Kirk-Othmer Encyclopedia of Chemical Technology.

PRESSURE MEASUREMENT

Pressure measurement is important in the chemical process industries (CPI) and in laboratories for a number of reasons: differential pressure is the driving force in fluid dynamics; product quality frequently depends on certain pressures (or vacuums) being reached and accurately maintained for specific lengths of time during a process; and pressure is a crucial safety consideration in the operation of process equipment particularly where boiler or reactor pressures must not exceed certain limits (see Fluid mechanics; High pressure technology; Vacuum technology).

1. Units of Measurement

Pressure is defined as force per unit of area. The International System of Units (SI) pressure unit is the pascal (Pa), defined as 1.0 N/m^2. Conversion factors from non-SI units to pascal are given in Table 1 (see also Units and conversion factors; front matter). An asterisk after the sixth decimal place indicates that the conversion factor is exact and all subsequent digits are zero. Relationships that are not followed by an asterisk are either the results of physical measurements or are only approximate. The factors are written as numbers greater than 1 and less than 10, with 6 or fewer decimal places (1).

2. Definition of Terms

Absolute pressure is pressure measured relative to a perfect vacuum, an absolute zero of pressure (2). Like the absolute zero of temperature, perfect vacuum is never realized in a real world system but provides a convenient reference for pressure measurement. The acceptance of strain gauge technology in the fabrication of pressure sensors is resulting in the increased use of absolute pressure measurement in the CPI (see Sensors). The pressure reference for most of the pressure gauges used in the CPI as of the mid-1990s is atmospheric or local barometric pressure. Barometric pressure varies with elevation and weather. These variables have been eliminated by establishing a standard atmospheric pressure of 101,325 Pa (14.696 psi) as a basis for correcting gauge indication for variations in barometric pressure. One standard atmosphere is equal to the pressure exerted by a column of mercury 760 mm high at a temperature of 0°C where the acceleration owing to gravity is 9.80665 m/s^2. The Pa is an absolute pressure unit. SI conventions make no provisions for differentiating between absolute and gauge pressure. Absolute and gauge pressure are often differentiated in psi by the notation psia and psig, respectively.

Gauge pressure is equal to absolute pressure minus barometric pressure. Absolute pressure is gauge pressure plus barometric pressure. If a gauge indicates, for example, that the pressure is 15 psig and the local barometric pressure is 14.7 psia, then the absolute pressure is 29.7 psia (205 kPa). Gauge pressure can be either positive or negative. When the term pressure gauge is used, the reference is almost always to a gauge that is used to measure positive pressures, ie, pressures that exceed local barometric pressure. A vacuum gauge

Table 1. Conversion of Pressure Units to the SI Unit[a]

To convert from	To	Muliply by[b]
atmosphere		
normal = 760 torr	pascal (Pa)	1.01325×10^5
technical = 1 kgf/cm^2	pascal (Pa)	$9.806650^* \times 10^4$
bar	pascal (Pa)	$1.000000^* \times 10^5$
centimeter of mercury (0°C)	pascal (Pa)	1.33322×10^3
centimeter of water (4°C)	pascal (Pa)	9.80638×10
decibar	pascal (Pa)	$1.000000^* \times 10^4$
dyne per $centimeter^2$	pascal (Pa)	$1.000000^* \times 10^4$
foot of water (39.2°F)	pascal (Pa)	2.98898×10^3
gram-force per $centimeter^2$	pascal (Pa)	$9.806650^* \times 10$
inch of mercury		
32°F	pascal (Pa)	3.386389×10^3
60°F	pascal (Pa)	3.37685×10^3
inch of water		
39.2°F	pascal (Pa)	2.49082×10^2
60°F	pascal (Pa)	2.4884×10^2
kilogram-force per $centimeter^2$	pascal (Pa)	$9.806650^* \times 10^4$
kilogram-force per $meter^2$	pascal (Pa)	9.806 650*
kilogram-force per $millimeter^2$	pascal (Pa)	$9.806650^* \times 10^6$
millibar	pascal (Pa)	$1.000000^* \times 10^2$
millimeter of mercury (0°C)	pascal (Pa)	1.333224×10^2
poundal per $foot^2$	pascal (Pa)	1.488 164
poundal-force per $foot^2$	pascal (Pa)	4.788026×10
pound-force per $inch^2$ (psi)	pascal (Pa)	6.894757×10^3
torr (mm Hg absolute, 0°C)	pascal (Pa)	1.33322×10^2

[a]Ref. 1.
[b]Asterisk means conversion is exact.

is used to measure negative pressures. A compound gauge is designed to measure both positive and negative pressures and indicates gauge pressure and vacuum on the same scale. A negative gauge pressure indicates that the system is operating under a vacuum, ie, the absolute pressure is less than barometric. For systems that operate under negative pressures, ie, under vacuum, absolute pressure is equal to the barometric pressure minus the vacuum. If a gauge, for example, indicates -25 in. of mercury (-25 in. Hg), the local barometric pressure is 29.9 in. Hg, and the ambient temperature is 60°F, then the absolute pressure is 4.9 in. Hg (16.5 kPa).

3. Mechanical Gauges

Pressure, particularly where pressure is monitored as opposed to being controlled, is generally measured by directly actuated mechanical elements. Mechanical gauges, reliable and inexpensive, dominate process applications in older plants. Moreover, the sensing elements for many of the more modern and sophisticated electronic transmitters are simple mechanical elements such as Bourdon tubes or diaphragms. Mechanical gauges may be divided into two groups. The first, which includes liquid manometers, bell gauges, and slack diaphragm gauges, measure pressure by balancing an unknown force against a known force. The second, Bourdon gauges, diaphragm gauges, and bellows elements, rely on elastic deformation of a sensing element for pressure measurement (3).

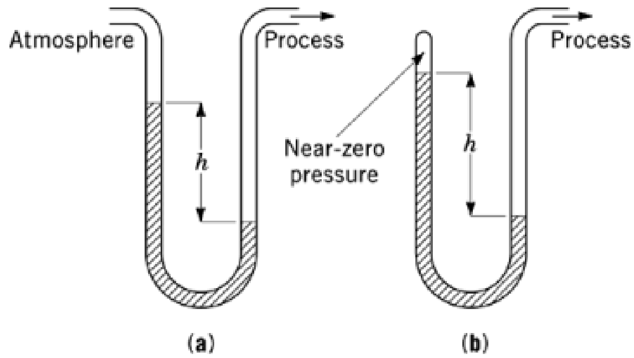

Fig. 1. U-Tube manometer where h is the height of the (▨) liquid employed: (**a**) open; (**b**) closed.

3.1. Liquid Manometers

Liquid manometers were used extensively by scientists in the seventeenth through the early twentieth centuries to measure pressure. The practice of expressing pressure as a certain height of liquid evolved from this usage. The typical liquid manometer consists of a cyclindrical glass U-tube partially filled with liquid. One end is connected to the process; the other can be either open or closed (Fig. 1).

An open manometer is normally used to measure pressure relative to local barometric pressure or to measure differential pressure, ie, the difference between two pressures. Open manometers are used, for example, for measuring pressure differentials across fans, heat exchangers, and distillation column trays. Almost any liquid of known density can be used. Water (qv), mercury (qv), and heavy oils are most common. Closed manometers are used to measure absolute pressures. The mercury barometer is a familiar example of the closed manometer. Liquid manometers are increasingly regarded as too fragile for general use in the CPI, and restrictions placed on the use of mercury in most processes frequently precludes consideration of mercury manometers for measuring process pressures. The principal use of liquid column manometers as of this writing (1996) is as a primary standard for calibrating other gauges.

3.2. Inverted Bell-Type Pressure Element

An inverted bell manometer, illustrated in Figure 2, consists of two inverted bells immersed in oil. The oil provides a liquid seal. The bells are suspended from opposite ends of a balance beam and are arranged so that pressure, P, can be introduced under each bell. One of the lines is usually open to atmospheric pressure, the other to the pressure to be measured. The bell subjected to the higher pressure rises in the oil, tilting the beam which moves a pointer on a scale. This instrument responds to a pressure difference, ΔP, as small as 0.1 Pa (0.0004 in. H_2O). The gauge ranges available range from 0–0.05 kPa (0–0.2 in. H_2O) up to 0–3.7 kPa (0–15 in. H_2O) pressure or vacuum. Inverted bell manometers are used for measuring very low positive pressures, such as those found in furnace kiln drafts and conveyor dryers (see Drying; Furnaces, fuel-fired).

