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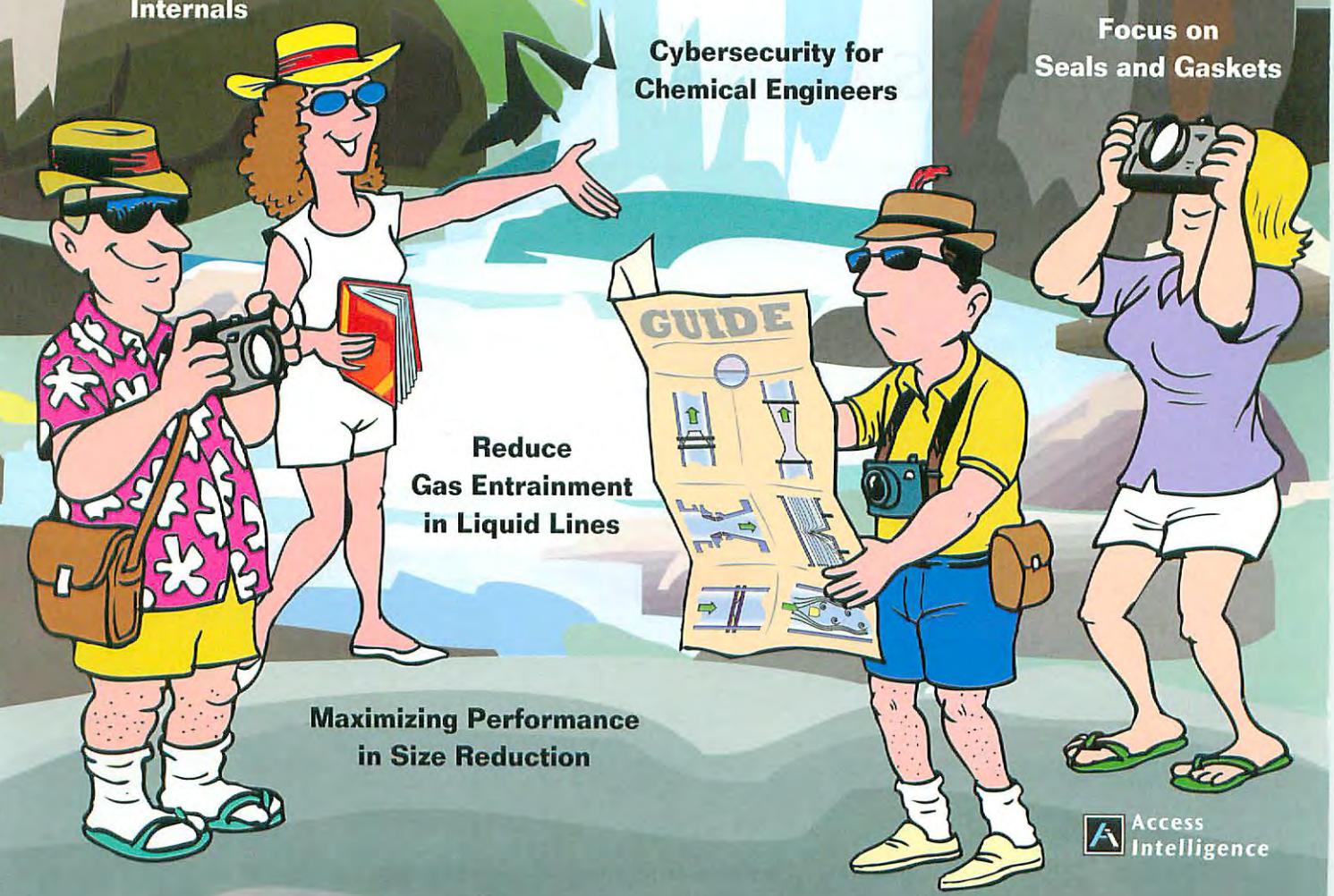


Access Intelligence

Measuring Flow

Understanding how flowmeters work and the pros and cons of each type of device can help in selecting the right one

Ron DiGiacomo
ABB Measurement Products

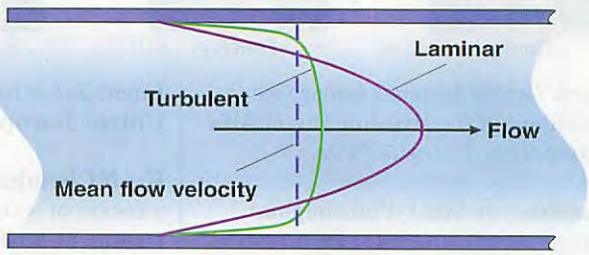


FIGURE 1. In specifying velocity meters, it is important to know if the flow profile of velocities is turbulent or laminar

