The Paradigm Case Method of Flowmeter Selection

By Jesse Yoder, Flow Research, Inc.

Overview

One of the most interesting developments in the flowmeter market today is the battle between the newer flow technologies and the traditional flowmeters. New-technology flowmeters include Coriolis, magnetic, ultrasonic, vortex, and thermal flowmeters. The traditional flow technologies include differential pressure (DP), turbine, positive displacement, and variable area devices. While there is a general trend towards the new-technology meters and away from the traditional meters, the rate of change varies greatly by industry and application.

When users select flowmeters today, they are faced with a variety of choices. Not only are many technologies available, but so are many suppliers for each technology. When ordering replacement meters, users often replace like with like. This is one reason that DP flowmeters still have the largest installed base of any type of flowmeter. In other cases, users need to select meters for new plants, or for new applications within existing plants. Users also sometimes replace one type of flowmeter with another type. How should this selection be made?

This chapter addresses the issue of flowmeter selection by examining the operating principles, advantages, and limitations of new-technology flowmeters. It then presents a step-by-step method of flowmeter selection that takes these factors into account, along with application, performance, cost, and supplier capabilities. This method is called the "paradigm case" method for selecting flowmeters.

Because the first step in the paradigm case method of flowmeter selection involves selecting flowmeters whose paradigm case application matches a particular application, the paradigm case application is identified for each type of flowmeter. A "paradigm case" application is one in which the conditions are optimal for the operation of that type of flowmeter. The paradigm case application for each flowmeter type is determined by the physical principle by which the flowmeter senses flow.

New-Technology Flowmeters

New-technology flowmeters are so-called because they represent technologies that have been introduced more recently than differential pressure flowmeters. Most of the new-technology flowmeters came into industrial use in the 1960s and 1970s, while the history of differential pressure flowmeters goes back to the early 1900s. Each new-technology flowmeter is based on a different physical principle, and represents a unique approach to flow measurement.

New-technology flowmeters share several characteristics. First, they have been introduced in the last sixty years. Second, they incorporate technological advances that avoid some of the problems inherent in earlier flowmeters. Third, they are more the focus of new product development efforts by the major flowmeter suppliers than traditional technology meters. Fourth, their performance, including criteria such as accuracy, is at a higher level than that of traditional technology meters.

Those flowmeters that incorporate newer technologies are classified here as new-technology flowmeters. This category includes Coriolis, magnetic, ultrasonic, vortex, multivariable differential pressure (DP), and thermal meters. These meters were all introduced in the past 60 years. Magnetic flowmeters were first introduced in Holland in 1952. Tokimec first introduced ultrasonic meters in Japan in 1963. Eastech brought out vortex flowmeters in 1969, while Coriolis meters came onto the market in 1979. Multivariable DP flowmeters were introduced in the mid-1990s. And thermal flowmeters were developed in the mid-1970s.

Just as flowmeters that incorporate new technologies are classified as new-technology meters, so flowmeters that incorporate more traditional technologies are classified as traditional technology meters. These include differential pressure, turbine, positive displacement, thermal, and variable area meters. As a group, these meters have been around longer than the new-technology meters. They generally have higher maintenance requirements than new-technology flowmeters. And while suppliers continue to bring out enhanced traditional technology flowmeters, they are less the focus of new product development than new-technology meters.

Included in the traditional technology category are differential pressure (DP), turbine, positive displacement, open channel, thermal, and variable area meters. The history of DP meters goes back to the early 1900s, while the beginnings of the turbine meter go back to at least the mid-1800s. Many of the problems inherent in DP meters are related to the primary elements that they use to measure flow. For example, orifice plates are subject to wear, and can also be knocked out of position by impurities in the flowstream. Turbine and positive displacement meters have moving parts that are subject to wear. The accuracy levels of open channel, thermal, and variable area meters are significantly lower than that of new-technology flowmeters.

Coriolis Flowmeters

Coriolis flowmeters are named after the French mathematician Gustave Coriolis. In 1835, Coriolis showed that an inertial force must be taken into account when describing the motion of bodies in a rotating frame of reference. The earth is commonly used as an example of this Coriolis force. Because the earth is rotating, an object thrown from the North or South Pole towards the equator will appear to deviate from its intended path.

Coriolis flowmeters are composed of one or more vibrating tubes, usually bent. The fluid to be measured passes through the vibrating tubes. The fluid accelerates as it passes towards the point of maximum vibration and decelerates as it leaves this point. The result is a twisting motion in the tubes. The degree of twisting motion is directly proportional to the fluid's mass flow. Position detectors sense the positions of the tubes. While most Coriolis flowmeter tubes are bent, and a variety of designs are available, some manufacturers have also introduced straight-tube Coriolis flowmeters.