3.3. Bourdon Tube

A Bourdon tube is made from a flattened or elliptical tube, where one end is sealed, the other open to the process. Figure 3 illustrates the three basic designs of this sensing element. All Bourdon tubes are based on the simple principle that a closed-end, flattened or elliptical coiled tube tends to straighten out when a gas or a liquid under pressure is allowed to enter the tube. The Bourdon tube responds to the pressure difference between the inside and the outside of the tube. If a Bourdon tube is connected to a system under vacuum, atmospheric

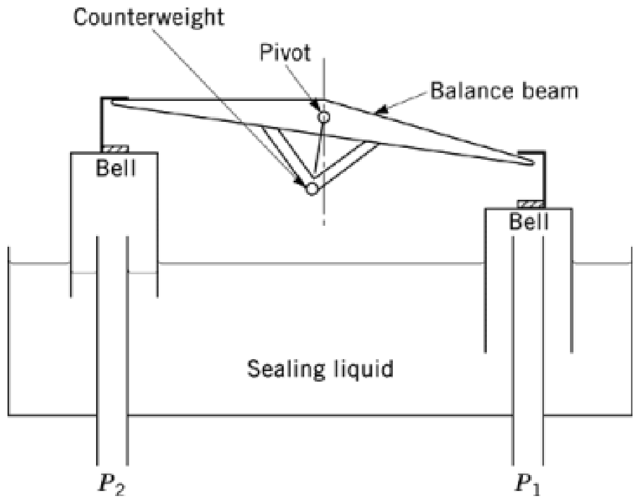

Fig. 2. Balanced-beam bell-type pressure gauge.

pressure causes the tube to curl inward. Bourdon tubes are, therefore, used extensively in pressure gauges, in vacuum gauges, and in compound gauges.

The C-Bourdon tube (Fig. 3**a**) usually has an arc of 250°. The open end of the tube is fixed. The closed end of the tube, ie, the tip of the tube, is connected through a mechanical linkage to a pointer or a pen. The principal limitation of the C-design is tip travel. The degree of movement per unit pressure change is small, and the design of the mechanical linkages required for amplification can be quite complex. The spiral Bourdon (Fig. 3**b**) is made by winding the tube in a spiral of several turns, instead of the relatively short 250° arc of the C-design. This gives the spiral a much higher degree of movement per unit of pressure change. The helical Bourdon tube (Fig. 3**c**) has the same advantage and even more tip travel than the spiral (4). The C-Bourdon tube is more often used as the sensing element for a pressure gauge, a vacuum gauge, or a transmitter. Spiral or helical Bourdon tubes are more likely to be used in receivers and recorders.

The advantages of Bourdon tube gauges include low cost, simple construction, availability of instruments for measuring both high and low pressures, and many years of application experience. Bourdon tube limitations include loss of precision below 345 kPa (50 psi) because the Bourdon tube has a very low spring gradient; mechanical linkages usually required for amplification being a source of hysteresis; accumulation of process materials in the Bourdon tube compromising accuracy; and gauges that are susceptible to damage resulting from shock and vibration. Instruments using C-Bourdon elements span the range from 1.3 kPa to 689×10^5 MPa (10 torr to 100,000 psi). The minimum span is about 69 kPa (10 psi). Spiral elements span the range from 0–138 kPa to 0–27.6 MPa (0–20 to 0–4,000 psi), and helical elements are used for 0–689 kPa to 0–689 MPa (0–100 to 0–100,000 psi). Bourdon tubes are fabricated from phosphor bronze, beryllium copper, steel, stainless steel, Monel, Ni-Span C, and special alloys.

3.4. Diaphragm Gauges

The sensing element for a diaphragm gauge is a flexible disk, either flat or having concentric corrugations, made of sheet metal. Some gauges use the diaphragm itself as the pressure sensor; others use it as the basic component for a capsule, manufactured by fusion-welding two diaphragms together at their peripheries. Figure 4 shows a flat diaphragm, a corrugated diaphragm, and two basic types of capsules. Most diaphragms have concentric corrugations which make possible deflection-to-pressure ratios many times greater than those of

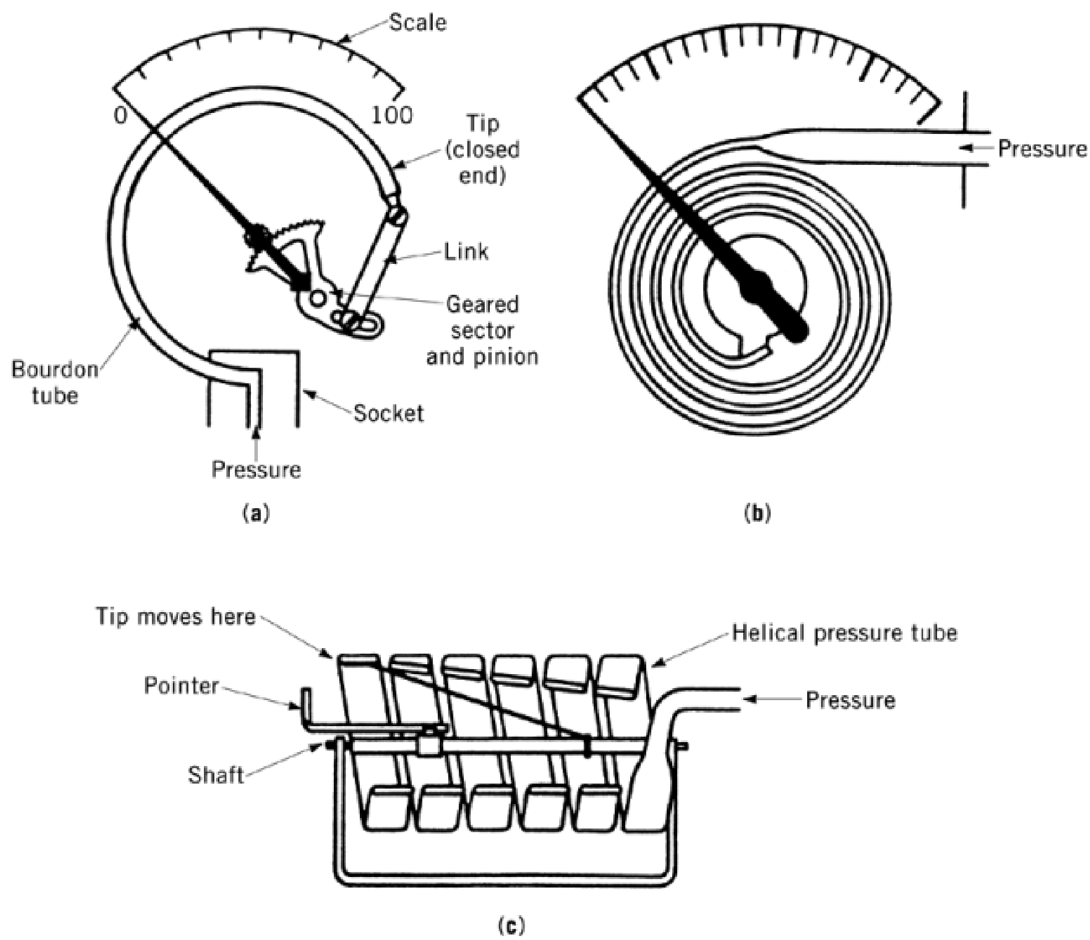

Fig. 3. Bourdon pressure elements: (**a**) C-Bourdon tube; (**b**) spiral Bourdon tube; (**c**) helical Bourdon tube.

flat plates. Capsules are of two types: convex (Fig. 4**d**), in which the orientation of the corrugations of the two diaphragms is opposed; and nested (Fig. 4**e**), in which the corrugations match.

Diaphragm elements are sensitive to small pressure changes and are therefore particularly useful in the measurement of low pressures. Absolute pressures approaching 13 Pa (0.1 torr) can be accurately measured by using thin-walled beryllium copper diaphragms and designing the gauge for a narrow pressure range. The diaphragm capsule behaves much like a simple bellows element, but the capsule is more accurate and more durable, because the movement of the diaphragm is small, ie, well within the elastic limits of the metal. Diaphragm capsules are used for the pressure ranges 0–0.5 kPa (0–2 in. H_2O) to 0–689 kPa (0–100 psi). Diaphragm and diaphragm capsules are fabricated from a wide variety of materials, including phosphor bronze, beryllium copper, stainless steel, Monel, Ni-Span C, Hastelloy, and Inconel.