One of the most important measurements in the chemical process industries (CPI) is rate of flow. Flowrates can be important to measure, and in fact can be critical to measure, throughout a process — from dosing components into a reactor to material transfers in-between process steps, to discharging products at the end. Flow metering technologies fall into four classifications: velocity, inferential, positive displacement and mass. This article summarizes the considerations in selecting and applying these different types of flowmeters, and provides examples 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 flowrates. For example, if the average fluid velocity is 2.5 ft/sec and the inside diameter of the pipe or flowmeter is 12 in. (0.79 ft^2 area), the volumetric flowrate equals 1.98 ft^3/s (2.5 × 0.79) or about 14.8 gal/s.

Laminar and turbulent flow profiles. When specifying velocity meters, chemical engineers must be concerned with the fluid's velocity profile in the pipe, and this profile depends on piping geometry and Reynolds number. Assuming there are sufficient straight-piping runs, the cross-sectional view shown in Figure 1 illustrates two flow-profile situations: turbulent and laminar.

In cases of relatively little piping-friction loss and low fluid viscosity, the flow profile of velocities is uniform across the entire cross-section of the pipe — this is 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 flowrates in this flow regime is relatively easy, as noted above.

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 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 flowrate.

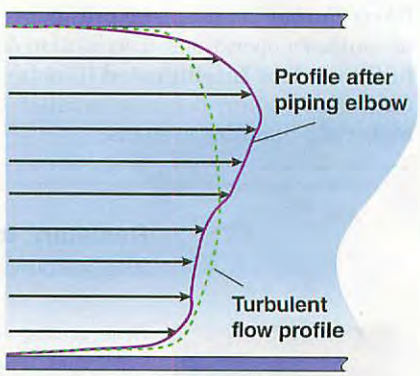
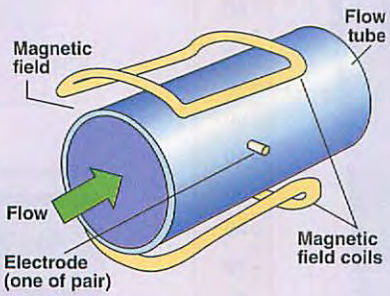


FIGURE 2. Pipe fittings such as elbows, tees and valves will distort the flow profile within a pipe

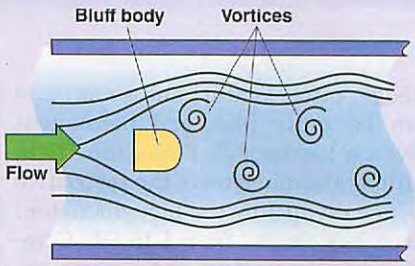
Pipe geometry plays a role. Manufacturers will specify the length of straight pipe upstream and downstream of a velocity flowmeter for achieving high accuracies. But often plant piping geometries in a chemical plant will be such that sufficiently long straight pipe runs are not feasible. The flowmeter 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 a distorted profile, such as in the example shown in Figure 2. Various flow straightening devices installed upstream of the flowmeter can help correct these distortions by

A SAMPLING OF VELOCITY FLOWMETERS AND THEIR PRINCIPLE OF OPERATION

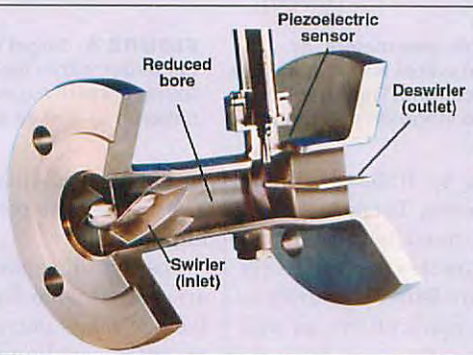
Electromagnetic flowmeters subject conductive liquids to alternating or pulsating direct-current magnetic fields. Electrodes on either side of the pipe wall pick up the induced voltage following Faraday's law, which is proportional to fluid velocity.



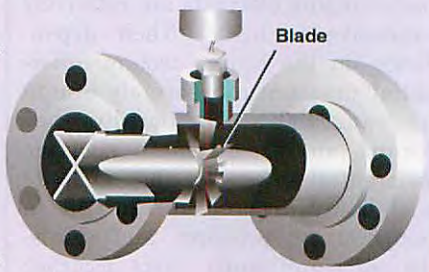
Vortex meters place a bluff obstacle in the flow stream, which creates vortices or eddies whose frequency is proportional to flow velocity. Sensors detect and count the pressure variations produced over a fixed time.



