1

Process Instrumentation

By Vernon L. Trevathan

Topic Highlights

Pressure
Level
Flow
Temperature
Smart Instruments

1.1 Introduction

Good control requires measurements that are accurate, reliable, responsive and maintainable. These factors are influenced by the choice of principle used for the measurement, the detailed specifications and features of the instrument selected and specified, how well the instrument and its installation is maintained, and particularly the installation details.

The vast majority of physical measurements in processes are of the big four: flow, pressure, level, and temperature. This topic will focus on the more popular methods for measuring these variables. Analytical measurements are covered in the next topic. While this topic is titled "process" instrumentation because the larger number of applications are in process and utility applications, much of this instrumentation is used in many other areas of automation application wherever continuous measurements are needed.

Much of the focus in this topic is on compact "transmitters"—devices that combine the sensor and communicating electronics in one package. Some temperature measurements are an exception to this, since those devices often separate the sensor and the communicating electronics. These transmitters sometimes take on different names: level transmitters become level gauges and flow transmitters become flowmeters.

1.1.1 Measurement Concepts

All continuous measurements share certain parameters of accuracy, repeatability, linearity, turndown and speed of response.

Accuracy is the ratio of the error to the full-scale output, generally expressed as a percentage of span.

Repeatability is how well an instrument gives the same output for the same input when the input is applied in the same way over a short time period. It is also often expressed as the error as a percent of span.

Linearity only applies to measurements that are supposed to be linear; then, it also is a percent of span of the deviation of the measurement versus actual value from a straight line.

Response speed is defined as the length of time required for the measured value to rise to within a certain percentage of its final value as a result of a step change in the actual value. A 98% response time, for example, while indicative of the time to get a good measurement, is much longer than a first order time constant. The first order time constant of the measurement is of most interest in the performance of a control loop.

Other response characteristics like hysteresis, dead band, and stiction are primarily related to mechanical equipment, such as control valves, and do not normally apply to electronic transmitters.

Measuring instruments can generally be adjusted for span and zero. Span error is how well the full scale output of the instrument matches a full span change in the actual variable, usually expressed as a percent of span. Zero error is the output of the instrument for a measurement that is at the low end of the span, usually expressed as a percent of span. A zero error causes a constant offset for any measurement.

The turndown ratio is the ratio of the maximum to minimum measurable value. For example, if the maximum flow that can be measured is 100 gallons per minute (gpm) and the turndown ratio is 3 (typical for an orifice), then the minimum flow that can be accurately measured will be 33 gpm. However, if the turndown ratio is 100 (possible for a Coriolis meter), then the minimum flow that can be accurately measured will be 1 gpm.

1.2 Pressure

Transmitters for measuring the pressure of a liquid or gas are very common in process and utility applications, since they are used both for actual pressure and also frequently used in the measurement of level and flow.

Pressure is generally measured in pounds per square inch or in inches of water column. The pressure measurement can be designed to measure the amount that the pressure is above atmospheric pressure (positive pressures only—a.k.a. “gauge”), the amount the pressure is above or below atmospheric pressure (positive and negative pressures—a.k.a. “compound range”), or it can be the amount that the pressure is above absolute zero pressure (“absolute”). At sea level, atmospheric pressure is 14.7 pounds, but it varies about 0.5 psi per 1,000 feet of elevation.

Pressure measurements can also be either simple pressures (i.e., a single input port) or differential pressure (i.e., two input ports). Differential pressure transmitters are critical—for example, when measuring a small differential pressure, say 20 inches of water in the presence of a high common pressure, say 1,000 pounds, it would not be possible to measure each pressure and then take the difference electronically. The inaccuracy of the transmitters and subtraction devices would make the resulting difference hopelessly inaccurate.

The ideal gas law says that pV/T is a constant where p is the pressure, V is the volume, and T is the absolute temperature. Obviously, then, the pressure is highly dependent on temperature and volume.

While a variety of pressure measurement methods are available, such as manometers, bourdon tubes and bellows, most pressure transmitters today, both single pressure and differential, measure pressure by sensing the deflection of a diaphragm. The sensing device for that deflection is a strain gauge or other technique and is often on a secondary diaphragm for temperature and shock protection. Figure 1-1 shows the internals of a differential pressure transmitter and the secondary diaphragm that is coupled by oil filled channels. The output of the sensor is then amplified for transmission. The sensor is analog whether the signal conditioning and transmission is digital or analog.

The diaphragm that contacts the process fluid must be of a material that will withstand the temperature and corrosive effects of the process. Since the diaphragms are thin, they have little tolerance for corrosion. Diaphragms are available in stainless steel, a variety of alloys, and ceramic.