Slack diaphragm gauges use diaphragms made from an elastomer such as silicone rubber (see Elastomers, synthetic). A slack diaphragm gauge does not rely on elastic deformation of the diaphragm for pressure measurement. The pressure-sensing element is a calibrated spring. The spring gradient determines the deflection of the discharge for an applied pressure. The gauge measures pressure by balancing an unknown force against a known force. The Magnehelic gauge is an example. The diaphragm is made of silicone rubber and is balanced

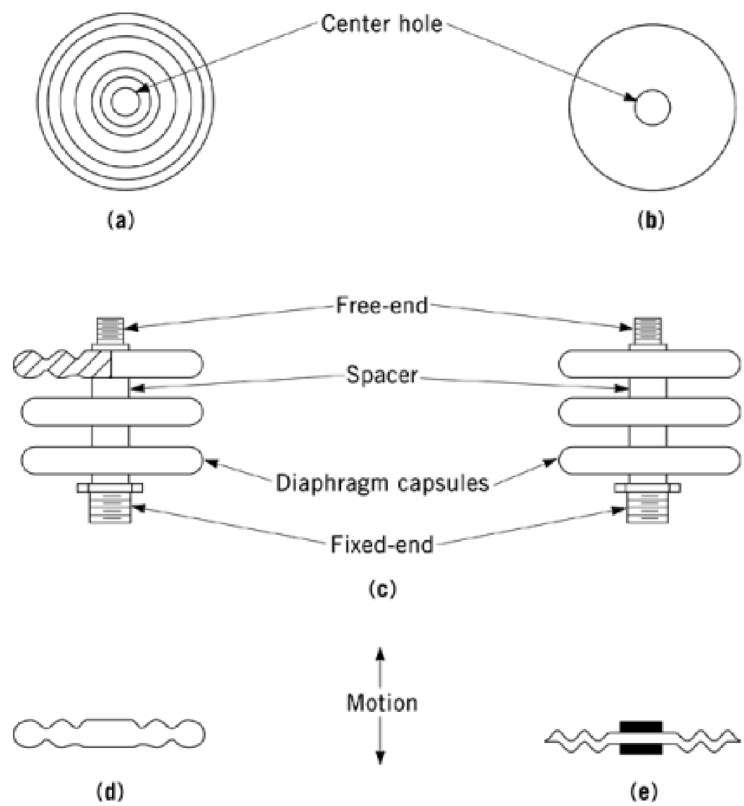

Fig. 4. Diaphragm pressure elements: (**a**) corrugated diaphragm; (**b**) flat diaphragm; (**c**) multielement diaphragm capsules; (**d**) convex capsule; and (**e**) nested capsule.

by a spring. The motion of the spring is transmitted through a magnetic linkage to the pointer. Slack diaphragm gauges, which cover the range 0–405 kPa (0–120 in. H_2O), are used extensively for measuring pressure drop across filters used in ventilating systems and to measure pressure drop in pneumatic conveying systems (see Conveying). In this and a number of similar applications, these gauges are both more accurate and more reliable than conventional Bourdon tube gauges.

3.5. Bellows Elements

A cross-section of a spring-and-bellows pressure element is shown in Figure 5. The bellows is enclosed in a metal housing connected by piping to the process and restrained at the top by a form-fitted nut. A rod resting on the bottom of the bellows transmits any vertical motion of the bellows through a suitable linkage to a pointer or pen. As the pressure inside the bellows increases, the bellows compresses the spring. The stiffness of the bellows is small compared to the stiffness of the spring, and therefore the pressure range is primarily a function of the stiffness of the spring. A spring-and-bellows pressure element can be used at pressures from approximately 0–1.24 kPa (0–5 in. H_2O) to 0–345 kPa (0–50 psi).

The bellows is formed from a length of thin-walled tubing by extrusion in a die. The metals used in the construction of the bellows must be ductile enough for reasonably easy fabrication and have a high resistance to fatigue failure. Materials commonly used are brass, bronze, beryllium copper, alloys of nickel and copper, steel, and Monel (5).

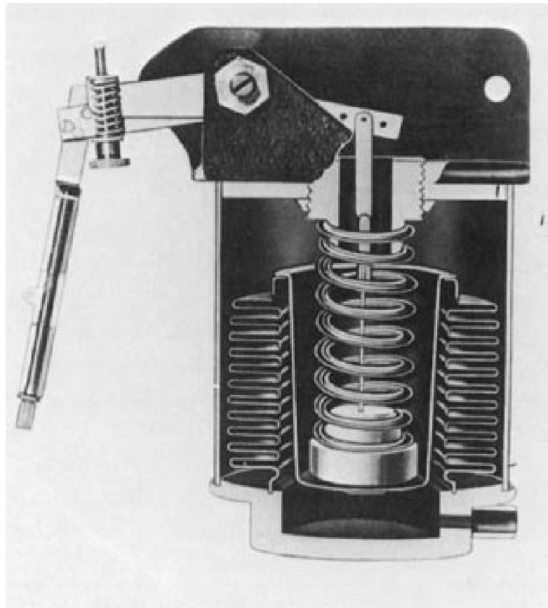

Fig. 5. Cross section of a spring-and-bellows pressure element.

3.6. Meters

Diaphragms, diaphragm capsules, and bellows elements are used extensively in meter bodies designed to measure differential pressure. These units can be used to measure the differences in pressure between two water lines, two steam headers, two stills, etc, from 25 Pa (0.1 in. H_2O) to 0–4826 kPa (0–700 psi) and are designed to operate at pressures as great as 69 MPa (10,000 psi). A bellows-actuated meter body is illustrated in Figure 6. The high pressure and low pressure bellows are joined by the center-stem assembly. The entire volume inside the bellows is filled with liquid, and the bellows is sealed. When the pressure at the high pressure tap exceeds the pressure at the low pressure tap, the high pressure bellows moves to the right and, by means of the center stem and the liquid fill, forces the low pressure bellows to the right. Motion stops when the force on the stabilizing spring equals the differential pressure, ie, the difference between the high and low pressures. The cable and motion take-off arm translate the center-stem movement to the torque tube assembly, and this is connected to the linkage mechanism for positioning of the pointer or pen arm.

4. Electronic Sensors

Electronic sensors and electronic control systems have displaced many of the mechanical sensors and pneumatic control systems in the CPI. This change, occurring in the 1980s and 1990s, is the result of the superiority of electronic sensor technology, as well as the superiority of electronic control systems. Mechanical gauges rely on a mechanical linkage to convey movement of the sensor to a pointer or a pen. This mechanical linkage has a high degree of hysteresis and deadband that limits accuracy and repeatability of the movement. Electronic sensing of element movement eliminates many such problems, and is inherently more accurate. Electronic transmitters have the additional advantages, compared to pneumatic transmitters, of built-in calibration

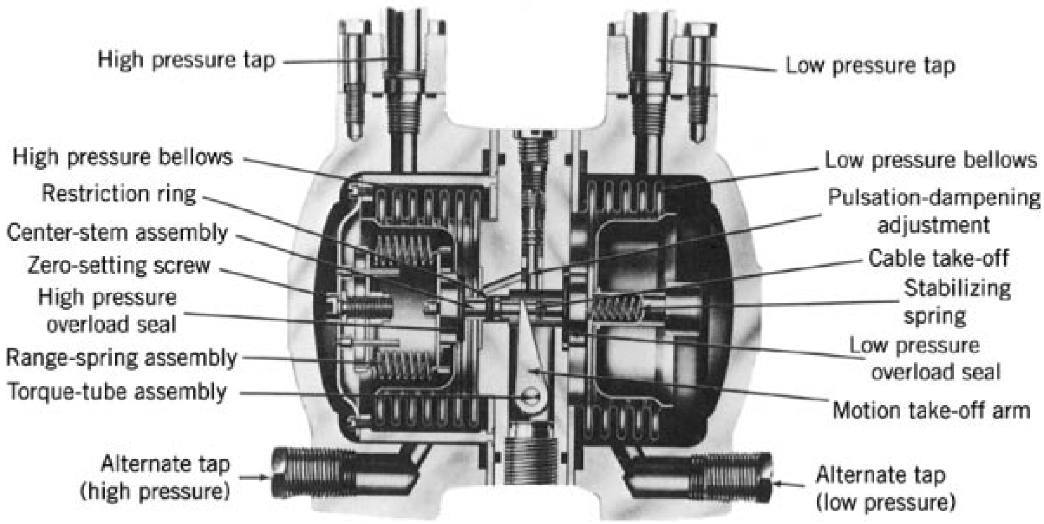

Fig. 6. Bellows-actuated differential-pressure element.

checks, temperature compensation, self-diagnostics, signal conditioning, and other features that may be derived from the use of microprocessors (6).

