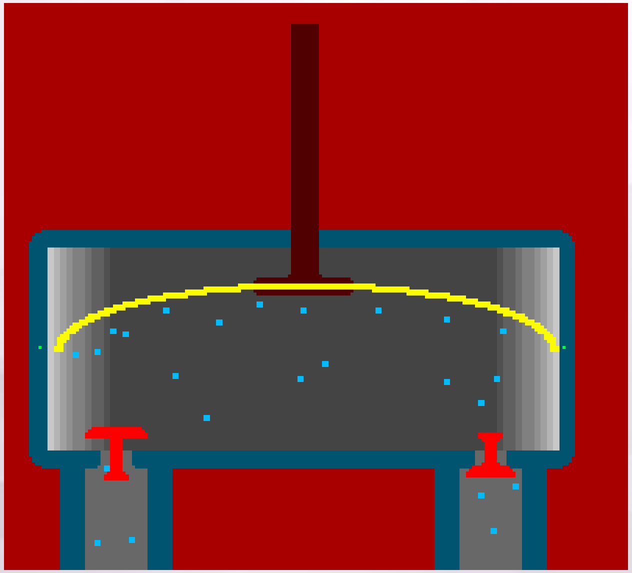
(ii) Plunger pump:

- Use for higher pressure.
- Contain heavy-walled cylinder with reciprocating plunger.
- During its stroke, plunger fills all space of the cylinder.
- Normally single acting and motor driven.
- Can discharge at pressure of ≥ 1500 atm.
- Not suitable for transferring toxic or explosive media.

(A)-RECIPROCATING PUMPS

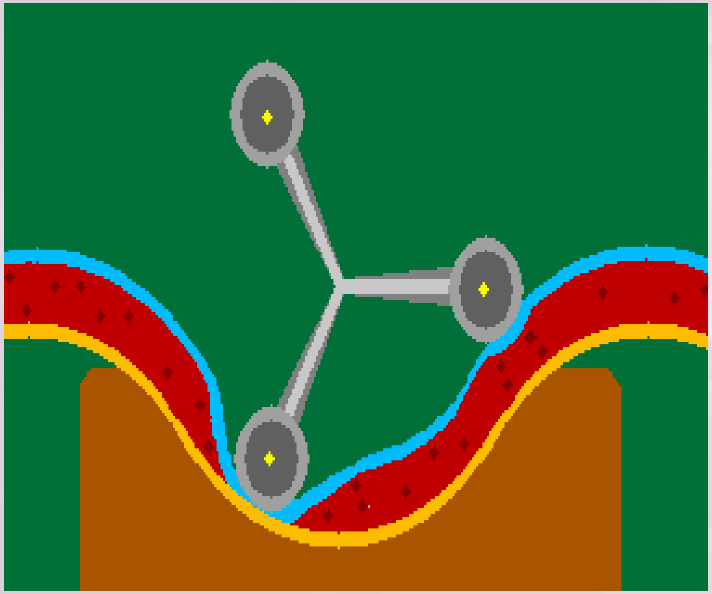
(iii) Diaphragm pump:

- Made of reciprocating flexible diaphragm metal/plastic/rubber.
- Can handle toxic/corrosive liquids.
- Handle only small to moderate amount of liquid ~ 100 gal/min.
- Develop pressure up to 100 atm.

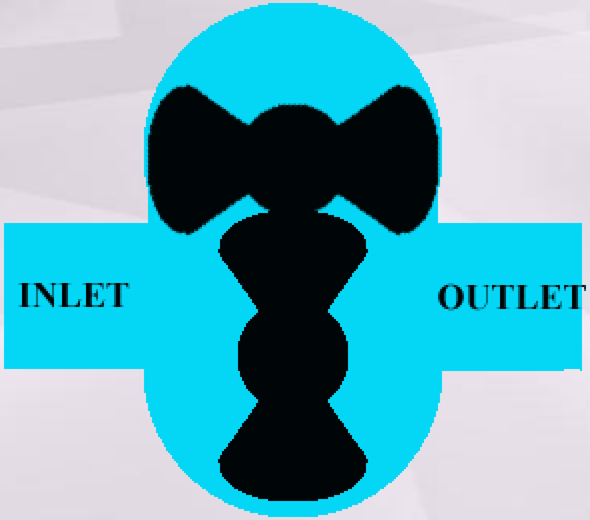


(B)-ROTARY PUMPS

- Contains no check valve.
- Minimize leakage due to close tolerance between moving and stationary parts.
- Work well with clean and moderately viscous liquids.
- Discharge pressure up to 200 atm or more.



Peristaltic Pump



Rotary Lobe Pump

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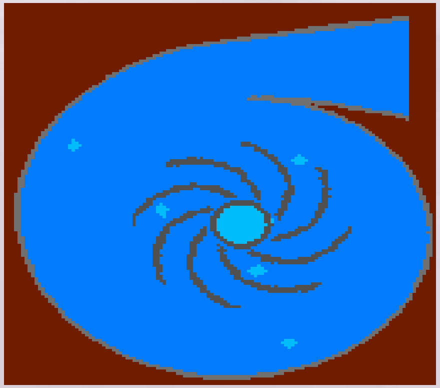
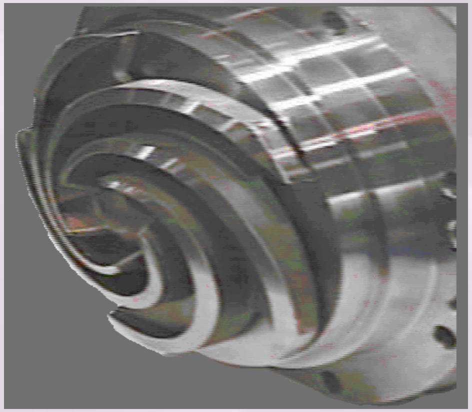
CENTRIFUGAL PUMP

- Most widely used in the chemical industries. It adds momentum to the fluid by means of fast moving blades (centrifugal force).
- It can provide a higher flowrate (up to 300,000 gal/min) with moderate pressure rises compare to the PDP type.
- Discharge is steadier but not effective in handling high viscosity liquids.





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CENTRIFUGAL PUMP

7–7 ■ FLOW RATE AND VELOCITY MEASUREMENT

A major application area of fluid mechanics is the determination of the flow rate of fluids, and numerous devices have been developed over the years for the purpose of flow metering.

