# FLOWMETERS

## FLOW MEASUREMENTS

The measurement of flow is important in many industrial, scientific, and research applications. Flowmeters are used to measure the quantity of moving fluids or solids in open or closed conduits. A large number of different flowmeters are available, and the instrument selected for a particular measurement depends on the physical variables and the cost. Historically, flowmeters were first used for open channel flow measurement of the most common fluid, water. In many industrial applications, the ability to accurately measure flow is important because these measurements can be related directly to overall profitability of the plant. In recent years, the advent of microelectronics in flowmeters has improved their accuracy, ease of use, and maintainability significantly. Nowadays, with the widespread use of microprocessors, intelligent flowmeters are being produced. They allow versatile communication capabilities, automatic compensations for temperature and pressure, alarm facilities, selection of display capabilities, and so on.

Applications of flowmeters may include liquids, vapors, gases, solids, or any combination of these. In some cases, the measurement at a point may be necessary, whereas in the others, measurement of volume flow rates or mass flow rates may be needed. Often, measuring flow with high accuracy over a wide range of operating conditions is necessary. Flow measurements are based on many different physical principles. Some of those principles may include conductivity; capacitive, radiation, and sonic characteristics; optics and lasers; and various mechanical methods.

Flowmeters are used most often for gas and liquid flow measurements. They can be categorized as either intrusive or nonintrusive. Intrusive flowmeters make contact with the flowing material with either moving parts or nonmoving parts. Positive displacement, variable area, and turbine flowmeters are examples of intrusive flowmeters with wetted moving components. Orifice plate, oscillatory, target, and thermal flowmeters are examples of intrusive types with wetted but no moving components. Nonintrusive flowmeters such as magnetic and coriolis flowmeters do not disturb the material flow, but they still have wetted parts. A subsection of nonintrusive flowmeters has no wetted components, such as clamp on ultrasonic flowmeters or some optical types.

Flowmeter selection depends on the physical requirements of the measurements. They could be employed to measure the volumetric flow, velocity, or mass. For example, a positive displacement flowmeter measures the volume flow. Whereas, magnetic, oscillatory, turbine, or ultrasonic flowmeters measure velocities from which the total flow can be determined. Coriolis and thermal flowmeters measure the mass directly. Apart from these, some flowmeters, such as differential pressure, target, and variable area flowmeters, may be classified as inferential types because they infer the flow through some physical phenomenon (e.g., pressure differences).

In many cases, the selection and application of flow-measuring devices require further information on variables such as pressure, density, viscosity, and temperature in order to obtain an accurate output from the instrument. The information about temperature and pressure is particularly important in gas flow measurements. Most commercial gas flowmeters specify flow ratings in volume at standard conditions of 1 atm and 20°C. However, information on viscosity may carry greater importance in liquid flow measurements, and density is important in solid flow applications. Accuracy of flowmeters is of utmost importance, especially when they are used for measuring expensive fluids like petroleum products. In order to effect correction for pressure and temperature, flowmeters are used in conjunction with flow computers when used for measurement of petroleum products in liquid and gaseous form.

### Characteristics of Liquids and Gases

Although liquids and gases are different in many respects, they change shapes in a similar manner under the influence of a deforming force. In general, most liquids cannot be compressed. That is, the change in the volume liquid under pressure may be negligible. Because gases are easy to compress and their densities depend on both temperature and pressure, the compressibility of gases must be considered carefully in flow measurements.

During the flow measurements, the density of a gas may vary significantly depending on the absolute pressure. An increase in the pressure of a gas at constant temperature causes the gas to be compressed to a smaller volume of the same mass. Boyle's Law states that for ideal gases or mixtures of ideal gases at constant temperature, the volume $V$ is inversely proportional to the absolute pressure, that is

$$V = \text{Constant}/P \tag{1}$$

Equation (1) may be rewritten to compare the volumes of an ideal gas at constant temperature but different pressures $P$:

$$V/V_0 = P_0/P \tag{2}$$

Charles's Law states that the density of gas will vary significantly with absolute temperature $T$. Increasing the temperature of a gas at constant pressure causes the gas molecules to increase their activities and motions in relation to each other, thereby increasing the volume and decreasing the density of gas for the same mass. Charles' Law may be stated in the following form:

$$V/V_0 = T/T_0 \tag{3}$$

Charles' and Boyle's Laws can be combined to yield the Ideal Gas Law:

$$PV = nRT \tag{4}$$

where $R$ is the universal gas constant in consistent units and $n$ is the number of moles.

The Ideal Gas Law can also be expressed in the following form for different temperatures and pressures:

$$V/V_0 = (TP_0)/(T_0/P) \tag{5}$$

During gas flow measurements, if the variations in pressure and temperature are small, the temperature and pressure act almost independently of each other. Thus, estimates of reasonable flow accuracy can be obtained by adding percentage temperature and pressure deviations from a given set of conditions. Corrections are necessary if the temperature and pressure of gas is changing during the process of flow measurements.

Often measuring the mass or volume flow of nonideal gases is necessary simply because they do not act like ideal gases at certain conditions, such as at high pressures or low temperatures or under saturation. Their nonideal behavior may be accounted for by modifying the Ideal Gas Law with a $Z$ factor:

$$V/V_0 = (TP_0Z)/(T_0PZ_0) \tag{6}$$

The $Z$ factor is numerically dependent on operating conditions and can be read from generalized compressibility charts with a reasonable degree of accuracy.

For these reasons, extra care and thought are necessary when measuring gas flow.

In the case of liquid and solid flow measurements, the volumetric effect of temperature on the density of liquid or solid may be expressed as

$$V = V_0(1 + \beta\Delta t) \tag{7}$$

where $\beta$ is the coefficient of solid or liquid expansion, which is consistent with the temperature units used.

Because the mass is the same before and after the temperature rise, the change in density is inversely proportional to the change in volume and can be expressed as

$$\rho/\rho_0 = V/V_0 \tag{8}$$

Nevertheless, in many applications, the effect of volumetric changes caused by temperature are negligible.

An important factor in the liquid flow measurements is the determination of velocity, which indicates the speed and direction of the flow. When the average velocity is slow, the flow is considered to be laminar. This indicates that material flows in layers with the slower moving layers in the other outer edges. As the velocity increases, the flow may become turbulent with the layers disappearing and the velocity across the flowing stream being more uniform. In this case, the term *velocity* refers to the average velocity of particular cross section of the stream.

The nature of the fluid flow can be described by the nondimensional Reynold's number. The Reynold's number $R$ is found by

$$R = vD\rho/\mu \tag{9}$$

where $v$ is the velocity, $D$ is the inside diameter of the pipe, $\rho$ is fluid density, and $\mu$ is the kinematic viscosity.

The Reynold's number is significant to determine whether the flow is laminar or turbulent. Correctly predicting the Reynold's number leads to accurate measurements when appropriate correction factors are applied. If $R$ is less than 2000, the flow is laminar; if $R$ is greater than 4000, the flow is turbulent. Between these two values, the flow is in the transition region.

## MASS FLOW MEASUREMENTS

Mass flowmeters are used extensively in oil and gas, iron and steel, power, water distribution, pharmaceutical, food and drink, and other industries. The techniques employed for mass flow measurements can be classified to be indirect or direct methods. In indirect methods, the velocity or volumetric flow of fluid is measured by a suitable flowmeter, and the necessary calculations are flow by considering such process conditions as density, volume, temperature, and pressure. Some of the devices that can be used in indirect measurements may be venturi, target, vibrating vane, ultrasonic, or electromagnetic flowmeters. The most commonly used direct methods using coriolis and thermal mass flowmeters and will be discussed next.