It is especially difficult in discussing electronic instruments to distinguish between a pressure sensor, a pressure transducer, and a pressure transmitter. Sensor and transducer are synonymous. The distinction between transducer and transmitter is, however, fundamental. All transmitters are transducers; not all transducers are transmitters. Most electronic transducers incorporate a mechanical element as the primary sensing element. An electronic transducer converts movement of a mechanical element, or the output from an electronic sensing element, to an electrical quantity such as resistance, capacitance, or voltage. In its simplest form, a pressure transmitter is a combination of a pressure transducer and a signal-conditioning circuit that outputs a current proportional to the process pressure. An electronic transmitter converts the movement of a mechanical element or the output from an electronic sensing element to a 4–20-mA signal, or to digital information, for transmission to an indicator, a recorder, a controller, or to a distributive control system (DCS).

4.1. Piezoelectric Elements

Designs of piezoelectric pressure elements are based on the principle that certain crystalline insulators, such as quartz (see Silica, synthetic quartz crystals), when properly cut and oriented with respect to their crystallographic axes, generate a small electric charge when stressed. In practice, a stack of quartz plates is mounted in a housing, which has a thin diaphragm at one end. The housing is usually designed to be mounted in the wall of a pressure vessel. The diaphragm is exposed to the pressure and deflects, thereby applying a compressive force to the stack, which in turn generates a charge that is directly proportional to the force. A typical design is shown in Figure 7. Piezoelectric sensors cannot measure static or absolute pressures for more than a few seconds, but this automatic elimination of static signals allows drift-free operation. Piezoelectric sensors are very rugged. Consequently these sensors are used extensively in demanding applications to measure the dynamic pressures associated with the operation of shock tubes, rocket motors, internal-combustion engines, mufflers, pumps (qv), compressors, pipelines (qv), and oil exploration imploders (7). Such devices are available in pressure ranges between 0–345 kPa (0–50 psi) and 0–69 MPa (0–10,000 psi). Some are available in ranges

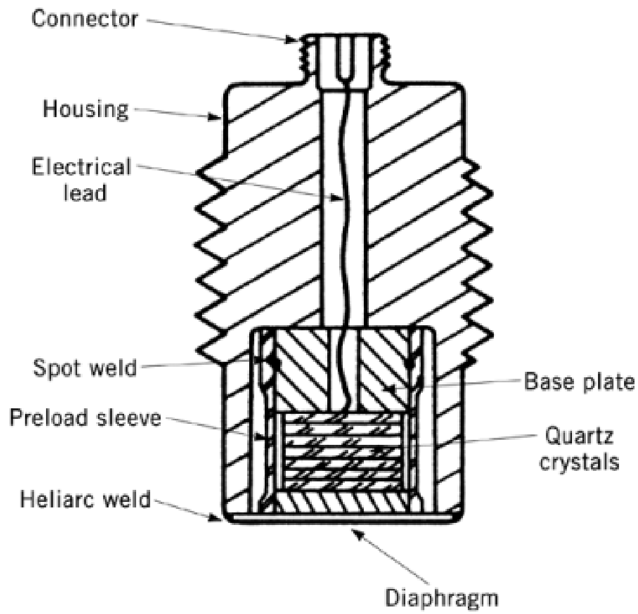

Fig. 7. Piezoelectric pressure sensor.

as low as 0–69 Pa (0–0.01 psi) and as high as 0–827 MPa (0–120,000 psi). Response time is generally very fast. Frequency response can be as high as 500 kHz.

4.2. Linear-Variable-Differential-Transformer and Reluctive Pressure Transducers

In a linear-variable-differential-transformer (LVDT) pressure transducer, the pressure to be measured is fed to a Bourdon tube or diaphragm. The motion of this element is transferred to the magnetic core of a transformer. Using a-c excitation of the primary coil of the transformer, a varying voltage is produced in the secondary coil as the core is moved. The two secondary coils are wound in opposite directions. Therefore, when the core is centered between them, the voltages cancel each other. When the core is moved from center, a differential voltage is produced. This voltage is proportional to the movement of the Bourdon tube or diaphragm, which is proportional to the pressure.

Measurement by a reluctive transducer is based on the ratio of the reluctance of the magnetic flux path of two coils. Reluctance is the resistance to magnetic flow offered by a magnetic substance to magnetic flux. Reluctance is the equivalent of electrical resistance in a magnetic circuit. In the sensor system shown in Figure 8, a diaphragm of magnetically permeable material is supported between two symmetrical E-core inductance assemblies and completes a magnetic circuit with each one. Application of pressure to the diaphragm causes it to deflect, thereby increasing the gap in the magnetic flux path of one core and decreasing the gap in the other by an equal amount. Because the magnetic reluctance varies with the gap, the inductance ratio changes with the position of the diaphragm. This can be measured in a bridge circuit, which produces an output voltage proportional to the pressure. Pressure ranges from 0–86 Pa (0–0.0125 psi) to 0–862 MPa (0–125,000 psi) are available. The pressure range can be changed in the field by simply replacing the diaphragm. The LVDT and reluctive pressure transducers are particularly well suited for low pressure measurement. This technology has been used extensively for absolute pressure measurements in the range 13–1333 Pa (0.1–10.0 mm Hg absolute).

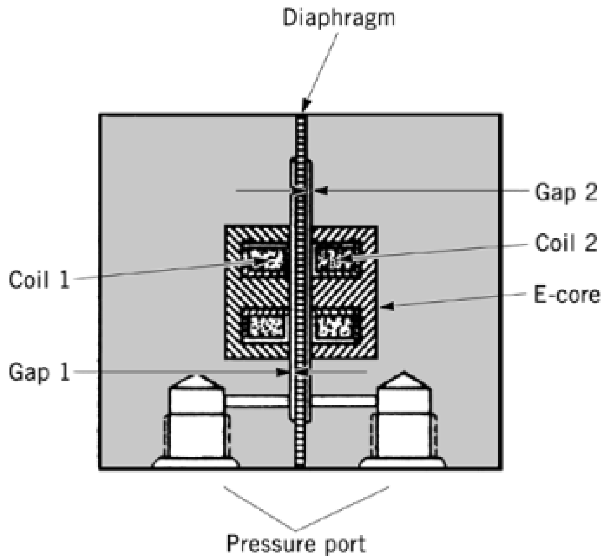

Fig. 8. Reluctance-type pressure sensor. The E-core corresponds to the area where the magnetic fields are produced. (Courtesy of Validyne Engineering Corp.)

4.3. Strain Gauges

The simplest version of a strain gauge uses the change in the electrical resistance of a metal wire under strain to measure pressure. A bonded strain gauge is constructed by using an adhesive to bond a metal wire (or a metal foil) to an elastic sensing element, usually a Bourdon tube, diaphragm, or a bellows element. Electrical insulation is provided by the adhesive or by backing material on the strain gauge. The gauge changes movement of the sensor to an electrical signal. When the length of the wire is changed by tension or compression, the result is a change in the diameter of the wire and, hence, a change in electrical resistance. The change in resistance is a measure of the pressure.

The construction of a bonded strain gauge is illustrated in Figure 9. The ideal strain gauge would change resistance in response to deformation of the surface to which it is bonded, and for no other reason (8). The measurement is obtained, however, by transferring strain from the sensing element through the adhesive and the backing material to the strain gauge. The accuracy of the measurement is, therefore, limited by the characteristics of the adhesive and the backing material. The adhesives (qv) and backing materials are usually epoxies.

