White paper

ABB Flowmeters
Review of industrial processing flowmeters

Understanding flowmeters and their pros and cons

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One of the most critical measurements in the processing industries is rate of flow. In 2010, the ARC Advisory Group estimated the total instrumentation market (not including process analytical devices) to be $13.4 billon. The chemical industry accounted for $2.5 billion of this figure. Flowmeters account for nearly 30% of the amount spent on these measurement products.

Flow metering technologies fall into four classifications: velocity, inferential, positive displacement, and mass. This article summarizes the considerations in selecting and applying these flowmeters, and provides examples of the kinds of flowmeters in each category.

Velocity meters

Many kinds of flowmeters on the market sense a fluid's average velocity through a pipe. Multiplying the measured average velocity by the cross-sectional area of the meter or pipe results in volumetric flow rates. For example, if the average fluid velocity is 2.5 ft/sec and the inside diameter of the pipe or flowmeter is 12 inches (0.79 sq ft area), the volumetric flow rate equals (2.5 x 0.79) or 1.98 cu ft/sec or about 14.8 gal/sec.

When specifying velocity meters, chemical engineers must be concerned with the fluid's velocity profile in the pipe, which depends on piping geometry and Reynolds number.

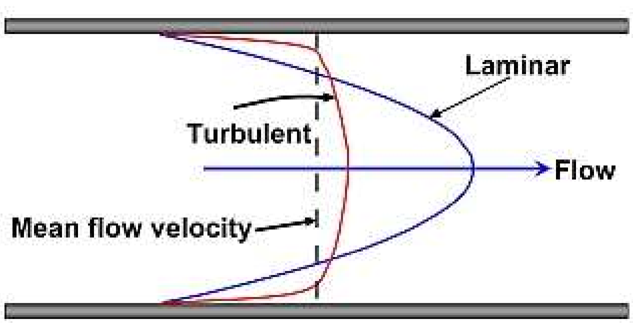


Figure 1. Fluid velocity profiles for turbulent and laminar flow.

Assuming sufficient straight piping runs, the cross-sectional view shown in Figure 1 illustrates two flow profile situations: turbulent (red) and laminar (blue).

With relatively small piping friction loss and low fluid viscosity, the flow profile of velocities is uniform across the entire cross-section of the pipe--called fully developed turbulent flow. In this case, the fluid velocity at the pipe walls closely matches the fluid velocity at the center and at all points in-between. The velocity at any point is the average velocity. This condition results when the Reynolds number is 10,000 or above. Calculating volumetric flow rates is relatively easy, as noted above.

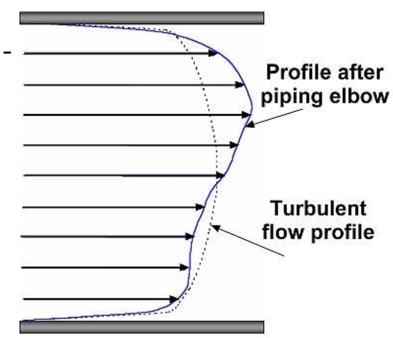


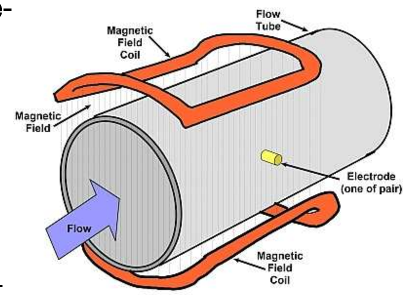
Figure 2. Pipe fittings such as elbows, tees, and valves will distort the flow profile.

But depending on the pipe diameter and the fluid's density, viscosity, and momentum (variables affecting the Reynolds number), the flow velocity within a pipe can vary significantly between the pipe wall and its center. The average velocity through a pipe becomes increasingly difficult to measure precisely when Reynolds numbers are low. For long, straight pipe runs and low Reynolds numbers, the flow velocity would be highest at the pipe's center, and trail off in symmetrical fashion toward the pipe wall; such conditions are typical of laminar flow profiles.

