Coriolis: The Direct Approach to Mass Flow Measurement

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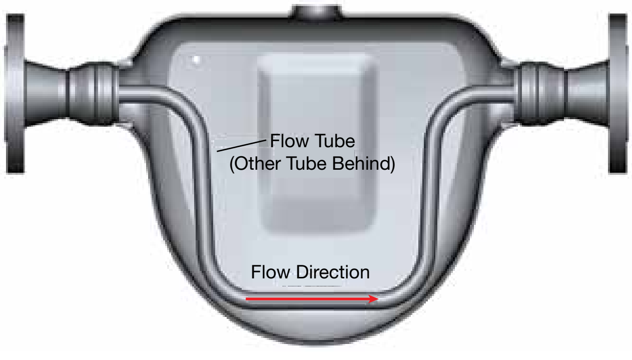
Coriolis meters eliminate the need to measure and correct for pressure, temperature, and density fluctuations to determine mass flowrate. Although their capital costs may be higher, they typically have a lower overall cost of ownership than other types of meters.

Industry faces unrelenting pressure to increase production from existing facilities. Greater process throughput, quality, profitability, and safety are desired. Coriolis meters, which directly measure both mass flow and density, provide the accurate measurements that are necessary to meet these demands.

Chemical processes, and the formulas that govern them, are based on the mass of the reactants. Likewise, many bulk materials are bought and sold by mass, which is unaffected by changes in process conditions or fluid properties. However, many instruments measure in units of volumetric flow, then correct for temperature, pressure, and density conditions to derive the mass flowrate. In addition, most traditional technologies require straight runs of piping upstream and downstream of the instrument, as swirl and asymmetrical flow profile reduce the accuracy of the velocity measurement. This tends to complicate their installation.

Measuring mass flow directly is usually more accurate, and does not require simultaneous measurement of multiple variables. In addition, Coriolis mass flowmeters do not have to be recalibrated to handle different fluids or when process conditions change. And, composition changes in product streams will not affect their accuracy.

This article explains how a Coriolis flowmeter works, its advantages and limitations, where it is best applied and where it is not appropriate, and how to select Coriolis meters.



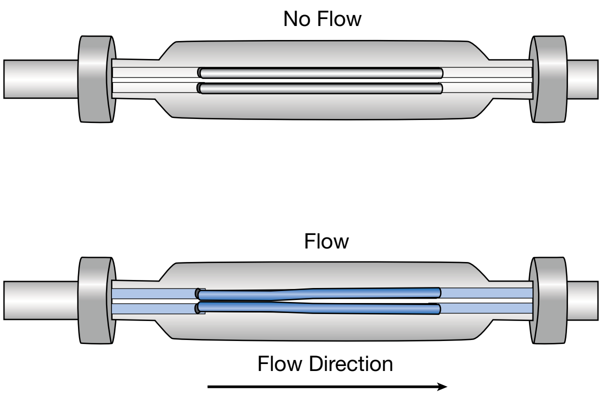
▲ **Figure 1.** A basic Coriolis meter has two curved tubes (only one is visible here) through which the flow passes, with an electromagnetic driver in the middle and motion sensors on each side.

How a Coriolis meter measures mass flow and density

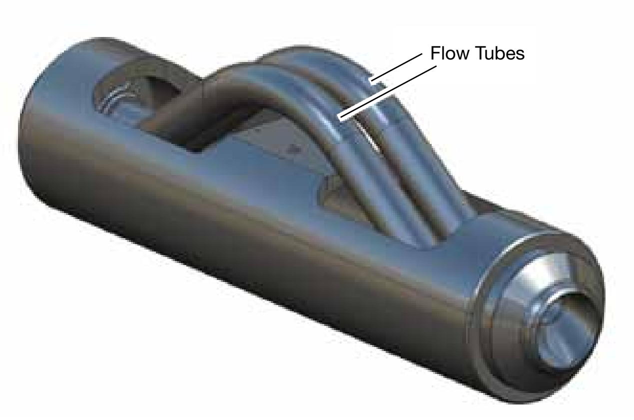
In a Coriolis meter, the material to be measured passes through one or more oscillating tubes; the rate at which mass flows affects the oscillation of the tubes, and from this both mass flow and density can be determined.

