Developments in DP Flowmeters

Improvements in Primary Elements Are Keeping Differential Pressure Flowmeters the First Choice for Many Process Applications

By Jesse Yoder

A n orifice plate with a differential pressure transmitter is the most traditional form of flowmeter. Despite the emergence of alternatives such as vortex and ultrasonic meters, differential pressure (DP) flowmeters still outnumber other technologies in most process industries. This article reviews the theory underlying the use of pressure transmitters to measure flow, and examines the advantages and disadvantages of each type of primary element. It then discusses the emergence of a new technology of DP flowmeters, and points to areas for future research. These areas include primary elements and the development of a new geometry of flow.

DP Flow Fundamentals

Differential pressure transmitters measure the difference between two pressures, a high pressure and a lower pressure, in a pipe or tank. In a pipe, the pressure drop is created by constricting the flow stream. The constricting device is called a primary element. A secondary element, the pressure transmitter, measures the differential pressure. The flow rate is proportional to the square root of the differential pressure and relies on Bernoulli's equation.

According to this equation, the sum of the static energy, kinetic energy, and potential energy is conserved in flow across a constriction in a pipe. Static energy takes the form of static pressure, which is the pressure the fluid would have even if it weren't moving. Kinetic energy takes the form of velocity pressure. Velocity pressure may be due to the presence of a pump that pushes the fluid through the pipe. Potential energy is a result of gravitational force due to the height of the fluid.

Bernoulli's equation is a form of the conservation of energy principle applied to fluids. While the sum total of energy is preserved, some energy is converted from one form to another. Bernoulli's equation, which applies to steady fluid flow without friction, can be formulated:

P + 1/2 rv2 + rgy = Constant (Bernoulli's equation)

Where P is the fluid pressure, 1/2 rv2 refers to the velocity pressure, and rgy refers to the pressure due to the elevation of the fluid. The term r means density, g is the gravitational constant, and y refers to the height of the fluid above some reference level. The pressure P + rgy is called the static pressure, while 1/2 rv2 is called the dynamic pressure.

Another important equation for flow measurement is called the equation of continuity. This equation expresses the law of conservation of mass in fluid dynamics. This equation is formulated as follows for two different points along the flow stream:
r1A1v1 = r2A2v2 (Equation of continuity)

cornucopia of concentric orifice plates
(IMAGE NOT AVAILABLE)
Of the three main types (concentric, eccentric, and segmental), concentric orifice plates are the most common, and are generally used with clean liquids.

In the above equation, r is density, A is the area of the pipe, and v is velocity. Assuming an incompressible liquid, density drops out of the equation, yielding the simplified equation:

A1v1 = A2v2

According to the Equation of Continuity, when the pipe narrows or the area through which fluid flows is reduced, fluid velocity increases. This equation is also formulated in simplified form for liquids as follows:

Q = Av

The term Q refers to volumetric flow rate in the above equation, while v refers to the average fluid velocity.

Why does flow speed up when the pipe narrows or flow is constricted? Consider the example of fluid passing through the hole in an orifice plate. As fluid passes through the hole, its velocity increases. This is due to increased pressure that builds up as fluid particles impact the area immediately surrounding the hole in the plate. As these particles pile up against the plate, they slow down and collide with each other, converting velocity energy into heat and pressure. The increased pressure increases the velocity of the particles that pass through the hole in the plate.

Bernoulli's equation can be combined with the equation of continuity to yield the equation used to calculate differential pressure.1 While the resulting equation has different formulations, a common one is as follows:

v = C (2gh) 1/2 (The DP flow equation)

Where v is average velocity, g is the gravitational constant, and h is the differential pressure. The term C is a constant that includes a number of empirical factors including discharge coefficient, specific gravity, pressure tap location, operating conditions, and Reynolds number. The volumetric flow rate Q can be calculated using the equation:

Q = C A (2gh) 1/2

Where A is the cross-sectional area of the pipe. According to the above equations, flow rate is proportional to the square root of the differential pressure. This is the most fundamental fact of flow measurement using primary elements. It is responsible for some of the disadvantages of orifice plates, such as their lower accuracy at the lower portion of the flow range.

The DP flow equation rests on many assumptions that are seldom if ever realized in practice. These assumptions relate to properties of the fluid, the primary element, and the pipe; and to pressure tap locations and internal energy losses. Typical assumptions include a rectilinear velocity profile, zero energy loss from friction and downstream turbulence, and the assumption that the orifice plate diameter is the diameter of minimum flow. Flow calculations also assume constant pressure and temperature values. The constant C compensates for the extent to which actual conditions depart from theory.