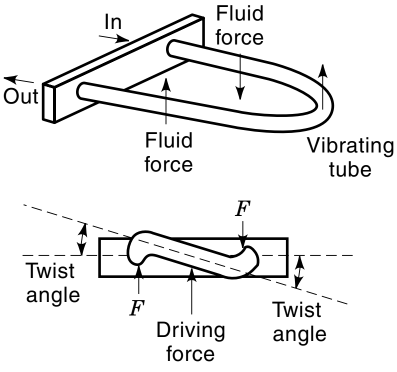


**Figure 1.** A coriolis flowmeter. The flowmeter consists of a vibrating tube carrying a portion of fluid flowing in the pipe. A force is created as a result of coriolis acceleration acting on the fluid as the fluid changes position in relation to movement of the tube. The direction of this force is perpendicular to both linear and angular velocities. Coriolis force results in the twist of the tube, which can be sensed magnetically or optically to indicate the mass inside the pipe.

### Coriolis Flowmeters

The coriolis flowmeter is a type of direct mass flowmeter where the output depends on the mass flow rate of fluid passing through. Coriolis flowmeters are used to measure harsh chemicals, low- and medium-viscosity fluids, foods, slurries, and the like. They find limited applications in gas technology because the density and pressure of gases are relatively low. Coriolis flowmeters can also be constructed and configured to measure the volumetric flows and the densities of liquids or gases.

The principle of the flowmeter depends on the conservation of angular momentum, such that if a mass $m$ is moving with a velocity $v$ along a rod, the rod itself is moving with an angular velocity $\omega$, and the mass experiences a Coriolis force of magnitude

$$F = 2mv\omega \tag{10}$$

The direction of the coriolis force is perpendicular to both linear and angular velocities. The coriolis force is created as a result of coriolis acceleration acting on the fluid as the fluid changes position in relation to the movement of the tube. The coriolis flowmeter consists of a vibrating tube, as shown in Fig. 1, in which the coriolis force is created and measured. This force results in the a twist of the tube, and this twist is sensed optically to indicate the mass inside the tube.

Coriolis flowmeters are largely applied to measure fluid flow. These flowmeters can measure flow rates from 0.04 kg/s to 15 kg/s in pipes with diameters of 3 mm to 50 mm. Accuracy better than 0.5% is possible between 5% and 100% of maximum flow rates.

The tube of coriolis flowmeters is constructed from stainless steel and vibrated by a drive mechanism. In a harsh environment, the inside of the tube is lined with Teflon to minimize corrosion and abrasion. Coriolis flowmeters can operate at high temperatures, but they are sensitive to pressure drops in the pipes. The accuracy of these flowmeters is in the region of 0.2% to 0.5% over the designed accurate measurement range. They are manufactured in different ranges and sizes. The selection of these flowmeters depends on the fluid characteristics, pressure drops in the piping systems, liquid friction losses, and so on. Manufacturers usually supply instructions, procedures, and graphs for particular applications. When installed, coriolis flowmeters must be oriented such that the meter is completely full of liquid that is free from air or gas bubbles. In gas applications, care must be exercised to not introduce liquid or condensed gas in the flowmeter.

### Thermal Flowmeters

Thermal flowmeters use thermal properties of fluids or gases. Depending on the flowmeter design, they can measure velocity or mass flow. There are many different types of which the thermal dispersion, hot wire anemometer, and constant-heat infusion types are the most widely used flowmeter.

The thermal dispersion flowmeter is based on the heat loss from a heated element placed in the flow path, as illustrated in Fig. 2. The element is heated above the ambient temperature and maintained at constant power. The cooling of the element is proportional to the mass flow, which can be described by King's Law as

$$P = A(T_e - T_f)(C_1 + C_2 v^{1/2}) \tag{11}$$

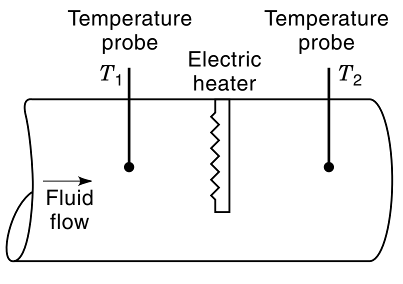


**Figure 2.** A thermal dispersion flowmeter is based on the heat loss from a heated element in contact with the flowing fluid. The element is heated above the ambient temperature, and the heating is maintained at constant power. Thus the cooling of the element is proportional to the mass flow inside the pipe. These flowmeters are suitable for gas and liquid flow measurements.

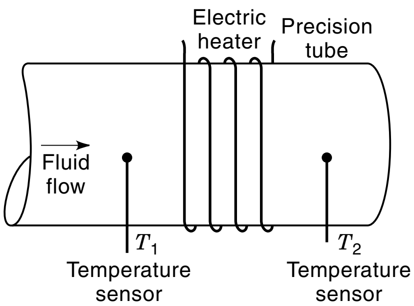


**Figure 3.** A constant-heat infusion flowmeter is based on the heat injected into the liquid, and the temperature is measured up and down the stream. In some cases, the temperature difference is maintained automatically, giving flow rate a function of heat injected to the flow stream.

where $P$ is the heat transfer (W); $A$ is the effective area of the heated element (m$^2$); $T_e$ and $T_f$ are temperatures of heated element and fluid, respectively; $C_1$ and $C_2$ are constants; and $v$ is the local speed of the fluid.

The temperature difference is converted to a linearized mass flow rate signal within the electronics.

Constant-heat infusion flowmeters are used to measure the average mass flow by externally injecting a known amount of heat into the flowing liquid, as shown in Fig. 3. The average mass flow can be calculated by measuring the temperatures upstream and downstream:

$$F = q/c_f \Delta T \tag{12}$$

where $F$ is the mass flow (kg/s), $q$ is the rate of heat added (W), $c_f$ is the specific heat of fluid (J/kg K), and $\Delta T$ is the temperature difference measured upstream and downstream in Kelvin.

In one version of the constant-heat infusion flowmeter, a control loop keeps the temperature difference constant. The resulting power input is a linear function of mass flow.

Hot wire anemometers use temperature rise in the flowing liquid. They have probes inserted into the flow stream, as shown in Fig. 4, to measure the temperature of the fluid. The velocity sensor is a fine metal wire made from tungsten, platinum, or nickel. In one version, the current through the sensor is kept constant, and the resistance change is then a measure of local fluid velocity. In the other version, resistance is kept constant, and the change in the input power is related to the local velocity. The heat from the heated probe is removed depending on the flow rate of the fluid. In some cases, a capillary tube is uniformly heated, and the temperature dissipation is sensed at different points of the tube; thus with a constant power input, the difference in the temperature at the sensing points is a linear function of the mass flow of the fluid.

Thermal flowmeters are used in applications where other types of flowmeters are not suitable, such as where fluids are not dense enough for mechanical sensing. They are usually applied to clean pure gases or mixtures of gases with predictable compositions. Typical applications are air, nitrogen, oxygen, $CO_x$, and methane. The body of the sensing system is usually constructed from stainless steel, brass, monel, or aluminum. Probes that usually come in replaceable tips are manufactured by using stainless steel. The thermal sensors or heaters are located in the probes. The capillary tubes are usually constructed from constantan to maintain a good thermal conductivity. They can operate at high-temperature applications (e.g., 450°C). The accuracy is typically ±2%.

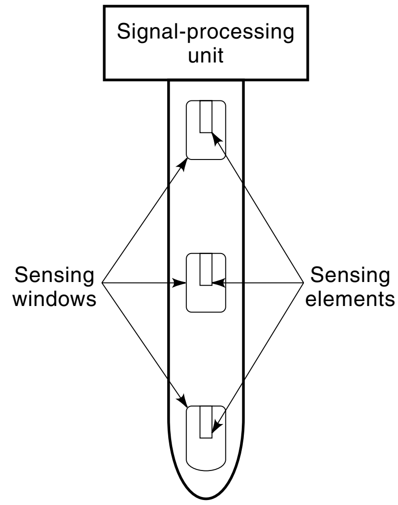


**Figure 4.** A hot wire anemometer uses probes inserted into the flowing stream. Current through the sensor is kept constant, and the resistance change is monitored; or resistance is kept constant, and the change in the input power is monitored. These devices are suitable for measuring local flow velocities of fluids.

