A Review of Flowmeters for Water Applications

By Ron DiGiacomo

Summarizing the considerations in selecting and applying flowmeters with examples of the kinds of flowmeters in each category.

A critical measurement in the water and processing industries is rate of flow. Flow metering technologies tend to 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 1 m/sec and the inside diameter of the pipe or flowmeter is 30 cm (0.071 m^2 area), the volumetric flow rate equals (1 m/sec x 0.071 m^2) or 0.071 m^3/sec or about 18.8 gal/sec.

When specifying velocity meters, water engineers must be concerned with the fluid's velocity profile in the pipe, which depends on piping geometry and Reynolds number. Assuming sufficient straight piping runs, which ensures a fully developed flow profile, the cross-sectional view shown in Figure 1 illustrates two flow profile situations: turbulent (red) and laminar (blue).

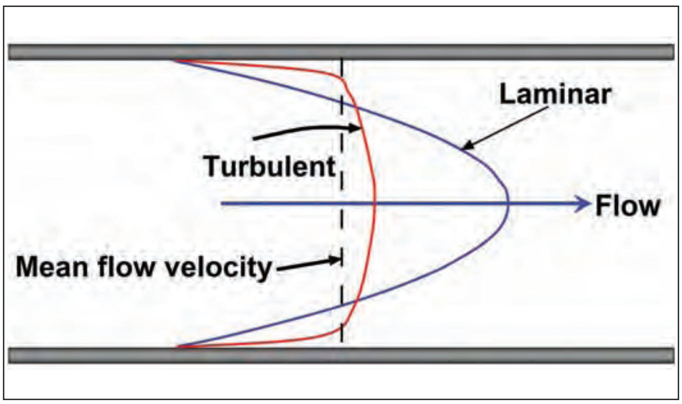

Figure 1: Flow Velocity Meters Work Best on Flows with Turbulent Profiles (Red Line).

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. Velocity flowmeters work best under conditions of turbulent flow. Otherwise different flow velocities occur throughout the pipe's cross section, and the above calculation for flow rate lends itself to more inaccuracy.

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 water system 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 such cases, the flow will not be fully developed and result in a distorted profile - one example shown in Figure 2. Various flow straightening devices (e.g. engineered, bundled tubes) installed upstream of the flowmeter can help correct these distortions by creating uniform flow profiles, permitting average velocity to be more easily inferred.

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The most practical liquid pipeline flow rates range from 0.15 to 3.5 m/sec (about 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). A sampling of velocity flowmeters for water and their principle of operation would include:

- Electromagnetic flowmeters subject conductive liquids to alternating

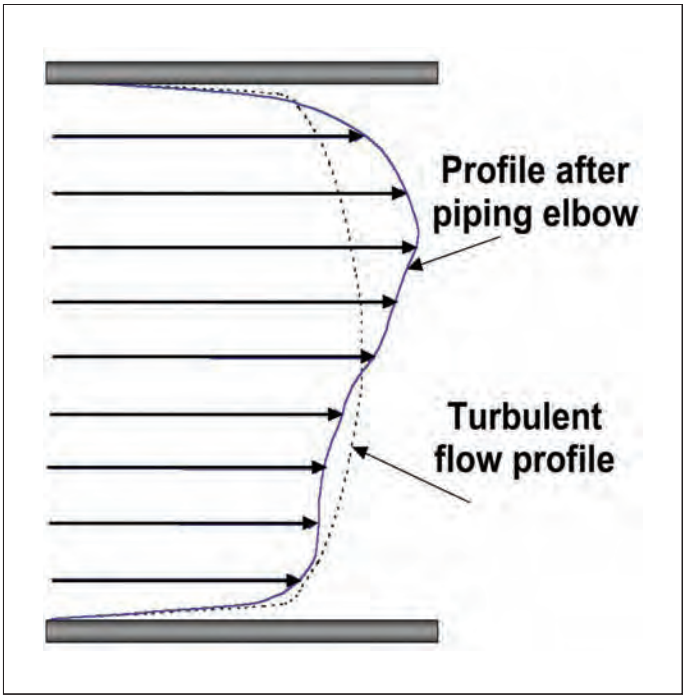

Figure 2: Pipe Fittings Near the Flowmeter can Distort the Flow Profile, Requiring Straightening Devices.

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 use 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 fixed (non-moving) 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 having vanes. 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.