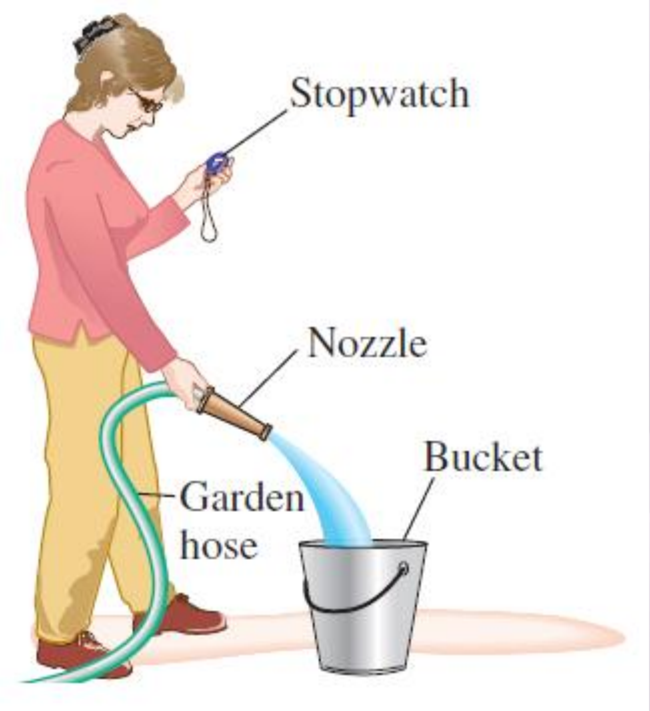
Flowmeters range widely in their level of sophistication, size, cost, accuracy, versatility, capacity, pressure drop, and the operating principle.

We give an overview of the meters commonly used to measure the flow rate of liquids and gases flowing through pipes or ducts.

We limit our consideration to incompressible flow.

$$\dot{V} = VA_c$$

Measuring the flow rate is usually done by measuring flow velocity, and many flowmeters are simply velocimeters used for the purpose of metering flow.

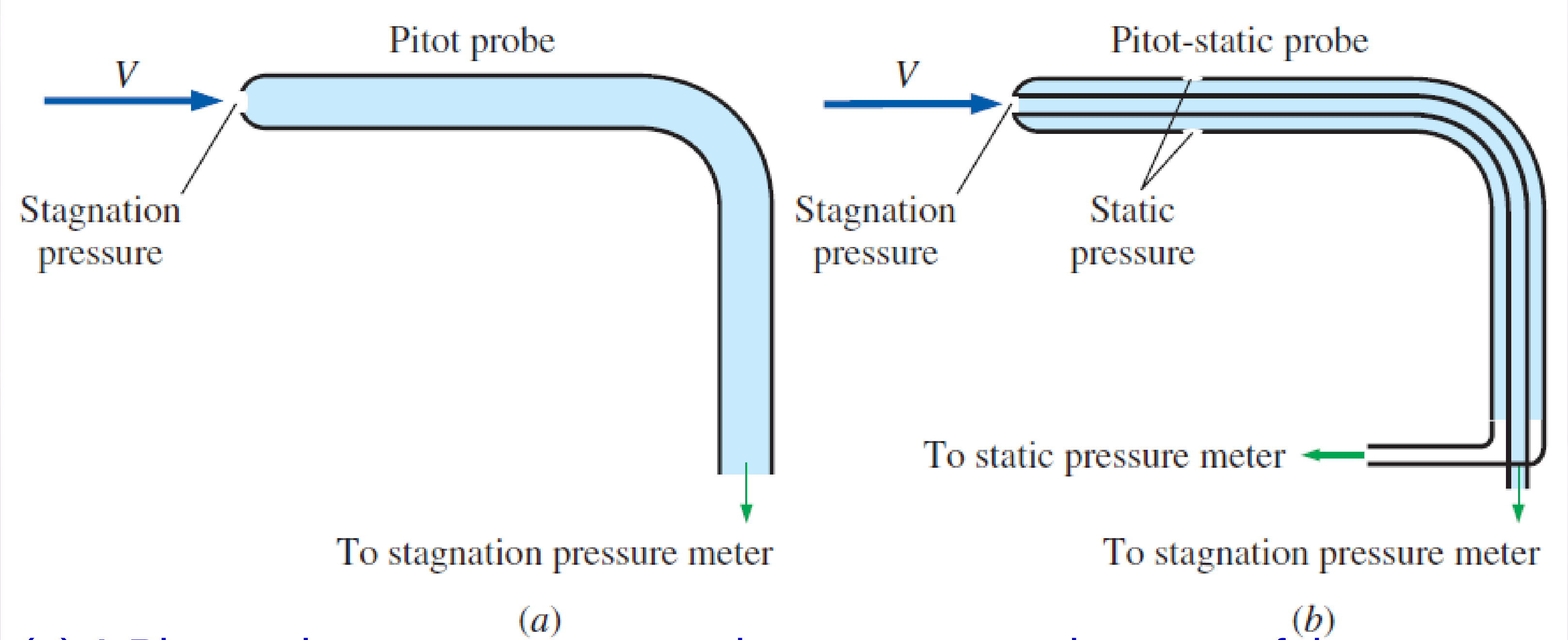


A primitive (but fairly accurate) way of measuring the flow rate of water through a garden hose involves collecting water in a bucket and recording the collection time.

Pitot and Pitot-Static Probes

Pitot probes (also called *Pitot tubes*) and **Pitot-static probes** are widely used for flow speed measurement.

A Pitot probe is just a tube with a pressure tap at the stagnation point that measures stagnation pressure, while a Pitot-static probe has both a stagnation pressure tap and several circumferential static pressure taps and it measures both stagnation and static pressures



(*a*) A Pitot probe measures stagnation pressure at the nose of the probe, while (*b*) a Pitot-static probe measures both stagnation pressure and static pressure, from which the flow speed is calculated.