A basic dual-tube Coriolis meter (Figure 1) contains two curved tubes through which the flow passes. An electromagnetic drive system causes the tubes to vibrate toward and away from each other at their resonant frequency like the tines of a tuning fork; the frequency is determined by the tubes' stiffness and their mass. A pair of electromagnetic sensors (called pickoff sensors) detects the vibrations at points on each side of the drive unit.

If there is no fluid flowing through the tubes, they simply vibrate toward and away from each other in parallel (Figure 2, top), and the outputs of the upstream and downstream motion sensors are in phase. But as material flows through the tubes, the Coriolis effect causes the downstream side of the loop to slightly lead the upstream side, which creates a slight twist in the loops of tubing (Figure 2, bottom). The amount of twist (which is exaggerated in the figure for illustration purposes), and hence the phase difference between the outputs of the upstream and downstream pickoff sensors, varies linearly with the rate at which mass is flowing through the tubes. Phase is converted to time, and time delay is directly proportional to mass flowrate. This principle applies regardless of whether the fluid is a liquid, gas, or slurry.



▲ **Figure 2.** In the meter on the top (viewed from the side), there is no flow through the tubes, so they vibrate toward and away from each other in phase. As material flows through the tubes of the meter on the bottom, the Coriolis effect causes the upstream side of the loop to fall slightly behind the downstream side, which the motion sensors detect as a time shift. (The deflection shown here has been exaggerated for illustration purposes.)



▲ **Figure 3.** Smaller Coriolis meters with slightly curved tubes are suitable for use in cramped areas.

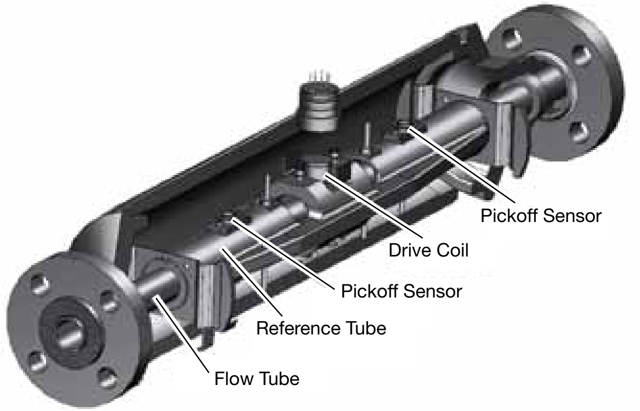
Measuring density. The natural vibration frequency of the tubes is determined by their stiffness and mass. Since the volume of fluid in the tubes is constant, a change in the density of the fluid causes a change in the mass within the tubes. When the mass inside the tubes changes, the natural frequency of the tubes also changes, and this change is detected by the pickoff sensors. The natural frequency is directly related to the density of the fluid inside the tubes.

Although temperature measurement is not necessary to determine mass flowrate, most Coriolis meters include a temperature sensor to compensate for the slight change in the tube stiffness (Young's modulus) with temperature. Temperature is typically offered as a third output variable, along with flowrate and density.

Other types of Coriolis meters

The Coriolis meter with two curved tubes has the highest flow sensitivity. Flow sensitivity is defined as microseconds of phase shift per unit of mass flowrate — the greater the signal per unit of flow, the more sensitive the device. Therefore, meters with high flow sensitivity can have larger-diameter flow tubes and a lower pressure drop. A dual-tube curved meter also has the greatest turndown (*i.e.,* the ability to operate at less than 100% capacity) and density accuracy, as well as the highest accuracy when handling gases. However, there are two other designs for special applications.