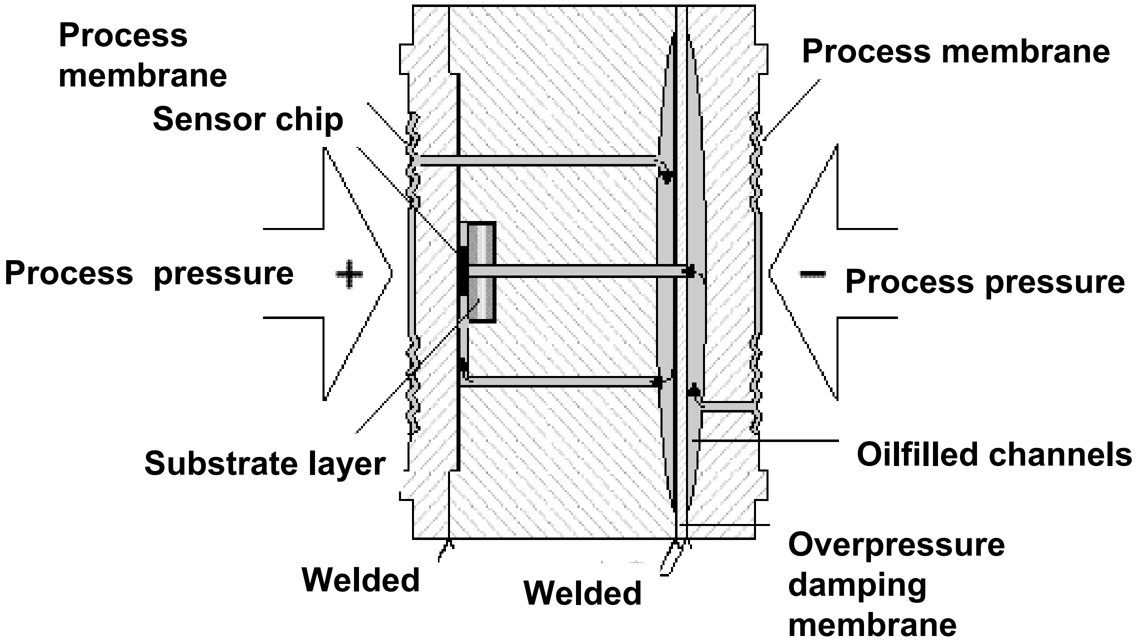

Figure 1-1: Differential Pressure Diaphragm and Sensor Assembly (Courtesy: Endress+Hauser)

Pressure transmitters may be connected to the process by a length of tubing or the diaphragm can be mounted flush to the process vessel using a pressure transmitter specially configured for that purpose. Some prefer the transmitter to be located for convenient maintenance access, which may mean that long tubing connections to the process piping or vessels are required. Others prefer for the transmitter to be close-coupled to the process piping or vessel to minimize leakages and tubing pluggauge and fill problems. That is, you can locate the transmitter for easy access so that, when it has a problem, it can be easily serviced. Or, you can locate it for reliability so it is less likely to need to be serviced.

Span and zero calibration is a major issue with analog pressure transmitters. Digital pressure transmitters tend to be much more accurate and stable than all analog transmitters. In addition, digital transmitters have a number of other functional advantages.

Various types of devices for developing pressures in the field have long been used by instrument technicians for calibration of span. These are used by first valving off the pressure transmitter from the process, and then connecting the transmitter to this portable pressure source. A known pressure measurement gauge can then be used to compare to the transmitter output. With analog instruments, this is the only way to change the span setting—from, say 0-100 in. H_2O to 0-200 in. H_2O. Calibration of digital transmitters can be done entirely within the digital electronics and remotely via the communications wiring. In addition, digital transmitters today are likely to be more accurate than the pressure gauge that can be handled in the field. Because of this, field calibration is diminishing.

1.3 Level

Level measurements of liquids or solids are used extensively in all types of bulk manufacturing and storage facilities plus many utilities. The level measurement may be for accurate inventory, to determine the contents in a vessel where reactions are taking place, or just be to keep the tank from overflowing or from going empty. The location of the surface may be measured directly for solids or liquids. For liquids, level can be inferred from the pressure at the bottom of the tank. In difficult applications, the tank can be weighed. Solid level measurement is often inaccurate because the surface is an upward cone shape under the filling location or downward cone shape over the discharge location.

Even liquids may have turbulent surfaces from boiling or agitation which can cause inaccuracies in some types of level measurements.

1.3.1 Direct Level Measurement

Float

The most obvious measurement method is to use a float to determine a liquid level. This method is used in process applications, but possibly its most important use is in very large tanks with expensive contents. In those large tank applications it is called tank gauging. To achieve maximum accuracy the gauging system also utilizes vessel shape changes due to atmospheric temperatures and fill bloating and many other seemingly minor things. The float connects via a cable or tape to a measuring device outside the tank that precisely measures the length to the float.

Ultrasonic and Radar (Microwave)

These measurements work by sending a pulsed wave signal from the top of the tank that hits the surface of the material and reflects back to the instrument. The distance to the surface is then determined by the transmission time. Ultrasonic measurements have the advantages of no contact with the process and are suitable for various liquids and bulk products. Their disadvantages are that the process must not produce too much surface foam, and they are not suitable for high temperature, pressure or vacuum. Radar has the advantage of broad applicability on most liquids and measurement independent of pressure, temperature and vapor. Disadvantages are that the measurement may be lost due to heavy agitation of the liquid or the formation of foam. Radar instruments are now approaching the price of ultrasonic and are the fastest growing type of level measurement.

Capacitance

A metal probe is located vertically in the tank and electrically isolated from the tank. The probe and the walls of the tank form a capacitor that has a value that depends on the amount of material in the tank and the medium between the probe and the wall. When only vapor is present, the capacitance will be low. The capacitance will increase incrementally as the process material covers the probe. This method is suitable for liquids or solids, has no moving parts, and is suitable for highly corrosive media. The disadvantages are limited application for products with changing electrical properties and may be sensitive to coatings on the probe. Sensor selection is critical to the measurement, particularly if the sensed material is conductive.

Radioactive

A radioactive source—either point or strip—is placed on one side and outside the tank, and a radiation detector (Geiger counter), or series of detectors, is placed on the other side. The amount of radiation reaching the detector(s) is dependent on the amount of material in the tank. This type is expensive and requires stringent personnel safety requirements and licensing, so it is used only as a last resort. The measurement is very nonlinear unless a strip source and a series of detectors are used.

1.3.2 Inferring Level from Head Measurement

Displacer

A displacer is a vertical body that is heavier than the fluid being measured. When placed so it is partly submerged, an upward force is generated that is based on the difference between the weight of the displacer and the amount of liquid displaced. Since the displacer is often installed in a vertical pipe attached to the tank at both ends, it can see a very still liquid surface and is very accurate. A displacer is expensive to install and maintain.

Bubbler

In this type of measurement, a tube is placed in the tank from the top and connected to a source of air. A needle valve in the air stream is adjusted to allow a slow flow of air at maximum level, as determined by bubbles escaping the bottom of the tube, and also typically by a flow indicator. The pressure of the air stream downstream of the needle valve is measured and is equal to the head generated at the bottom of the tube. This method is very simple and is widely used in open vessels and sumps.