Straight-tube flowmeters work on the same principle as do the bent-tube meters. The inertia of the fluid causes acceleration of fluid particles in the first half of the flowmeter, and deceleration of fluid particles in the second half of the meter. This inertia generates a Coriolis force that slightly distorts the measuring tube. This distortion, which is detected by special sensors, is proportional to mass flowrate. Because the oscillatory properties of the measuring tube vary with temperature, temperature is continuously measured so that the necessary adjustments can be made in the measurement.

It is often said that Coriolis flowmeters measure mass flow "directly", unlike other flowmeters that calculate mass flow by using an inferred density value. Volumetric flow (Q) is calculated by multiplying the cross-sectional area of a pipe by the fluid's average velocity. Mass flow is then determined by multiplying volumetric flow (Q) by the density of the fluid. Some multivariable flowmeters measure the pressure and temperature of the process fluid, and then use these values to infer fluid density. Mass flow can then be calculated.

Coriolis flowmeters are used on both liquids and gases. While they are highly accurate, they are limited in size to six inches or less, with a few exceptions. Coriolis flowmeters have relatively high initial cost, although some models are now available in the $3,000 range. Their high initial cost is offset by their normally low maintenance costs. Coriolis meters can handle some fluids with varying densities that cannot be measured by other flowmeters.

Paradigm Case Application. The paradigm case application for Coriolis meters is with **clean liquids and gases flowing sufficiently fast to operate the meter through pipes two inches or less in diameter**. The primary limitation on Coriolis meters is size, since they become quite unwieldy in sizes over two inches. While three-inch and four-inch Coriolis meters are available, conditions are not ideal for meters of these diameters, due to the required size of the meter. Some low-pressure gases do not have sufficient density to operate Coriolis flowmeters. One advantage of Coriolis meters is that the same flowmeter can be used to measure different types of fluids, including fluids of different density. Coriolis meters can measure the mass flow of slurries and dirty liquids, but these fluids should be measured at relatively low flowrates to minimize meter wear.

Magnetic Flowmeters

Magnetic flowmeters use Faraday's Law of Electromagnetic Induction. According to this principle, a voltage is generated in a conductive medium when it passes through a magnetic field. This voltage is directly proportional to the density of the magnetic field, the length of the conductor, and the velocity of the conductive medium. In Faraday's Law, these three values are multiplied together, along with a constant, to yield the magnitude of the voltage.

Magnetic flowmeters use wire coils mounted onto or outside of a pipe. A voltage is then applied to these coils, generating a magnetic field inside the pipe. As the conductive liquid passes through the pipe, a voltage is generated and detected by electrodes, which are mounted on either side of the pipe. The flowmeter uses this value to compute the flowrate.

Magnetic flowmeters are used to measure the flow of conductive liquids and slurries, including paper pulp slurries and black liquor. Their main limitation is that they cannot measure hydrocarbons (which are nonconductive), and hence are not widely used in the petroleum industry. "Magmeters," as they are often called, are highly accurate and do not create pressure drop. Their initial purchase cost is relatively high, though most magmeters are priced lower than equivalent Coriolis meters.

Paradigm Case Application. The paradigm case application for magmeters involves **conductive fluids flowing through a full pipe that do not contain materials that damage the liner or coat the electrodes.** The most obvious and serious limitation on the use of magnetic flowmeters is that they only work with conductive fluids. This principle works with conductive liquids but not with gases or steam, so magmeters only work with conductive liquids. Because they compute flowrate based on velocity times area, accurate readings require that the pipe be full. In addition, electrode coating and liner damage can degrade the accuracy of magnetic flowmeters.

Ultrasonic Flowmeters

Ultrasonic flowmeters were first introduced for industrial use in 1964. There are two main types of ultrasonic flowmeters: transit time and Doppler. Transit time ultrasonic meters have both a sender and a receiver. They send an ultrasonic signal across a pipe at an angle and measure the time it takes for the signal to travel from one side of the pipe to the other. When the ultrasonic signal travels with the flow, it travels faster than when it travels against the flow. The ultrasonic flowmeter determines how long it takes for the signal to cross the pipe in one direction, and then determines how long it take the signal to cross the pipe in the reverse direction. The difference between these times is proportional to flowrate. Transit time ultrasonic flowmeters are mainly used for clean liquids.