The coefficient C depends on the type of fluid, flow speed, and primary element-for example, the assumption of a uniform velocity profile is valid only for very high Reynolds numbers. Primary element geometry is also a major factor, and varies widely with different primary elements and pipe sizes-there is no vena contracta (minimum flow area) for Venturis. While liquids are widely assumed to be incompressible, this assumption does not hold true for some liquids at high pressures. And actual pressure and temperature conditions may differ from assumed conditions-this is especially important when measuring gas flow.

The coefficient compensates for velocity profile, pressure tap location, primary element geometry, and internal energy losses that cannot be measured directly. These energy losses include pipe losses due to friction, molecular energy losses, and loss of energy due to downstream turbulence.2 Just as there is no way to measure the diameter of the vena contracta, there is currently no way to directly measure these energy losses. The discharge coefficient is calculated by taking the ratio of the actual flow rate to the theoretical flow rate-a typical value is 0.6.

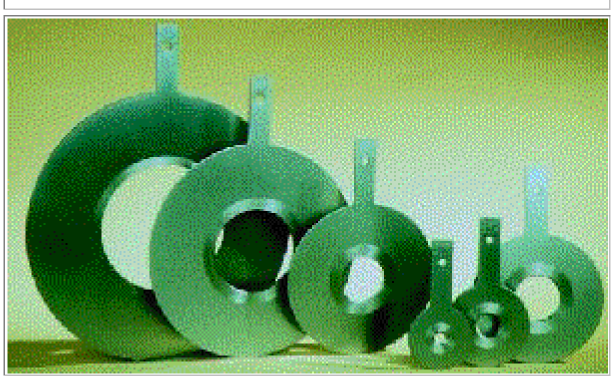
Industry experts generally agree on the above equations, but there is less agreement about how to calculate the empirical coefficients that are used to arrive at the constant C. There are actually three different equations used for this purpose. The American Petroleum Institute (API), together with the American Gas Assn. (AGA) has one equation. ASME has its own equation, which is contained in the ASME MFC-3M standard. In addition, the International Standards Organization (ISO), based in Europe, has developed a separate equation based on independent test data.3 Which equations are used in a particular case depends on which industry is involved.

It is unsettling that these three separate equations yield similar but not identical results when calculating the empirical coefficients that go into the constant C. Differences are in the range of 0.5% to more than 1%, depending on Reynolds number. Since the different equations are based on independent sets of test data, there is no obvious way to reconcile them. The differences are based in part on different methodologies for data analysis. These differences are likely to remain until someone figures out a way to quantify currently unmeasurable factors such as internal energy losses, or until a method of measuring DP flow is developed that does not rely on the use of empirical coefficients and constants.

Types of Primary Elements

Orifice plates, Venturi tubes, averaging Pitot tubes, and flow nozzles are the primary elements considered here. Others include elbow flowmeters, laminar flow elements, low-loss flow tubes, the segmental wedge, and the V-cone. Table I shows the advantages and disadvantages of different types of primary elements.

CORNUCOPIA OF CONCENTRIC ORIFICE PLATES



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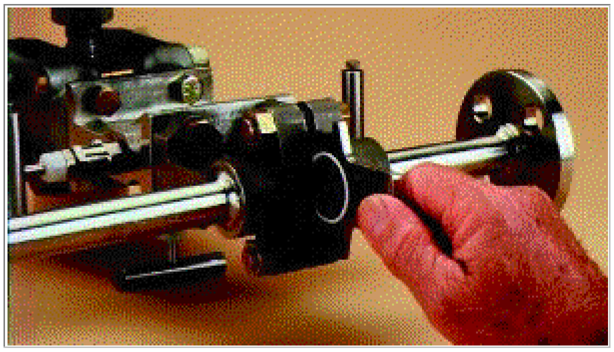
INTEGRAL ORIFICE ASSEMBLY



A variation on the orifice plate is the integral orifice assembly, which is mainly used with small pipe sizes from 1/2 -2 in. It contains an orifice plate that is integrated with a pressure transmitter.

Orifice plates have three main types of edges: square, quadrant, and conical. The square-edge concentric orifice plate is the most common of all the types of orifice plates, and dates back to at least 1915. Table II compares different types of orifice plates, and Table III compares different types of orifice plate edges.

Venturis go back to 1797, when G. B. Venturi published his work on what are today called Venturi tubes, or simply Venturis: short tubes with throat-like passages that increase flow velocity and reduce pressure. Clemens Herschel developed the first commercial Venturi tube in 1887. They are mainly used as primary elements when pressure loss is a major consideration. Venturis are most commonly used in pipe sizes of two inches and larger. In the water and power industries, some Venturis are quite large and can cost as much as $300,000 (Figure 3).