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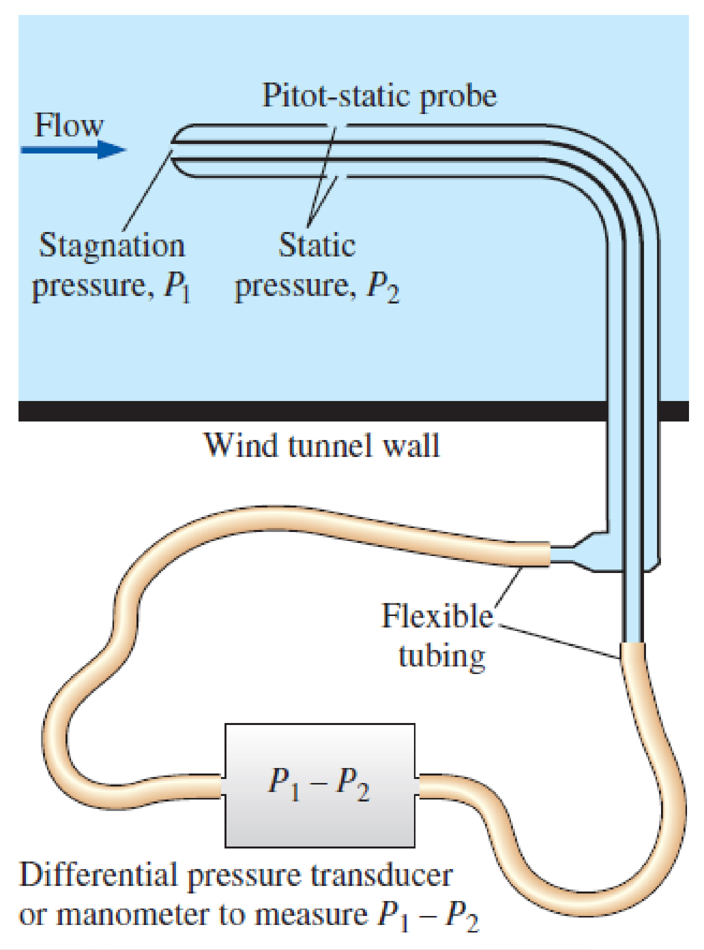
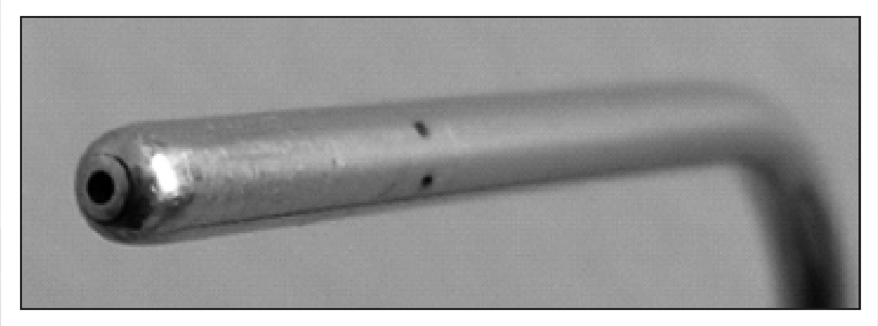


$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + z_2$$

Pitot formula: $$V = \sqrt{\frac{2(P_1 - P_2)}{\rho}}$$

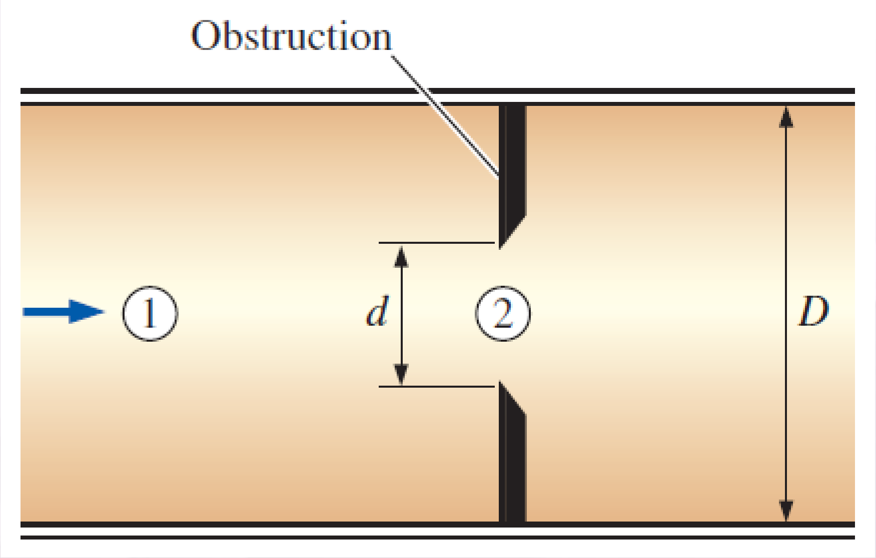
Measuring flow velocity with a Pitotstatic probe. (A manometer may be used in place of the differential pressure transducer.)



Close-up of a Pitot-static probe, showing the stagnation pressure hole and two of the five static circumferential pressure holes.

Obstruction Flowmeters: Orifice, Venturi, and Nozzle Meters

Flowmeters based on this principle are called **obstruction flowmeters** and are widely used to measure flow rates of gases and liquids.



Flow through a constriction in a pipe.

Mass balance: $\dot{V} = A_1V_1 = A_2V_2 \quad \rightarrow \quad V_1 = (A_2/A_1)V_2 = (d/D)^2V_2$

Bernoulli equation ($z_1 = z_2$):
$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} = \frac{P_2}{\rho g} + \frac{V_2^2}{2g}$$

Obstruction (with no loss):
$$V_2 = \sqrt{\frac{2(P_1 - P_2)}{\rho(1 - \beta^4)}}$$

$\beta = d/D$

$\dot{V} = A_2V_2 = (\pi d^2/4)V_2$

The losses can be accounted for by incorporating a correction factor called the **discharge coefficient C_d** whose value (which is less than 1) is determined experimentally.

Obstruction flowmeters:

$$\dot{V} = A_0 C_d \sqrt{\frac{2(P_1 - P_2)}{\rho(1-\beta^4)}}$$

$$A_0 = A_2 = \pi d^2/4 \qquad \beta = d/D$$

The value of C_d depends on both b and the Reynolds number, and charts and curve-fit correlations for C_d are available for various types of obstruction meters.

Orifice meters:

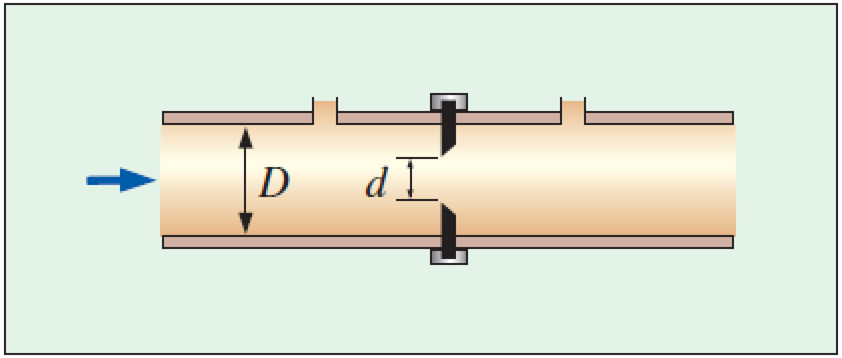
$$C_d = 0.5959 + 0.0312\beta^{2.1} - 0.184\beta^8 + \frac{91.71\beta^{2.5}}{\mathrm{Re}^{0.75}}$$