Differential Pressure Transmitter

Probably the most common method of determining level of a liquid is by measuring the pressure or head at some point in the tank below the zero level. Since this method is often used in closed tanks, it is necessary to also measure the pressure in the vapor space at the top of the tank and subtract that pressure. A differential pressure (dP) transmitter is ideal for this application.

Since there will be process fluid in the tubing connecting the dP cell to the bottom of the tank, this has to be taken into account in the calibration of the transmitter. It may be intended that the tubing connecting the dP cell to the top of the tank contains only gas which has little impact on the calibration, but often that leg will become filled with liquid from condensation or from an occasional high level in the tank. Alternately, if it is intended that that tubing be filled with liquid, the liquid may evaporate unless it is continually replenished with a purge flow. Either unintended situation will cause a significant error in the reading.

Transmitters are available that bolt flush to the bottom of the tank and thus eliminate that tubing connection; transmitters are also available that have a hydraulic filled tube between the dP cell diaphragm and a remote diaphragm. These remote diaphragms can be connected flush to the top and bottom of the tank, eliminating all tubing with process fluid. Figure 1-2 shows a differential pressure transmitter with diaphragm seals. Filling these systems requires utmost care to eliminate all air bubbles before being filled with the hydraulic fluid. In spite of their additional cost, the advantages of filled systems make them popular and some companies use them for all appropriate applications.

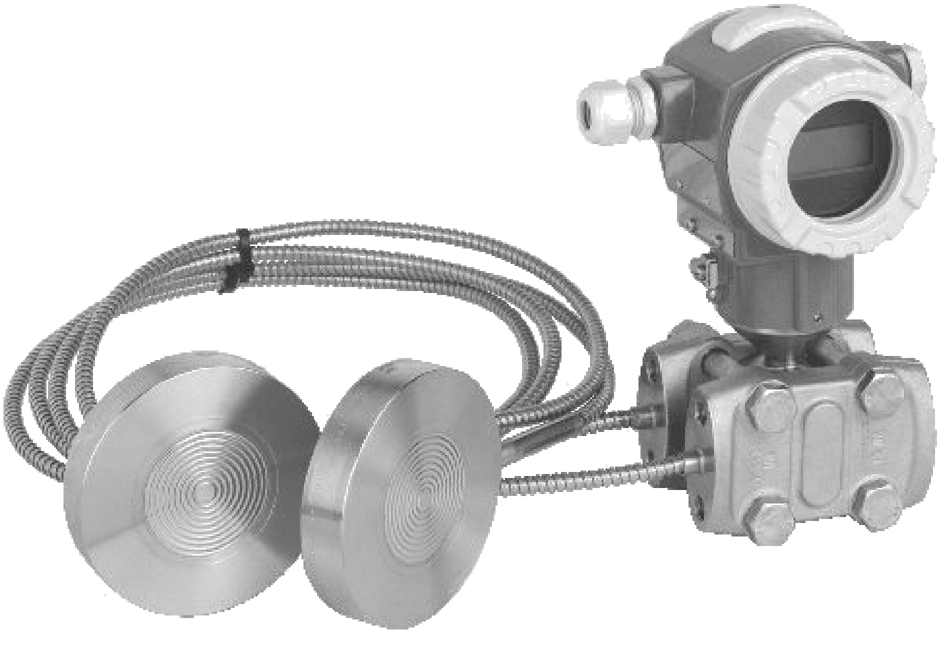

Figure 1-2: dP Transmitter with Filled System Connecting to Remote Diaphragms (Courtesy: Endress+Hauser)

Since the head or pressure of the material in the tank is a function of both level and density, changes in density will introduce errors into the level calculation.

1.3.3 Level Switches

Since high and low levels are so important in tanks, level switches are often used instead of a continuous measurement. Several types are available, such as a rotating paddle wheel for solids and a tuning fork for either liquids or solids.

In the paddle wheel type, the paddle is rotated by an electric motor through a clutch. When the paddle becomes covered with material, the paddle stalls and triggers a microswitch.

In the tuning fork type, the vibrating fork is driven to its resonant frequency in air by a piezoelectric crystal. When immersed in a liquid, the resonant frequency will shift approximately 10-20%. This shift in resonant frequency is picked up by a receiver crystal. Figure 1-3 shows a tuning fork switch. Tuning forks used in solids/particulates also vibrate at their resonant frequency, but detection is based on monitoring the decreased amplitude of fork motion when covered by solids.

These level switches are low cost and likely more accurate and reliable than a continuous level measurement, even if buildup occurs on the sensor.

Figure 1-3: Tuning Fork Level Switch (Courtesy: Endress+Hauser)

1.4 Flow

This flow discussion will focus on measuring flow in closed pipes. Flow measurement in open channels is not discussed, though that is an important type of measurement in large utility streams.

Flow is laminar or turbulent, depending on the flow rate and viscosity. This can be predicted by calculating the Reynolds number, which is the ratio of inertial forces to viscous forces:

$$Re = 123.9\ pVD/u \tag{1-1}$$

where:

Re = Reynolds number
p = density in lbs./ft.^{3}
V = average velocity in ft/sec.
D = pipe diameter in inches
u = viscosity in centipoises

Reynolds numbers less than 2000 indicate laminar flow and above 4000 indicate turbulent flow. However, some velocity meters require values above 20,000 to be absolutely certain that the flow is truly turbulent and that a good average velocity profile is established that can be measured from a single point on the flow profile. Most liquid flows are turbulent while highly viscous flows like polymers or very low flow rates are laminar.

Flow measurements can be of the average velocity, velocity at one point, volume of material flowing, or the mass of material. Velocity measurements in particular require that the flow stream velocity be relatively consistent across the diameter of the pipe. Less than fully turbulent flow creates lower velocities near the pipe wall.