### Mass Flow Measurement of Solids

Often mass flow rate measurements of solids are necessary where processing granular or powdered materials. In some systems, solid materials are allowed to fall from a fixed height from suitable slots on to sensors that can indicate the flow rate. In other systems, the capacitive properties are used as the solids pass through a number of electrodes suitably arranged on the flow path. However, weighing systems are most widely used in solid mass flow measurements. Load cells are often mounted under the conveyor systems to monitor continuously the solids on the conveyor, as illustrated in Fig. 5. The belt speed is sensed by a tachogenerator giving

$$Q = mv/l \tag{13}$$

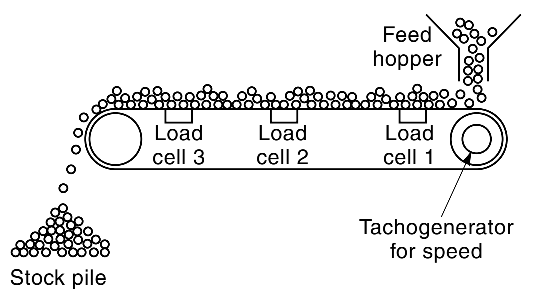


**Figure 5.** A solid flow-measuring arrangement. A number of load cells are located under the conveyor belt carrying solids. The output of the cells and the conveyor speed indicate the flow rate of solids. In some cases, instead of load cells, gamma ray devices are used, and attenuation through the solids is monitored.

where $Q$ is the mass flow rate, $m$ is the load cell output, $v$ is the belt velocity, and $l$ is the length of the belt being weighed.

An alternative technique uses isotopes emitting gamma rays. The transmitter and the receiver are placed on the opposite sides of the belt, and the gamma rays are allowed to penetrate through the solid materials. The rate of absorption of the gamma rays is directly proportional to the solid mass on the belt. The flow rate is then calculated by taking into account the belt speed, density, and temperature.

## VELOCITY AND VOLUMETRIC FLOW MEASUREMENTS

In many applications, measuring velocity may be necessary, whereas in others volumetric flow is more important. Some flowmeters will give a direct indication of the volume flow (e.g., positive displacement), and others will measure the velocity (e.g., ultrasonic, magnetic, turbine) from which volume flows can be determined. Inferential flowmeters (e.g., differential pressure, target, and variable area) are also used for velocity and volume measurements. These flowmeters can be classified as mechanical including differential, electrical, sonic, or optical types. Here, operational principles and applications of commonly used mechanical flowmeters together with differential pressure types will be discussed first, followed by optical, electrical, and sonic types.

### Turbine Flowmeters

Turbine flowmeters, sometimes called fixed-vane flowmeters, are typical mechanical flowmeters. They are known to be highly accurate with good repeatability, particularly for turbulent flow applications. There are many different types such as axial, propeller, and paddle wheel.

The most frequently used flowmeter is the axial type shown in Fig. 6. A multiblade rotor is positioned in the flow stream with the axis of rotation parallel to the direction of the flow. The fluid impinges on the blades causing a rotation with an angular velocity approximately proportional to flow rate. The number of machine cycles per second can be related directly to the volume flow rate by using a constant as the meter factor. Generally, turbine flowmeters are highly nonlinear at low flow rates, and they are not suitable to measure flows that reverse in direction.

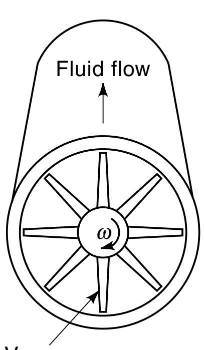


**Figure 6.** A turbine flowmeter consists of a multiblade rotor positioned suitably in the flowing stream of fluid. The fluid impinges on the blades and causes the rotor to rotate with an angular velocity proportional to the flow rate. The rotation of the rotor is sensed mechanically or electrically for further signal processing.

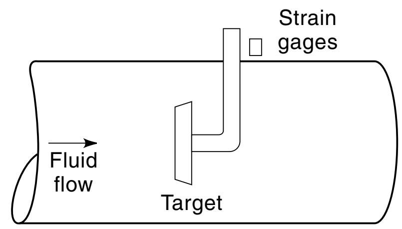


**Figure 7.** Target flowmeters are used for gas and liquid flow measurements especially in large pipes. A target suspended in the flow stream experiences a force proportional to the square of the velocity of the fluid. The force on the target is usually picked up by strain gauges.

In some cases, dual rotors are used to eliminate the errors inherent in the single-rotor designs. The rotors are designed to be as light as possible so that the momentum of fluid is relatively larger. In this way, the rotor can respond rapidly to the changes in the velocity of fluid. The rotation of the rotor is generally sensed magnetically or by tachogenerators. Other techniques such as radiofrequency (RF) methods are also used for sensing rotation.

Turbine flowmeters are manufactured in different ranges and sizes to measure liquid flows from a few centiliters to 200,000 L/min. The accuracy of these meters is typically about ±0.5%. The pressure drop range in gases is from 0.2 psi to 90 psi and in liquids from 1 psi to 20 psi. They are to be installed as per standards in order to achieve the levels of accuracy claimed. Orifice flowmeters are being replaced with these meters in many petroleum and natural gas metering stations.

### Target Flowmeters

Target flowmeters, also named as drag flowmeters, are convenient to use for liquid and gas flow measurements in large pipes. They operate on the principle of measurement of force exerted on body. A target is suspended, as shown in Fig. 7, in the flow stream, and the force on that target is the difference between the upstream and downstream pressures, which can be expressed as

$$F = k\rho A v^2 \tag{14}$$

where $k$ is a constant, $\rho$ is the density of fluid, $A$ is the target area, and $v$ is the velocity of the fluid.

The force on the target is sensed by a force balance system or strain gages. The accuracy of these devices is relatively inferior, in the region of ±1% to 2% full scale, mainly as a result of the square root relationship between the flow rate and drag force. These devices are usually applied in turbulent flows with sufficient momentum to exert force on the target. In laminar flow applications, the fluid velocity becomes a function of fluid viscosity, which may necessitate the use of calibration curves. They are sensitive to installation effects requiring straight runs of piping.

### Positive Displacement Flowmeters

Positive displacement flowmeters are based on the principle of entrapping a known amount fluid as it passes through the flowmeter. The entrapped fluid rotates the lobes whose rota-

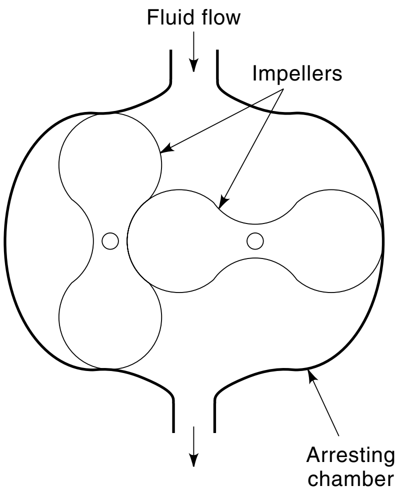


**Figure 8.** A positive displacement flowmeter is based on the principle of entrapping a known amount of flowing fluid. There are many different types available, and they are often used in water-metering applications.

tion in turn generates electrical pulses. Many types of flowmeters such as helical gear, nutating disc, oscillating piston, oval gear, piston, and rotary vane positive displacement flowmeters are available. A typical example of this flowmeter is shown in Fig. 8. The flow of fluid through a volume of fixed size causes rotation of an output shaft. This rotation can be sensed by many methods including optical techniques.

Positive displacement flowmeters are sensitive to viscosity of the fluid. Also, maximum allowable pressures and flow rates are limited. Although they are accurate over a wide flow ranges (e.g., 1000 : 1), friction, inertia, and fluctuating flow rates can cause serious errors. Also minimum measurable flow may also be limited as a result of leakage between the lobe and casing. They have accuracy of the order of $\pm 0.1\%$. These are extensively used in the petroleum industry, especially for tanker loading.

### Variable Area Flowmeters

In these flowmeters, a float, which is dynamically balanced by the flowing liquid, is positioned in the flow line, as illustrated in Fig. 9. The upward force on the float as a result of liquid velocity is equal to the weight of the float less the weight of the liquid that it displaces. An increase in the flow makes the metering tube rise. As the float rises, the annular area between the float and the metering tube increases until the upward and downward forces are dynamically equalized. Thus the level of the float is an indication of the flow through the flowmeter.