The development of thin-film and diffused semiconductor strain gauges represents significant advances in strain-gauge technology. A thin-film strain gauge is produced by depositing a thin layer of metal on a metal diaphragm by either vacuum deposition or sputtering (see Thin films). To produce thin-film strain-gauge transducers, first an electrical insulator such as a ceramic is deposited on the diaphragm (see Ceramics as electrical materials). The strain-gauge alloy is deposited on the insulator. This technique produces a strain gauge that is molecularly bonded to the element, thus eliminating temperature effects and stress creep associated with organic adhesives. The result is long-term stability, which is the principal advantage of thin-film strain-gauge technology.

In the construction of a diffused semiconductor strain gauge, the gauge is diffused directly into the surface of a silicon diaphragm, using photolithographic masking techniques and solid-state diffusion of an impurity element, such as boron. Bonding does not involve an adhesive. Creep and hysteresis are, therefore, eliminated. The diffusion process does, however, require that the diaphragm be made from silicon.

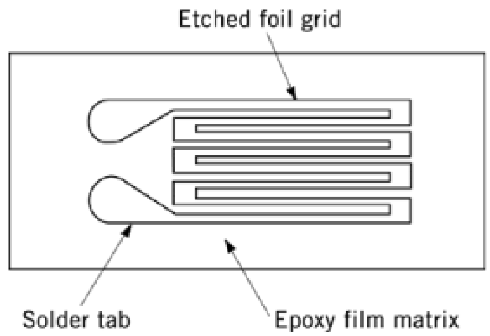

Fig. 9. Bonded metal foil strain gauge showing etched foil grid.

All strain gauges convert a pressure change to a change in electrical resistance. The resistors are usually arrayed in the four arms of a Wheatstone bridge. The advantages of the strain-gauge transducer are fast response, practically infinite resolution, minimum movement of elastic elements, high accuracy, comparative ease of compensation for temperature effects, low source impedance, and relative freedom from acceleration effects. The disadvantages include the difficulty of obtaining zero output at zero pressure, ie, bridge imbalance, low output levels, difficulties associated with isolating the excitation ground from the output ground, and signal conditioning requirements that include zero nulling and calibration. Generally, strain-gauge accuracies range from ±0.1 to ±2% of full scale. Strain-gauge pressure transducers are available for measurement of 0–3.3 kPa (0–25 mm Hg) to 0–1379 MPa (0–200,000 psi).

4.4. Piezoresistive Sensors

The distinction between strain-gauge sensors and piezoresistive (integrated-circuit) sensors is minor. Both function by measuring the strain on an elastic element as it is subjected to pressure. A piezoresistive transducer is a variation of the strain gauge that uses bonded single-crystal semiconductor wafers. Pressure applied to one side of a silicon wafer strains resistors diffused into the wafer. The change in applied pressure causes a linear change in the resistance value, which can then be converted and amplified to a usable output signal. In some designs, the transducer consists of a single silicon crystal sensor and its supporting electronics mounted in a pressure-tight housing on a ceramic substrate. If the transducer is to be used in an application that involves a corrosive or a conductive process fluid, the housing is filled with silicone oil. An elastic diaphragm isolates the oil from the process fluid, as it allows pressure to be applied to the oil. Because of high natural frequencies (greater than 50 kHz), single silicon crystal sensors are very reliable for use under conditions of severe shock and vibration. These sensors can be used to measure pressure from 69–34,000 kPa (10–5,000 psi). Operating temperatures are −1 to 85°C.

In other designs, a diffused silicon sensor is mounted in a meter body that is designed to permit calibration, convenient installation in pressure systems and electrical circuits, protection against overload, protection from weather, isolation from corrosive or conductive process fluids, and in some cases to meet standards requirements, eg, of Factory Mutual. A typical process pressure meter body is shown in Figure 10. Pressure measurement from 0–746 Pa (0–3 in. H_2O) to 0–69 MPa (0–10,000 psi) is available for process temperatures in the range −40 to 125°C. Differential pressure- and absolute pressure-measuring meter bodies are also available. As transmitters, the output of these devices is typically 4–20 mA dc with 25-V-dc supply voltage.

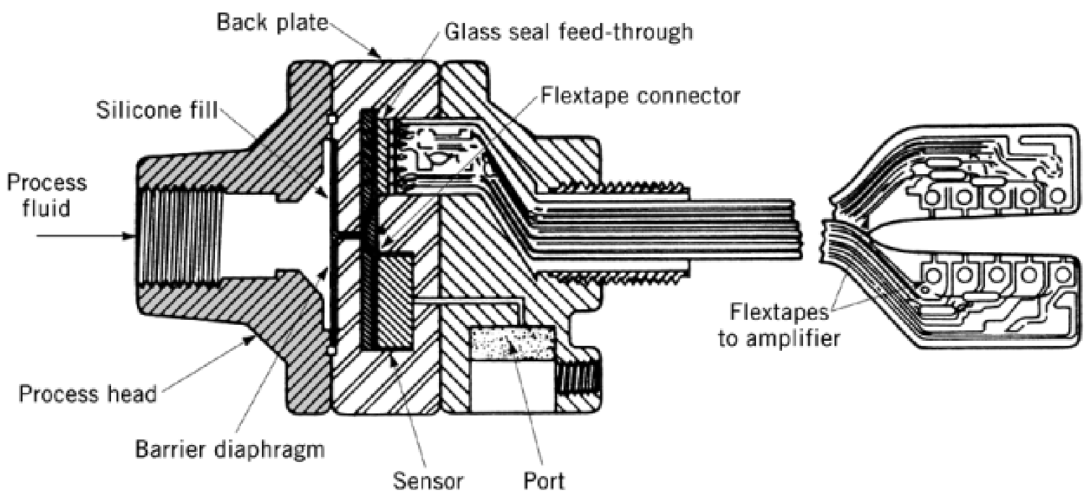

Fig. 10. Cross-section of meter body having a piezoresistive pressure sensor. (Courtesy of Honeywell, Inc.)

4.5. Capacitive Pressure Transducers

In all capacitive pressure detectors, the basic operating principle is that a change in capacitance occurs owing to the movement of an elastic element. In a conventional capacitance-type pressure transducer, the sensing element is a diaphragm. A cutaway view of a transducer designed to measure differential, absolute, or gauge pressure is shown in Figure 11. The process comes in contact with an isolating diaphragm, a metal diaphragm used to isolate the sensing element from the process. Process pressure is hydraulically coupled to the sensing element. A change in process pressure is hydraulically transmitted by the silicone oil fill fluid from the isolating diaphragm to the sensing element. Deflection of the sensing diaphragm is detected by capacitor plates positioned on either side of it. Diaphragm movement changes the capacitance between the plates and the diaphragm; one side increases while the other decreases. Signal conditioning converts the capacitance change to a stable direct current or voltage signal. Standard output for a two-wire transmitter is 4–20 mA dc.

The transducer is very rugged. The most sensitive components in the transducer are isolated from the process, and movement of the sensing diaphragm is restricted to give over-pressure protection as high as 31 MPa (4500 psi). Fabrication of wetted parts from stainless steel, Hastelloy C-276, or Monel ensures that exposure to the process does not drastically reduce transducer life. Capacitive pressure transducers are available for measurement of gauge pressures in the range 0–1.24 kPa (0–5 in. H_2O) to 41.4 MPa (0–6000 psi). The lower end of the range for transducers designed to measure differential pressure is 0–124 Pa (0–0.5 in H_2O). Absolute pressure transducers have been designed to measure pressures as low as 0–6.8 kPa (0–2 in. Hg absolute), but the conventional capacitive pressure transducer is significantly less accurate than a capacitance manometer for absolute pressures less than approximately 1.3 kPa (10 torr).

