Volume and Mass Flow Rate Measurement

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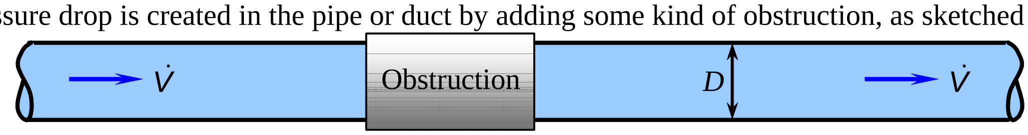
Introduction and notation

- In many engineering applications, either mass flow rate or volume flow rate must be measured.
- Notation used in this learning module:
  - Velocity V and volume V are distinguished either by adding a bar through the V to indicate volume ($\not{V}$) or by using a different font ($\mathcal{V}$).
  - Mass flow rate $\dot{m}$ and volume flow rate $\dot{V}$ are indicated by adding an overdot on m or V respectively.
  - Some authors use Q for volume flow rate, but this gets confused with heat transfer – I prefer $\dot{V}$.
- If the density ρ of the fluid is known, mass flow rate and volume flow rate are related by $\dot{m} = \rho \dot{V}$.
- In all the examples used in this learning module, we consider only ***incompressible flow***. Special care must be taken when the flow is compressible, such as the flow of air or natural gas through a pipeline.
- Most of the instruments discussed here measure volume flow rate; other instruments measure *mass flow rate*. Mass flow rate measurements are more common in gases [gas density varies more than does liquid density].
- Instruments that measure volume flow rate are called ***flowmeters***.
- There are two broad categories of flowmeter:
  - An ***end-line flowmeter***, also called a ***discharge flowmeter***, is used at the outlet or discharge of the flow – at the end of the line.
    - To measure volume flow rate, we measure how much time Δt it takes to fill up a container of known volume, and calculate $\dot{V} = V / \Delta t$.
    - A simple example of an end-line flowmeter is measurement of the volume flow rate through a garden hose using a bucket and stopwatch, as sketched to the right.
    - There are some variations of the bucket and stop-watch approach – for example, we may *weigh* the fluid instead, and calculate the mass flow rate instead of the volume flow rate.
    - End-line flow measurement is extremely accurate, and *is often used to calibrate in-line flowmeters*.

- An ***in-line flowmeter*** is a device that is placed *in line* with the pipe or duct rather than at the outlet.
  - An in-line flowmeter is necessary when the outlet or discharge is not available or splits into many separate outlets. For example, the water company must measure the volume of water used in your home or apartment. Obviously, an end-line technique would not work here.
  - There are five main categories of in-line flowmeters:
    - ***Obstruction flowmeters*** – measure the pressure drop across an obstruction placed in the flow.
    - ***Positive displacement flowmeters*** – fill up a known volume and then pass it on down the line.
    - ***Turbine flowmeters*** or ***paddlewheel flowmeters*** – spin a shaft and measure its rpm.
    - ***Rotameters*** – raise an object due to aerodynamic drag, and measure its height.
    - ***Miscellaneous flowmeters*** – use magnetic, optical, sonic, ultrasonic, vortex shedding, or various other means to measure volume flow rate.
  - We discuss each of these types of end-line flowmeters individually in the notes below.

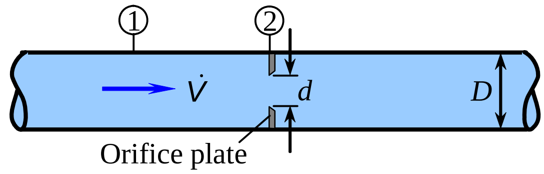
Obstruction flowmeters

- The operating principle of an obstruction flowmeter is as follows:
  - A pressure drop is created in the pipe or duct by adding some kind of obstruction, as sketched below.

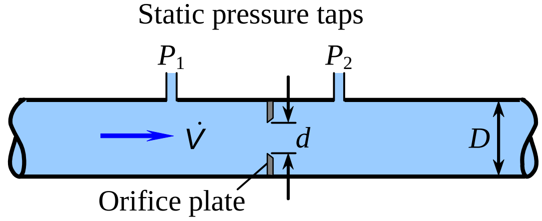


  - The pressure drop associated with the obstruction is measured.
  - The volume flow rate is calibrated as a function of measured pressure drop.
- All obstruction flowmeters cause a pressure drop (irreversible head loss) in the piping system – this pressure drop is called a ***minor loss***.
- There are three main types of obstruction flowmeter – orifice, flow nozzle, and Venturi. All work on the same principle, but have different performance characteristics.
- We develop the equations for the orifice flowmeter – the equations for the flow nozzle and Venturi flowmeters are the same, but with a different discharge coefficient.