Nozzle meters:

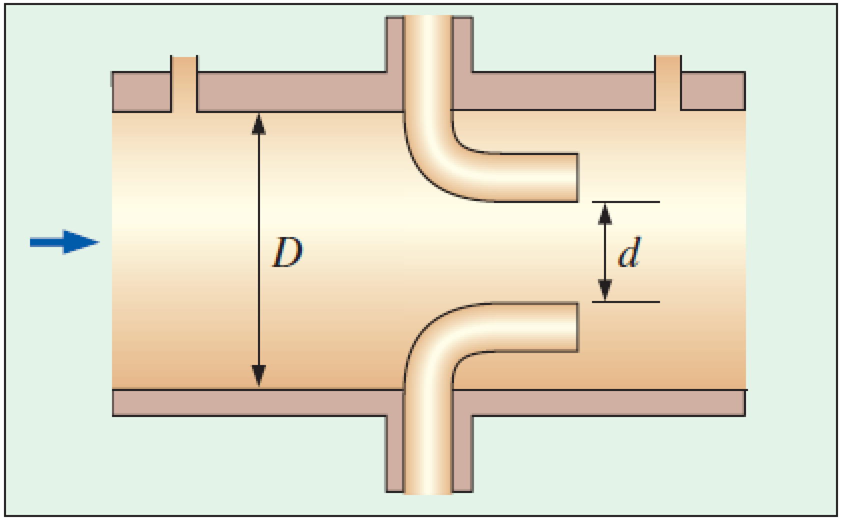
$$C_d = 0.9975 - \frac{6.53\beta^{0.5}}{\mathrm{Re}^{0.5}}$$

$$0.25 < \beta < 0.75 \text{ and } 10^4 < \mathrm{Re} < 10^7$$

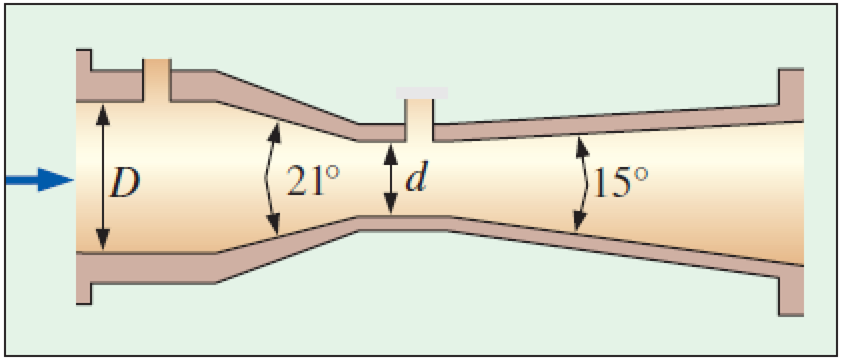
For flows with high Reynolds numbers (Re > 30,000), the value of C_d can be taken to be 0.96 for flow nozzles and 0.61 for orifices.



(*a*) Orifice meter



(*b*) Flow nozzle



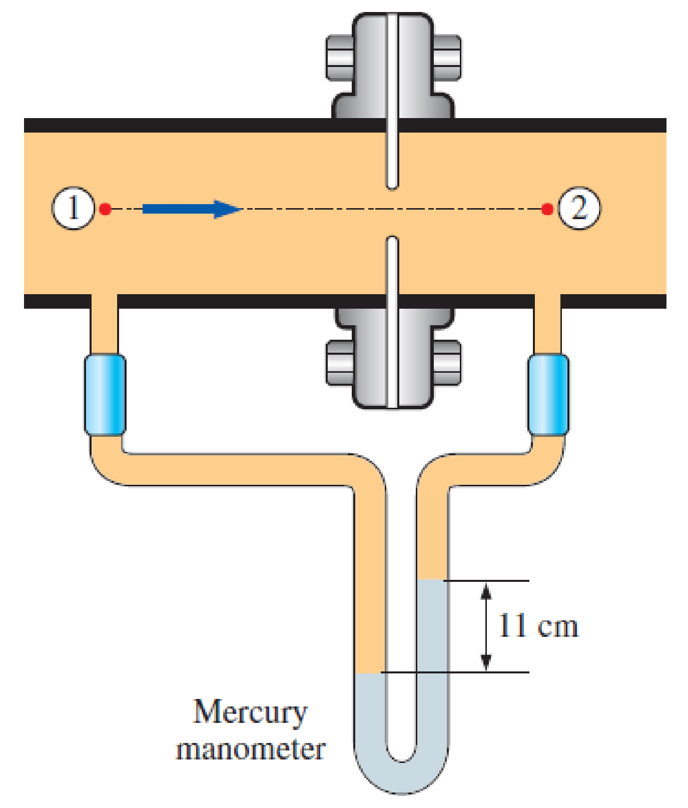
(*c*) Venturi meter

Common types of obstruction meters.

faiq@unimap.edu.my

EXAMPLE 8–10 Measuring Flow Rate with an Orifice Meter

The flow rate of methanol at 20°C (ρ = 788.4 kg/m^3 and μ = 5.857 × 10^{-4} kg/m·s) through a 4-cm-diameter pipe is to be measured with a 3-cm-diameter orifice meter equipped with a mercury manometer across the orifice plate, as shown in Fig. 8–62. If the differential height of the manometer is 11 cm, determine the flow rate of methanol through the pipe and the average flow velocity.



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Properties The density and dynamic viscosity of methanol are given to be $\rho = 788.4\ \text{kg/m}^3$ and $\mu = 5.857 \times 10^{-4}\ \text{kg/m·s}$, respectively. We take the density of mercury to be $13{,}600\ \text{kg/m}^3$.