5. Vacuum Measurement

Vacuum measurement spans the range from 10^5 Pa (atmospheric pressure) to pressures that are less than 10^{-10} Pa (7.5×10^{-13} torr), ie, more than 16 orders of magnitude. Subatmospheric pressures are divided into six regions for convenience (9):

Vacuum region	Pressure, Pa	Torr
low	$10^5 - 3.3 \times 10^3$	750–25
medium	$3.3 \times 10^3 - 10^{-1}$	$25 - 7.5 \times 10^{-4}$
high	$10^{-1} - 10^{-4}$	$7.5 \times 10^{-4} - 7.5 \times 10^{-7}$
very high	$10^{-4} - 10^{-7}$	$10^{-6} - 10^{-10}$
ultrahigh	$10^{-7} - 10^{-10}$	$7.5 \times 10^{-10} - 7.5 \times 10^{-13}$
extreme ultrahigh	$\leq 10^{-10}$	7.5×10^{-13}

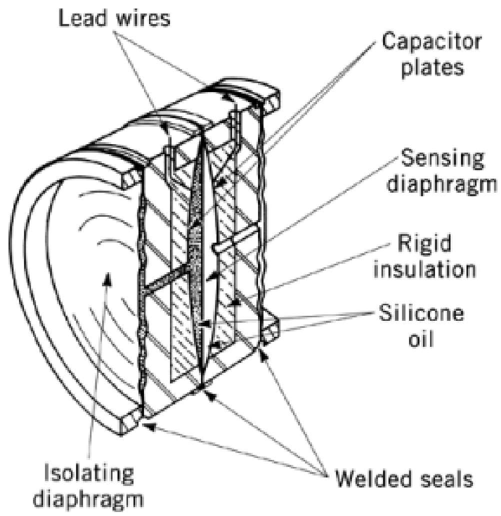

Fig. 11. Capacitive pressure sensor in the differential measurement configuration. Courtesy of Rosemount, Inc.

The pressure sensors discussed herein are reasonably accurate for measurement into the low vacuum region. Upon some modification, these sensors can be extended into the lower end of the range, to approximately 1.3×10^{-1} Pa (10^{-3} torr). Vacuum gauges are required for accurate measurement of lower pressures.

Vacuum gauges may be broadly classified as either direct or indirect (10). Direct gauges measure pressure as force per unit area. Indirect gauges measure a physical property, such as thermal conductivity or ionization potential, known to change in a predictable manner with the molecular density of the gas.

The definition of vacuum advanced herein assumes that pressure in the gaseous phase adequately characterizes vacuum environments. This assumption is normally good for processing applications in the range $10^5 - 1.3 \times 10^3$ Pa (760 torr to 100 μm Hg). Medium vacuum operations, and in particular high vacuum and ultrahigh vacuum operations, cannot be characterized by this simple, single-parameter approach. Molecular concentrations and the chemical identity of the molecules present in the vapor space and on the walls of the process vessel are important parameters in describing the vacuum environment in those pressure regions.

5.1. Capacitance Manometers

Capacitance manometers were first used in research laboratories in the early 1950s. The development of capacitance manometers designed specifically for the harsh environments that characterize chemical processes is, however, a more recent development. The near-phenomenal accuracy of capacitance manometers, typically 0.10% of a reading $\geq$13.3 Pa ($\geq$0.1 torr) to 3% of a reading at 10^{-2} Pa (10^{-4} torr), excellent linearity over a wide range of pressures, and the development of sensors that are rugged and reliable, increasingly makes this

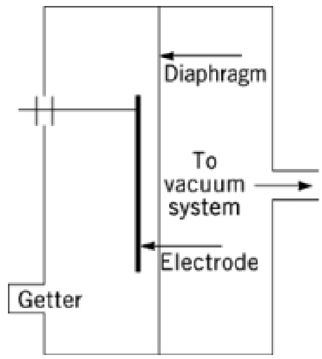

Fig. 12. Schematic of a capacitance manometer. (Courtesy of MKS Instruments.)

the technology of choice for vacuum measurements in the range $10^{-3} - 10^{3}$ Pa ($10^{-5} - 10$ torr). Capacitance manometers are rugged for two reasons. Gauge electronics never come in contact with the process, and the sensor body and metal diaphragm are fabricated from stainless steel, Monel, Inconel, or other high nickel alloys.

A pressure sensor for a capacitance manometer (Fig. 12) measures absolute pressure independent of gas composition. A permanently sealed cavity evacuated to a very low pressure, $10^{-5} - 10^{-6}$ Pa ($10^{-7} - 10^{-8}$ torr), and maintained by a getter material, ie, an adsorbent, provides an absolute pressure reference. The device is remarkably sensitive. Diaphragm deflections as small as 10^{-11} m (10^{-9} in.) can be detected. Using the thinnest diaphragms, this corresponds to a pressure of approximately 10^{-4} Pa (10^{-6} torr). The lower limit for accurate measurement, however, is approximately 10^{-3} Pa (10^{-5} torr). Nonlinearity is the most important single source of error, representing approximately 80% of all accumulated errors. Temperature effects, typically 0.06% of a reading for a 1°C change in temperature, are also important (11). A change in the temperature of the sensor causes it to undergo dimensional changes that affect sensor output. The effects of changes in ambient temperature on process gas temperature can be minimized by using sensor heaters to maintain the sensor at a constant elevated temperature (typically 40–80°C).

The capacitance manometer is in essence an electronic diaphragm gauge. It differs from the mechanical diaphragm gauge in the way diaphragm deflections are translated into pressure readings. The mechanical gauge employs a mechanical linkage. The capacitance manometer uses capacitance changes to measure diaphragm deflections. Capacitance manometers are very accurate and exhibit excellent retention of calibration. They have, therefore, been almost universally adopted as secondary calibration standards for pressure measurement in the range $10^{-2} - 10^{5}$ Pa ($10^{-4} - 760$ torr). Capacitance manometers exhibit excellent linearity over a wide range of pressures, and sensors are routinely designed to cover three or four decades, ie, three or four orders of magnitude. Sensors that cover six decades have also been developed.

5.2. Thermal Conductivity Gauges

Thermal conductivity gauges measure thermal conductivity and are thus indirect gauges. Pressure is measured indirectly. The thermal conductivity of a gas is essentially independent of pressure for pressures greater than approximately 1.33 kPa (10 torr). As the pressure is reduced below 1.33 kPa (10 torr), the thermal conductivity of a gas decreases, first by a logarithmic relation, then linearly as the pressure approaches 10^{-1} Pa (10^{-3} torr). The range of thermal conductivity gauges spans almost eight decades, from atmospheric to 10^{-3} Pa, but application is limited almost exclusively to the pressure range 133–0.1 Pa ($1 - 10^{-3}$ torr).

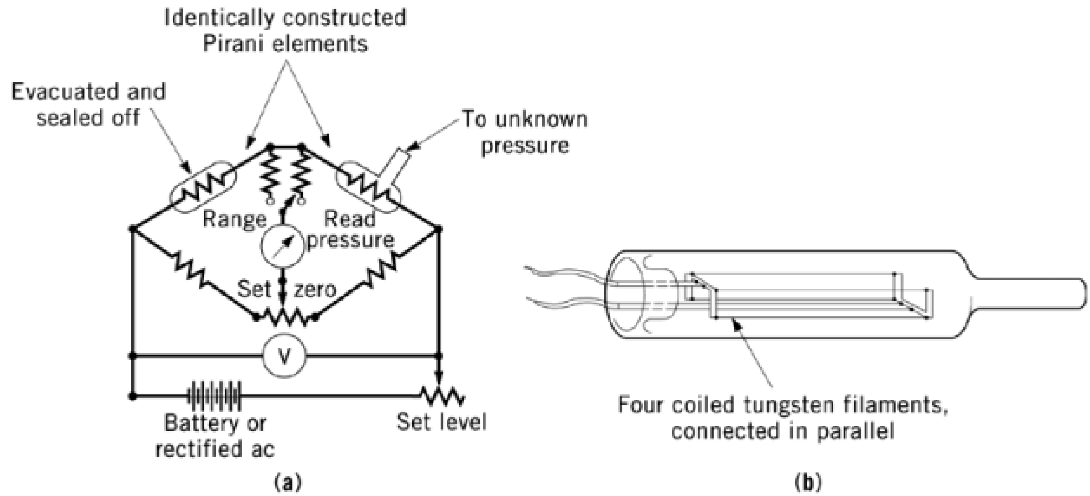

Fig. 13. Pirani gauge circuit: (**a**) gauge in a fixed-voltage Wheatstone bridge; (**b**) sensing element (6).