Doppler ultrasonic flowmeters also send an ultrasonic signal across the pipe. However, instead of sending it to a receiver on the other side of the pipe, the signal is reflected off particles traveling in the flowstream. These particles are traveling at the same speed as the flow. As the signal passes through the stream, its frequency shifts in proportion to the mean velocity of the fluid. A receiver detects the reflected signal and measures its frequency. The meter calculates flow by comparing the generated and detected frequencies. Doppler ultrasonic flowmeters are used with dirty liquids or slurries.

Ultrasonic flowmeters are used with both liquids and gases. One significant development in the area was the approval by the American Gas Association (AGA) in June 1998 of criteria for using ultrasonic flowmeters for custody transfer of natural gas. This approval gave a major boost to the ultrasonic market in the oil production and transportation industry. Only multipath flowmeters are approved for use in custody transfer. Most multipath flowmeters use four to six different paths of ultrasonic signals to determine flowrate.

Multipath ultrasonic flowmeters use multiple pairs of sending and receiving transducers to determine flowrate. The transducers alternate in their function as sender and receiver over the same path length. The flowrate is determined by averaging the values given by the different paths, providing greater accuracy than single path meters.

Paradigm Case Application. The paradigm case application for transit time ultrasonic flowmeters is **clean, swirl-free liquids and gases of known velocity profile**. The need for high accuracy may require the use of a multipath meter. The most important constraint on ultrasonic flowmeters is that the fluid be clean, although today's transit time meters can tolerate some impurities. A single-path ultrasonic meter calculates flowrate based on a single path thorough the pipe, making it susceptible to flow profile aberrations. Multipath flowmeters are more accurate, since they use multiple paths to make the flow calculation, usually between four and six paths. Ultrasonic flowmeters can handle liquids and gases. They can be affected by swirl.

Ultrasonic flowmeters are available as in-line and clamp-on models. The paradigm case application for clamp-on models requires taking characteristics of the pipe into account, as well as fluid characteristics.

Vortex Flowmeters

Vortex flowmeters employ a principle called the von Karman effect. According to this principle, flow will alternately generate vortices when passing by a bluff body. A bluff body has a broad, flat front. In a vortex meter, the bluff body is a piece of material with a broad, flat front that is mounted at right angles to the flowstream. Flow velocity is proportional to the frequency of the vortices. Flowrate is calculated by multiplying the area of the pipe times the velocity of the flow.

In some cases, vortex meters require the use of straightening vanes or a specified length of straight upstream piping to eliminate distorted flow patterns and swirl. Low flowrates present a problem for vortex meters, because low flowrates generate vortices irregularly. The accuracy of vortex meters is from medium to high, depending on model and manufacturer. In addition to liquid and gas flow measurement, vortex flowmeters are widely used to measure steam flow.

Paradigm Case Application. Paradigm case applications for vortex meters are **clean, low viscosity, swirl-free fluids flowing at medium to high–speed**. Because formation of vortices is irregular at low flowrates, ideal conditions for vortex flowmeters include medium to high flowrates.   Since swirls can interfere with the accuracy of the reading, the stream should be swirl-free. Any corrosion, erosion, or deposits that affect the shape of the bluff body can shift the flowmeter calibration, so vortex meters work best with clean liquids. Vortex meters also work best with low-viscosity fluids.

Table 3-1 summarizes the advantages and disadvantages of DP and new-technology flowmeters, along with some additional application criteria. The characteristics of the main types of DP flowmeters and various primary element types are also included in this table.

Table 3-2 summarizes the operating principles of new-technology flowmeters. Because users often need to choose between new-technology and some type of DP flowmeters, the table also summarizes the main types of DP flowmeters.

Table 3-1
Advantages and Disadvantages of DP and New-Technology Flowmeters

Flowmeter Type	Advantages	Disadvantages	Liquid, Steam, or Gas	Pipe Size	Comment
DP-Orifice Plate	Low initial cost; Ease of installation; Well understood	Limited range; Permanent pressure drop; Uses square root method to calculate flowrate	Liquid, Steam, Gas	½ inch and up	Most traditional meter
DP-Venturi Tube	Suitable for clean and dirty liquids;	Can be unwieldy and difficult to install due to size	Liquid, Gas	2-30 inches	Greater size for gas
DP-Pitot Tube	Low cost; Virtually no pressure drop	Low accuracy; Limited sampling	Liquid, Gas	> 1 inch	Measures only at a single point
DP-Averaging Pitot Tube	More accurate than single Pitot tube; Virtually no pressure drop	Limited range; Not suitable for dirty fluids	Liquid, Gas	> 1 inch	Available as Annubar
DP Flow Nozzle	Good for high velocity fluids; Handles dirty fluids better than orifice plate	High initial cost; Difficult to remove for inspection and cleaning	Steam	2-30 inches	Used for steam applications

Table 3-1
Advantages and Disadvantages of DP and New-Technology Flowmeters (Cont.)