Orifice flowmeter



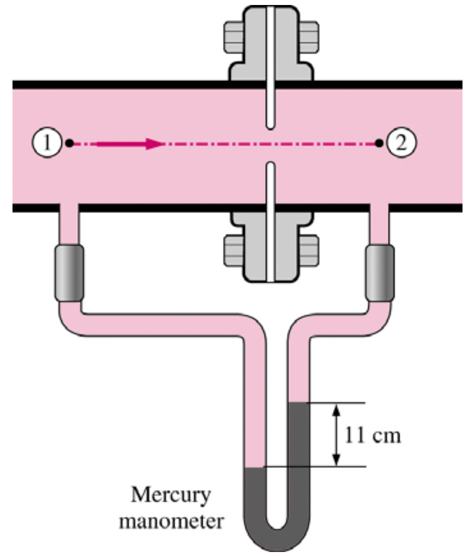
- The obstruction in an ***orifice flowmeter*** is simply a blunt plate called an ***orifice plate*** with a hole of diameter d – an ***orifice*** – in the middle, as sketched to the right.
- We define β as the ratio of orifice diameter d to the inner diameter of the pipe D, $\boxed{\beta = d / D}$. Most commercially available orifice meters use a β between 0.25 and 0.75.
- The flow constriction forces the fluid to accelerate through the orifice, increasing the fluid velocity and decreasing its pressure.
- For incompressible flow between cross-sectional location 1 upstream of the orifice and cross-sectional location 2 *at* the orifice, conservation of mass is $V_1 A_1 = V_2 A_2$, where V_1 and V_2 are the average velocities and A_1 and A_2 are the cross-sectional areas at locations 1 and 2 respectively. Since $A_1 = \pi D^2/4$ and $A_2 = \pi d^2/4$, $V_1 = (d/D)^2 V_2$, or $\boxed{V_1 = \beta^2 V_2}$.
- Neglecting irreversible losses for the moment, we apply Bernoulli's equation, $\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + z_1 \approx \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + z_2$.
- But z_1 and z_2 are the same since the pipe is horizontal. Also, the gravity constant cancels out in the remaining terms, leaving four terms, $\frac{P_1}{\rho} + \frac{V_1^2}{2} \approx \frac{P_2}{\rho} + \frac{V_2^2}{2}$.
- After substitution of the equation for V_1, we solve the Bernoulli equation for V_2, yielding $V_2 \approx \sqrt{\frac{2(P_1 - P_2)}{\rho(1-\beta^4)}}$.
- Since V_2 is the average velocity at location 2, where the cross-sectional area is A_2, we calculate the volume flow rate as V_2 times A_2. However, it is common among manufacturers of orifice flowmeters to label the orifice area A_o instead of A_2 ($A_o = A_2$, where "o" stands for "orifice"). Thus, $\boxed{\dot{V} = A_o V_2 \approx A_o \sqrt{\frac{2(P_1 - P_2)}{\rho(1-\beta^4)}}}$.
- In any real flow, there *are* significant irreversible losses due to friction, flow separation from the walls, turbulent eddies in the flow, etc., and these losses *cannot be neglected*. The actual volume flow rate turns out to be less than the value given by the above approximate equation, which neglects irreversible losses.
- To correct for irreversible losses, we introduce a ***discharge coefficient*** C_d – a kind of "fudge factor". The final equation for volume flow rate is thus $\boxed{\dot{V} = A_o C_d \sqrt{\frac{2(P_1 - P_2)}{\rho(1-\beta^4)}}}$.
- Finally, it is difficult to measure the pressure right at the orifice; the static pressure tap at location 2 must be located somewhat *downstream* of the orifice. The actual locations of the upstream and downstream pressure taps are not critical since the discharge coefficient must be calibrated anyway, but the best designs locate the downstream pressure tap at the location of lowest pressure in order to *maximize sensitivity*.