Fittings, valves—anything else other than straight, open pipe upstream of the sensor—will cause velocity variations across the diameter of the pipe. Figure 1-4 illustrates the variations in velocity that can occur from pipe fittings. To achieve uniform flow, different types of flowmeters require straight pipe runs upstream and downstream of the measurement. These run requirements are expressed as a certain number of straight, open pipe diameters. For example, for a 6-inch pipe, 20 diameters would be 10 feet. There are no consistent recommendations even for a particular flowmeter type; it is best to follow the manufacturer's recommendations. Recommendations vary from 1 to 20, or even more, upstream diameters and a smaller number of downstream diameters.

Flow measurements can be grouped into four categories:

- Inferential methods
- Velocity methods
- Mass methods
- Volumetric methods

1.4.1 Inferential Methods

Placing an obstruction in the flow path causes the velocity to increase and the pressure to drop. The difference between this pressure and the pressure in the pipe can be used to measure the flow rate of most liquids, gases, and vapors, including steam. In turbulent flow, the differential pressure is proportional to the square of flow rate.

An orifice plate is the most common type of obstruction, and, in fact, differential pressure across an orifice is used more than any other type of flow measurement. The installed base of orifice meters is probably as great as all other flowmeters combined. The orifice plate is a metal disc with typically a round hole in it, placed between flanges in the pipe. Differential pressure can be measured at the pipe flanges directly upstream and downstream of the orifice or further upstream and downstream. The calculation formulas of differential pressure for a given orifice size and given location of the pressure taps are well developed, so no field calibration based on actual flow is needed (although the dP cell may have to be calibrated).

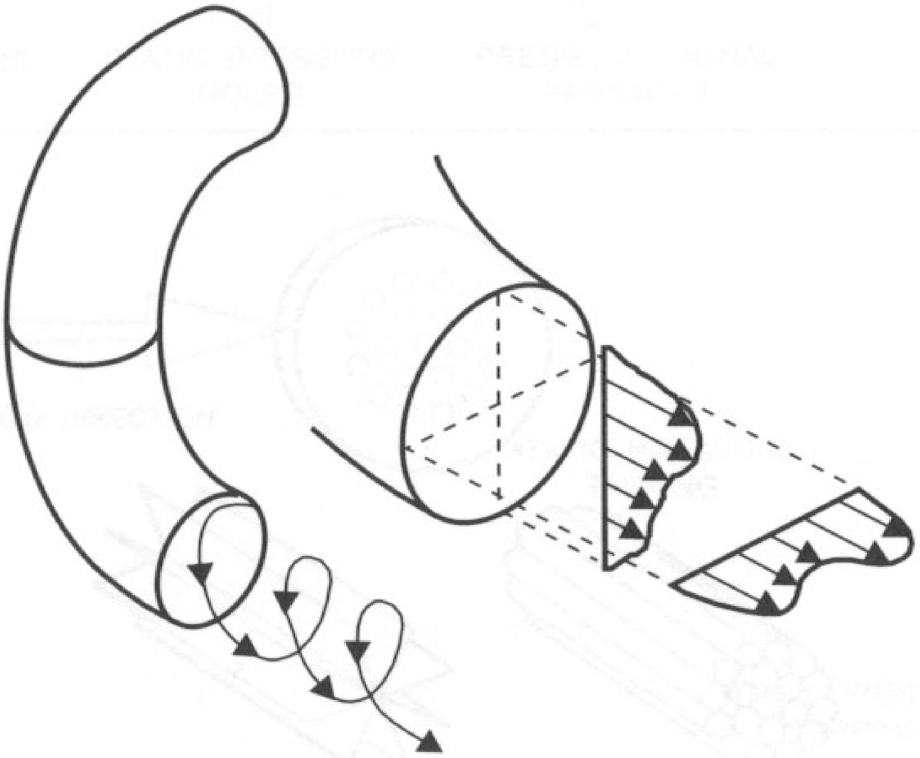

Figure 1-4: First Fitting Causes Profile Distortion; Second Fitting Superimposes the Swirl

Orifice flow measurements are relatively cheap to purchase but have relatively high installation costs. They have high operating costs because they create a fairly large unrecoverable pressure loss. Also, they have low turndown, in part due to the squared relationship. Orifices are suitable for high temperature and pressure, and are best for clean liquids, gases, and low velocity steam flows. They require long straight runs upstream and downstream. They are subject to a number of errors, such as flow velocity variations across the pipe and wear or buildup on the orifice plate. Because of these error sources, they are not generally very accurate even when highly accurate differential pressure transmitters are used.

Other types of obstructions include venturis and flow tubes which have less unrecoverable flow loss. A pitot tube is a device that can be inserted in large pipes or ducts to measure a differential pressure.

1.4.2 Velocity Methods

Magnetic Flowmeters

Magnetic flowmeters depend on the principle that motion between a conductor (the flowing fluid) and a magnetic field develops a voltage in the conductor that is proportional to the velocity of the fluid.

Coils outside the pipe generate a pulsed DC magnetic field. The material to be measured flows through the meter tube, which is lined with a non-conductive material such as Teflon, polyurethane, or rubber. Measuring electrodes protrude through the liner and contact the fluid and sense the generated voltage. Figure 1-6 shows the location of the coils and sensing electrodes.