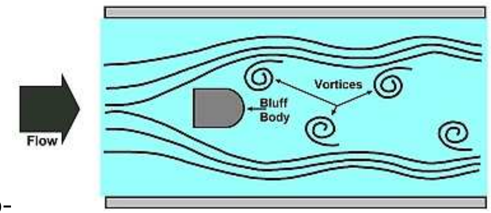
With an insertion probe flowmeter, engineers can establish the fluid velocities across the diameter of a pipe at multiple cross-sectional locations. By determining the

A sampling of velocity flowmeters and their principle of operation

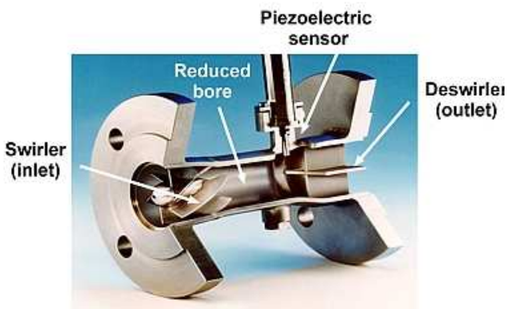
Electromagnetic flowmeters subject conductive liquids to alternating or pulsating DC magnetic fields. Electrodes on either side of the pipe wall pick up the induced voltage following Faraday's Law, which is proportional to fluid velocity.



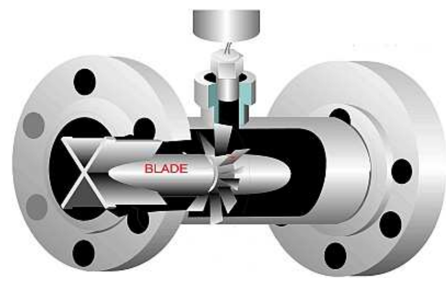
Vortex meters place a bluff obstacle in the flow stream, which creates vortices or eddies whose frequency is proportional to flow velocity. Sensors detect and count the pressure variations produces over a fixed time.



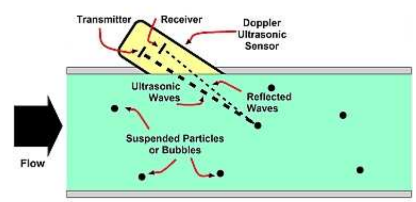
Swirl meters are similar to vortex meters, except vanes at the inlet swirl the flow, creating the pressure variations. Straightening vanes at the outlet de-swirl the flow.



Turbine meters contain a turbine. The flow against the turbine's vanes causes the turbine to rotate at a rate proportional to flow velocity. A sensor detects the rotational rate.



Ultrasonic meters come in two types. The Doppler flowmeter sends an ultrasonic beam into the flow and measures the frequency shift of reflections from discontinuities in the flow. Transit-time flowmeters have an ultrasonic transmitter and receiver separated by a known distance. The difference in transit time for a signal aided by the flow versus the signal moving against the flow is a function of fluid velocity.



pipe's actual flow profile, and integrating the data to determine the mean flow velocity, they can check on how accurately a flowmeter measures the true flow rate.

Manufacturers will specify the length of straight pipe upstream and downstream of a velocity flowmeter for achieving high accuracies. But often plant piping geometries in a chemical plant will be such that sufficiently long straight pipe runs are not feasible. The flowmeter may have to be located near an elbow, tee, valve, or change in pipe diameter. In this case the flow will not be fully developed and result in the distorted profile—one example shown in Figure 2. Various flow straightening devices (engineered, bundled tubes) installed upstream of the flowmeter can help correct these distortions by creating uniform flow profiles, permitting average velocity to be inferred.

The most practical liquid pipeline flow rates in the chemical and processing industries range from 0.5 to 12 ft/sec, providing a range (turndown) of 24:1. Lower rates can be difficult to measure accurately and higher rates result in higher pressure drops, pumping energy costs, and erosion (if abrasive solids are present). In the case of pipelines carrying gases, the practical flow velocities range from 15 to 200 ft/sec, a range of about 13:1. Many actual applications have flow rate ranges well within these extremes.