Flowmeter Type	Advantages	Disadvantages	Liquid, Steam, or Gas	Pipe Size	Comment
Coriolis	High accuracy; Measures mass flow directly	Not available for pipe sizes over six inches; High initial cost; Sensitive to vibration	Liquid, Gas	1/16 inch to 6 inches	Measures mass flow directly
Magnetic	Obstruction-less; High accuracy; No pressure drop	Cannot meter nonconductive fluids (e.g., hydrocarbons); Relatively high initial cost; Electrodes subject to coating	Liquid	1/10 to 100 inches	Limited use in the petroleum industry because it does not meter hydrocarbons
Ultrasonic – Single Path Transit Time	High accuracy; Nonintrusive	High initial cost; Requires clean fluids; Sensitive to swirl	Liquid, Gas	½ inch and up	Used for check metering applications
Ultrasonic – Multipath Transit Time	High accuracy; Nonintrusive	High initial cost; Requires clean fluids; Sensitive to swirl	Liquid, Gas	4 inches to 36 inches	Approved for custody transfer of natural gas
Ultrasonic – Doppler	Low-medium accuracy; Operates on dirty liquids; Nonintrusive	Low-medium accuracy	Liquid	½ inch and up	Limited accuracy but one of few meters designed for dirty liquids
Vortex	Medium-high accuracy	Vibration can affect accuracy; Lacks industry approvals	Liquid, Steam, Gas	½ inch to 12 inches	Widely used for steam measurement

Table 3-2
New-Technology and DP Flowmeter Principles of Operation

Flowmeter Type	Technology
Coriolis	Fluid is passed through a vibrating tube; this causes the tube to twist. Mass flow is proportional to the amount of twisting by the tube
Magnetic	Creates a magnetic field within a pipe, typically using electrical coils. As electrically conductive fluid moves through the pipe, it generates a voltage. Flowrate is proportional to amount of voltage, which is detected by electrodes
Ultrasonic-Single Path Transit Time	Measures the time it takes for an ultrasonic pulse or wave to travel from one side of a pipe to the other. This time is proportional to flowrate.
Ultrasonic – Multipath Transit Time	Uses multiple ultrasonic paths to calculate flowrate; typical paths are two to six.
Ultrasonic - Doppler	Calculates flowrate based on the shift in frequency observed when ultrasonic waves bounce off particles in the flowstream
Vortex	A bluff body is placed in a flowstream; as flow passes this bluff body, vortices are generated. The flowmeter counts the number of vortices, and flowrate is proportional to the frequency of vortices generated.
DP-Orifice Plate	A flat metal plate with an opening in it; a DP transmitter measures pressure drop and calculates flow rate
DP-Venturi Tube	A flow tube with a tapered inlet and a diverging exit; a DP transmitter measures pressure drop and calculates flowrate
DP-Pitot Tube	An L-shaped tube inserted into a flowstream that measures impact and static pressure; the opening of the L-shaped tube faces directly into the flowstream. The difference between impact and static pressure is proportional to flowrate.
DP-Averaging Pitot Tube	A Pitot Tube having multiple ports to measure impact and static pressure at different points. Flowrate is calculated by DP transmitter based on average of difference in pressure readings at different points.
DP-Flow Nozzle	A flow tube with a smooth entry and sharp exit; flowrate is calculated based on difference between upstream and downstream pressure

Paradigm Case Selection Method

While various selection methods have been devised, this chapter presents a step-by-step method that begins by matching the application involved with the paradigm case applications for various types of flowmeters. It then advocates looking at application, performance, cost, and supplier criteria in order to select a flowmeter. A statement of this paradigm case method follows. Table 3-3 sums up the paradigm case conditions for new-technology flowmeters.