- A typical orifice meter has the two pressure taps located either symmetrically about the orifice plate, or with the upstream pressure tap slightly farther away from the orifice plate, as in the sketch to the right.
- For most commercial orifice flowmeters, the discharge coefficient is around 0.61, but C_d varies with geometry ($\beta = d/D$) and the Reynolds number ($\text{Re} = \rho V_1 D/\mu$) of the flow.
- For high Reynolds number flows (Re > 30,000), $C_d \cong 0.61$ for many commercial orifice flowmeters.
- Manufacturers calibrate their flowmeters and provide tables, plots, and/or curve-fitted equations for discharge coefficient C_d as a function of β and Reynolds number. A typical equation for orifice meters is $\boxed{C_d = 0.5959 + 0.0312\beta^{2.1} - 0.184\beta^{8.0} + 91.71\beta^{2.5}/\text{Re}^{0.75}}$, valid for $0.25 \le \beta \le 0.75$ and $10^4 \le \text{Re} \le 10^7$.
- Alternatively, for a given orifice meter (fixed β) and a given fluid (e.g., water at 20°C), some manufacturers choose to skip C_d altogether, and instead simply supply tables, plots, or curve fits of volume flow rate directly as a function of pressure drop $P_1 - P_2$.

- Orifice meters are simple to use, but must be calibrated. Compared to flow nozzles and Venturi flowmeters (to be discussed next), they contribute a larger minor loss to the flow system due to their abrupt geometry.
- **Example**:

Given: Methanol at 20°C and one atmosphere (ρ_{methanol} = 788.4 kg/m^3 and μ = 5.857 × 10^{-4} kg/m·s) flows through a pipe with inner diameter D = 4.00 cm. An orifice meter with d = 3.00 cm is installed to measure the volume flow rate. The discharge coefficient matches the typical equation provided above, $C_d = 0.5959 + 0.0312\beta^{2.1} - 0.184\beta^{8.0} + 91.71\beta^{2.5}/\text{Re}^{0.75}$. The two pressure taps are connected to a mercury U-tube manometer (ρ_{Hg} = 13,600 kg/m^3), and the column height difference is h = 11.0 cm, as sketched to the right.



To do: Calculate the volume flow rate in liters per second (L/s).

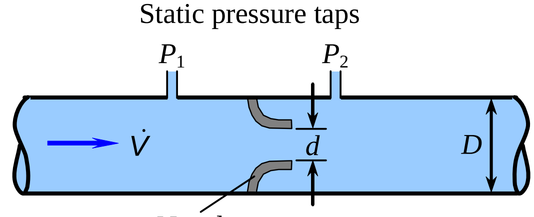
Solution:

- First, we calculate $\beta = d/D$ = 0.75, and the cross-sectional area at the orifice, $A_o = \pi d^2/4 = 7.069 \times 10^{-4}$ m^2.
- The pressure drop across the two pressure taps is $\Delta P = P_1 - P_2 = (\rho_{\text{Hg}} - \rho_{\text{methanol}})gh$ (review of U-tube manometry).
- Thus, the above equation for volume flow rate becomes
$$\dot{V} = A_o C_d \sqrt{\frac{2(\rho_{\text{Hg}} - \rho_{\text{methanol}})gh}{\rho_{\text{methanol}}(1-\beta^4)}}$$
- Problems like this involve some ***iteration***. Specifically, since we do not know the volume flow rate, we do not know the Reynolds number, and thus we do not know the discharge coefficient C_d.
- So, we *guess* C_d = 0.61, and solve for volume flow rate: $\dot{V}$ = 3.088 × 10^{-3} m^3/s = 3.088 L/s.
- To correct the guessed value of C_d, we need to calculate the average velocity in the pipe at location 1, where $A_1 = \pi D^2/4$: $V_1 = \dot{V}/A_1$ = 2.457 m/s.
- Now we calculate the Reynolds number, Re = $\rho V_1 D/\mu$, where we use the properties of the flowing fluid, methanol. We get Re = 1.323 × 10^5.
- For β = 0.75 and Re = 1.323 × 10^5, the manufacturer's equation for C_d yields C_d = 0.601, which is not very far from our initial guess!
- Using this new value of C_d, we repeat the calculations and get $\dot{V}$ = 3.042 × 10^{-3} m^3/s = 3.042 L/s.
- This value does not change to three significant digits upon further iteration, and the final result is $\dot{V} = 3.04$ L/s to three significant digits.

Discussion: Even if our initial guess for C_d were not as good, the iteration scheme used here converges quite rapidly – only two or three iterations are generally required to converge to three significant digits.