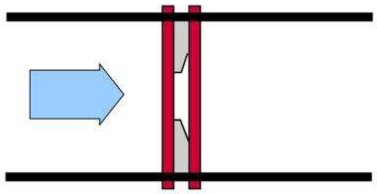
Velocity flowmeters include electromagnetic, vortex, Swirl, turbine, and ultrasonic types, as indicated in the diagrams at right and on the next page.

Inferential flowmeters

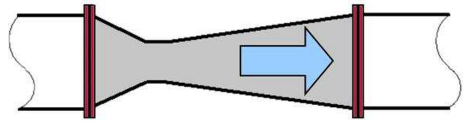
An inferential flowmeter calculates flow rates based on a

Flowmeters based on differential pressure measurements

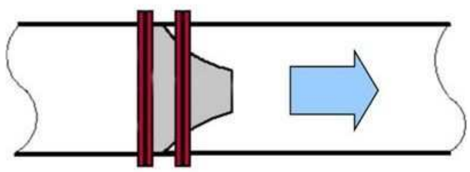
Orifice plates--These are the most common DP element in the processing industries. Their flow characteristics are well documented in the literature. They're inexpensive and available in a variety of materials. The rangeability, however, is less than 5:1, and accuracy is moderate -- 2 to 4 percent of full scale. Maintenance of good accuracy requires a sharp edge to the upstream side, which degrades with wear. Pressure loss is high relative to other DP elements.



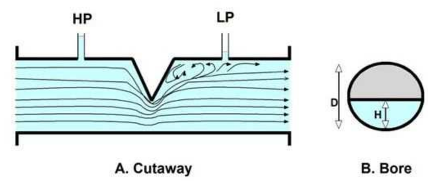
Venturi meter--Characterized by a gradual tapered restriction on inlet and outlet, this element has high discharge coefficients near the ideal of 1. Pressure loss is minimal. It finds use primarily in water and wastewater applications and has limited acceptance in the processing industries. Rangeability of about 6:1 is better than orifice plates. Performance characteristics are well documented.



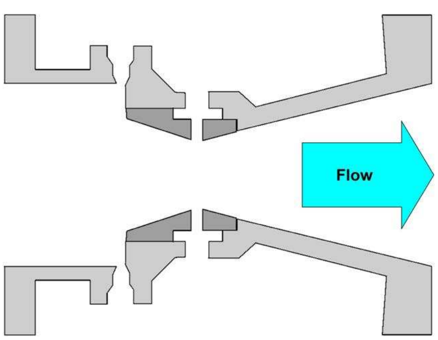
Nozzles--These elements mimic the properties of the Venturi. They come in three standard, documented types: ISA 1932 nozzle, common outside of the U.S.; the long radius nozzle; and Venturi nozzle, which combines aspects of the other two



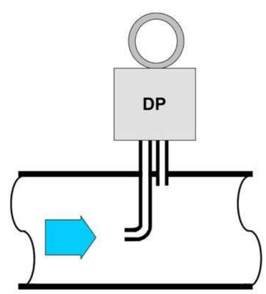
Wedge--This element consists of a V-shaped restriction molded into the top of the meter body. This basic meter has been on the market for more than 40 years, demonstrating its ability to handle tough, dirty fluids. The slanted faces of the wedge provide self-scouring action and minimize damage from impact with secondary phases. Wedge meter rangeability of 8:1 is relatively high for a DP element. Accuracies are possible to ± 0.5 percent of full scale.



Flow tubes--The ASME defines flow tubes as any DP element whose design differs from the classic Venturi, which includes short-form Venturies, nozzles, and wedges. Flow tubes come in several proprietary shapes, but all tend to be more compact than the classic and short-form Venturies. Being proprietary, flow tubes vary in configuration, tap locations, differential pressure, and pressure loss for a given flow. Their manufacturers must supply test data for flow tube.



Pitot tubes--These are low-cost DP elements used to measure fluid flow, especially air flow in ventilation and HVAC systems. They work by converting the kinetic energy of the flow velocity into potential energy (pressure). Engineers can easily insert pitot tubes into existing piping, minimizing installation costs. One type makes a measurement at a point within the pipeline or ductwork, requiring knowledge of the flow profile. Another, photo, contains multiple orifices, providing an averaging effect.



non-flow measurement that has widely accepted correlations to rate of flow.