The sensor for a thermal conductivity gauge is a thin metal wire or heat-sensitive element enclosed in a metal cyclinder. The element is electrically heated. If a constant current is maintained across the element, the temperature of the element increases as the pressure in the metal cylinder is reduced below 1.33 kPa (10 torr). The rate at which heat is transferred from the element to the cylinder wall decreases, because the thermal conductivity of the gases surrounding the element decreases with pressure. Convection is insignificant and radiation and conduction through the connecting wires can usually be ignored at pressures $>10^{-1}$ Pa (10^{-3} torr). The thermal conductivity of the gases surrounding the element, and indirectly the pressure, can therefore be measured by measuring the temperature of the element. The different means used to measure the temperature of the heated element distinguish the two main types of thermal conductivity gauges, the Pirani gauge, shown schematically in Figure 13, and the thermocouple gauge (12).

The Pirani gauge is so constructed that the resistance of the heated element is directly proportional to the element temperature. System pressure is measured by measuring the resistance of the element. The heated element comprises one arm of a Wheatstone bridge. An identical element, sealed in an evacuated tube, makes up an adjacent arm of the network. The sealed element, or compensating element, partially compensates for small changes in bridge voltage and ambient temperature. In the operation of a thermocouple gauge, the temperature of the heated element is measured directly by a thermocouple. The thermocouple, usually iron or copper–constantan, is spot welded to the element. The current used to heat the element is kept constant, and the pressure is indicated by the output of the thermocouple. The current produced by the thermocouple is measured by a microammeter that is calibrated in pressure units. The pressure indicated by a thermal conductivity gauge is composition-sensitive. The thermal conductivity of a gas depends on the gas composition. Dry air or nitrogen are used in calibrating the gauge. Gauge readings must, therefore, be corrected if an absolute indication of pressure is required and gases other than those used for calibration are present in the system.

Thermal conductivity gauges are simple and robust, but not very accurate. Accuracy quoted in instrument specifications is typically $\pm 20\%$ of reading across the range 0.1–133 Pa ($10^{-3} - 1$ torr). Thermal conductivity gauges are generally used as pressure indicators, to monitor rather than measure system pressure. The advantages of these gauges include low cost, simplicity, and interchangeability of the sensing elements. They are well adapted for applications in which a single power supply and measuring circuit is used, with sensing elements located at different parts of the same vacuum system or on several different systems.

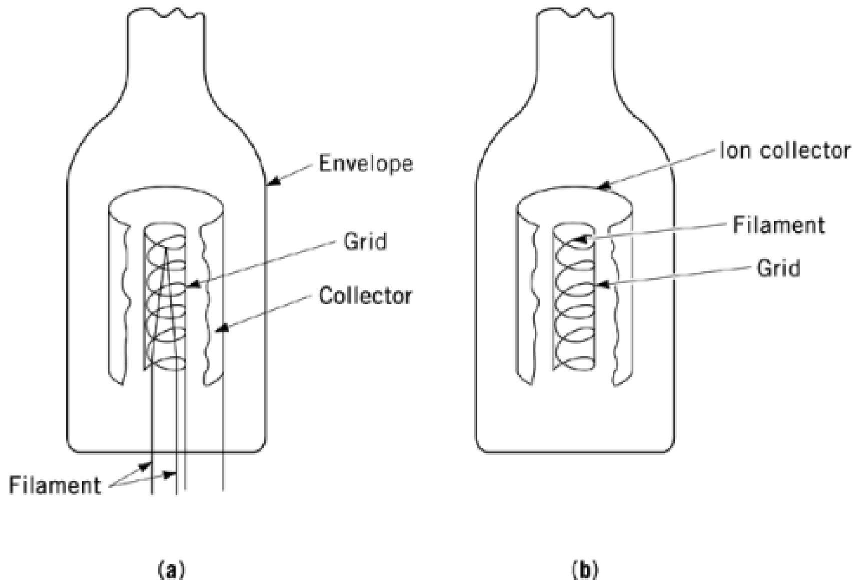

Fig. 14. Ionization gauges: (**a**) triode head and (**b**) Bayard-Alpert.

5.3. Hot-Cathode Ionization Gauges

For pressures below approximately 10^{-4} Pa, it is not possible, except under carefully controlled conditions, to detect the minute forces that result from the collision of gas molecules with a solid wall. The operation of the ion gauge is based on ionization of gas molecules as a result of collisions with electrons. These ions are then subsequently collected by an ion collector. Ionization gauges, used almost exclusively for pressure measurement in high, very high, ultrahigh, and extreme ultrahigh vacuums, measure molecular density or particle flux, not pressure itself.

The earliest form of ion gauge, the triode gauge, looks much like a triode vacuum tube (Fig. 14**a**). The gauge consists of three electrodes in a hermetically sealed tube: a filament surrounded by a grid wire helix and a large-diameter, solid cylinder. The filament, typically tungsten, serves as the cathode. It is heated by an electric current, and electrons are released from the filament surface into the surrounding vacuum. Emission of electrons is controlled by controlling the electric current to the cathode. The grid serves as the anode and is set at a positive potential of 100–300 V with respect to the cathode. The grid attracts the electrons emitted by the cathode. The third electrode, the plate, is set at a potential of from -2 to -25 V with respect to the cathode. The plate, the ion collector, attracts positive ions generated by collisions between the electrons emitted by the cathode and molecules of gas. The usual practice using commercial hot-cathode ionization gauges is to precisely control the emission current to the cathode and measure pressure by measuring the ion current at the plate.

The operating range of conventional triode ionization gauges is $10^{-1} - 10^{-6}$ Pa $(10^{-3} - 10^{-8}$ torr). Burnout caused by positive ions reaching the cathode dramatically reduces filament life for gauges operating above approximately 10^{-1} Pa $(10^{-3}$ torr). The lower limit for the operating range is established by a phenomenon known as the x-ray effect and an associated phenomenon, the photoemission current. Electrons striking the anode, or grid, produce low energy x-rays. Photoemission of electrons occurs when x-rays produced at the anode strike the ion collector. Gauge electronics cannot distinguish between the current produced by positive ions striking the plate and the photoemission current, the current produced by the loss of electrons

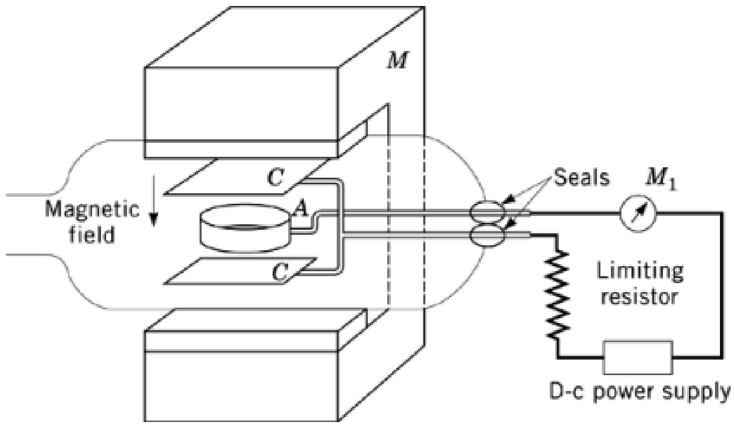

Fig. 15. Cold-cathode ionization gauge, where A=anode, C=cathode, M=horseshoe magnet, and M_1=microammeter (15).

from the plate. The photoemission current is independent of pressure, and the minimum plate current, a result of the x-ray effect, corresponds to a pressure of approximately 10^{-6} Pa (10^{-8} torr).

The discovery of the x-ray effect spurred the development of a new generation of hot-cathode gauges designed to minimize this effect. One of the earliest, and commercially the most successful, the Bayard-Alpert gauge shown in Figure 14**b**, was developed in 1950 (13). A fine wire, the ion collector, is suspended along the axis of a cylindrical grid. The two-cathode design illustrated is typical. When one filament burns out, the other can be put into service, thus doubling the life of the gauge head. The most important feature of the Bayard-Alpert gauge is the use of a fine wire for the ion collector. The oncoming x-rays see a cross section that is at least two orders of magnitude less than the cross-section of a plate collector. X-ray effects are proportionately less and lower pressure readings are therefore possible. The lower limit for Bayard-Alpert gauges is $10^{-10} - 10^{-11}$ Pa ($10^{-12} - 10^{-13}$ torr).