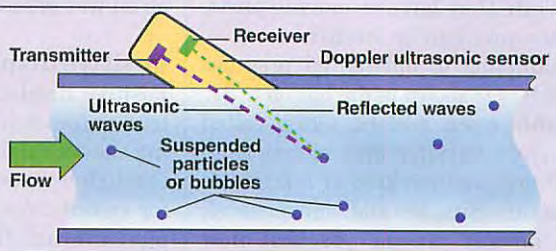
Swirl meters are similar to vortex meters, except vanes at the inlet swirl the flow, creating the pressure variations. Straightening vanes at the outlet de-swirl the flow.



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.



creating uniform flow profiles, and thereby permitting average velocity to be inferred. (Straightening vanes are engineered, bundled tubes that are installed upstream of a meter in order to ensure a more uniform flow profile.)

The most practical, liquid pipeline flowrates in the CPI range from 0.5 to 12 ft/s, 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/s, a turndown range of about 13:1. Many actual applications have flowrate ranges well within these extremes.

A sampling of velocity flowmeters and their principles of operation are given in the box above.

Inferential flowmeters

An inferential flowmeter calculates flowrates based on a 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, with or without 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 pressure drop across the restriction is a function of the fluid velocity, which can be calculated. Variables in the calculation of flowrate for differential flowmeters include the following:

- The square root of the measured differential pressure
- Fluid density
- Pipe cross-sectional area
- Area through the restriction
- A coefficient specific to the application, which includes 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. Consequently, calculated flowrates from measured pressure drop and a known restriction bore diameter would tend to overstate the fluid flowrate. Therefore the rate must be corrected downward from the ideal discharge coefficient, which is equal to one. 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 differential pressure flowmeters.

Flowmeters based on differential pressure represent a popular choice in the CPI, constituting nearly 30% 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,

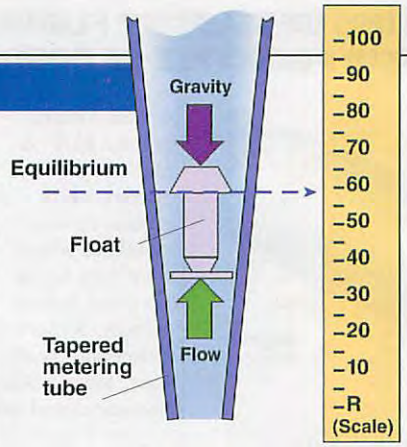


FIGURE 3. Variable area meters, or rotameters, are a practical way to measure flow in many applications. They are, however, susceptible to vibration and plugging

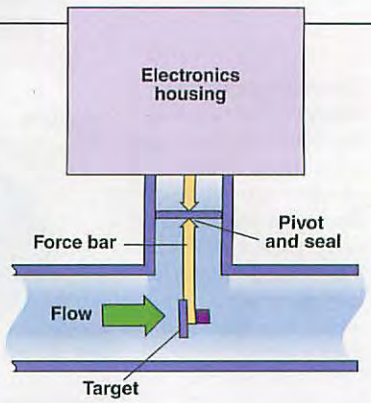


FIGURE 4. Target meters insert a physical target within the fluid flow. They are found primarily in water and steam applications, as well as on wet gases

wedge, pitot, Venturi and so on) 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 to 5%. Compensation techniques can improve accuracy to 0.5–1.5 %.

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 differential pressure flowmeters. And while they have no moving parts, maintenance can be intensive.

A sampling of differential pressure flowmeters is shown in the box on p. 33.

Variable area meters. Often called rotameters, variable area meters (Figure 3) 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 flowrate. Operators can take direct readings based on the float position with transparent glass and plastic tubes. Rotameters with 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% 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 flowrates below 200 gal/min and pipe sizes less than 3 in.

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 in. By changing the target size and material, engineers can adapt them to different fluids and flowrate ranges. In most cases, their calibration must be verified in the field. Target meters are relatively uncommon and are found primarily in water and steam applications, as well as on wet gases.

Positive displacement meters

Positive displacement flowmeters 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 flowrate 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 flowrate. Some examples include the following:

- 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% of full scale with a rangeability of 70:1 or better. They require no power and can handle high pressures.

Positive displacement flowmeters are not suitable for applications that include solids, entrapped air in liquids or entrained liquids in gases. They are expensive to install and maintain, having many moving parts. The pressure drop across these meters is high.