Differential pressure--Most of these flow measurement devices depend on three principles. First, despite the restriction in a pipe, the overall flowrate remains the same, which pertains to the continuity equation. Second, Bernoulli's Law says the fluid flow velocity (kinetic energy) through the restriction must increase. Third, the law of conservation of energy says the increased kinetic energy comes at the expense of fluid pressure (potential energy). The unrecoverable pressure drop across the restriction is a function of the fluid velocity, which can be calculated. Variables in the calculation of flow rate for differential flowmeters include:

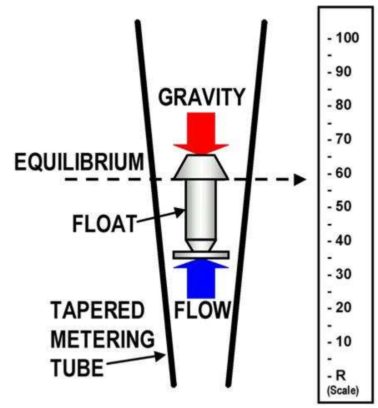
- the square root of the measured differential pressure
- the fluid density,
- pipe cross sectional area
- area through the restriction
- a coefficient that's specific to the device.

When a fluid passes through a restriction in a pipe it does not follow the contour of restriction perfectly. It produces a “jet” stream that's narrower than the restrictive bore. The smaller jet diameter results in a faster stream velocity through the restriction, resulting in higher pressure loss than if the fluid perfectly followed the contour of the bore. Calculated flow rates from measured pressure drop and a known restriction bore diameter would tend to overstate the fluid flow rate. So the rate must be corrected downward from the ideal discharge coefficient of 1. The overall flow coefficient applied to the basic equation is often specific to both the device and the application, and depends on additional factors involving gas expansion and velocity of approach. This coefficient (K factor) can range from 0.6 to 0.98 for DP flowmeters.

Flowmeters based on differential pressure represent a popular choice in the processing industries, constituting nearly 30 percent of installations. They have good application flexibility since they can measure liquid, gas, and steam flows and are suitable for extreme temperatures and pressures with moderate pressure losses. These losses depend on restriction size and type (orifice; wedge; pitot; Venturi, etc) and can be quite high and permanent given a low enough Beta ratio. (Beta ratio is the diameter of the restrictive orifice divided by the pipe diameter). Accuracy ranges from 1 percent to 5 percent. Compensation techniques can improve accuracy to 0.5 percent to 1.5 percent.

On the other hand restrictive flowmeter piping elements are relatively expensive to install. Their dependence on the square root of differential pressure can severely diminish rangeability. Additionally they require an instrument to measure differential pressure and compute a standard flow signal. Changes in temperature, pressure, and viscosity can significantly affect accuracy of DP flowmeters. And while they have no moving parts, maintenance can be intensive.

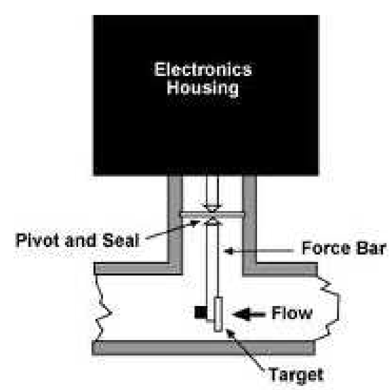
Variable area meters



Often called rotameters, these are another kind of inferential flowmeter. Simple and inexpensive, these devices provide practical flow measurement solutions for many applications. They basically consist of two components: a tapered metering tube and a float that rides within the tube. The float position, a balance of upward flow and float weight, is a linear function of flow rate. Operators can take direct readings based on the float position with transparent glass and plastic tubes. Rotameters having metal tubes include a magnetically coupled pointer to indicate float position.

Rotameters are easy to install and maintain, but must be mounted perfectly vertical. Accuracy (± 2 percent of full scale) is relatively low and depends on precise knowledge of the fluid and process. They're also susceptible to vibration and plugging by solids. They apply primarily to flow rates below 200 gpm and pipe sizes less than 3 inches.