The metering tubes are available in different sizes and shapes to suit specific application requirements. Often the motion of the float is magnetically sensed. These devices are suitable for pipes that are less then 10 cm in diameter. Pressure of operation is limited by the glass material of the tube. Their accuracy is $\pm 1\%$. Variable area flowmeters are suitable for all kinds of gas and clean liquid applications.

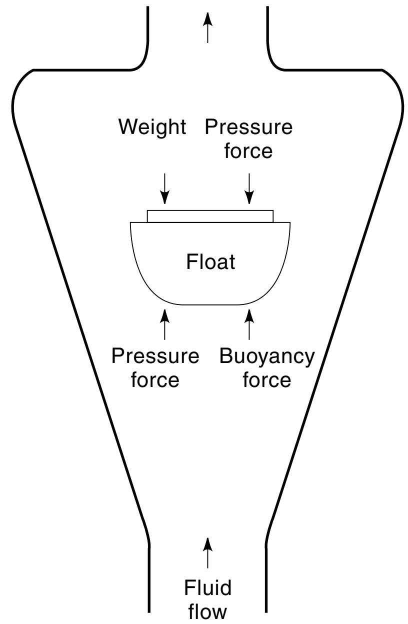


**Figure 9.** A variable area flowmeter uses a float dynamically balanced by the flowing fluid. An increase in the flow rate increases the level of the float. The level of the float is sensed mechanically, electrically, or optically. They are suitable in gas and clean liquid applications because contaminated liquids may block the flow path between the float and the container.

### Insertion Flowmeters

In insertion flowmeters, transducers such as differential pressure, magnetic, oscillatory, target, thermal, turbine or ultrasonic are inserted in the flow stream, as shown in Fig. 10. A representative velocity at a critical point is measured to represent the average velocity in the flow stream. After the average velocity is determined, the volumetric flow in the pipe can be calculated. In the applications, piping effects must carefully be considered. These devices are most suitable in determining local velocities of the flowing liquids or gases. Errors in the positioning of the transducers can cause serious errors in measurements.

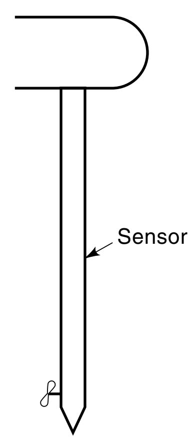


**Figure 10.** An insertion flowmeter contains various types of sensors, such as magnetic or differential pressure, that are inserted in the flow stream and that sense the local velocities of fluids. The representative velocity is then averaged to find the volumetric or mass flow rates.

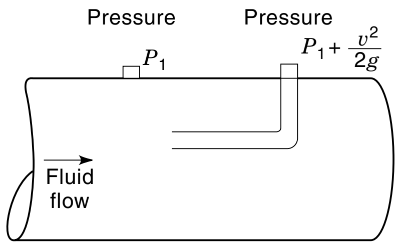


**Figure 11.** A pitot tube flowmeter inserted in the flow stream arrests fluid flowing in the pipe. The head of the fluid represents the potential energy stored in the tube, which can be related to the velocity. Pitot tube devices are well-established flowmeters, and there are many different versions.

### Differential Pressure Flowmeters

Differential flowmeters are used extensively for liquid and gas flow measurement applications. It is based on empirical correlation of the relationship between the differential pressure and volumetric flow through a restriction pipe. True flow rate is generally determined by weighing or volumetric collection of fluid over a measured time interval. Theoretical flow is calculated from flow equations using the measured differential pressure and known properties of the fluid. There are many types of flowmeters such as pitot tube, orifice plate, elbow, flow-nozzle, segmental wedge, V-cone, venturi, and bypass flowmeters. Here only a selected few will be discussed.

*Pitot tube devices* are typical examples of differential pressure flowmeters. This is used for point velocity measurement. A simple example is shown in Fig. 11. The liquid moving with a velocity $v$ is arrested in the tube inserted into the flowing liquid. By using the conservation of energy, the velocity of the fluid may be expressed as a function of head as $v = \sqrt{2gh}$. There are many versions of pitot tubes including multiple openings to the fluid and complex differential pressure transmitters and other complex gauge arrangements. For measurement of flow rate, the Pitot tube is traversed through the pipe diameter and the point velocities are measured. The velocity is integrated and multiplied by the flow area to get the flow rate. This can not be generally included in the category of flow meters.

*Orifice plate flowmeters* operate on Bernoulli's Principle, which states that the sum of the static energy, the potential energy and kinetic energy is conserved in a restriction pipe that is carrying fluid as shown in Fig. 12. Here the fluid flow rate of an incompressible fluid may be written as

$$Q = A_1 v_1 = A_2 v_2 \tag{15}$$

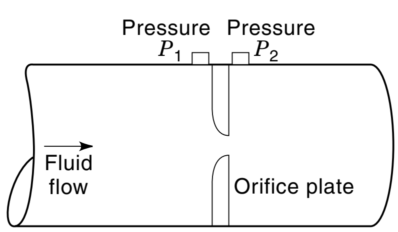


**Figure 12.** Orifice-type flowmeter are most widely used, and they operate on Bernoulli's Principle. The potential energy and kinetic energy indicate the flow rates in a restricted section of the pipe. These devices have accuracy levels of 0.5%.

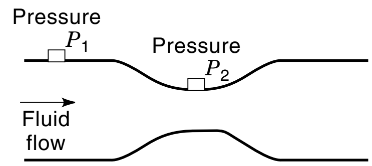


**Figure 13.** A venturi flowmeter has a restriction throat. The pressure drop before and in the restriction throat is measured to be related to the flow rate inside the pipe. Venturi flowmeters are accurate and widely used in industry for liquid and gas flow measurements.

The velocity of fluid increases as the cross-sectional area of the pipe is reduced. Applying Bernoulli's equation to the upstream and downstream location of the orifice gives the pressure difference as

$$P_1 - P_2 = \tfrac{1}{2}\rho[(D/d)^4 - 1]^2 Q^2 / A_1^2 \tag{16}$$

Equation (16) indicates that the differential pressure generated across an orifice is proportional to the square of the flow through the orifice plate.

The accuracy of orifice plate flowmeters is in the range of 0.5% to 3%. They are suitable in applications with Reynold's numbers from 5000 to $2 \times 10^6$ depending upon the size; however, they are highly sensitive to installation effects. Valves, pipe fittings, and the like can distort the velocity profile leading to inaccurate readings. When installed as per Internation Standard Organization (ISO) standards, higher accuracies can be obtained. They were used until recently in conjunction with flow computers for custody transfer flow measurement of natural gas.

*Venturi flowmeters* are a type of obstruction device, as shown in Fig. 13. This classical Herschel venturi has a very long flow element with tapered inlet and diverging outlet. Inlet pressure is measured at the entrance section. The inlet diameter is reduced to a throat section, and the static pressure is measured at this section. Venturi flowmeters find applications in fluid flows having a Reynold's number as high as 100,000. These flowmeters give relatively small pressure drops and are highly accurate, about 0.5%. They are not affected by velocity profiles. The construction and applications of venturi devices have been standardized by international standards (e.g., ISO 5167 and DIN 1952). These flowmeters find many applications in power, water, and water treatment industries.

*Bypass flowmeters* are obtained by employing a bypass stream created by differential pressure in the main stream. A flowmeter in the bypass stream measures the flow as illustrated in Fig. 14. The flow in the bypass stream is then inferred to the main stream. The accuracy of the system is limited by the accuracy of the bypass flowmeter. In many critical applications, the bypass flowmeter is used to increase the accuracy of the primary flowmeter, which is located in the main stream.