Flow nozzle flowmeter

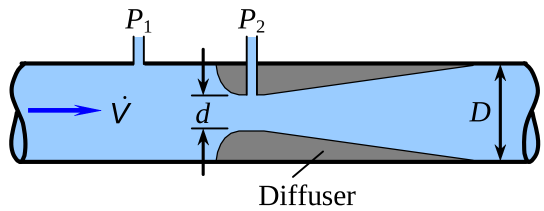
- The obstruction used in a ***flow nozzle flowmeter*** (usually called simply a ***flow nozzle***) is more aerodynamic than the orifice plate used in an orifice flowmeter, but the flow nozzle works under the same principle.
- The obstruction in a flow nozzle is rounded on the upstream side as sketched to the right. The flow is more efficiently guided through the opening, and thus the discharge coefficient is much larger than that of an orifice meter.



- For high Reynolds number flows (Re > 30,000), $C_d \cong 0.96$ for a typical commercial flow nozzle flowmeter. Like the orifice meter, however, C_d varies with β and Re.
- A typical equation for the discharge coefficient of a flow nozzle is $C_d = 0.9975 - 6.53\beta^{0.50}/\text{Re}^{0.50}$.
- The minor loss associated with a flow nozzle is somewhat smaller than that of an orifice flowmeter, but is still significant since most of the irreversible losses occur in the highly turbulent mixing zone *downstream* of the nozzle.
- Flow nozzle flowmeters are somewhat more expensive than orifice meters because of the more complicated geometry, but have increased sensitivity due to the larger value of the discharge coefficient.

Venturi flowmeter

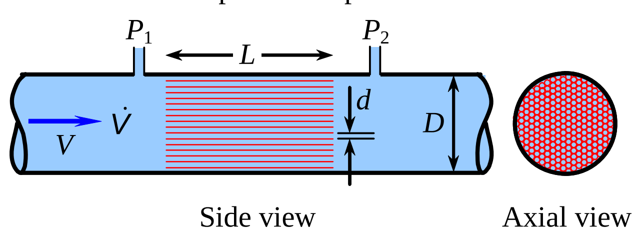
- A ***Venturi flowmeter*** (usually called simply a ***Venturi meter***) works under the same operating principle as the other two obstruction flowmeters – pressure drop through an obstruction.
- The obstruction in a Venturi meter is not only rounded on the *upstream* side, as in a flow nozzle, but also has a gradual expansion (a ***diffuser***) on the *downstream* side from throat diameter *d* to pipe inner diameter *D*, as sketched to the right.



- The flow is efficiently guided through the opening, just as in the flow nozzle flowmeter, and thus the discharge coefficient is similar to but slightly larger than that of a flow nozzle.
- To maximize sensitivity, the downstream (low pressure) pressure tap is located in the smallest diameter portion of the Venturi meter – the ***throat***, where the pressure is a minimum and the velocity is a maximum.
- For high Reynolds number flows (Re > 30,000), $C_d = 0.98$ for a well designed Venturi flowmeter; Reynolds number correction is typically not necessary since C_d is so large and nearly constant.
- The most significant improvement in the Venturi meter compared to the flow nozzle is in the minor loss (irreversible loss). Because of the gradual diffuser in the Venturi meter, the highly turbulent mixing zone that is present downstream of the nozzle is eliminated, and the pressure recovery is much greater, thereby reducing the irreversible losses significantly.
- Venturi flowmeters are more expensive than orifice flow meters or flow nozzle flowmeters because of their more complicated geometry, but have maximum sensitivity due to the larger value of the discharge coefficient, and contribute the smallest minor loss of the three to the overall pipe or duct system.
- In applications where large pressure drops cannot be tolerated, the Venturi meter is a wise choice.

Laminar flow element

- A ***laminar flow element*** (also called a ***laminar flowmeter*** or ***flow element***) works under the same operating principle as all obstruction flowmeters – pressure drop through an obstruction.
- However, the distinguishing factor here is that the flow through the pipe or duct is distributed through hundreds or thousands of *small diameter tubes*, as illustrated in the diagram to the right. [Note that the tubes need not be round in cross section.]