The flowing fluid must be conductive, but there are very few other restrictions—most aqueous fluids are suitable. There are fewer Reynolds number limitations; the instrument is the full diameter of the pipe so there is no pressure loss; a wide range of sizes are available from a very small 1/8 inch to an enormous 10 feet in diameter; the flowing material can be liquids, slurries and suspended solids; and

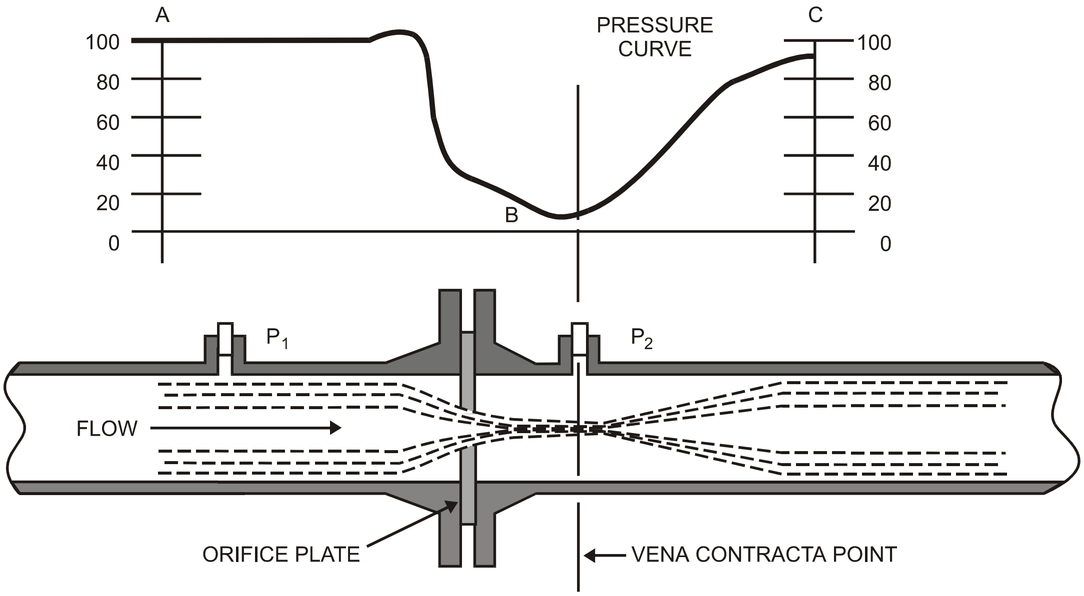

Figure 1-5: Typical Pressure Profile of an Orifice

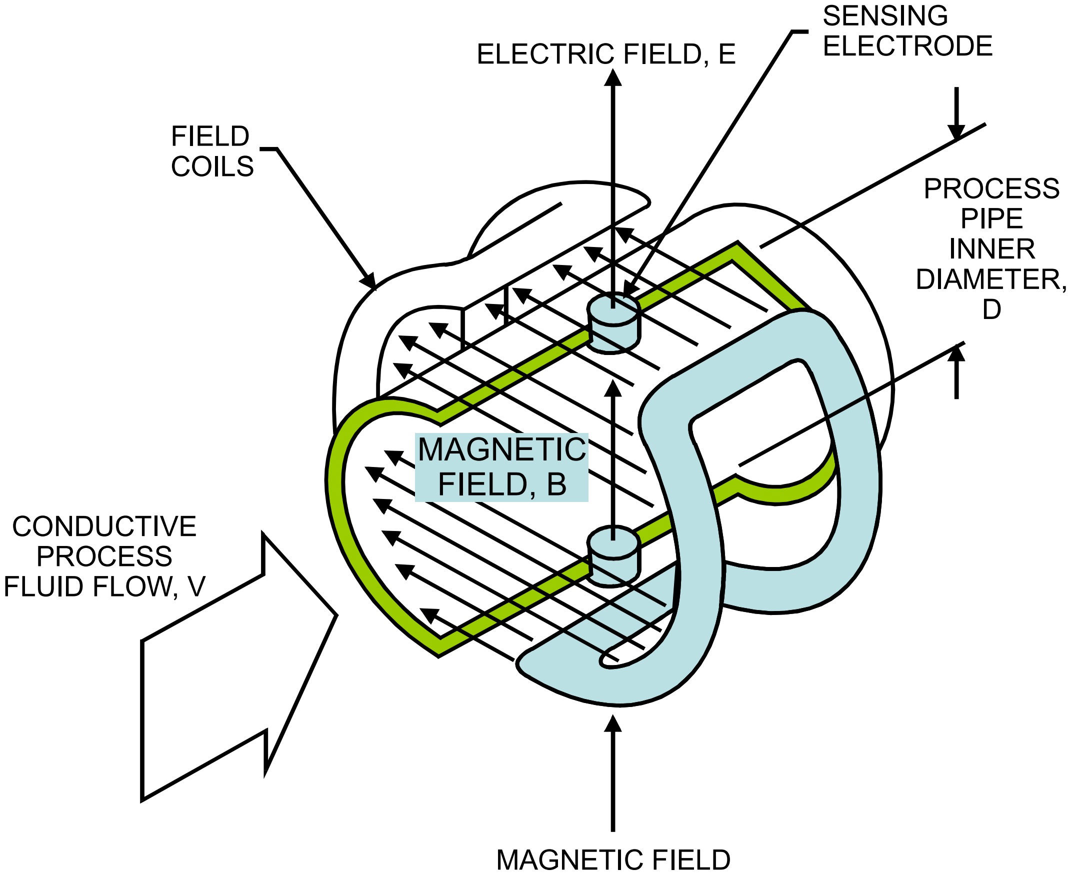

Figure 1-6: Magnetic Flowmeter Principle of Operation

there are minimum straight run requirements. Figure 1-7 shows two very large meters. These meters are widely used in utility as well as process applications and are particularly widely used in Europe. Calibration is factory determined and is rarely checked in the operating facility.