### Vortex-Shedding Flowmeters

Mathematically, the phenomenon of vortex shedding is described by the von Karman Effect. When a bluff body is placed in a flow stream, as the fluid passes the body, vortices are shed alternately from the back side of the body. The vortex

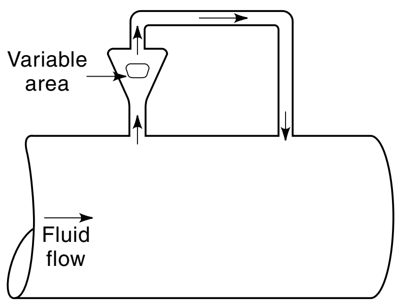


**Figure 14.** A bypass flowmeter is obtained by providing a bypass line to the main flow stream. The pressure drop of the bypass stream is inferred to the flow characteristics of the main stream. These flowmeters are often used as backup measurements in conjuction with main flowmeters in some critical and sensitive applications.

shedding of the device is illustrated in Fig. 15. The frequency of the vortex shedding is directly proportional to the velocity of liquid. The frequencies of vortex shedding are monitored by appropriate sensors. The fluid parameter that describes the operation of this device is a nondimensional Strouhal number $S$

$$S = f_s d/v \quad (17)$$

where $f_s$ is the vortex shedding frequency, $d$ is the diameter of the bluff body, and $v$ is the velocity.

Writing

$$Q = Av \quad (18)$$

where $A$ is the flow area, and substituting for $v$ gives

$$Q = Af_s d/S \quad (19)$$

The Strouhal number is constant for particular shapes of bluff body. For the body in Fig. 15 the number is about 0.88 for Reynold's numbers from $10^4$ to $10^6$.

To measure the frequencies of the vortices, various forms of sensors are used. These sensors include diaphragms, magnetic sensors, pressure sensors, suitable torque tubes, and ultrasonic methods. Measurements by vortex shedding can indicate instantaneous flow rates or totalized flow rates over a known time interval. The meters are calibrated by the manufacturers for specific pipe sizes. They give the best results for low-viscousity fluids and unsuitable for most high-viscousity liquids. Manufacturers specify special installation requirements of their devices.

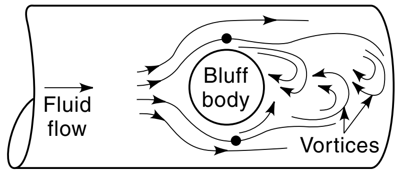


**Figure 15.** A vortex-shedding flowmeter is based on the creation of vortices in the flow stream. A suitably shaped buff body is placed in the flow stream, and the frequency of vortices is measured by various techniques such as pressure or ultrasonic methods. They are suitable for applications using low-viscosity fluids.

These flowmeters are available in different sizes, and they can handle from a few liters of flow to 15,000 L. They are used in liquid, gas, and vapor applications with relatively steady flow rates. The overall accuracy for gases is in the region of 1% to 2%. Accuracy in liquid applications is about 0.5%.

There are many different versions of devices based on vortex-shedding principle, including some devices using two bluff bodies to make stronger vortices. An improved version of the vortex-shedding transducers is the velocity probes. In this case, sensors are mounted together with the bluff body in a section of a short tube. This assembly can be inserted in various sections of the flow field to measure the local velocity.

## OPTICAL METHODS

Optical methods are extensively used in flow measurements involving analytical applications. The properties of light are used to measure the flow of liquids and gases. Some of these properties may include shadowing, relative illuminations, deflections, interference, and Doppler shift. There are many different flowmeters based on optical principles. Flowmeters based on the laser Doppler effect will be discussed next.

### Laser Doppler Anemometers

Like Pitot tubes, laser Doppler anemometers are also used for point velocity measurements. In laser Doppler anemometers, the properties of scattering of a laser beam are utilized. For the correct operation of the device, the fluid must contain particles to scatter laser beam. A typical example of such devices is shown in Fig. 16. The laser beam is focused on a small volume element, and the scattered beams are received by an appropriate arrangement of lenses. The scattered light experiences a frequency shift directly proportional to the velocity. The scattered and unscattered beams are combined through a beam splitter. The resultant beam is put through a photomultiplier tube to give an output proportional to flow velocity. The data from the photomultiplier is processed carefully by employing appropriate signal processors.

He–Ne gas lasers operate at a frequency of $5 \times 10^{14}$ Hz (wavelength of 632.4 nm) and are preferred over argon lasers. There are laser flowmeters that measure more than one velocity component simultaneously. Laser techniques are useful to

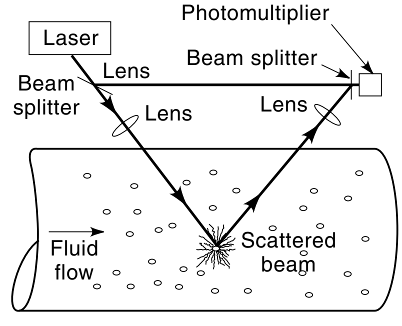


**Figure 16.** A laser Doppler anemometer is based on scattered laser beams. As the laser light encounters particles in the flowing fluid, it gets scattered. Some of the scattered light is picked up by suitably located lenses. The frequency shift of the returned light depends on the velocity of particles in the fluid.

determine turbulence and other flow phenomena. Focused laser beams can measure flows of samples as small as tens of cubic micrometers. The use of this is generally limited to laboratory studies related to point velocity measurements. Moreover, it requires the pipe carrying fluid to be transparent to the laser beam.

## ULTRASONIC FLOWMETERS

In ultrasonic flowmeters, acoustic waves detect the flow of liquids and gases in pipes. There are a few different types, such as the Doppler effect, transit time, correlation, and ultrasonic vortex types.

In *Doppler effect flowmeters,* ultrasonic signals of a fixed frequency are transmitted through the flowing fluid, and the frequency shift of the returned signals is measured. The transmitted signals can be continuous or in pulse-modulated form. Such impurities as solids, bubbles, or any other discontinuity in the liquid reflect the signals back to the transmitter. A simplified example of this flowmeter is depicted in Fig. 17. The frequency of the reflected signal shifts from the transmitted frequency in proportion to the velocity. The frequency $f_r$ of reflected signals can be expressed as

$$f_r = f(c + v\cos\theta)/c \tag{20}$$

where $f$ is the frequency of transmitted ultrasonic wave, $c$ is the velocity of sound in the still fluid, $v$ is the relative velocity of fluid with respect to transmitter, and $\theta$ is the angle of transmission with respect to direction of fluid flow.

Particles reflecting the ultrasonic signals act as a source moving with a velocity $v$ relative to the receiver. Now the frequency of reflected signals to the receiver may be expressed as

$$f_{rr} = f_r c/(c - v\cos\theta) \tag{21}$$

It can further be proved that the frequency shift between the transmitted and received signal is

$$\Delta f = f_{rr} - f = (2fv\cos\theta)/c \tag{22}$$

The particles scatter the transmitted signal in all directions; therefore, the received signals by the receiver are attenuated severely. During the signal-processing stages, the receiver signals are amplified to the level of transmitted signal and

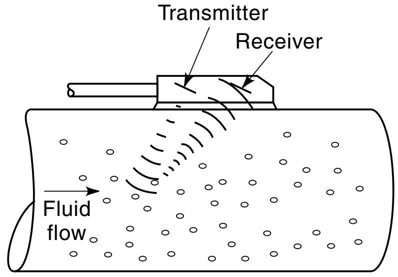


**Figure 17.** A Doppler effect ultrasonic flowmeter is based on the reflection of ultrasonic beams from particles or air bubbles carried in the flowing fluid. For signal processing, proper amplification, filtering, modulation, and demodulation of returned signals is necessary.

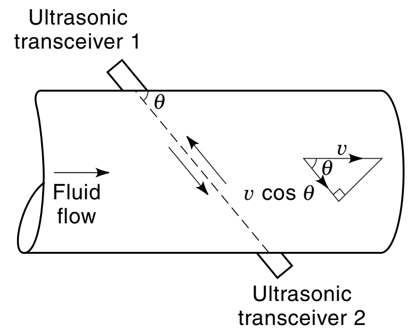


**Figure 18.** A transit time ultrasonic flowmeter uses the time of flight between two transducers. The two transducers are used as transmitters and receivers alternately. The transit time difference can be directly related to the flow rate of the fluid. Because the time difference is small, careful signal processing is necessary for accurate measurements.

added to the transmitted signals. This gives an amplitude modulated signal with a carrier frequency of $(f + f_{rr})/2$ and a modulating frequency of $\Delta f/2$. Rectification of the output of the adder and low-pass filtering gives a demodulated signal proportional to fluid velocity $v$.