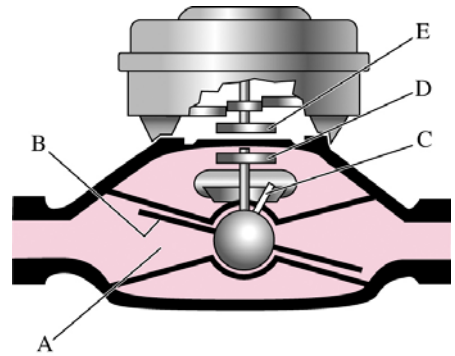


- The Reynolds number is $\mathrm{Re}_{\mathrm{pipe}} = \frac{\rho V D}{\mu}$ for the pipe flow itself, where ρ is the fluid density, V is the average velocity through the pipe or duct, D is the pipe's inner diameter, and μ is the viscosity of the fluid.
- However, the Reynolds number through each individual tube is $\mathrm{Re}_{\mathrm{tube}} = \frac{\rho V d}{\mu}\frac{A}{A_c}$, where d is the inner diameter of the tube, $A = \pi D^2/4$ is the cross-sectional area of the pipe, and A_c is the ***open*** cross-sectional area as seen looking down the pipe (the axial view in the above sketch).
- Since the tubes have small but finite wall thickness, A_c is smaller than A (sometimes by a factor approaching 2 for very small tubes). The average velocity through an individual tube is VA/A_c, which is larger than V.
- As is known from your study of fluid mechanics, the flow through one of the small tubes remains laminar provided that $\mathrm{Re}_{\mathrm{tube}}$ is less than about 2000. Thus, if sized properly, the flow through each individual small tube is laminar, even though the flow through the pipe itself may be turbulent.
- Since tube length is large compared to tube diameter ($L/d >> 1$), entrance losses are small compared to the so-called ***major loss*** through the tube, and the pressure drop $\Delta P = P_1 - P_2$ for laminar flow through the tube is nearly linearly proportional to volume flow rate.
- The main advantage of the laminar flow element is that volume flow rate is proportional to ΔP, unlike other obstruction flowmeters (orifice, flow nozzle, and Venturi), in which volume flow rate is proportional to the square root of ΔP. This allows the laminar flow element to operate over a wider range of volume flow rates without compromising the accuracy – after calibration, accuracies can be as good as ±0.25%.
- Some disadvantages of the laminar flow element: The blockage (a so-called ***minor loss***) is large compared to that of other obstruction flowmeters. Large volume flow rates require tiny diameter tubes to keep the flow laminar. If the flow is dirty, the tubes can become clogged and may need occasional cleaning.

Positive displacement flowmeters

- The operating principle of a ***positive displacement flowmeter*** is as follows:
  - o Fluid flows into a chamber or compartment of known volume and is "trapped" there.
  - o The fluid in the chamber is displaced from the upstream to the downstream side, where it is discharged.
  - o The number of discharges is counted per unit time to calculate the volume flow rate.
- Positive displacement flowmeters are quite similar to positive displacement pumps (PDPs) – in fact, you can think of a positive displacement flowmeter as a PDP running backwards.
- Two typical examples are shown below. On the left is a photograph of a ***double helical three-lobe impeller positive displacement flowmeter***, which is similar to a gear pump running backwards. In the middle and on the right is a ***nutating disk flowmeter***, commonly used as a water or gasoline meter.