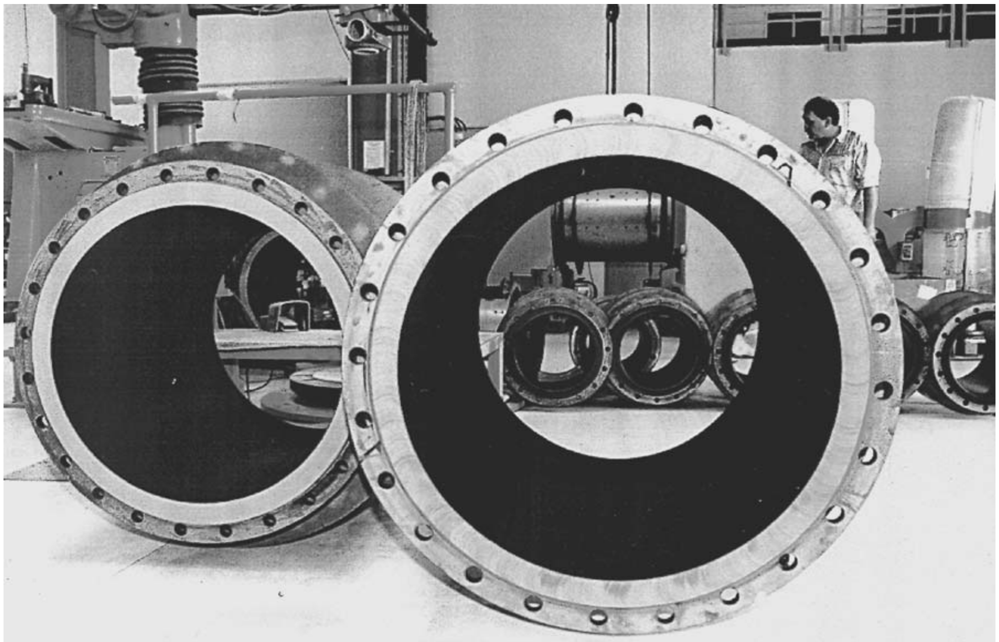

Figure 1-7: Magnetic Flowmeter (Courtesy: Endress+Hauser)

Vortex Shedding Flowmeters

Vortex shedding flowmeters measure the frequency of vortices shed from a blunt obstruction, called a “bluff body”, placed in the pipe. As the flow divides to go around the bluff body, vortices are created on each side of the divided stream. The rate of vortex creation is proportional to the stream velocity. Since each vortex represents an area of low pressure, the presence-then-absence of low pressures is counted and the count is proportional to the velocity. Vortex flowmeters provide good measurement accuracy with liquids, gases, or steam and are tolerant of fouling. They have high accuracy at low flow rates and the measurement is independent of material characteristics. They require long runs of straight pipe. Even though the accuracy of vortex meters is often stated as a percent of flow rate rather than of full scale which does indicate higher accuracies, below a certain flow rate they cannot measure at all. At some low flow rate the Reynolds number will be low enough so that no vortices will be shed.

Turbine Meters

Turbine meters use a multi-bladed rotor supported by bearings in the pipe. The flowing fluid drives the rotor at a speed that is proportional to the fluid velocity. Movement of the rotor blades is sensed by a magnetic pickup outside the pipe and the number of blade tips passing the pickup is counted to get rotor speed.

These meters have high accuracy for a defined viscosity. They are suitable for very high and low temperatures and high pressures. However, they are sensitive to viscosity changes, and the rotor is easily damaged by overspeed. Because of the relatively high failure rate of their moving parts, they are not used as much as in the past.

Ultrasonic Flowmeters

Ultrasonic flowmeters send sound waves through the flowing stream. They can measure either the Doppler shift as ultrasonic waves are bounced off particles in the flow stream, or the time differential of ultrasonic waves with the flow stream compared to against the flow stream. Either method gives a