Direct mass flow measurement

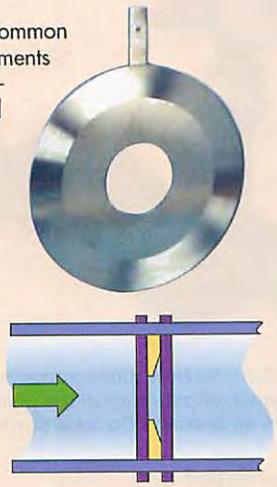
In the CPI, two kinds of flowmeters directly measure mass rates of fluid flow: Coriolis flowmeters for liquids and gases; and thermal flowmeters for gases. Chemical processes are generally concerned more with rates of mass flow because reactions within the plant depend on mass rather than volume ratios.

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 affect the weather, ballistics and oceanography.

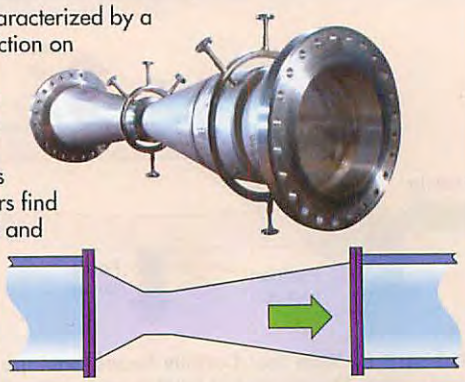
To get an understanding of this principle, suppose you stood very near the north pole of the earth. The rotational distance you would travel over 24 hours would be relatively small. But as you walked toward the equator, you would gain rotational speed. At the equator your rotational distance traveled in 24 hours would be about 25,000 miles, amounting to a rotational speed of more than 1,000 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

FLOWMETER ELEMENTS BASED ON DIFFERENTIAL PRESSURE MEASUREMENTS

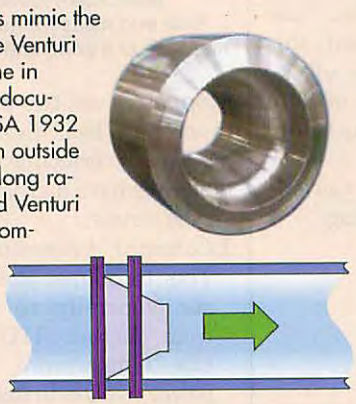
Orifice plates are the most common differential pressure (DP) elements in the CPI. Their flow characteristics are well documented in the literature. They're inexpensive and available in a variety of materials. The rangeability, however, is less than 5:1, and accuracy is moderate at 2–4% of full scale. 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.



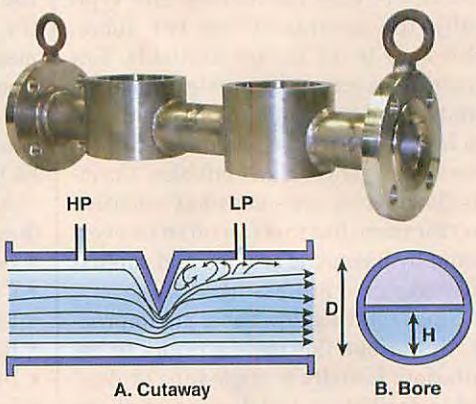
Venturi meters are characterized by a gradual tapered restriction on the inlet and outlet. This element has high discharge coefficients near the ideal value of one. Pressure loss is minimal. Venturi meters find use primarily in water and wastewater applications and have limited acceptance elsewhere in the CPI. The rangeability of about 6:1 is better than orifice plates. Performance characteristics are well documented.



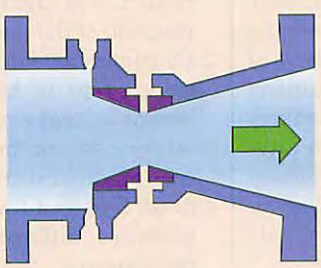
Nozzle elements mimic the properties of the Venturi meter. They come in three standard, documented types: ISA 1932 nozzle, common outside of the U.S.; the long radius nozzle; and Venturi nozzle, which combines aspects of the other two.