The *transit time* ultrasonic flowmeters are based on the measurement of the difference in travel time between pulses transmitted along or against the fluid flow in a pipe. A typical arrangement is shown in Fig. 18. Transducers 1 and 2 act as transmitters and receivers. As transmitter 1 sends a pulse, the corresponding transit time may be expressed as

$$t_d = L/(c + v\cos\theta) \tag{23}$$

where $t_d$ is time taken for pulse to travel from transducer 1 to 2, $L$ is the distance between transducers, $c$ is the velocity of sound in still fluid, $v$ is the velocity of the fluid, and $\theta$ is the angle between transducers with the pipe.

When transducer 2 sends a pulse, the corresponding transit time becomes

$$t_u = L/(c - v\cos\theta) \tag{24}$$

From these two equations, the differential time $\Delta T$ can be found as

$$\Delta T = t_d - t_u = (2Lv\cos\theta)/c^2 \tag{25}$$

The differential time $\Delta T$ is very small, of the order of a few hundred nanoseconds. Therefore, carefully designed electronic circuits are necessary for a reasonable accuracy. In some systems (e.g., sing around systems) transmitters continuously switch between transmitter and receiver modes, which leads to better accuracy. There are two different types—wet and clamp-on. In the wet type, the transducers are inserted in the stream making direct contact with the fluid. In the clamp-on type, the transducers are attached to the pipes externally. The clamp-on types are used for rough estimate of flow in pipes of large diameters.

Ultrasonic *cross-correlation flowmeters* consist of two transducers sensing fluctuations in the properties of the fluid. For example, the properties of the fluid may be variations in the acoustic impedance resulting from the presence of particles and air bubbles. The variations in the sensing of the fluid properties are randomly changing but present in each sensor. Therefore, the delayed version of the output signal $x(t)$ of sensor 1 is correlated with the output $y(t)$ of the sensor 2 through a correlator to determine the cross-correlation function. The output of the correlator has a maximum value proportional to $L/v$ against delayed versions of $x(t)$. The received signals are amplified, demodulated, and filtered to eliminate the high-frequency carrier signal. The remaining demodulated signals are amplified and input to the correlator to determine the flow rates. There are many other cross-correlation flowmeters based on different techniques and sensors such as capacitance transducers, electrodes, and infrared or optical sensors. The fluid properties that may be used for measurements can be densities, temperatures, conductivity, acoustic impedance, and the like.

*Ultrasonic transducers* are available for gas and liquid flow measurements. The accuracy of these devices can vary between ±0.5% and 10% of full-scale (FS). The liquid must contain solid particles or air bubbles in the stream for Doppler-type flowmeters to operate effectively. The amount of solid particles must not exceed a certain limit (e.g., 30%) so that ultrasonic energy can penetrate into the stream for the measurement of average velocity. Also, for accurate results, the particles must also flow with the same speed as the liquid. The time-of-flight type of ultrasonic transducers are more suitable for gas applications.

## ELECTROMAGNETIC FLOWMETERS

Magnetic flowmeters have been widely used in industry for many years. Unlike many other types of flowmeters, they offer true noninvasive measurements. They can measure reverse flows and are insensitive to viscosity, density, and flow disturbances. Electromagnetic flowmeters can rapidly respond to flow changes and are linear devices for a wide range of measurements. Recently, the technological refinements have resulted in much more economical, more accurate, and smaller instruments than the previous versions.

The underlying principle of the electromagnetic flowmeter is Faraday's Law of Electromagnetic Induction. This law states that if a conductor of length $l$ (m) is moving with a velocity $v$ (m/s), perpendicular to a magnetic field of flux density $B$ (T), then the induced voltage $e$ across the ends of conductor may be found by

$$e = Blv \tag{26}$$

The application of Faraday's Law to electromagnetic flowmeters is shown in Fig. 19. The magnetic field, the direction of the movement of the conductor, and the induced electromotive force (emf) are all perpendicular to each other. The induced voltages are linearly proportional to the mean velocity of liquids or to the volumetric flow rates.

In the case of electromagnetic flowmeters, the conductor is the liquid flowing through the pipe, and the length of conductor is the distance between the two electrodes, which is equal to the tube diameter. The velocity of the conductor is proportional to the mean flow velocity of the liquid. Hence, the induced voltage becomes

$$e = BDv \tag{27}$$

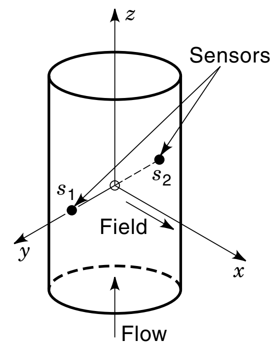


**Figure 19.** Operational principle of an electromagnetic flowmeter is based on Faraday's Law, which states that a voltage is induced in a conductor moving in a magnetic field. In electromagnetic flowmeters, the direction of movement of conductor, the magnetic field, and the induced emf are perpendicular to each other in $X$, $Y$, and $Z$ axes. Electrodes $S_1$ and $S_2$ experience a virtual conductor resulting from liquid in the pipe.

where $D$ (m) is the diameter of pipe. If the magnetic field is constant and the diameter of the pipe is fixed, the magnitude of the induced voltage will only be proportional to the velocity of the liquid. If the ends of the conductor, in this case the sensors, are connected to an external circuit, the induced voltage causes a current $i$ to flow. The current can be processed suitably as a measure of the flow rate. The resistance of the moving conductor may be represented by $R$ to give the terminal voltage $v_T$ of the moving conductor as $v_T = e - iR$. Using modern amplifiers with very high input impedance, the current $i$ is minimized to such an extent that $v_T$ is almost equal to $e$.

Electromagnetic flowmeters are often calibrated to determine the volumetric flow of the liquid. The volume of liquid flow $Q$ (L/s) may be related to the average fluid velocity as

$$Q = Av \tag{28}$$

Writing the area $A$ ($m^2$) of the pipe as

$$A = \pi D^2/4 \tag{29}$$

gives the induced voltage as a function of the flow rate

$$e = \frac{(4BQ)}{(\pi D)} \tag{30}$$

This equation indicates that, in a carefully designed flowmeter, if all the other parameters are kept constant, then the induced voltage is linearly proportional only to the liquid flow.

Many different types of electromagnetic flowmeters are available, and all are based on Faraday's Law of Induction. The two most commonly used electromagnetic flowmeters are the ac and the dc types.

### Alternating Current Flowmeters

In many commercial electromagnetic flowmeters, an alternating current of 50 Hz to 60 Hz in coils creates a magnetic field to excite the liquid flowing in the pipe. A voltage is induced in the liquid as described by Faraday's Law of Induction. A typical value of the induced emf in an ac flowmeter fixed on a 50 mm internal diameter pipe carrying 500 L/min is about 2.5 mV.

Historically, ac magnetic flowmeters were the most commonly used types because they reduced polarization effects at the electrodes. In general, they are less affected by the flow profiles of the liquid inside the pipes. They allow the use of high-power amplifiers with low drifts and high-pass filters to eliminate slow and spurious voltage drifts that emanate mainly from thermocouple and galvanic actions. These flowmeters find many applications as diverse as measuring blood flow in living specimens. Miniaturized sensors allow measurements on pipes and vessels as small as 2 mm in diameter. In these applications, the excitation frequency is higher than industrial types, varying between 200 Hz and 1000 Hz.