Target meters



These flowmeters insert a physical target within the fluid flow. The moving fluid deflects a force bar attached to the target. The deflection depends on the target area, as well as the fluid density and velocity. Target meters measure flows in line sizes above 0.5 inches. By changing the target size and material, engineers can adapt them to different fluids and flow rate ranges. In most cases their calibration must be verified in the field. Target meters are relatively uncommon. They're found primarily on water, steam applications and on wet gases.

Positive displacement flowmeters

These are true volumetric flow devices, measuring the actual fluid volume that passes through a meter body with no concern for velocity.

Accordingly, fluid velocity, pipe internal diameters, and flow profiles are not a concern. Volume flow rate is not calculated but rather measured directly. These flowmeters capture a specific volume of fluid and pass it to the outlet. The fluid pressure moves the mechanism that empties one chamber as another fills. Residential gas meters are a common example. Counting the cycles of rotational or linear motion provides a measure of the displaced fluid. A transmitter converts the counts to true volumetric flow rate. Some examples include:

- Single or multiple reciprocating piston meters.
- Oval-gear meters with synchronized, close fitting teeth.
- Movable nutating disks mounted on a concentric sphere located in spherical side-walled chambers.
- Rotary vanes creating two or more compartments and sealed against the meter's housing.

Engineers can apply these flowmeters to a wide range of non-abrasive fluids, including high-viscosity fluids. Examples include heating oils, lubrication oils, polymer additives, and ink. Accuracy may be up to +/- 0.1 percent of full scale with a rangeability of 70:1 or better. They require no power and can handle high pressures.

Positive displacement flowmeters cannot handle solids, entrapped air in liquids, or entrained liquids in gases. They are expensive to install and maintain, having many moving parts. Pressure drop across the meters is high.

Direct measurement of mass flow rates

In the processing industries two kinds of flowmeters directly measure mass rates of fluid flow: Coriolis flowmeters for liquids and gases and thermal flowmeters for gases. Chemical processes are generally concerned more with rates of mass flow because reactions within the plant depend on mass rather than volume ratios.

Coriolis flowmeters--In the early 1800s Gustave-Gaspard Coriolis, a French engineer and mathematician, discovered and described Coriolis forces. These forces come into play on rotating (or oscillating) bodies. Since the earth is a rotating body, Coriolis forces

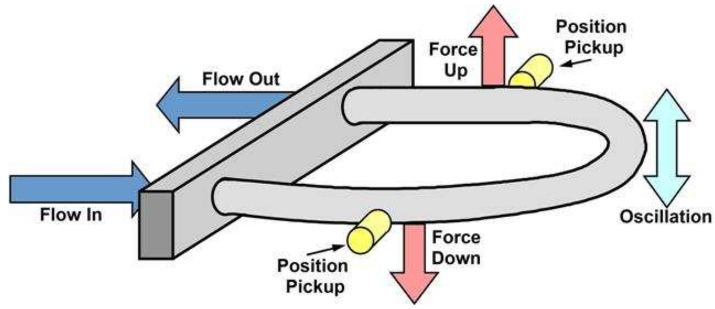


Figure 3. With flow, Coriolis forces twist the oscillating tube. The amount of twist is proportional to the mass flow.

affect the weather, ballistics, and oceanography.

To get an understanding of this principle, suppose you stood very near the north pole of the earth. The rotational distance you would travel over 24 hours would be relatively small. But as you walked toward the equator, you would gain rotational speed. At the equator your rotational distance traveled in 24 hours would be about 25,000 miles, amounting to a rotational speed of more than 1000 miles per hour. Obviously, while walking away from the rotational axis, you would be experiencing acceleration. Any acceleration requires a force--in this case the Coriolis force. Physics tells us that force equals mass times acceleration. So the force developed is proportional to mass.

Commercial Coriolis flowmeters are a relatively recent innovation, having emerged in the mid to late 70s. Steady technical improvements since then have greatly increased their acceptance in the process industries.