The accuracy of indirect-reading gauges is always a source of concern. This is especially true of ionization gauges, because the ionization gauge is a particle density gauge. The ion current measured at the plate is a function of particle density and ionization probability. Particle density is proportional to pressure if, and only if, temperature is constant. Dry air or nitrogen is used in calibrating ionization gauges. These gauges must be recalibrated when used to measure the pressure of other gases. The ionization probability depends on the gas species (14). Hot-cathode ionization gauges are built to very demanding tolerances, and carbon contamination of electrodes over time compromises accuracy. In spite of these problems and under the less-than-ideal conditions that characterize industrial application of these gauges, hot-cathode ionization gauges are generally accurate to within $\pm 25\%$ for measurements in high and very high vacuum. The various ultrahigh versions of the triode and Bayard-Alpert gauges are accurate to within an order of magnitude.

5.4. Cold-Cathode Ionization Gauges

The cold-cathode gauge, the Penning gauge shown schematically in Figure 15, is more rugged, but less accurate, than the hot-filament ionization gauge (15). A potential of 2–10 kV is applied between the cathodes and the anode. The cathodes are constructed of zirconium, thorium, or another surface-active material. Free electrons are formed by the collision of positive ions with the cathodes. Electrons ejected from the cathodes collide with gas molecules to produce additional positive ions, setting up a Townsend discharge between the cathode and the anode. An essential element of this gauge is the permanent magnet positioned outside the gauge tube. Without it, the discharge cannot be maintained at pressures below approximately 1 Pa (10^{-2} torr). The magnetic field prevents electrons from traveling directly from cathode to anode. The electrons are constrained to move in helical paths along the lines of magnetic flux.

Electrons emitted by the cathode pass through the anode and continue until repelled by the other cathode. The electrons oscillate between the cathodes and eventually are captured by the anode. Because the electrons are forced to travel several meters before reaching the anode, the probability of colliding with gas molecules and forming positive ions is greatly enhanced. This allows a discharge to be maintained at pressures as low as 10^{-4} Pa (10^{-6} torr). Sensor output, the sum of the positive ion current to the cathode and the electron current leaving the cathode, is proportional to pressure over the range $1 - 10^{-4}$ Pa ($10^{-2} - 10^{-6}$ torr), the nominal pressure range for Penning cold-cathode ionization gauges.

Cold-cathode gauges are simpler, less expensive, and more rugged than hot-cathode gauges. One advantage of the cold-cathode gauges, as compared to hot-cathode gauges, is that cold-cathode gauges withstand accidental exposure to atmospheric pressure without damage. Because of safety concerns, the requirement for maintaining a potential of several thousand volts between the cathodes and the anode can be a significant disadvantage. The cold-cathode gauge is less accurate than the hot-cathode gauge. Under ideal conditions the Penning gauge is accurate to within $\pm 25\%$ over the range $1 - 10^{-4}$ Pa ($10^{-2} - 10^{-6}$ torr), but manufacturers' specifications that the accuracy of the gauge is within a factor of two is a more realistic estimate (16). The various ultrahigh versions of the gauge, the magnetron and the inverted magnetron, for example, are accurate to within an order of magnitude.

6. Smart Pressure Transmitters

In the mid-1980s, microprocessors were mated to pressure transmitters, and the first smart transmitters were the result (17). Conventional electronic pressure transmitters are strictly analogue in nature, converting the motion or changes in the electrical resistance of a sensor to standard 20–100-kPa (3–15-psig) pneumatic signals or to 4–20-mA d-c electrical signals. Smart transmitters convert the response of the sensor to a high resolution digital signal (Fig. 16). This signal is then linearized and compensated for temperature and, in the case of differential pressure transmitters, for static pressure effects. Once configured, the accuracy of the smart transmitter is dependent only on the accuracy of the sensor.

Intelligent or smart transmitters feature digital electronics, remote communication and configuration, and high turndown. The digital electronics that characterize the transmitter virtually eliminate errors introduced by rearranging. A smart transmitter has the ability to continuously monitor its operating conditions and correct itself for potential errors such as nonlinearity, ambient temperature effects, static pressure effects, etc. A smart transmitter performs continuous diagnostics of its sensing element, ie, the meter body, and electronics and of the loop power supply and wiring. Smart transmitters have the advantage, as compared to conventional analogue electronic transmitters, of greater accuracy and stability, and much greater range, ie, order one model, install it anywhere, and respan (without recalibration) at any time. Smart transmitters are easier to specify and use, inherently more reliable, and have lower maintenance costs. The advantages of smart transmitters are increasingly understood by the process control (qv) engineers who specify the control systems and the associated transmitters and by the instrument mechanics who maintain the system. Higher price tags notwithstanding, smart transmitters are rapidly replacing conventional transmitters.

The advent of the smart transmitter revolutionized the CPI's approach to process instrumentation. However, the widespread acceptance of smart transmitters, as of 1996, has been less than that expected. In applications where smart transmitters are being used, they have, for the most part, simply replaced conventional analogue transmitters. Full communication capabilities have not been utilized because of the need to maintain existing control systems that rely on 4–20-mA signals. Because all smart transmitters use digital electronics, the digital signal must pass through a digital-to-analogue (D/A) converter in order to transmit the 4–20-mA analogue signal. The D/A converter can be a significant source of error, and the time lag associated with the D/A

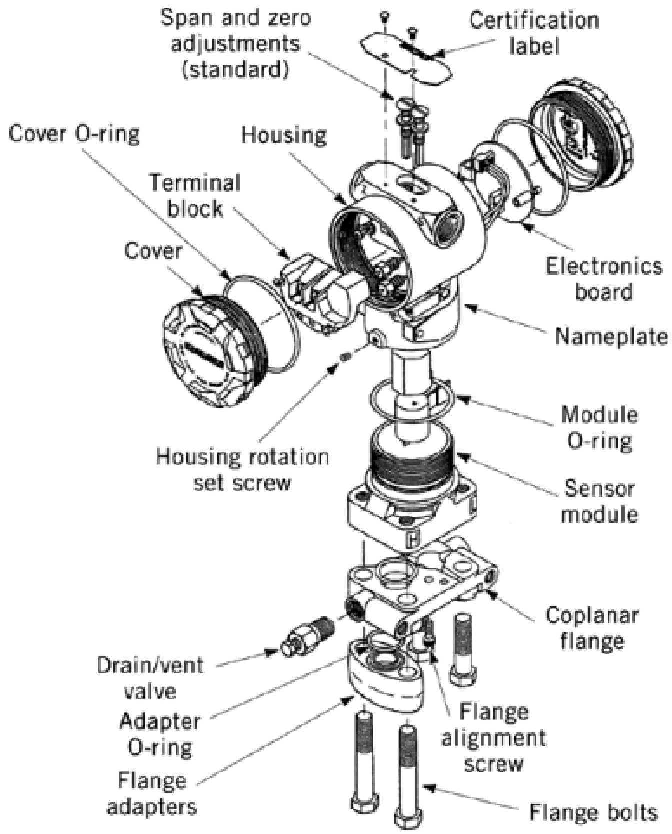

Fig. 16. Exploded view of a smart transmitter based on variable capacitance sensor technology. (Courtesy of Rosemount, Inc.)

conversion can be an issue in some applications. For example, for many years, 20–100 kPa (3–15 psig) and 4–20 mA have functioned as open protocols for conventional analogue systems universally adopted by instrument manufacturers and users worldwide. There is, however, no open, comprehensive, universally accepted digital communications protocol, ie, no fieldbus standard.

At first, each smart transmitter manufacturer had a unique and proprietary digital protocol which greatly reduced the user's flexibility in configuring control systems. Products from different vendors were simply not compatible. The ISA Standards and Practices Committee 50 (SP50) began working on a universal fieldbus standard in 1985. SP50 was given the mission of developing a nonproprietary (open), comprehensive, universal digital communications protocol. As of this writing (ca 1996), SP50 and a number of trade organizations that are pushing adoption of a fieldbus standard, are slowly making progress. Addition of fieldbus capability is an issue that can no longer be postponed by manufacturers. The next generation of smart transmitters, multivariable smart transmitters that can, for example, simultaneously measure absolute pressure, differential pressure, and temperature, are already in production. Adoption of a fieldbus standard will ensure compatibility of digital instrumentation, and the enhanced digital integration that is expected to follow should result in significant improvements in the CPI's process control systems (see Process control).

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J. L. RYANS
Eastman Chemical Company

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