1. Every type of flowmeter is based on a physical principle that correlates flow with some set of conditions. This principle determines the paradigm case application for this type of flowmeter. When selecting a flowmeter, begin by selecting the types of flowmeters whose **paradigm case applications** are close to your own.
2. Make a list of **application criteria** that relate to the flow measurement you wish to make. These conditions may include type of fluid (liquid, steam, gas, slurry), type of measurement (volumetric or mass flow), pipe size, process pressure, process temperature, condition of fluid (clean or dirty), flow profile considerations, fluid viscosity, fluid density, Reynolds number constraints, range, and others. From those types of flowmeters selected in step 1, select those that best meet these application criteria.
3. Make a list of **performance criteria** that apply to the flowmeter you wish to select. These include reliability, accuracy, repeatability, range, and others. From those types of flowmeters selected in step 2, select the ones that meet these performance criteria.
4. Make a list of **cost criteria** that apply to your flowmeter selection. These include initial cost, cost of ownership, installation cost, maintenance cost, and others. From the types of flowmeters chosen in step 3, select the types that meet your cost conditions.
5. Make a list of **supplier criteria** that govern your selection of a flowmeter supplier. These include type of flowmeter, company location, service,

responsiveness, training, internal requirements, and others. From the types of flowmeters listed in step 4, select the suppliers that meet your criteria.

6. For the final step, review the meters that are left as a result of step 4 and the suppliers listed as a result of step 5. Review the application, performance, and cost conditions for the remaining flowmeter types, and select the one that best meets all these conditions. Now select the best supplier for this flowmeter from those suppliers listed as a result of step 5.

Table 3-3
Paradigm Case Conditions for New-Technology Flowmeters

Type of Flowmeter	Paradigm Case Conditions	Comment
Coriolis	Clean liquids and gases flowing sufficiently fast through pipes two inches or less in diameter.	Measure mass flow directly; some provide density measurement
Magnetic	Conductive liquids flowing through full pipes that do not contain materials that could damage the liner or coat the electrodes.	Do not work with gas or steam
Ultrasonic – Transit Time	Clean, swirl-free liquids and gases of known profile	High accuracy may require the use of a multipath meter
Vortex	Clean, low viscosity, swirl-free, medium to high-speed fluids.	Work for liquids, gas, and steam

The above discussion identifies the paradigm case conditions for these four new-technology flowmeters. An application may fit the paradigm case for more than one flowmeter, although not always.

Surveys of flowmeter users consistently show that reliability and accuracy are the two performance criteria that are rated highest in importance by users when selecting flowmeters. Among new-technology flowmeters, Coriolis flowmeters provide the highest accuracy, followed by ultrasonic and magnetic meters. In terms of cost, many users are now distinguishing between purchase cost and cost of ownership. As a result, they may be willing to pay more for a flowmeter if it promises reduced maintenance costs.

How are decisions actually made in a plant about what flowmeter to buy? Often, users choose to replace like with like, for several reasons. Often, inventories of parts and supplies are built up in a plant based on a particular type of flowmeter. It can be very expensive to train personnel to install, use, and maintain a new type of flowmeter. Changing flowmeter types sometimes means changing flowmeter suppliers, which can be difficult.

The above helps to explain why differential pressure flowmeters still have the largest installed base of any flowmeter type. The battle for the hearts and minds of users is largely between the suppliers of new-technology flowmeters and the suppliers of differential pressure flowmeters. It is less of a battle among the suppliers of new-technology flowmeters, although new lower-cost Coriolis flowmeters may begin to impinge on the magmeter market.

Multivariable flowmeters represent one way that differential pressure flowmeter suppliers are responding to the challenge of new-technology flowmeters. Multivariable flowmeters usually measure pressure and temperature, in addition to flow. Multivariable vortex and multivariable magnetic flowmeters have also been developed, and it is likely that more types of multivariable flowmeters will be introduced in the future. This ongoing drama is definitely worth watching.

About the Author

Jesse Yoder, PhD, is president of Flow Research, Inc. in Wakefield, Massachusetts (www.flowresearch.com), a company he founded in 1998. He has nineteen years' experience as an analyst and writer in process control. Yoder specializes in flowmeters and other field devices, including pressure, level, and temperature products. He has written over 65 market research studies in industrial automation and process control, and has published numerous journal articles.

Dr. Yoder is the author of **The World Market for Differential Pressure (DP) Flowmeters and Primary Elements**, which is currently available from Flow Research. Other recent studies from Flow Research include worldwide studies on magnetic and vortex flowmeters, and a worldwide survey of flowmeter users. Flow Research has also recently published a study on temperature sensors in the Americas. Flow Research's quarterly **Market Barometer** chronicles the flowmeter industry, while the **Energy Monitor** tracks developments in the petroleum and power industries. Dr. Yoder has also written individual studies on all the main types of flowmeters. You can contact him at (781) 245-3200 or jesse@flowresearch.com.