A major disadvantage of the ac flowmeters is that the powerful ac field induced spurious ac signals in the measurement circuits. This necessitates periodical adjustment of zero output at zero velocity conditions. Also, in some harsh industrial applications, currents in the magnetic field may vary as a result of voltage fluctuations and frequency variations in the mains. The effect of fluctuations in the magnetic field may be minimized by the use of a reference voltage proportional to the strength of the magnetic field to compensate for these variations. To avoid the effects of noise and fluctuations, special cabling and calibration practices recommended by the manufacturers must be used to ensure accurate operations.

Readily available are ac flowmeters operating at 50 Hz, 60 Hz, or 400 Hz. In general, ac flowmeters can operate at 10 Hz to 5000 Hz. High frequencies are preferred in determining the instantaneous behavior of transients and pulsating flows. Nevertheless, in applications where extremely good conducting fluids and liquid metals are used, the frequency must be kept low to avoid skin effects. On the other hand, if the fluid is a poor conductor, the frequency must not be so high that dielectric relaxation is not instantaneous.

### Direct Current Flowmeters

Direct current or pulsed magnetic flowmeters excite the flowing liquid with a field operating at 3 Hz to 6 Hz. As the current to the magnet is turned on, a dc voltage is induced at the electrodes. The signals observed at the electrodes represent the sum of the induced voltage and the noise, as illustrated in Fig. 20. When the current in the magnetic coils is turned off, the signal represents only the noise. Subtracting the measurement of the flowmeter when no current flows through the magnet from the measurement when current flows through the magnet effectively cancels out the effect of noise.

If the magnetic field coils are energized by normal direct current, then there occur several problems such as polarization, which is the formation of a layer of gas around the measured electrodes, as well as electrochemical and electromechanical effects. Some of these problems may be overcome by energizing the field coils at higher frequencies or ac. However, higher frequencies and ac generate transformer action in the signal leads and fluid path. Therefore, the coils are excited by dc pulses at low repetition rates to eliminate the transformer action. In some flowmeters, by appropriate sampling and digital signal-processing techniques, the zero errors and the noise can be rejected easily.

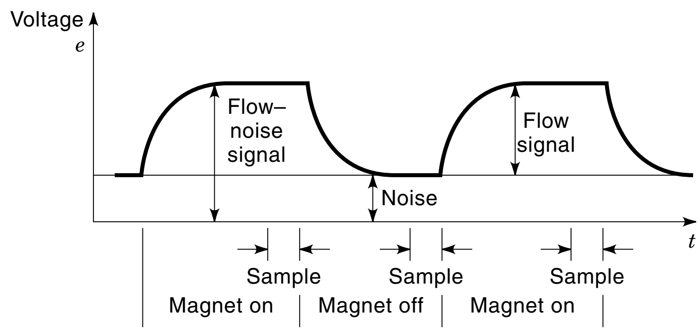


**Figure 20.** The signals observed at the electrodes represent the sum of the induced voltage and the noise. When the current in the magnetic coils is turned off, the signal across the electrodes represents only the noise. Subtracting the measurement of the flowmeter when no current flows through the magnet from the measurement when current flows through the magnet effectively cancels out the effect of noise.

The zero compensation inherent in the dc magnetic flowmeters eliminates the necessity of zero adjustment. This allows the extraction of flow signals regardless of zero shifts due to superious noise or electrode coating. Unlike ac flowmeters, larger insulating electrode coating that may shift the effective conductivity significantly without affecting performance can be tolerated. It can be said that as long as effective conductivity remains high enough, a dc flowmeter will operate satisfactorily. Therefore, dc flowmeters are less susceptible to drifts, electrode coatings, and changes in the process conditions in comparison to conventional ac flowmeters.

Because of the slow pulsed nature of operations, dc magnetic flowmeters do not have good response times. However, as long as there are not rapid variations in the flow patterns, zero to full-scale response times of a few seconds do not create problems in the majority of applications. Power requirements are also much less because the magnet is energized part of the time. This gives an advantage in power saving of up to 75%.

Application of all types of magnetic flowmeters can be realized only on conductive liquids such as acids, bases, slurries, foods, dyes, polymers emulsions, and suitable mixtures that have conductivities greater than minimum conductivity requirements. Generally, magnetic flowmeters are not suitable for liquids containing organic materials and hydrocarbons. As a rule of thumb, the magnetic flowmeters can be applied if the process liquids that constitute a minimum of about 10% conductive liquid in the mixture.

For electromagnetic flowmeters to operate accurately, the process liquid must have minimum conductivity of 1 $\mu$s/cm to 5 $\mu$s/cm. Most common applications involve liquids whose conductivity is grater than 5 $\mu$s/cm. Nevertheless, for accurate operations, the requirement for the minimum conductivity of liquid can be affected by length of leads from sensors to transmitter electronics.

The wetted parts of a magnetic flowmeter include the liners, electrodes, and electrode holders. Many different materials such as rubber, Teflon, polyurethane, and polyethylene are used in the construction to suit process corrosivity, abrasiveness, and temperature constraints. The main body of a flowmeter and electrodes can be manufactured from stainless

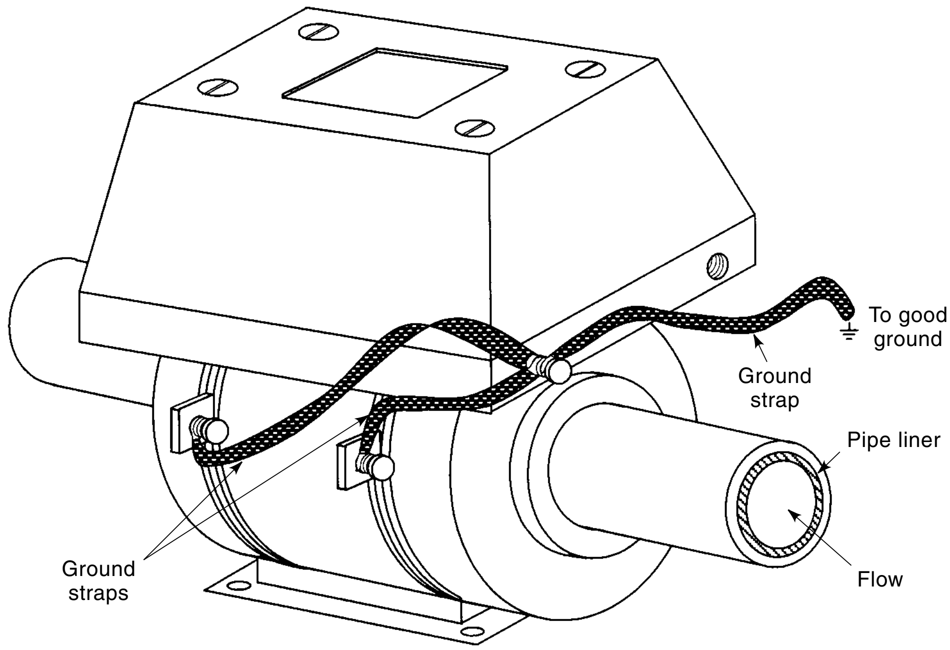


**Figure 21.** Good grounding of electromagnetic flowmeters is absolutely essential to isolate noise and high common-mode potential. If the pipe is conductive and makes contact with the liquid, the flowmeter should be grounded to the pipe. If the pipe is made from nonconductive materials, the ground rings should be installed to maintain contact with the process liquid. Improper grounding results in excessive common-mode voltages that can severely limit the accuracy and damage the processing electronics.

steel, tantalum, titanium, and various other alloys. Liners are selected mainly to withstand the abrasive and corrosive properties of the liquid. The electrodes must be selected such that they cannot be coated with insulating deposits of the process liquid during long period of operations. The main problem in electromagnetic flowmeter is due to the electrodes getting coated over a period of time, thereby leading to malfunctions. Present day flowmeters have means to overcome this by sensing high frequency pulses to the electrodes, thereby the coasting gets removed automatically.

During the selection of electromagnetic flowmeters, the velocity constraints should be evaluated carefully in order to secure accurate performance over the expected range. The full-scale velocity of the flowmeter is typically 0.3 m/s to 10 m/s. Some flowmeters can measure lower velocities with somewhat deteriorated accuracy. Generally, employment of electromagnetic flowmeters over a velocity of 5 m/s should be considered carefully because erosion of the pipe and damages to liners can be significant.