Analysis The diameter ratio and the throat area of the orifice are

$$\beta = \frac{d}{D} = \frac{3}{4} = 0.75$$

$$A_0 = \frac{\pi d^2}{4} = \frac{\pi(0.03\ \text{m})^2}{4} = 7.069 \times 10^{-4}\ \text{m}^2$$

The pressure drop across the orifice plate is

$$\Delta P = P_1 - P_2 = (\rho_{\text{Hg}} - \rho_{\text{met}})gh$$

Then the flow rate relation for obstruction meters becomes

$$\dot{V} = A_0 C_d \sqrt{\frac{2(P_1 - P_2)}{\rho(1-\beta^4)}} = A_0 C_d \sqrt{\frac{2(\rho_{\text{Hg}} - \rho_{\text{met}})gh}{\rho_{\text{met}}(1-\beta^4)}} = A_0 C_d \sqrt{\frac{2(\rho_{\text{Hg}}/\rho_{\text{met}} - 1)gh}{1-\beta^4}}$$

Substituting, the flow rate is determined to be

$$\dot{V} = (7.069 \times 10^{-4}\ \text{m}^2)(0.61)\sqrt{\frac{2(13{,}600/788.4 - 1)(9.81\ \text{m/s}^2)(0.11\ \text{m})}{1 - 0.75^4}}$$

$$= 3.09 \times 10^{-3}\ \text{m}^3/\text{s}$$

which is equivalent to 3.09 L/s. The average flow velocity in the pipe is determined by dividing the flow rate by the cross-sectional area of the pipe,

$$V = \frac{\dot{V}}{A_c} = \frac{\dot{V}}{\pi D^2/4} = \frac{3.09 \times 10^{-3}\ \text{m}^3/\text{s}}{\pi(0.04\ \text{m})^2/4} = 2.46\ \text{m/s}$$

The Reynolds number of flow through the pipe is

$$\mathrm{Re} = \frac{\rho V D}{\mu} = \frac{(788.4\ \mathrm{kg/m^3})(2.46\ \mathrm{m/s})(0.04\ \mathrm{m})}{5.857 \times 10^{-4}\ \mathrm{kg/m \cdot s}} = 1.32 \times 10^5$$

Substituting $\beta = 0.75$ and $\mathrm{Re} = 1.32 \times 10^5$ into the orifice discharge coefficient relation

$$C_d = 0.5959 + 0.0312\beta^{2.1} - 0.184\beta^8 + \frac{91.71\beta^{2.5}}{\mathrm{Re}^{0.75}}$$

gives $C_d = 0.601$, which differs from the original guessed value of 0.61. Using this refined value of C_d, the flow rate becomes 3.04 L/s, which differs from our original result by 1.6 percent. After a couple iterations, the final converged flow rate is **3.04 L/s,** and the average velocity is **2.42 m/s** (to three significant digits).

Discussion If the problem is solved using an equation solver such as EES, then it can be formulated using the curve-fit formula for C_d (which depends on the Reynolds number), and all equations can be solved simultaneously by letting the equation solver perform the iterations as necessary.

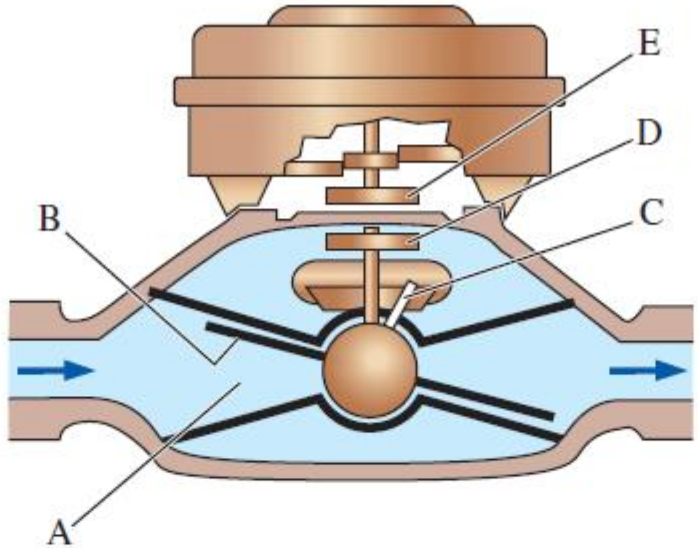
faiq@unimap.edu.my

Positive Displacement Flowmeters

The total amount of mass or volume of a fluid that passes through a cross section of a pipe over a certain period of time is measured by **positive displacement flowmeters**.

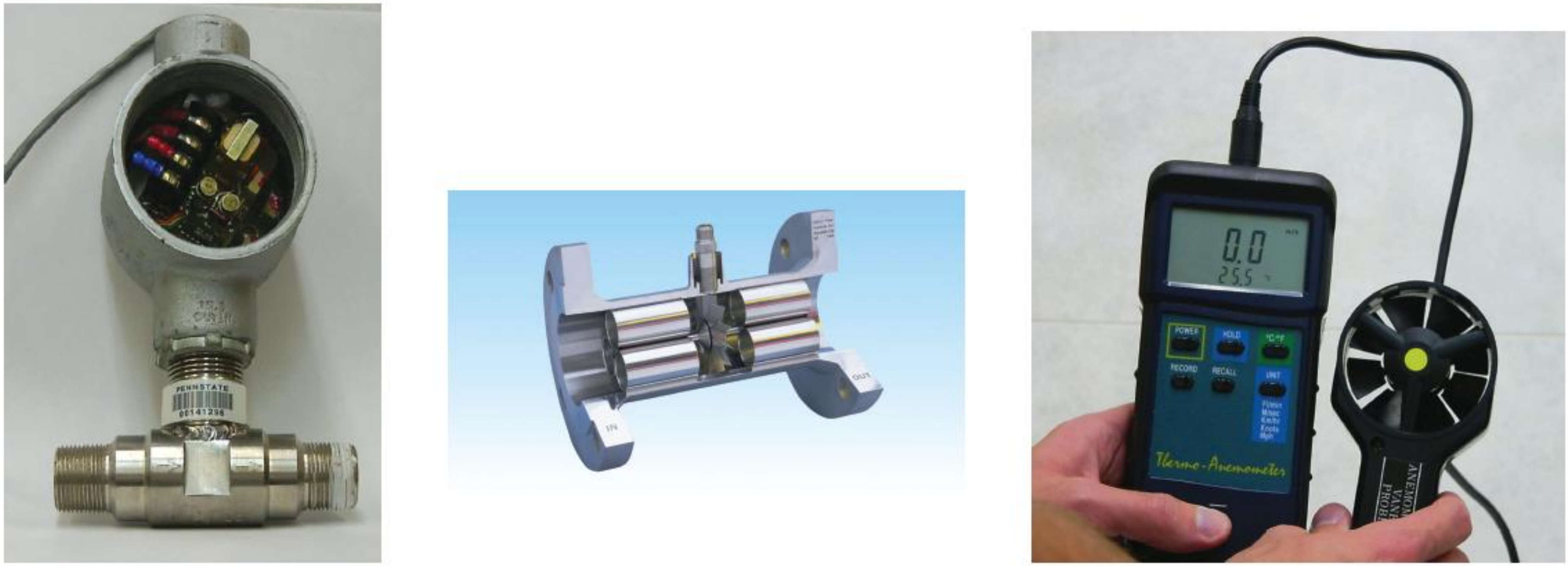
There are numerous types of displacement meters, and they are based on continuous filling and discharging of the measuring chamber. They operate by trapping a certain amount of incoming fluid, displacing it to the discharge side of the meter, and counting the number of such discharge–recharge cycles to determine the total amount of fluid displaced.