For use in cramped installations, much smaller Coriolis meters with tubes that are only slightly curved are available (Figure 3). However, the restricted space reduces the flow sensitivity and density accuracy, which in turn decreases the usable range and turndown. These meters are not as well suited for gas flows; because gas flows are low-mass/high-volume applications, high sensitivity is required for accurate



▲ **Figure 4.** In another type of Coriolis meter, the fluid flows through a straight or slightly curved tube inside an outer reference tube. As the two tubes vibrate in opposite directions, electromagnetic sensors mounted on each side of the driver pick up their relative motion.

Application Examples

Catalyst preparation and feed. In a copolymer production line, catalyst was manually added to the catalyst pot. A nominal 15% concentration of the catalyst was assumed as judged by visual estimation. This system was vulnerable to variation in both human observation and the catalyst slurry.

Coriolis mass flowmeters were added to the feed line to monitor catalyst density. Although only one meter was required, two meters were installed because Coriolis technology was new to the company and confidence in it was low.

After the meters had been in place for a few months, a second production line was built. Based on the observed consistency and accuracy of the density measurement in the first line, the new production line was designed so that the catalyst was added directly to the reactor, with a single Coriolis meter to measure and automate the catalyst feed. By eliminating the catalyst pot, the plant realized a capital savings of $250,000.

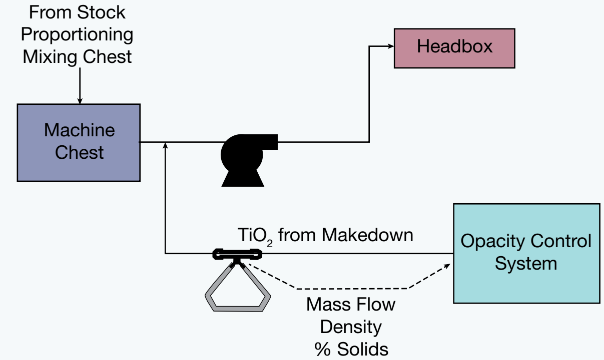
Ethylene delivery. A chemical company was using DP/orifice meters that provided only a volume-based measurement; additional pressure and temperature measurements were needed to determine ethylene density. The plant was experiencing ongoing issues with accounting and billing based on the indirect mass measurement provided by DP/orifice meters. A mass balance revealed that the company was under-billing customers by 1% — more than $100,000 per month. And because DP/orifice meters were used in the custody-transfer measurement, it was not possible to prove or easily verify the billing discrepancy.

The facility installed two Coriolis flowmeters in one of the custody-transfer stations, one as a billing meter and the other as a verification meter. Directly measuring the mass flowrate simplified measurement verification and billing. Following the successful trial, the company installed an additional 14 Coriolis flowmeters.

TiO_2 addition in fine paper manufacturing. Titanium dioxide (TiO_2) is added to fine paper to help meet requirements for brightness and whiteness. TiO_2 is an expensive but critical ingredient; using too little produces off-spec paper, while using too much increases costs and reduces mill profitability.

A facility used magnetic flowmeters to measure slurry flow and determined TiO_2 concentration via time-consuming laboratory analysis. This time delay resulted in opacity control problems. Inaccurate measurement caused flow variations and resulted in a 15% rejection rate for the paper — one batch in seven did not meet brightness and whiteness specifications.

The solution to this control problem lay in implementing a Coriolis flowmeter for real-time, online measurement of mass flow, percent solids (TiO_2), and net flow (see figure below). This eliminated sampling and laboratory analysis. The Coriolis meter interfaced directly with the opacity control system, which greatly improved response time. Better real-time measurement significantly reduced variability in paper brightness and whiteness. TiO_2 usage was optimized and reduced by 0.44 ton/d, saving more than $250,000 per year.



▲ In a fine paper application, a Coriolis meter interfaced directly with the opacity control system eliminated sampling and laboratory analysis for mass flow, solids content, and net flow.

flow measurement. In addition, the tubes vibrate at higher frequencies than those in the deep-U shape, which limits their use with fluids containing entrained gases.