Like Venturis, Pitot tubes have a long history. They go back to 1732, when Henri Pitot presented his paper on flow measurement. A Pitot tube is a small, L-shaped tube that is inserted vertically into the flowstream with its open end facing upstream. A disadvantage of Pitot tubes is that they sample pressure at a single point in the flowstream, which limits accuracy.

Averaging Pitot tubes were developed to counteract the limited accuracy of single-point Pitot tubes. The averaging Pitot tube computes an average of pressures measured at a number of points on the tube, significantly improving accuracy. There is substantial disagreement about the best sensor design, however. Different shapes include round, diamond, bullet, and ellipse.
Flow nozzles have a rounded inlet area and a shorter throat than a Venturi. Discharge coefficients for high Reynolds numbers are better documented than for orifice plates. A nozzle-Venturi design provides a shorter length than the traditional Venturi but with higher pressure loss.

Staying Number One

While the pressure transmitter market worldwide is still growing, newer flow technologies are cutting into the market share of DP transmitters that compute flow based on pressure drop across a primary element. To counteract this trend, pressure transmitter suppliers have responded with two innovative products: multivariable transmitters and integrated DP flowmeters that marry a primary element to the transmitter.

Multivariable pressure transmitters measure more than one process variable. Typically, they measure either gauge or absolute pressure, differential pressure, and process temperature. An onboard flow computer uses this information to calculate flow rate. Some also calculate the empirical factors used to determine the constant for the DP flow equation. Calculating these values is more accurate than assuming them. Some major advantages of multivariable transmitters are that they require only a single pipe penetration to do the job of three transmitters and a flow computer, and they cost less than buying these devices separately.

One of the more interesting recent developments is the introduction of pressure transmitters that are integrated with a primary element and sold as a DP flowmeter (Figure 4). While this new design is mainly being used on averaging Pitot tubes, it will soon be available with other primary elements, including Venturis. The integral orifice design, typically used with pipes smaller than 2 in., incorporates a similar concept.

The integration of primary elements and transmitters creates a new category of flow measurement: differential pressure flowmeters. No longer will users have to buy a DP transmitter and then search for a primary element supplier. Instead, the DP transmitter will come with the primary element already in place, providing a single integrated solution. Users can reduce their vendor list, and will have a single supplier to call if a problem occurs. The emergence of DP flowmeters as a unique type gives users a way to upgrade without abandoning familiar DP flow technology.

The Accuracy Gap

For a number of years, much flow-related research and development money has been tied up in fieldbus-related issues. During this time, companies have made great strides in developing smarter and more accurate pressure transmitters. Unfortunately, there has been little corresponding progress in developing more accurate primary elements. While the accuracy of many averaging Pitot tubes is in the 1% range, the accuracy of orifice plates can degrade to 3% or worse over time if they are not properly maintained.

As a result, there is an accuracy gap between primary elements and pressure transmitters. Transmitters with an accuracy of 0.1% are transmitting a sensor measurement with a much lower accuracy value. Digitally integrating the transmitter with the control room does not improve primary element accuracy, even if it does speed the measurement on its way. With fieldbus battles inching toward resolution, more suppliers are likely to put their research dollars into primary elements. The emergence of averaging Pitot tubes as an alternative to orifice plates, and the expanded use of Venturis, show that there is still room for further development efforts. This development should include research into the sensor components of other flow technologies where similar accuracy gaps exist. Perhaps someone will also discover how to better measure internal energy losses, reducing reliance on primary elements. Primary elements and flow sensors are an important frontier for flowmeter research.

References

- The derivation of this formula is somewhat complex and will not be repeated here. See David Spitzer, Industrial Flow Measurement, 1990, Instrument Society of America, pp. 113-115.
- Stephen Rudback and Charlie Mayo, "Differential Pressure Flowmeters," Measurements & Control, September 1995. See also Richard Miller, 1996, Flow Measurement Engineering Handbook, 3rd edition, McGraw Hill, pp. 9.8 - 9.10, for a discussion of corrections to the theoretical equations.
- For an interesting discussion of the history of these equations, see Miller, pp. 7.1-7.3. According to Miller, sufficient test data to generate a coefficient-prediction equation was not generated until 1930.

- This idea is further developed in "A Circular Geometry of Flow," forthcoming in ISA's "Process Measurements and Control Division Newsletter," Spring 1998.

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