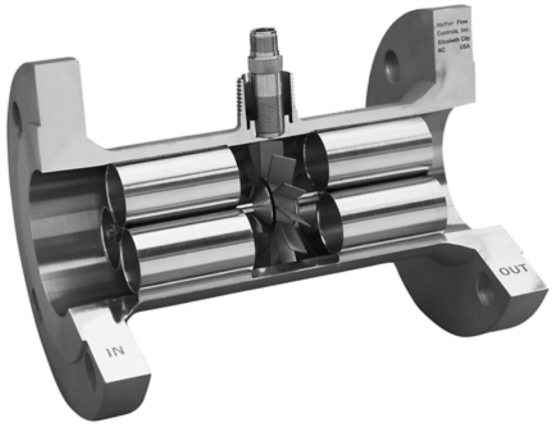


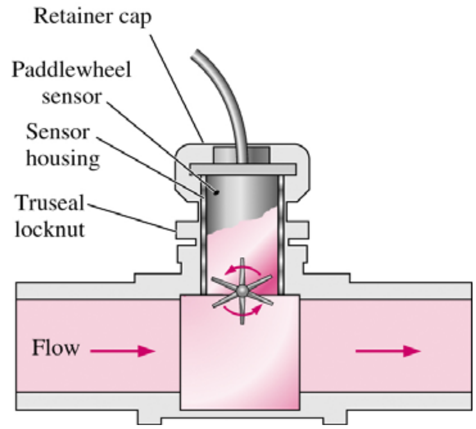


- The operation of the nutating disk flowmeter is as follows, as labeled on the diagram:
  - o The fluid enters the nutating disk meter into chamber (A).
  - o The offset (tilt) of the geometry causes the nutating disk (B) to nutate or wobble.
  - o This results in the rotation of a spindle (C).
  - o The rotation excites a magnet (D) that is on a rotating disk housed within the fluid.
  - o The signal is transmitted *through the casing of the meter* to a second magnet (E).
  - o The volume flow rate is obtained by counting the number of these periodic signals per unit time.
- Other nutating disk flowmeters use mechanical linkages instead of magnets to turn an odometer-like dial – such devices do not measure volume flow rate, but rather the total volume of fluid that has passed through the meter. These are useful as water meters in homes and gasoline meters in gas stations.
- Positive displacement flowmeters are extremely accurate, but create a relatively large pressure drop.

Turbine and paddlewheel flowmeters

- The operating principle of a ***turbine flowmeter*** or a ***paddlewheel flowmeter*** is as follows:
  - o The fluid flows through the meter, spinning a turbine or paddlewheel connected to a shaft.
  - o The rotation rate of the shaft is measured to calculate the volume flow rate, based on a calibration.
- Some people call turbine flowmeters ***propeller flowmeters***, since the turbine blades remind them of a propeller running backwards. However, this is a misnomer since, by definition, propellers add energy *to* a fluid, while turbines extract energy *from* a fluid.
- The difference between a turbine flowmeter and a paddlewheel flowmeter is summarized here:
  - o Turbine flowmeter: *The turbine is entirely immersed in the pipe or duct*, fluid flows *axially* through the turbine, and the axis of the turbine is in the same direction as the flow and the axis of the pipe or duct.
  - o Paddlewheel turbine: *The paddles cover only a portion of the flow cross section* (typically less than half). In addition, the axis of the paddlewheel is *perpendicular* to the flow direction.
- In either case, the rotation rate of the turbine or paddlewheel increases with the volume flow rate of the flow, and the instrument must be calibrated to measure volume flow rate.
- A 3-D view of a typical turbine flowmeter is shown below left, and a 2-D schematic of the cross section of a typical paddlewheel flowmeter is shown below right, for comparison.





- When properly calibrated for the anticipated flow conditions, a turbine flowmeter yields very accurate results (as accurate as 0.25 percent) over a wide range of flow rates.
- A paddlewheel flowmeter is a low-cost alternative to a turbine flowmeter, and is not as accurate.
- However, the irreversible head loss caused by a paddlewheel flowmeter is smaller than that of a turbine flowmeter, because:
  - The paddles block less of the flow than does the turbine.
  - Unlike a turbine flowmeter, flow straighteners or stator vanes are usually not required in a paddlewheel flowmeter.

Rotameters (variable-area flowmeters)

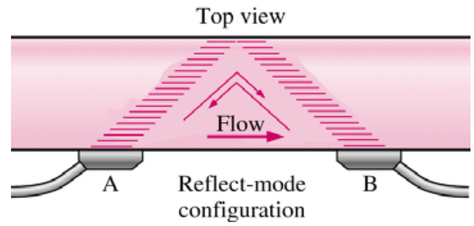
- The operating principle of a ***rotameter***, also called a ***variable-area flowmeter*** or a ***floatmeter***, is as follows:
  - The fluid flows *vertically* through a transparent diverging channel.
  - A floating mass (usually a sphere or a loose-fitting cylindrical piston) called a ***float*** rises due to aerodynamic drag. Since the cross-sectional area of the channel increases with height, the average fluid speed *decreases* with height, and the floating mass therefore hovers at a vertical location where the float weight, drag force, and buoyancy force balance each other (the net force acting on the float is zero).
  - The flow rate is determined by matching the float position to a calibrated vertical scale.
  - In some designs, the float spins or rotates during operation, which allows the user to easily see if the float is stuck since it rotates only if it is free.
- "Rotameter" is derived from ROTA, the European company that invented the device.
- Rotameters are easy to install, do not need electricity, and the scale is usually calibrated in units of volume or mass flow rate, so they give a quick visual reading of the flow rate.
- Many commercial rotameters have a built-in valve at the bottom to control the flow rate.
- Rotameters are gravity based, and therefore must be mounted vertically, with fluid entering at the bottom and exiting at the top. The photograph to the right shows a typical rotameter.
- A variation of the rotameter that can be mounted horizontally is a ***spring-opposed flowmeter***, where the drag force is balanced not by weight and buoyancy force, but by a spring force.
- The accuracy of rotameters and spring-opposed flowmeters is typically about 1 to 5% – these flowmeters are not appropriate for applications that require high precision and accuracy.
- One example is a rotameters used in ambulances to measure the flow of oxygen, as in the figure to the right, taken by Stephen Quinn.