Inferential Flowmeters

An inferential flowmeter calculates flow rates 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, despite the restriction in a pipe, the overall flow rate 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

Calculated flow rates from measured pressure drop and a known restriction bore diameter 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. 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 many 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, 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

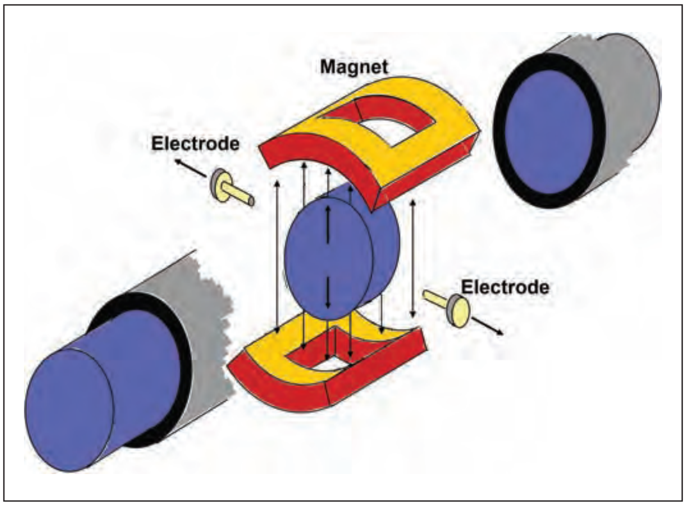

Figure 3: Magmeter

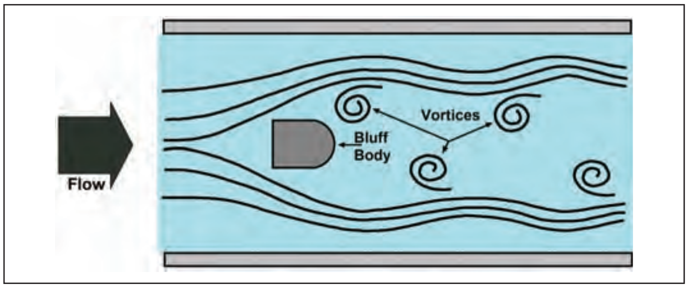

Figure 4: Vortex

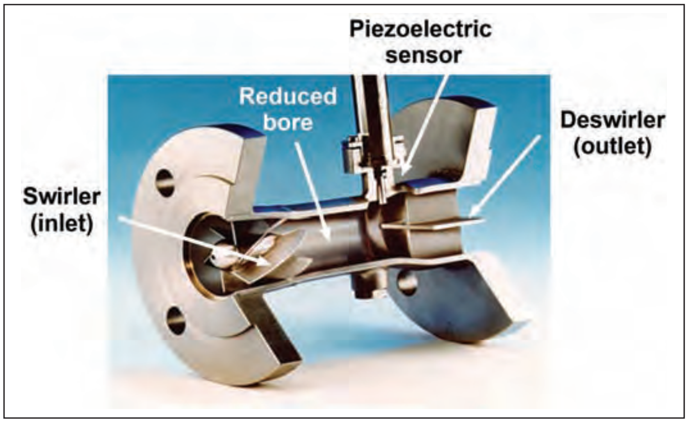

Figure 5: Swirl Cutaway

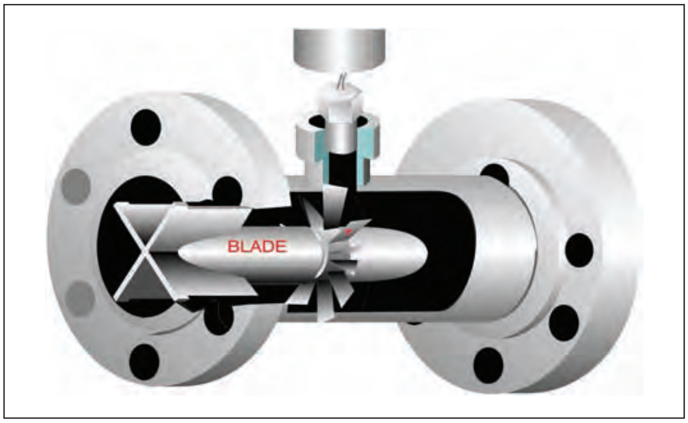

Figure 6: Turbine

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 diminish rangeability. They also require an instrument or transmitter to measure differential pressure and compute a standard flow signal (ABB recently announced an extended family of one-piece DP flowmeters that include the display and/or transmitter).

Flowmeter restrictive elements for differential pressure measurements include:

- **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. 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; 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. The wedge can handle with Reynolds numbers as low as 500. Accuracies are possible to ± 0.5 percent of full scale.
- **Flow Tubes:** These 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 calibration data and information.

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 and can include a transmitter to send the signal to a remote location.