A positive displacement flowmeter with double helical three-lobe impeller design.



A nutating disk flowmeter.

Turbine Flowmeters



(*a*) (*b*) (*c*)

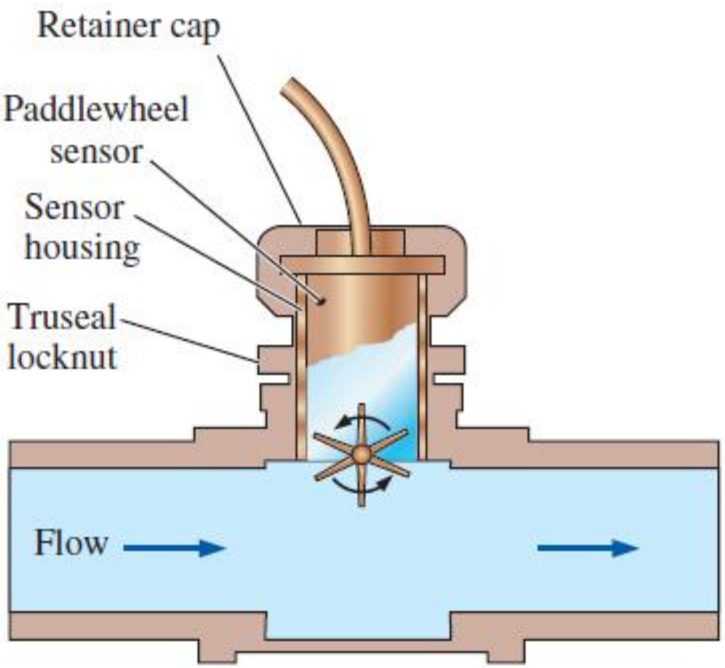
(*a*) An in-line turbine flowmeter to measure liquid flow, with flow from left to right, (*b*) a cutaway view of the turbine blades inside the flowmeter, and (*c*) a handheld turbine flowmeter to measure wind speed, measuring no flow at the time the photo was taken so that the turbine blades are visible. The flowmeter in (*c*) also measures the air temperature for convenience.

faiq@unimap.edu.my

Paddlewheel Flowmeters

Paddlewheel flowmeters are low-cost alternatives to turbine flowmeters for flows where very high accuracy is not required.

The paddlewheel (the rotor and the blades) is perpendicular to the flow rather than parallel as was the case with turbine flowmeters.



Paddlewheel flowmeter to measure liquid flow, with flow from left to right, and a schematic diagram of its operation.

faiq@unimap.edu.my

Variable-Area Flowmeters (Rotameters)

A simple, reliable, inexpensive, and easy-to-install flowmeter with reasonably low pressure drop and no electrical connections that gives a direct reading of flow rate for a wide range of liquids and gases is the **variable-area flowmeter**, also called a **rotameter** or **floatmeter**.

A variable-area flowmeter consists of a vertical tapered conical transparent tube made of glass or plastic with a float inside that is free to move.

As fluid flows through the tapered tube, the float rises within the tube to a location where the float weight, drag force, and buoyancy force balance each other and the net force acting on the float is zero.

The flow rate is determined by simply matching the position of the float against the graduated flow scale outside the tapered transparent tube.

The float itself is typically either a sphere or a loose-fitting piston-like cylinder.

Two types of variable-area flowmeters: (*a*) an ordinary gravity-based meter and (*b*) a spring-opposed meter.

Ultrasonic Flowmeters

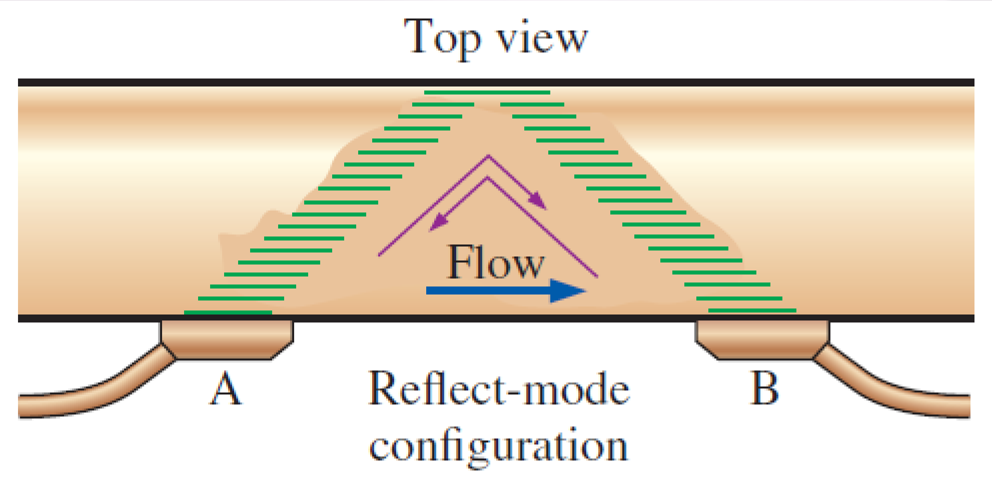
Ultrasonic flowmeters operate using sound waves in the ultrasonic range (beyond human hearing ability, typically at a frequency of 1 MHz).

Ultrasonic (or acoustic) flowmeters operate by generating sound waves with a transducer and measuring the propagation of those waves through a flowing fluid.

There are two basic kinds of ultrasonic flowmeters: *transit time* and *Doppler-effect* (or *frequency shift*) flowmeters.

$$V = KL\,\Delta t$$

L is the distance between the transducers and K is a constant



The operation of a transit time ultrasonic flowmeter equipped with two transducers.