The third type of Coriolis meter has one straight or slightly curved tube through which the fluid flows, enclosed by an outer dry reference (balance) tube or bar (Figure 4). An electromagnetic driver causes the two tubes to vibrate in opposite directions, while a pair of electromagnetic sensors mounted on each side of the driver picks up the relative motion of the two tubes.

When fluid is not flowing, the tubes vibrate in unison, and the outputs from the pickoff sensors are in phase. As fluid flows through the inner tube, it creates inertial effects, causing the sensor outputs to move slightly out of phase (the inside sensor falls slightly behind). This phase difference can be related to mass flowrate.

Straight-tube meters are optimized to limit plugging, and are easy to drain and clean. On the other hand, their accuracy and turndown are limited compared to dual-tube curved meters.

Advantages and limitations

The most fundamental advantage of the Coriolis meter is that it provides a true mass flow and density reading. Since its output is directly proportional to mass flowrate, there is no need to compensate for temperature and/or pressure. It often eliminates the need for complex flow computers to integrate the output from multiple devices and perform the complex calculations (*e.g.,* PVTz corrections) required by traditional gas flowmeters.

Because a single device provides multivariable outputs — such as flow, density, and temperature — there are fewer instruments to specify, install, calibrate, and maintain. And, the Coriolis meter is bidirectional, handling flow in either direction with no adjustments.

Coriolis meters are extremely accurate. In fact, a Coriolis meter is often used as a standard for checking other flowmeters. A liquid mass flow accuracy of 0.10% is common, and 0.05% is readily available. Gas mass flow accuracy to 0.25% is available, although 0.35–0.5% is more common. Liquid density accuracies up to 0.0002 g/cm^3 are available. Newer Coriolis meters have onboard diagnostics such as meter verification, which allows the user to confirm accuracy while the meter is operating.

Coriolis meters have large turndown ratios — up to 80:1, as determined by a 10-psi pressure drop at the top end and 0.5% of the actual mass flowrate at the low end. There is no industry standard to define how turndown is measured. However, in one established technique, a minimum accuracy is defined, which sets the low-end flowrate, and a maximum pressure drop is defined, which determines the top-end flowrate. The ratio of the top-end to low-end flowrates is the turndown ratio. Large turndown ratios are particularly beneficial for batch reactions, multiproduct fiscal transfer, and process startup applications.

With no moving parts, Coriolis meters require little maintenance, which reduces personnel exposure to the process for servicing and calibration, thereby enhancing safety. They also enhance installation safety because they require fewer pipe breaks to install than other types of meters. And, they do not require long upstream or downstream straight piping runs, which reduces installed cost.

Limitations. The capital costs of a Coriolis meter are often higher than those of other types of flowmeters, and their price increases rapidly with size. They are not suitable for applications where the value of the fluid or the criticality of the process does not justify the high capital costs. However, with a growing shortage of experienced instrument operators in the field, sometimes a Coriolis flowmeter is a wise investment.

Coriolis meters are available in a limited range of sizes — for lines up to 14–16 in. in diameter. The weight, too, goes up rapidly with size — a Coriolis meter for a 12-in. line weighs 1,000 lb.

Table 1. Although the capital cost of a Coriolis meter is typically higher, the overall cost of ownership of a small Coriolis meter is typically lower than that of other meter types.