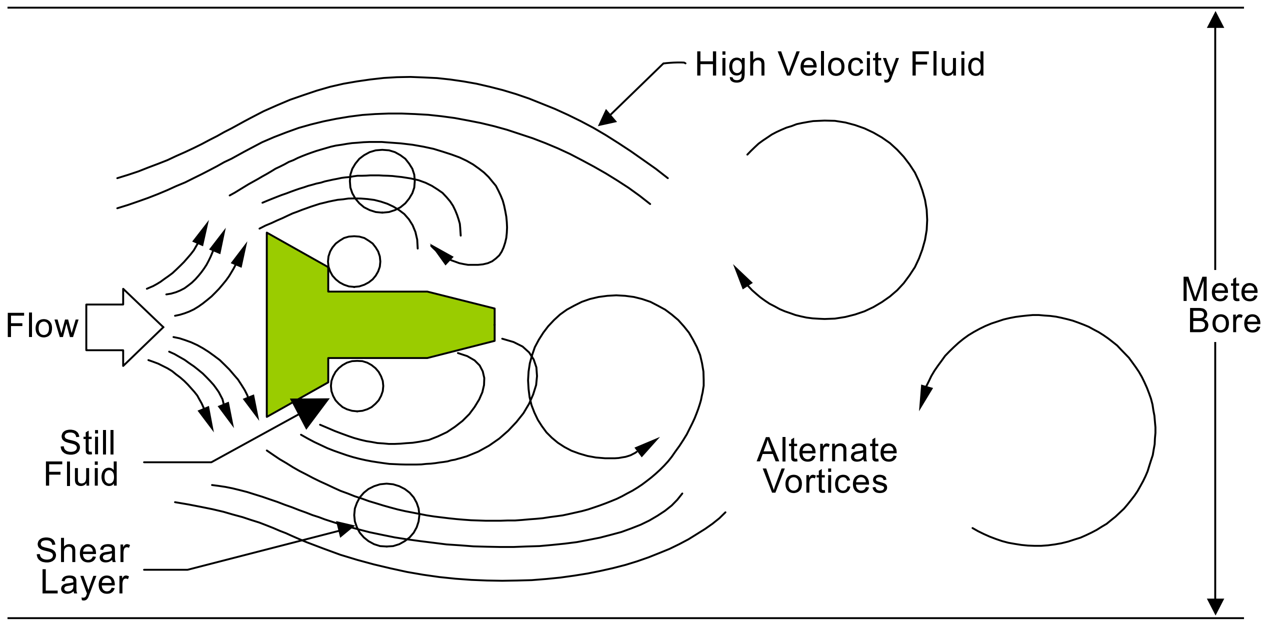

Figure1-8: Vortex Shedding Phenomenon

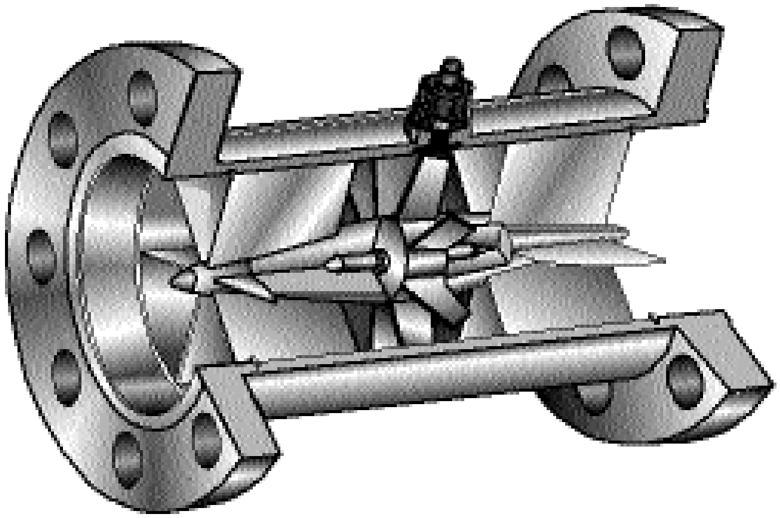

Figure 1-9: Turbine Meter

signal which is proportional to flow velocity. The Doppler method works with liquids with suspended solids, and the Transit time method works with liquids and gases. In both methods, the signal is proportional to flow velocity.

Ultrasonic meters are non-invasive but are relatively low accuracy. A clamp on meter is shown in Figure 1-10, which requires no connection to the pipe. Because these clamp-on meters are so easy to install, they can be used temporarily to verify the flowmeter that is permanently installed in the pipe. Since the same meter can do a variety of sizes, they are particularly cost effective in large sizes.

1.4.3 Mass Methods

Mass flowmeters measure actual mass flow. While it is possible to calculate mass flow from a velocity or inferential measurement and other variables like temperature for known fluids, only one meter

Figure 1-10: Clamp-on Ultrasonic Flow Meter (Courtesy: Endress+Hauser)

type commonly measures liquid mass directly, the Coriolis meter. This meter used to be applied only for when highly accurate, mass flow was required. Now with lower prices, a wider range of configurations and easier installation, it is being applied more routinely.

The heart of a Coriolis meter is a tube(s) that is vibrated at resonant frequency by magnetic drive coils. When fluid flows into the tube during the tube's upward movement, the fluid is forced to take on the vertical momentum of the vibrating tube. Therefore, as the tube moves upwards in the first half of the vibration cycle, the fluid entering the tube resists the motion of the tube and exerts a downward force. Fluid in the discharge end of the meter has momentum in the opposite direction, and the difference in forces causes the tube to twist. This tube twist is sensed as a phase difference by sensors located on each end of the tube arrangement, and twist is directly proportional to mass flow rate.

In addition to having high accuracy and a true mass flow measurement, Coriolis meters have no upstream and downstream straight run requirements, are independent of fluid properties, are low maintenance, and have a turndown ratio of as much as one hundred. While the meters originally were only available in a double U-shape, they are now available in a variety of configurations. Figure 1-11 shows a single, straight, full bore tube design. Coriolis meters are available in sizes up to 10 inches.

1.4.4 Positive Displacement Meters

This type of meter separates the flow stream into known volumes and by vanes, gears, pistons or diaphragms, and then counts the segmented volumes. They have good-to-excellent accuracy, can measure viscous liquids, and have no straight run requirements. However, they do have a non-recoverable pressure loss, and their moving parts subject to wear.

1.5 Temperature

Temperature is measured in Kelvin, Celsius, Fahrenheit, or Rankin. Unlike the other "big four" measurements, in many temperature applications the sensor is separate from the transmitter. While the

Figure 1-11: Coriolis Mass Flowmeter with Single, Straight Tube (Courtesy: Endress+Hauser)

transmitter or amplifier can be located in the housing of the sensor, it can also be remote—either in a field box containing a number of temperature transmitters, in the control room, or the output of the sensor can be connected directly to a temperature logger or directly to a DCS or PLC controller.

1.5.1 Thermocouples

The thermocouple is the most popular type of sensor. Thermocouples are based on the principle that two wires made of dissimilar materials connected at either end will generate a potential between the two ends that is a function of the materials and temperature difference between the two ends.