No other flow device is more versatile and capable. Aside from measuring mass flow rates, Coriolis flowmeters can provide simultaneous outputs for volumetric flow rate, total flow, density, temperature, and percent concentration. These meters are unaffected by flow profiles or viscosity, so they don't require long runs of straight pipe upstream and downstream. The fluid flow can be turbulent, laminar, or anything in between. The fluid can be viscous or freely flowing. Additionally, mass is not affected by changes in temperature or pressure. Accuracies can be as high as +/- 0.05% of rate.

Purchase prices are relatively high but falling as these meters become more popular. Pressure drop through the meters is relatively high because of circuitous tube geometries, and, typically, its separation into two tubes. Available sizes are up to 12 inch. Entrained gases can be problematical, so control valves should be downstream to keep pressure on the meter to prevent emergence of gas bubbles. Coriolis flowmeters are somewhat sensitive to vibration, but this can often by overcome by harmonic studies and sophisticated signal processing.

Since rotating flow tubes are impractical, Coriolis flowmeters resort to oscillation. Usually a single tube or dual tubes oscillating 180 degrees out of phase take the fluid away from the axis of oscillation and back again. The Coriolis forces developed within the fluid push against the elastic tubes, twisting them. Strategically mounted magnetic pickup coils measure the degree of tube twist or distortion, which corresponds to the mass flow rate. At zero flow rate no Coriolis forces are developed, so the tubes retain their normal shape. With flow, signals from the pickoff coils experience a difference in phase that's proportional to the mass flow rate.

Figure 4. Coriolis flow tubes come in a variety of shapes, depending on the manufacturer. Above is the S-shape of ABB's Coriolis flowmeter.

In short, a Coriolis flowmeter comprises the following parts:
- flow tube or tubes that take the fluid away from and back toward the axis of oscillation
- a flow splitter to divert the fluid into two flow tubes
- a drive coil to oscillate the flow tubes at their natural (resonant) frequency
- pickoff coils that measure the distortion of the tubes
- a resistance thermometer (RTD) to measure tube temperature, which can affect the elasticity of the tubes and thus their degree of twisting.

The resonant frequency developed by the drive coil depends on the mass that's oscillating. Since the tube mass and volume are constant, this frequency is also a measure of the fluid's density. Measurement of fluid density is a bonus provided by Coriolis flowmeters.

Applications in the chemical industry for Coriolis flowmeters include:
- custody transfer
- critical process control
- filling and dosing
- reactor charging
- blending
- loading and unloading.

Their accuracy makes Coriolis flowmeters obvious candidates for custody transfer. The capability for a single flowmeter to measure a variety of different fluids suggests applications such as batch operations and tanker truck loading/unloading. For anything sold by weight, they can replace load cells for filling and dosing. They're good candidates for material balances and blending by weight.

Thermal mass flow meters--Introducing heat into fluids (mostly gases) offers a way to measure their mass flow rates. The heat dissipated by the flow stream, using temperature sensors, is a measure the mass flow rate. Thermal mass flowmeters have no moving parts, are easy to install, and provide a relatively unobstructed flow path, Since they're measuring mass, temperature and pressure corrections are unnecessary. They are accurate over a wide range of gaseous flow rates. But because they essentially measure flow at a point within the gas stream, they require some flow conditioning or knowledge of the flow profile.

Figure 5. Thermal mass flowmeters introduce heat into the flow and measure its dissipation. They measure at a point within the gas stream.

Manufacturers of thermal mass flowmeters use two different methods to measure heat dissipation. Both depend on the principle that higher mass flow rates have a greater cooling effect on the sensors.

- Constant temperature differential--This technique uses a heated sensor (generally a resistance temperature detector) upstream from another RTD that measures gas temperature. The electrical power needed to maintain the same temperature difference between the heated and unheated sensor is a function of the mass flow.

- Constant current--Here the electrical current to heat the upstream sensor is kept constant. The downstream sensor measures the heat gain. In this case mass flow is a function of the temperature difference between the two sensors.

Applications include boiler control, biogas measurements, compressed air accounting, pharmaceuticals, pneumatics, and the food and beverage industries.

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WP_FLOWMETER_SELECTION_02-2012

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