Miscellaneous flowmeters

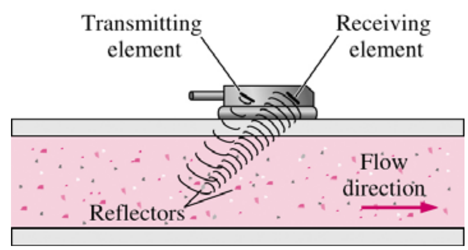
- Engineers have invented a fascinating variety of other instruments to measure mass flow rate and/or volume flow rate. We discuss a few of these "miscellaneous" flowmeters here.

Ultrasonic flowmeter

- An ***ultrasonic flowmeter*** uses sound waves to infer volume flow rate.
- *Ultrasonic means that the frequency is higher than the range of human hearing* – the frequency used in these instruments is typically around 1 MHz.



- There are two basic kinds of ultrasonic flowmeter: *transit-time* and *Doppler-effect*.
- A ***transit-time ultrasonic flowmeter*** operates as follows:
  - An upstream transmitter transmits sound waves downstream, and a downstream transmitter transmits sound waves upstream, as sketched to the right.
  - The downstream sound waves are carried along by the flow and therefore travel faster than the upstream waves.
  - Receivers near the transmitters measure the sound waves reflected by the pipe wall, and built-in electronic circuitry measures the difference in travel time to calculate the average flow velocity.
  - Finally, since the diameter of the pipe is known, the volume flow rate is calculated as average velocity times cross-sectional area of the pipe.
- A ***Doppler-effect ultrasonic flowmeter*** operates as follows:

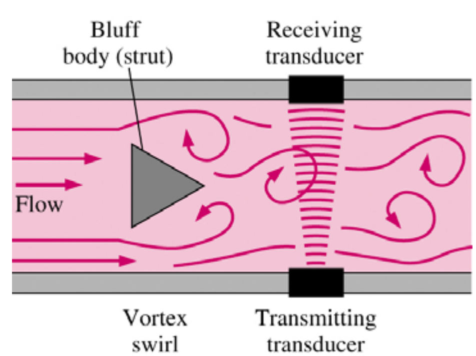


  - A piezoelectric transducer is pressed against the outside surface of a pipe, as sketched to the right.
  - The transducer transmits a sound wave at some fixed frequency through the pipe wall and into the flowing fluid.
  - The sound waves are reflected by impurities, such as suspended solid particles or entrained gas bubbles, and the reflected waves are sensed by a receiver mounted near the transmitter. Due to the Doppler effect, the frequency shift between the reflected sound waves and the transmitted sound waves is proportional to the average flow velocity in the pipe.
  - Finally, since the diameter of the pipe is known, the volume flow rate is calculated in the usual manner.

- Some more sophisticated Doppler-effect ultrasonic flowmeters do not require impurities in the fluid, but instead sense the waves reflected by ***turbulent eddies*** in the flow.
- The primary advantage of ultrasonic transducers is that they can be installed by clamping them to the outside of the pipe, and have *no pressure drop and no influence on the flow* – they are ***nonintrusive***, as illustrated in the photograph to the right.
- Most ultrasonic flowmeters are portable and can measure volume flow rates in pipes of various diameters.
- The accuracies of commercial ultrasonic flowmeters are typically 1 to 2% – not as good as that of turbine flowmeters, but they are much simpler to install and use.

Vortex flowmeter

- A ***vortex flowmeter*** (see photo below) operates on the principle that a ***bluff body***, such as a disc or a stubby cylinder or a body of square or triangular cross section, sheds vortices periodically, and *the shedding frequency is proportional to the flow velocity*.