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

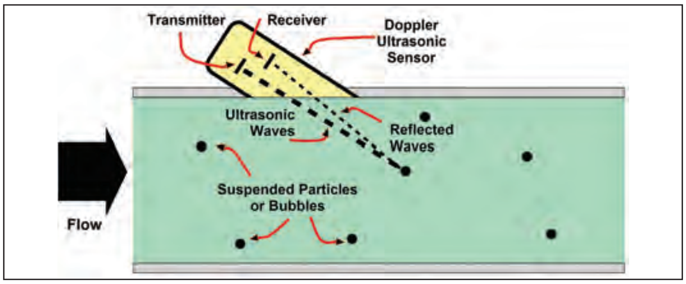

Figure 7: Ultrasonic

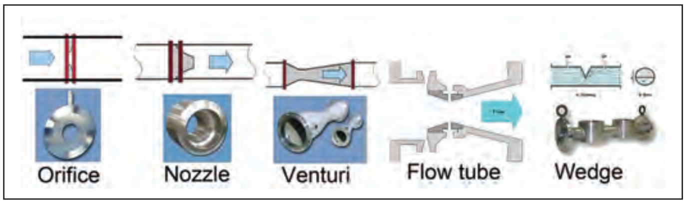

Figure 8: DP Composite

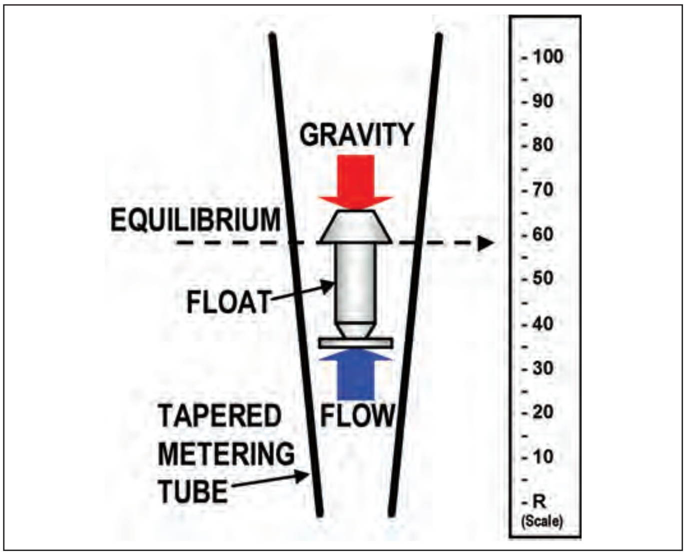

Figure 9: Rotameter

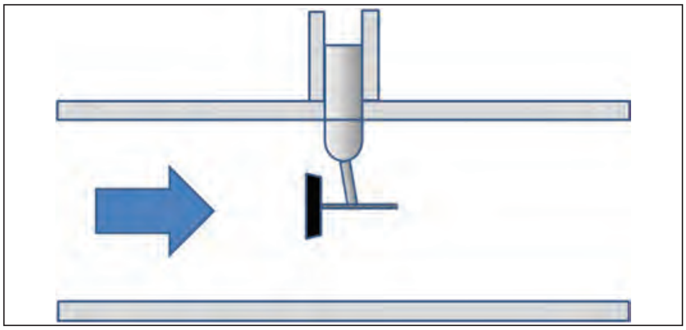

Figure 10: Target

vibration and plugging by solids.

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 12 mm (about 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.

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. 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. 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 don't work well with solids, entrapped air in liquids, or entrained liquids in gases. They are expensive to install and maintain, having many moving parts. Pressure drop

Figure 11: Recently Announced ABB CoriolisMaster Flowmeters

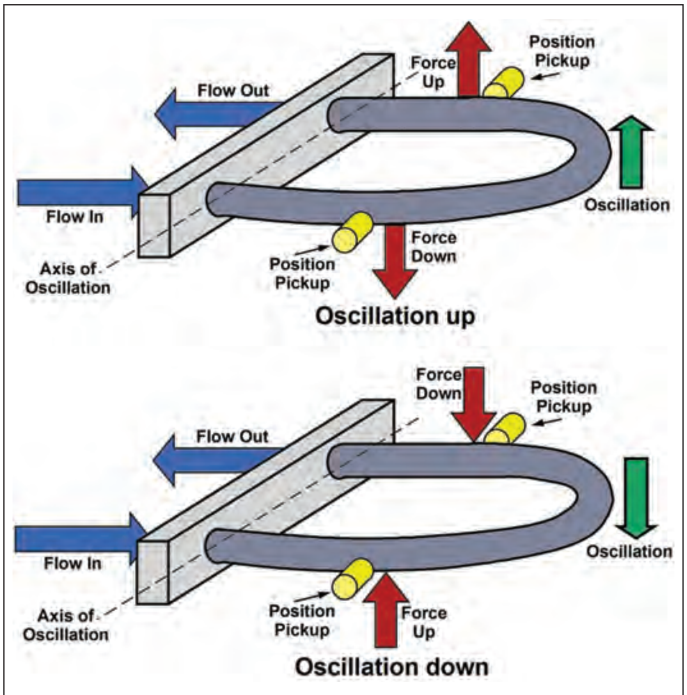

Figure 12: Principle of Operation for Coriolis Flowmeters

across the meters is high.

Direct Measurement of Mass Flow Rates

For liquids, the primary flowmeter for directly measuring mass rates is the Coriolis flowmeter. 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.

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 orientation or 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 can be relatively high because of circuitous tube geometries, and, typically, its separation into two tubes (unless the tubes have an overall ID larger than the pipe.) 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 first one way, then the other. 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.

In short, a Coriolis flowmeter typically 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, as mentioned earlier. Their accuracy makes Coriolis flowmeters obvious candidates for custody transfer.

About the Contributor

Ronald W. Digiacomo manages business development for flow technologies in North America for ABB Inc. He has more than 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.

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