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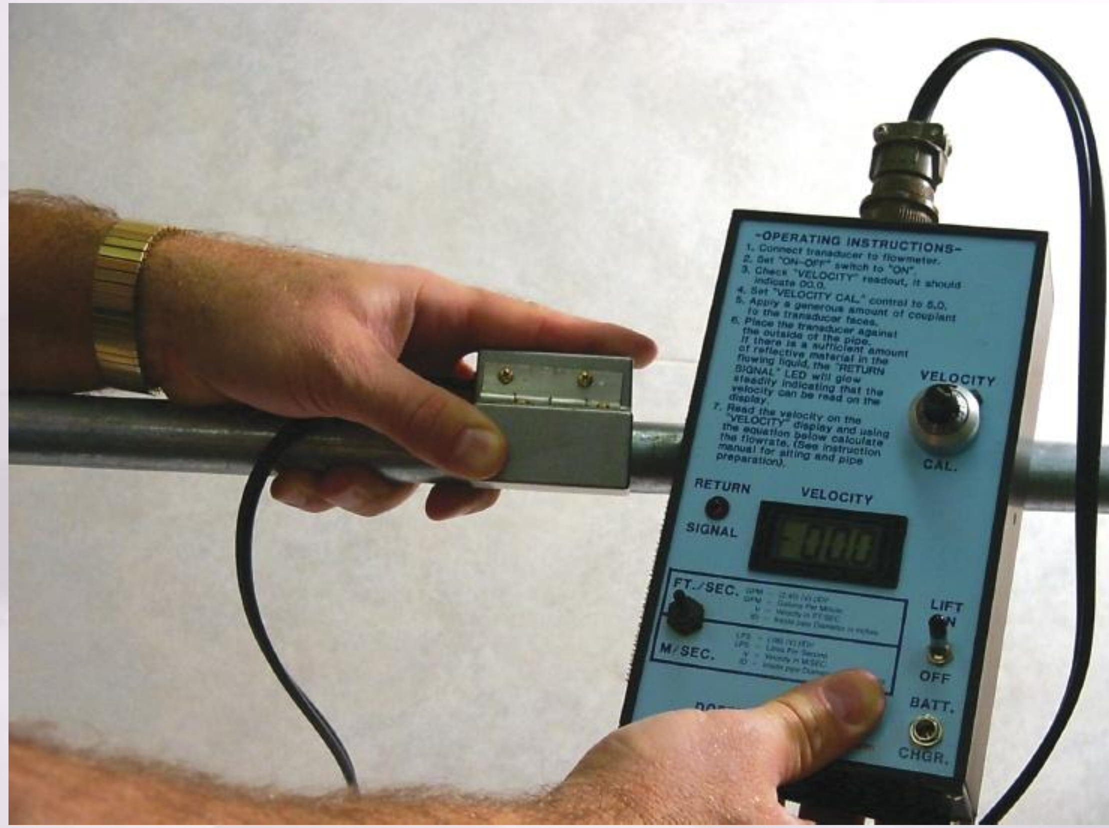
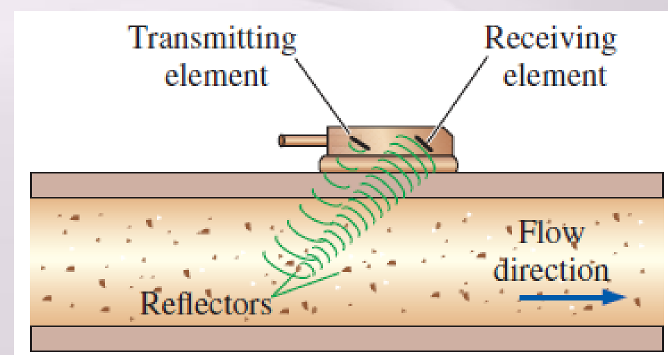
Doppler-Effect Ultrasonic Flowmeters



Doppler-effect ultrasonic flowmeters measure the average flow velocity along the sonic path.

Ultrasonic clamp-on flowmeters enable one to measure flow velocity without even contacting (or disturbing) the fluid by simply pressing a transducer on the outer surface of the pipe.

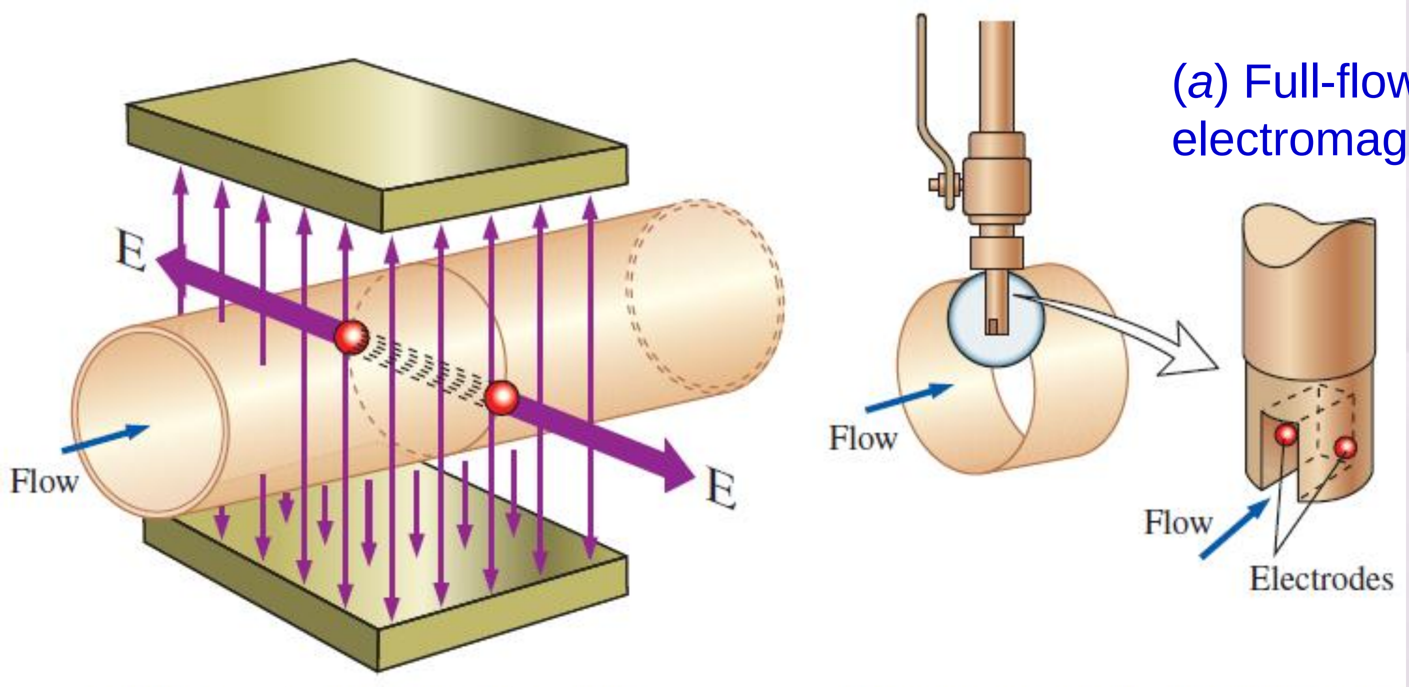
The operation of a Doppler-effect ultrasonic flowmeter equipped with a transducer pressed on the outer surface of a pipe.