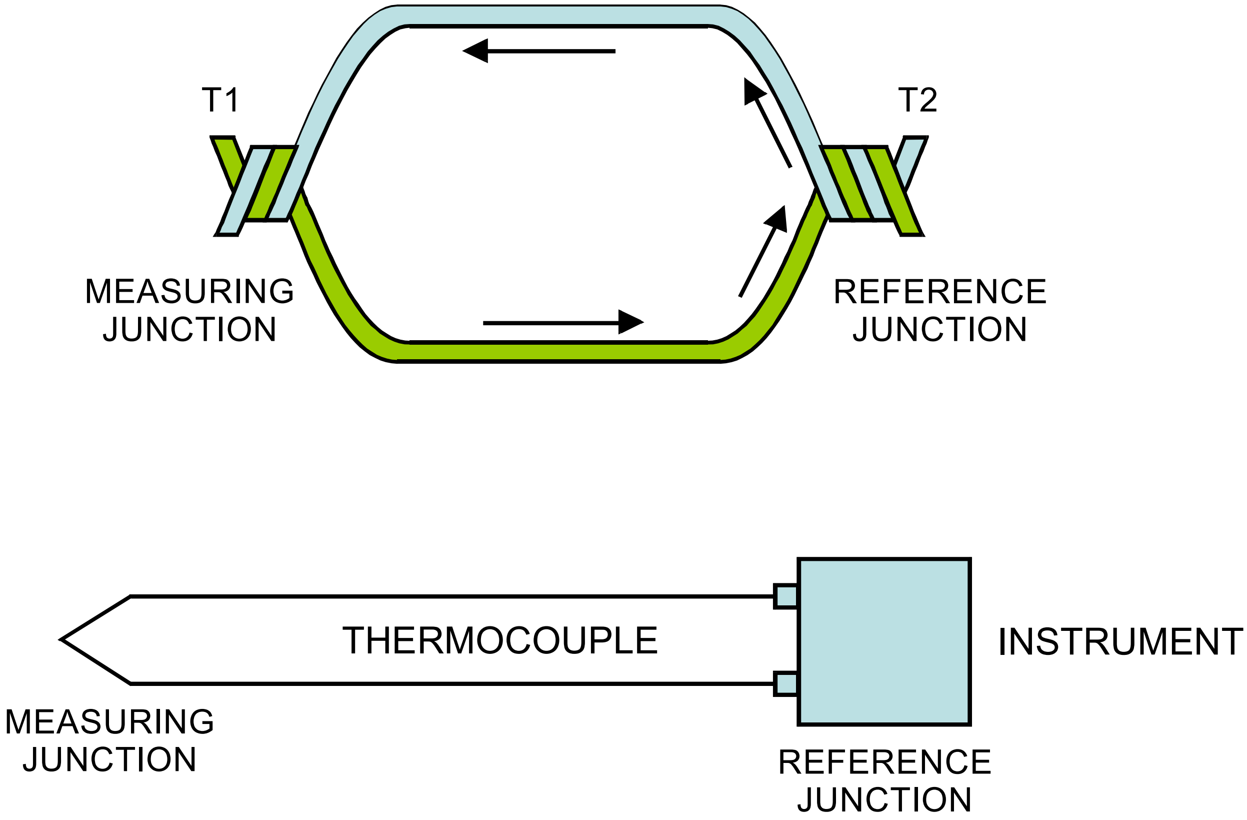

Figure 1-12: Thermocouples

A number of material choices are in common use. Base metal thermocouples are useful for measuring temperatures under 1000 degrees C. This class includes iron/constantan (Type J), Chromel/Alumel (Type K) and a number of others. Nobel metal thermocouples are useful to about 2000 degrees C. This class includes tungsten-rhenium alloy thermocouples and others.

The potential generated is in millivolts and is a nonlinear function of temperature. In practice, one end is placed near the material to be measured and the other end is connected to the instrument. Since the thermocouple materials are not typically good materials for transmission, wires with similar characteristics are used when the transmitting instrument is remote.

1.5.2 Resistive Temperature Detectors (RTDs)

RTDs are made of a metal wire or fiber or of semiconductor material that responds to temperature change by changing its resistance. Platinum, nickel, and tungsten and other metals are used that have high resistivity, good temperature coefficient of resistance, good ductile or tensile strength, and chemical inertness with packaging and insulation materials. When the material is a semiconductor, the sensor is called a thermistor.

The change in resistance can be determined using a bridge circuit. Since resistance changes in the connection wire due to ambient temperature changes can also affect the resistance reading, a third wire is used from another leg in the bridge to balance that change.

RTDs are generally more accurate than thermocouples, but are less rugged and cannot be used at as high temperatures.

All types of temperature measuring devices suffer from slow response, since it is necessary for the heat to conduct through the protective sheath, and through any installed well. Locating the well (or unprotected sensor) so that it sees as high a velocity of process material as possible helps reduce this lag, as does having the sensor contact the well. A bare thermocouple touching the sheath and/or well, however, generates a ground and requires an isolated amplifier.

1.6 Smart Instruments

The ISA *Automation, Systems, and Instrumentation Dictionary* defines a “smart” instrument as one that is microprocessor-based, may be programmed, has memory, can be communicated with from a remote location, and is capable of reporting faults and performing calculations and self-diagnostics. This does not specifically say that they have to communicate digitally, but they do.

For some automation professionals, common usage is to call transmitters “smart” that use the HART protocol and to call transmitters that communicate with some type of fieldbus as simply “fieldbus” transmitters. Regardless of the name, these transmitters give tremendous benefits:

- The calibration can be changed remotely by pushing a few buttons on a hand-held calibrator connected anywhere to the signal wiring or by entering the information from a computer connected to the control/asset management system. This makes it unnecessary, for example, to go to the field with a stack of equipment, pump up a pressure, and carefully turn screws until the span of a dP cell is changed to a new value. (Reading this “smart” information from transmitters is beyond the capability of past generation control systems, and the need to provide this capability has been part of the justification for some control system upgrades.)
- Many of the instruments can measure and report several variables: a pressure transmitter may also report temperature for example.
- The transmitter may be capable of reporting its specifications such as model number, materials of construction, calibration, tag number, and other items.

- Many types of transmitter failures can be detected by the transmitter itself and reported—ideally to an asset management system that will in turn, report the failure to a computerized maintenance management system (CMMS) so a repair work order can be issued.
- The transmitter can monitor its internal parameters: for example, a Coriolis meter might report its excitation current, frequency of the tubes, and other internal variables which can assist in troubleshooting and error detection.
- Some transmitters are even able to detect a change in the noise level of the signal and relate that to plugged process connection tubing and also call for repair.

1.7 References

Anderson, Norman A. *Instrumentation for Process Measurement and Control*. Third Edition. CRC Press, 1998.

Boyes, Walt, Editor. *Instrumentation Reference Book.* Third Edition. Butterworth-Heinemann, 2003.

Coggan, D.A., Editor. *Fundamentals of Industrial Control.* Second Edition. Practical Guides for Measurement and Control Series. ISA, 2005.

Goettsche, L. D., Editor. *Maintenance of Instruments and Systems.* Second Edition. Practical Guides for Measurement and Control Series. ISA, 2005.

Hashemian, H. M. *Sensor Performance and Reliability*. ISA, 2005.

Hughes, T. A. *Measurement and Control Basics.* Third Edition. ISA, 2002.

ISA. *The Automation, Systems, and Instrumentation Dictionary*. Fourth Edition. ISA, 2003.

Lipták, Béla G., Editor-in-Chief. *Instrument Engineer's Handbook: Process Measurement and Analysis, Volume I, Fourth Edition.* ISA & CRC Press, 2003.

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