		Coriolis	DP/Orifice	Turbine
Capital Costs, $	Meter	5,000–8,000	1,200	2,500
	Straight pipe runs	0	1,000	1,000
	Filter/strainer	0	0	500
	Pressure sensor	0	500	400
	Temperature sensor	0	250	250
	Flow computer	0	1,000	1,000
	Wiring	500	2,300	200
Engineering Costs, $	Flowmeter	500	1,000	1,000
	Flow computer	0	200	200
	Wiring, etc.	200	200	200
Installation Costs, $	Meter	500	1,000	1,000
	Straight pipe runs	0	500	500
	Filter/strainer	0	500	500
	Pressure sensor	0	100	100
	Temperature sensor	0	100	100
	Flow computer	0	200	200
	Wiring	200	400	400
Maintenance Costs (over a 10-yr life), $	Meter repair*	1,000	2,000	5,000
	Meter flow calibration	0	2,000	5,000
	Pressure	0	1,000	1,000
	Temperature	0	500	500
	Flow computer	0	500	500
Total		$7,900–10,900	$14,350	$26,850

*Periodic meter zeroing

Comparing costs

Table 1 compares the costs of three types of meters in natural gas service. These costs are for a 1-in. meter with wetted parts made of Type 316L stainless steel, operating at temperatures of 100–200°F and pressures of 100–500 psi (at these conditions, DP/orifice and turbine meters must have compensation). Labor (burdened) costs are $150/h for engineering, and $100/h for installation and maintenance. The DP/orifice and turbine meters are both inferred mass flowmeters. Because these meters do not measure mass directly, the volumetric flow measurement must be multiplied by the density to calculate mass flow. Therefore, temperature and pressure must also be measured to obtain the density — which increases installation and maintenance costs and makes these meters inherently less accurate than Coriolis meters.

The comparison in Table 1 is for a fairly small unit. Larger Coriolis meters will be significantly more expensive. While the capital costs of a Coriolis meter tend to be higher, in small sizes the total cost of ownership tends to be less than other meters when all associated costs are factored in.

Where Coriolis meters are used

Coriolis meters operate in a wide range of applications, including process evaluation and optimization, feed characterization, product quality control, concentration measurement, and chemical additive metering, to name a few.

Because of their high accuracy, they are often selected for mass/energy balancing, loss control, and custody transfer. Their ability to measure mass flow in gases allows them to be used for improving control in boilers subject to rapid changes in fuel gas composition. Additionally, their ability to handle pulsating flows makes them suitable for measuring the flowrates of materials delivered by pulsating injection pumps.

They are able to operate over a wide range of temperatures and product characteristics, and can handle a wide variety of media, from gases to slurries, emulsions, suspensions, pastes, and even molten asphalt. They are especially useful for fluids with changing density, viscosity, and compressibility (*e.g.,* nonideal gases, compressible liquids, and non-Newtonian fluids).

Coriolis flowmeters are suitable for sterilizable service, and for steam-in-place (SIP) and clean-in-place (CIP) applications. This is an important factor in the making of personal care products. Because preservatives are often not allowed in products such as mouthwash or shampoo, they are made via ultrasterile processes, with sterilized deionized water. In these applications, magnetic flowmeters cannot accurately measure flowrate.

Coriolis flowmeters are not recommended for measuring density in gas applications, because changes in density are too small to resolve with Coriolis technology. Some manufacturers have dedicated gas density/specific gravity unit (SGU) devices that are adept at this.

Coriolis meters are typically not used in steam, because the steam is too hot or too wet, or the lines are too big. Vortex meters are more suited to this application.

Although in recent years the ability of Coriolis meters to handle two-phase flow has improved, their performance under these conditions is not optimal. They are much more accurate in single-phase flow.

Choosing Coriolis meters

The process for selecting a flowmeter begins with a careful evaluation of the application's accuracy, turndown, pressure drop, velocity, direct vs. inferred mass measurement, volumetric flow, and material of construction requirements, as well as the tendency for plugging and fouling.