Electromagnetic Flowmeters

A *full-flow electromagnetic flowmeter* is a nonintrusive device that consists of a magnetic coil that encircles the pipe, and two electrodes drilled into the pipe along a diameter flush with the inner surface of the pipe so that the electrodes are in contact with the fluid but do not interfere with the flow and thus do not cause any head loss.

Insertion electromagnetic flowmeters operate similarly, but the magnetic field is confined within a flow channel at the tip of a rod inserted into the flow.



(*a*) Full-flow electromagnetic flowmeter (*b*) Insertion electromagnetic flowmeter

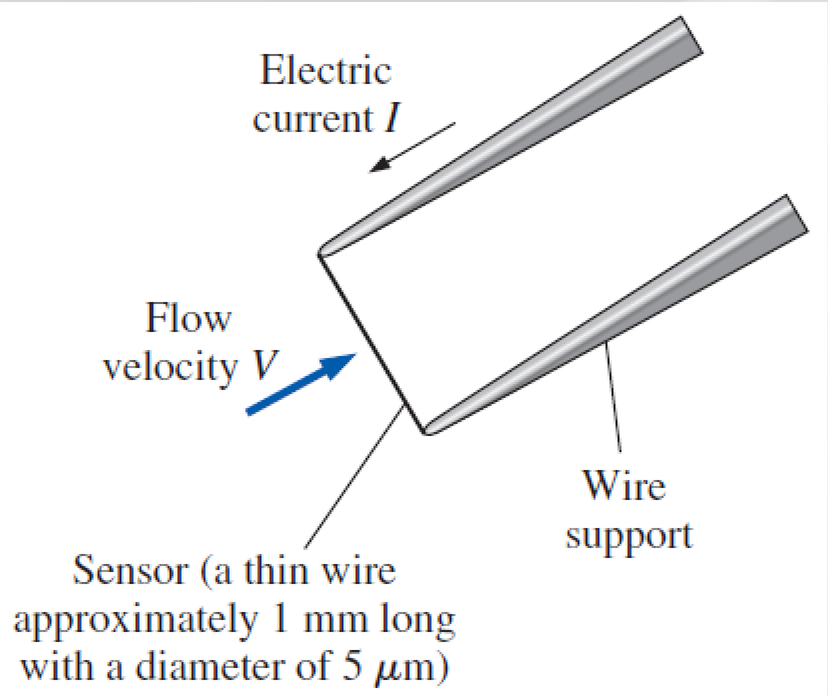
(*a*) Full-flow and (*b*) insertion electromagnetic flowmeters,

Thermal (Hot-Wire and Hot-Film) Anemometers

Thermal anemometers involve an electrically heated sensor and utilize a thermal effect to measure flow velocity.

Thermal anemometers have extremely small sensors, and thus they can be used to measure the instantaneous velocity at any point in the flow without appreciably disturbing the flow.

They can measure velocities in liquids and gases accurately over a wide range—from a few centimeters to over a hundred meters per second.



A thermal anemometer is called a **hot-wire anemometer** if the sensing element is a wire, and a **hot-film anemometer** if the sensor is a thin metallic film (less than 0.1 μm thick) mounted usually on a relatively thick ceramic support having a diameter of about 50 μm.

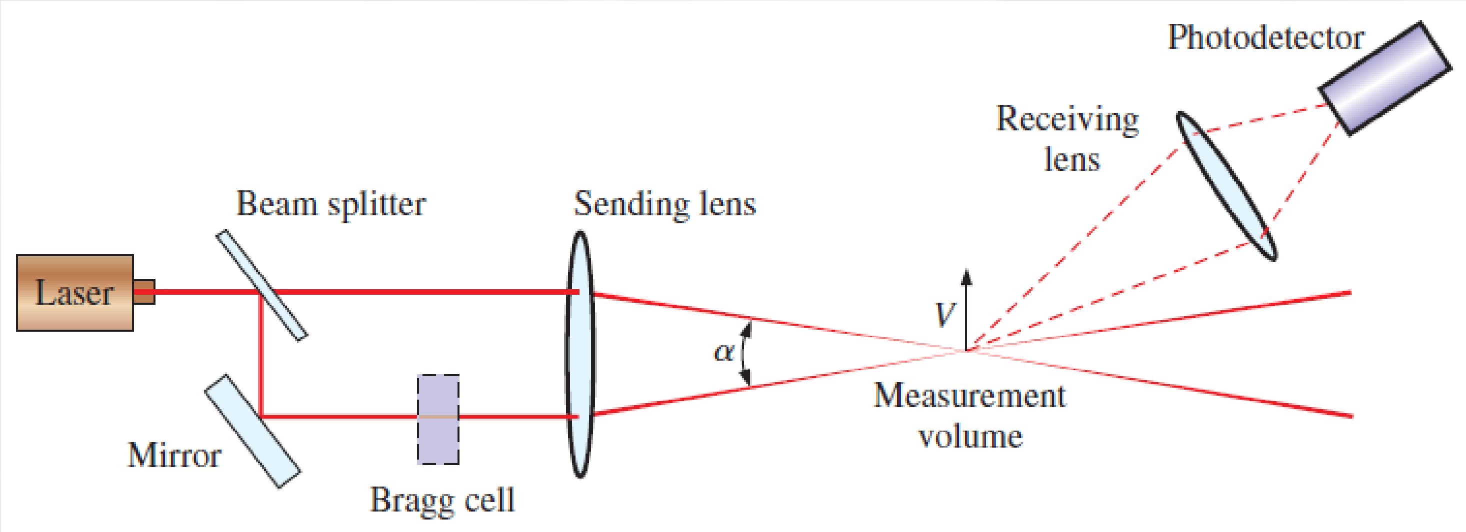
The electrically heated sensor and its support, components of a hot-wire probe.

Laser Doppler Velocimetry

Laser Doppler velocimetry (LDV), also called **laser velocimetry (LV)** or **laser Doppler anemometry (LDA)**, is an optical technique to measure flow velocity at any desired point without disturbing the flow.

Unlike thermal anemometry, LDV involves no probes or wires inserted into the flow, and thus it is a nonintrusive method.

Like thermal anemometry, it can accurately measure velocity at a very small volume, and thus it can also be used to study the details of flow at a locality, including turbulent fluctuations, and it can be traversed through the entire flow field without intrusion.



A dual-beam LDV system in forward scatter mode.

REFERENCE

Cengel, Y. A. Cimbala, J. M. "Fluid Mechanics: Fundamental and Applications, First edition in SI units" McGraw-Hill. 2006