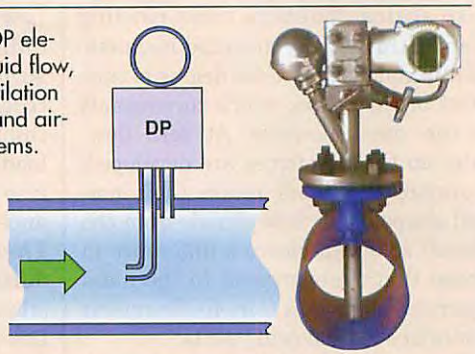
Wedge elements consist of a V-shaped restriction molded into the top of the meter body. This basic meter has been on the market for more than 40 years, demonstrating its ability to handle tough, dirty fluids. The slanted faces of the wedge provide self-scouring action and minimize damage from impact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



Flow tubes are defined by the American Society of Mechanical Engineers (ASME) 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. With proprietary designs, flow tubes vary in configuration, tap locations, differential pressure and pressure loss for a given flow. Manufacturers must supply test data for flow tubes.



Pitot tubes are low-cost DP elements used to measure fluid flow, especially air flow in ventilation and heating, ventilating and air-conditioning (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, as shown in the photo, contains multiple orifices, providing an averaging effect.



tells us that force equals mass times acceleration. So the force developed is proportional to mass.

Commercial Coriolis flowmeters (Figures 5 and 6) are a relatively recent innovation, having emerged in the mid to late 1970s. Steady technical improvements since then have greatly increased their acceptance in the CPI. No other flow device is more versatile and capable. Aside from measuring mass flowrates, Coriolis flowmeters can provide simultaneous outputs for volumetric flowrate, total flow, density, temperature and percent concentration. These meters are unaffected by flow profiles and 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 free flowing. Additionally, mass is not affected by changes in temperature or pressure. Accuracies can be as high as ±0.05% of rate.

Purchase prices for Coriolis meters are relatively high, but they are decreasing as these meters become more popular. Pressure drop through these

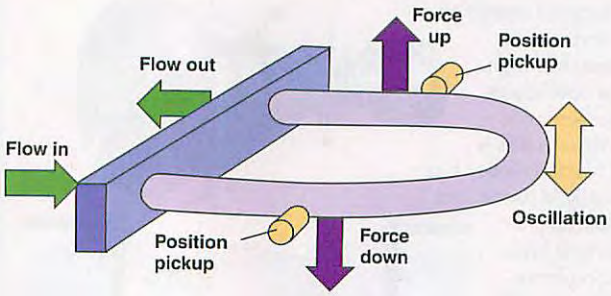


FIGURE 5. With flow, Coriolis forces twist the oscillating tube. The amount of twist is proportional to the mass flowrate

FIGURE 6. Coriolis flow tubes come in a variety of shapes, depending on the manufacturer. Above is an S-shape Coriolis flowmeter

meters is relatively high because of circuitous tube geometries, and typically, the separation into two tubes. Sizes up to 12 in. are available. 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 be 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 deg. 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 flowrate. At zero flowrate, no Coriolis forces are developed, therefore the tubes retain their normal shape. With flow, signals from the pickoff coils experience a difference in phase that's proportional to the mass flowrate. 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 temperature detector (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 is 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 CPI for Coriolis flowmeters include the following:

- 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 and unloading. For anything sold by weight, they can replace load cells for filling and dosing. They're also good candidates for material balances and blending by weight.

Thermal mass flowmeters. Introducing heat into fluids (mostly gases) offers a way to measure their mass flowrates. The heat dissipated by the flow stream — measured by temperature sensors — is a measure of the mass flowrate. Thermal mass flowmeters (Figure 7) have no moving parts, are easy to install, and provide a relatively unobstructed flow path. Since they are measuring mass, corrections for temperature and pressure are unnecessary. They are accurate over a wide range of gaseous flowrates. But because they essentially measure flow at a point within the gas stream, they require some flow conditioning or knowledge of the flow profile.

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

1. *Constant temperature differential*: This technique uses a heated sensor (generally an RTD) 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.
2. *Constant current*: Here the electrical current to heat the upstream sensor is kept constant. The downstream sensor measures the process temperature. In this case mass flow is a function of the temperature difference between the two sensors.

Applications for thermal mass flowmeters include boiler control, biogas measurements, compressed air accounting, pharmaceuticals, pneumatics, and applications in the food-and-beverage industries. ■

Edited by Dorothy Lozowski

FIGURE 7. Thermal mass flowmeters introduce heat into the flow and measure its dissipation. They measure at a point within the gas stream

Author

Ronald W. DiGiacomo manages business development for flow technologies in North America for ABB Inc. (125 E. County Line Rd., Warminster, PA 18974; Phone: 215-589-4350; Email: ron.w.digiacomo@us.abb.com). He has 25 years of experience in process instrumentation and control, primarily in flow measurement. Previously, he spent 15 years with two Emerson divisions and five years with Invensys companies.