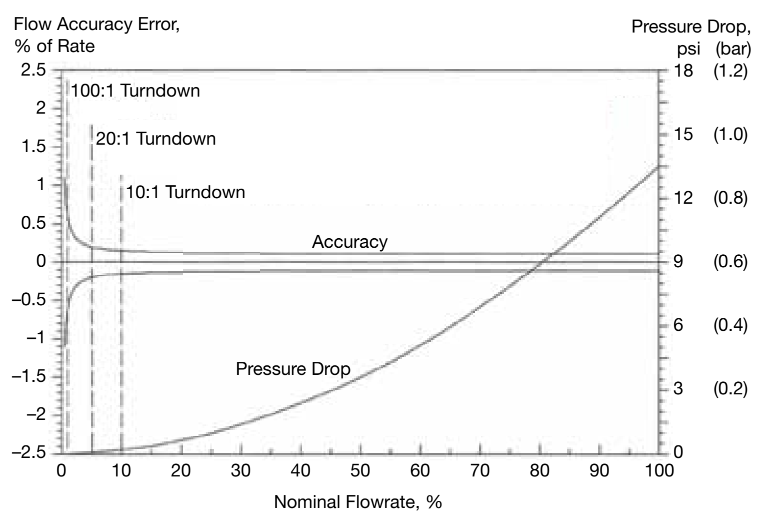
The user prepares a data sheet that contains information on the process, such as: flowrate, pressure, and temperature (minimum, normal, maximum); fluid density; fluid viscosity; maximum allowable pressure drop; required accuracy; etc.

If a DP/orifice meter is selected, the orifice size dictates the accuracy and pressure drop. Because this orifice size is infinitely variable, pressure drop can be fine-tuned for the application.

However, for discrete-sized flowmeters, such as the Coriolis meter, the user must choose a specific meter size with a set pressure drop and accuracy range. Every given size and type of Coriolis meter has an associated zero stability (zs). The zero stability is a measure of the meter's sensitivity, and is determined by the manufacturer. The flow accuracy is defined as the zero stability divided by the mass flowrate.

Each meter size and type has a pressure drop characteristic curve that is prepared by the manufacturer (Figure 5). This curve shows the tradeoff between pressure drop and flow accuracy. A specific Coriolis meter is chosen after comparing the needs of the system with the pressure drop characteristic curves of many types and sizes of Coriolis meters. The user must optimize the pressure drop and accuracy — based on the system's requirements — in order to determine and select the best Coriolis meter for the application.

If Coriolis technology is deemed appropriate, the next step is to select the sensor and transmitter. The type of trans-



▲ **Figure 5.** Pressure drop is proportional to the flowrate squared. High flowrates result in higher pressure drops but greater accuracies. At lower flowrates (high turndown), pressure drop is lower, but accuracy is lower as well.

mitter — integral or remote — is typically based on process characteristics (*e.g.,* temperature), accessibility for installation, local display, output protocols, etc. Sensor selection is based on performance, drainability, and material compatibility considerations, in addition to temperature and pressure limits within the tubes, manifolds, and process connections.

For applications where the equipment must be cleaned out, a straight-through Coriolis flowmeter design is preferred. For applications where the meter is drained before it is used with a different fluid, the unit may need to be installed in a vertical line where the fluid flows upward to facilitate draining. If cleaning fluids are to be used, an appropriate material of construction must be specified for the sensor. For example, a titanium straight-tube meter is incompatible with a caustic wash in a hygienic process.

Dual-tube meters whose tubes have a deep U shape have the highest sensitivity to flow and the lowest pressure drop at a given accuracy. Thus, they can be used over the widest range of flowrates. Deep-U meters are optimal for low-mass-flow applications (*e.g.,* gases and high-viscosity liquids). Deep-U designs are preferred for fiscal transfer and critical process control (*e.g.,* catalyst feed). Lower-profile meters, such as those with slightly curved tubes and straight tubes, are more compact, but less sensitive. Basic process control or monitoring applications can be served by a variety of geometries, as they require only mid-range (*e.g.,* 0.2%) flow accuracy and turndown (*e.g.,* 10:1).

Closing thoughts

The Coriolis mass flowmeter measures both mass flow and density directly, and provides excellent accuracy for fluids ranging from gases to sludge. It can improve measurement and control performance in a wide range of applications, but cost increases rapidly with size. However, a Coriolis meter's total cost of ownership is often less than that of the alternatives. CEP

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