A good electrical grounding of magnetic flowmeters, as illustrated in Fig. 21, is required to isolate relatively high common-mode potential. The sources of ground potential may be in the liquid or in the pipes. In practice, if the pipe is conductive and makes contact with the liquid, the flowmeter should be grounded to the pipe. If the pipe is made from nonconductive materials, the ground rings should be installed to maintain contact with the process liquid.

The accuracy of conventional magnetic flowmeters is usually expressed as a function of full scale, typically 0.5% to 1% FS. However, dc flowmeters have a well-defined zero because of the automatic zeroing nature; therefore, they have percentage rate of accuracy better than ac types, typically at 0.5% to 2% rate.

## CALIBRATION, ACCURACY, PRECISION, AND STANDARDS

There are many manufacturers of flowmeters, as listed in Table 1. They are used in diverse industries such as oil and gas, iron and steel, power, food and drink, water distribution, pharmaceutical, agricultural, mineral processing, and manufacturing.

In the past, the flowmeter repeatability rather than accuracy is the main concern. However, nowadays, with the use of microprocessors together with improved transducers, better accuracies are possible. For example, it is possible to obtain mass flowmeters having accuracies of 0.2% to 0.5% after having compensated for temperature and pressure effects. A list of flowmeters together with their accuracy and suitability for various applications are given in Table 2.

It is necessary to calibrate flowmeters because of the possible changes in fluid properties. In field applications where characteristics of fluids change often or mixtures of fluids are used, frequent rechecking and recalibration of flowmeters may be necessary for continual and accurate operations. There are a number of national and international codes of practice for calibrating flowmeters. A number of organizations such as ASME, ISO, and British Standards codify standards about flowmeters. The standards are codified for accuracy of components, calculating precision, bias errors, in situ testing, uncertainty analysis, and the like. The American Petroleum Institute (API) standards pertain to measurement of liquid petroleum products, and American Gas Association (AGA) standards pertain to measurement of natural gas. Also, a number of committees are looking into flow measurement standards such as ISO/TC28/SC2/WG6 of Israel and the United States and BSI/PCL/2/9 of the United Kingdom. Calibrations of flowmeters are done in a standards laboratory.

**Table 1. List of Manufacturers**

ABB K-Flow, Inc.
P.O. Box 849
45 Reese Road
Millville, NJ 08332
Tel: 1-800-294-8116
Fax: 609-825-1678

Brooks Instrument
407 West Vine Street
Hatfield, Pennsylvania 19440
USA
Tel: 215-362-3500
Fax: 215-362-374

Danfoss Inc.
4971 Mercantile Road
Baltimore, Maryland 21236,
USA
Tel: 410-931-8250
Fax: 410-931-8256

Daniel Industries, Inc.
P.O. Box 19097
Houston, Texas 77224 USA
Tel: 713-467-6000
Fax: 713-827-3880

Davis Instruments
4701 Mount Hope Drive
Baltimore, MD 21215
Tel: 410-358-3900
Fax: 410-358-0252

FCI Fluid Components
International
1755 La Costa Meadows Drive
San Marcos, CA 92069-5187
Tel: 619-744-6950
Fax: 619-736-6250

Fischer Porter
50 Northwestern Drive
P.O. Box 1167T
Salem, NH 03079-1137
Tel: 603-893-9181
Fax: 603-893-7690

Flowmetrics, Inc.
7959 Alabama Avenue
Conoga Park, CA 91304
Tel: 818-346-4492
Fax: 818-346-8991

Hastins
P.O. Box 1436
Hampton, VA 23661
Tel: 800-950-2468
Fax: 804-723-3925

Hoffer Flow Controls
107 Kitty Hawk Lane
P.O. Box 2145
Elizabeth City, NC 27909
Tel: 800-628-6586
Fax: 252-331-2886

Johnson Yokogawa
Dept. P, Dart Road
Newman, GA 30265
Tel: 800-394-9134
Fax: 770-251-6427

Key Instruments
250 Andrews Road
Trevosa, PA 19053
Tel: 215-357-0893
Fax: 215-357-9239

King Instrument Company
16792 Burke Lane
Huntington Beach, CA
92647-4559
Tel: 714-841-3663
Fax: 714-847-2062

Krohne America, Inc.
7 Dearborn Rd.
Peabody, MA 01960
Tel: 978-535-6060
Fax: 978-535-1760

Lambda Square, Inc.
P.O. Box 1119M
Bay Shore, NY 11706
Tel: 516-587-1000
Fax: 516-587-1011

Marsh-McBirney, Inc.
4539 Metropolitan Court
Frederick, MD 21704
Tel: 301-879-5599
Fax: 301-874-2172

Micromotion Inc.,
7070 Winchester Circle,
Boulder, CO 80301
800-522-MASS, 522-6277
303-530-8100
USA

Nice Instrumentation, Inc.
1122 Campus Drive West
Morganville, NJ 07751
Tel: 908-591-8899
Fax: 908-591-8909

Rosemount Inc.
Dept. MCA 15
12001 Technology Drive
Eden Prairie, MN 55344
Tel: 612-828-3006
Fax: 612-828-3088

Schlumberger
Fluid Power Div.
8635 Washington Avenue
Racine, Washington 53406,
USA
Tel: 414-884-7400
Fax: 414-884-7440

Signet
George Fischer, Inc.
2882 Dow Avenue
Tustin, CA 92680
Tel: 800-280-5544
Fax: 714-731-6201

Smith Meter, Inc.
Smith Building
1602 Wagner Avenue
Erie, PA 16510
Tel: 814-898-5000
Fax: 814-899-8927

Sparling Instruments Company,
Inc.
4097 Temple City Boulevard
P.O. Box 5988
El Monte, CA 91734-1988
Tel: 800-423-4539

Universal Flow Monitors, Inc.
1751 E. Nine Mile Road
Hazel Park, MI 48030
Tel: 313-542-9635
Fax: 313-398-4274

Xolox Corporation
6932 Gettysburg Pike
Ft. Wayne, IN 46804
Tel: 800-348-0744
Fax: 219-432-0828

**Table 2. Accuracy and Applications of Flowmeters**

| | Liquid | | | | | |
|---|---|---|---|---|---|---|
| Flowmeter | Clean | Slurry | Gas | Accuracy (%) | Reynold's Number | Example Standards |
| Coriolis | Yes | Yes | Yes | ±0.2–1.0 | No limit | |
| Magnetic | Yes | Yes | No | ±0.5–1.0 | No limit | ISO 6817, ASME 16Mt |
| Orifice plate | Yes | Yes | Yes | ±0.5–3.0 | >1,000 | ANSI/ASME MFC 3M, ISO 5167 |
| Oscillating vane | Yes | Yes | Yes | ±0.5 | Depends on size | |
| Pitot tube | Yes | No | Yes | ±5.0 | No limit | ASME/MFC SC16 |
| Positive displacement | Yes | No | Yes | ±0.5–1.0 | <8,000 | OIML R31 |
| Target | Yes | Yes | Yes | ±0.5–2.0 | >1,000 | |
| Thermal mass | Yes | Yes | Yes | ±1.0 | No limit | ISO TC30 |
| Turbine | Yes | No | Yes | ±0.5–1.0 | Viscous | ASME/ANSI 4M |
| Ultrasonic | Yes | Yes | Yes | ±1.0–5.0 | No limit | ANSI/ASME MFC 5M |
| Variable area | Yes | No | Yes | ±0.5–1.0 | Viscous | |
| Venturi | Yes | No | Yes | ±0.5–2.0 | <75,000 | ASME/ANSI ISO 5167 |
| Vortex | Yes | No | Yes | ±0.5–1.5 | <10,000 | ASME/ANSI MFC 6M |

Flow being a derived quantity, its calibration should be traceable to the fundamental units of Length, Mass, and Time (L, M, and T). The gravimetric methods of calibration as per ISO 4185 is the method for calibration of flowmeters used for liquid application. The Bell power is used for primary calibration of gas flowmeters.

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