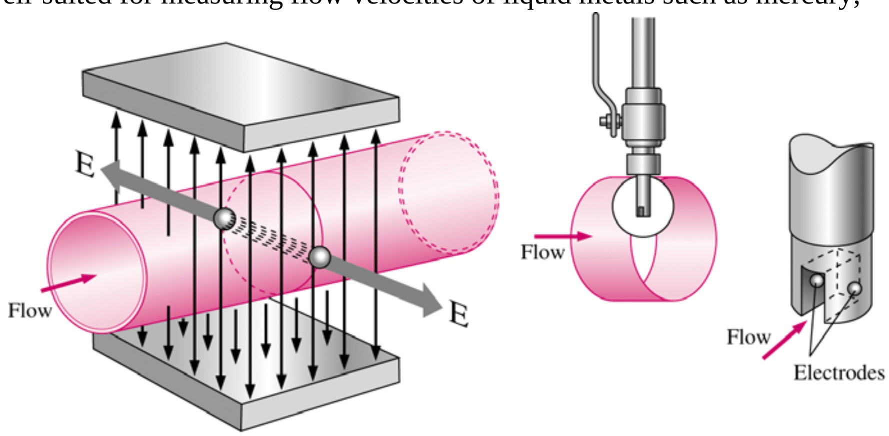
- In particular, it has been found that the nondimensional Strouhal number St = fd/V is constant at high Reynolds numbers, where d is the characteristic dimension of the bluff body, f is the vortex shedding frequency, and V is the average velocity.
- A vortex flowmeter contains three basic components, as sketched to the right:
  - The bluff body, that serves as the vortex generator.

- A detector, placed a short distance downstream on the inner surface of the casing, that measures the shedding frequency. The detector can be a pressure transducer that records the oscillation of pressure, or an ultrasonic, electronic, or fiber-optic sensor – any sensor that picks up and transmits an oscillating signal due to the vortex shedding.
- Electronics that measure the shedding frequency and calculate average velocity, which is then converted to volume flow rate in the usual fashion.

- The vortex flowmeter has no moving parts; typical accuracy is around 1%.
- The bluff body obstructs the flow and leads to a significant head loss.

Electromagnetic flowmeter

- An ***electromagnetic flowmeter*** operates on the principle that when a conductor is moved in a magnetic field, an electromotive force develops across the conductor as a result of magnetic induction:
  - ***Faraday's law*** states that *the voltage induced across any conductor as it moves at right angles through a magnetic field is proportional to the velocity of that conductor*.
  - If the fluid flowing through an electromagnetic flowmeter is a conducting fluid, the voltage produced across the conductor is proportional to the average velocity of the flowing fluid.
- There are two basic kinds of electromagnetic flowmeter: *full-flow* and *insertion*.
- A ***full-flow electromagnetic flowmeter*** is nonintrusive and operates as follows:
  - A magnetic coil encircles the pipe.
  - Two electrodes are drilled into the pipe, flush with the inner surface of the pipe walls so that the electrodes are in contact with the fluid, but do not interfere with the flow and do not cause any head loss.
  - The coil generates a magnetic field when subjected to electric current, and a voltmeter measures the electric potential (voltage) between the electrodes.
  - Finally, since the diameter of the pipe is known, the volume flow rate is calculated in the usual manner.
- An ***insertion electromagnetic flowmeter*** operates the same way as the full-flow meter, with these exceptions:
  - A rod is inserted into the flow. The tip of the rod contains both the magnetic coils and the electrodes.
  - Because of the rod that protrudes into the flow, the insertion electromagnetic flowmeter is *intrusive*, and there is a small head loss.
- Schematic diagrams of a full-flow and an insertion electromagnetic flowmeter are shown below left and below right, respectively. A magnified view of the tip of the insertion rod is shown on the far right.
- Electromagnetic flowmeters are well-suited for measuring flow velocities of liquid metals such as mercury, sodium, and potassium that are used in some nuclear reactors.
- Blood and seawater contain sufficient amounts of ions, and electromagnetic flowmeters are ideal for these types of fluids. Other naturally conducting fluids include many types of chemicals, pharmaceuticals, cosmetics, corrosive liquids, beverages, fertilizers, and numerous slurries and sludges.
- Magnetic flowmeters can also be used with liquids that are poor conductors, provided that they contain an adequate amount of charged particles (seeding is sometimes required in these cases).



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

- The primary disadvantage of electromagnetic flowmeters is their high cost and power consumption. Also, they must be carefully calibrated and are limited to conductive fluids, as discussed above.

Can you think of *other* ways in which volume flow rate can be measured?