Pressure measurement

Pressure measurement is a very common requirement for most industrial process control systems and many different types of pressure-sensing and pressure-measurement systems are available. However, before considering these in detail, it is important to explain some terms used in pressure measurement and to define the difference between absolute pressure, gauge pressure and differential pressure.

Absolute pressure: This is the difference between the pressure of the fluid and the absolute zero of pressure.

Gauge pressure: This describes the difference between the pressure of a fluid and atmospheric pressure. Absolute and gauge pressure are therefore related by the expression:

$$\text{Absolute pressure} = \text{Gauge pressure} + \text{Atmospheric pressure}$$

Thus, gauge pressure varies as the atmospheric pressure changes and is therefore not a fixed quantity.

Differential pressure: This term is used to describe the difference between two absolute pressure values, such as the pressures at two different points within the same fluid (often between the two sides of a flow restrictor in a system measuring volume flow rate).

In most applications, the typical values of pressure measured range from 1.013 bar (the mean atmospheric pressure) up to 7000 bar. This is considered to be the 'normal' pressure range, and a large number of pressure sensors are available that can measure pressures in this range. Measurement requirements outside this range are much less common. Whilst some of the pressure sensors developed for the 'normal' range can also measure pressures that are either lower or higher than this, it is preferable to use special instruments that have been specially designed to satisfy such low- and high-pressure measurement requirements.

The discussion below summarizes the main types of pressure sensor that are in use. This discussion is primarily concerned only with the measurement of static pressure, because the measurement of dynamic pressure is a very specialized area that is not of general interest. In general, dynamic pressure measurement requires special instruments, although modified versions of diaphragm-type sensors can also be used if they contain a suitable displacement sensor (usually either a piezoelectric crystal or a capacitive element).

15.1 Diaphragms

The diaphragm, shown schematically in Figure 15.1, is one of three types of elastic-element pressure transducer. Applied pressure causes displacement of the diaphragm and this movement is measured by a displacement transducer. Different versions of diaphragm sensors can measure both absolute pressure (up to 50 bar) and gauge pressure (up to 2000 bar) according to whether the space on one side of the diaphragm is respectively evacuated or is open to the atmosphere. A diaphragm can also be used to measure differential pressure (up to 2.5 bar) by applying the two pressures to the two sides of the diaphragm. The diaphragm can be either plastic, metal alloy, stainless steel or ceramic. Plastic diaphragms are cheapest, but metal diaphragms give better accuracy. Stainless steel is normally used in high temperature or corrosive environments. Ceramic diaphragms are resistant even to strong acids and alkalis, and are used when the operating environment is particularly harsh.

The typical magnitude of diaphragm displacement is 0.1 mm, which is well suited to a strain-gauge type of displacement-measuring transducer, although other forms of displacement measurement are also used in some kinds of diaphragm-based sensors. If the displacement is measured with strain gauges, it is normal to use four strain gauges arranged in a bridge circuit configuration. The output voltage from the bridge is a function of the resistance change due to the strain in the diaphragm. This arrangement automatically provides compensation for environmental temperature changes. Older pressure transducers of this type used metallic strain gauges bonded to a diaphragm typically made of stainless steel. However, apart from manufacturing difficulties arising from the problem of bonding the gauges, metallic strain gauges have a low gauge factor, which means that the low output from the strain gauge bridge has to be amplified by an expensive d.c. amplifier. The development of semiconductor (piezoresistive) strain gauges provided a solution to the low-output problem, as they have gauge factors up

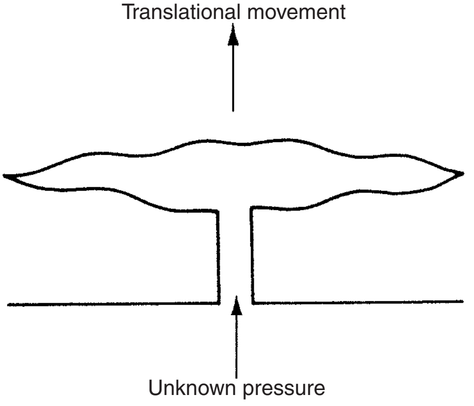

Fig. 15.1 Schematic representation of diaphragm pressure sensor.

to one hundred times greater than metallic gauges. However, the difficulty of bonding gauges to the diaphragm remained and a new problem emerged regarding the highly non-linear characteristic of the strain–output relationship.

The problem of strain-gauge bonding was solved with the emergence of monolithic piezoresistive pressure transducers. These have a typical measurement uncertainty of ±0.5% and are now the most commonly used type of diaphragm pressure transducer. The monolithic cell consists of a diaphragm made of a silicon sheet into which resistors are diffused during the manufacturing process. Such pressure transducers can be made to be very small and are often known as *micro-sensors*. Also, besides avoiding the difficulty with bonding, such monolithic silicon measuring cells have the advantage of being very cheap to manufacture in large quantities. Although the inconvenience of a non-linear characteristic remains, this is normally overcome by processing the output signal with an active linearization circuit or incorporating the cell into a microprocessor-based intelligent measuring transducer. The latter usually provides analogue-to-digital conversion and interrupt facilities within a single chip and gives a digital output that is readily integrated into computer control schemes. Such instruments can also offer automatic temperature compensation, built-in diagnostics and simple calibration procedures. These features allow measurement inaccuracy to be reduced to a figure as low as ±0.1% of full-scale reading.

15.2 Capacitive pressure sensor

A capacitive pressure sensor is simply a diaphragm-type device in which the diaphragm displacement is determined by measuring the capacitance change between the diaphragm and a metal plate that is close to it. Such devices are in common use. It is also possible to fabricate capacitive elements in a silicon chip and thus form very small *micro-sensors*. These have a typical measurement uncertainty of ±0.2%.

15.3 Fibre-optic pressure sensors

Fibre-optic sensors provide an alternative method of measuring displacements in diaphragm and Bourdon tube pressure sensors by optoelectronic means, and enable the resulting sensors to have lower mass and size compared with sensors in which the displacement is measured by other methods. The shutter sensor described earlier in Chapter 13 is one form of fibre-optic displacement sensor. Another form is the Fotonic sensor shown in Figure 15.2 in which light travels from a light source, down an optical fibre, is reflected back from a diaphragm, and then travels back along a second fibre to a photodetector. There is a characteristic relationship between the light reflected and the distance from the fibre ends to the diaphragm, thus making the amount of reflected light dependent upon the diaphragm displacement and hence the measured pressure.

Apart from the mass and size advantages of fibre-optic displacement sensors, the output signal is immune to electromagnetic noise. However, the measurement accuracy is usually inferior to that provided by alternative displacement sensors, and choice of such sensors also incurs a cost penalty. Thus, sensors using fibre optics to measure diaphragm or Bourdon tube displacement tend to be limited to applications where

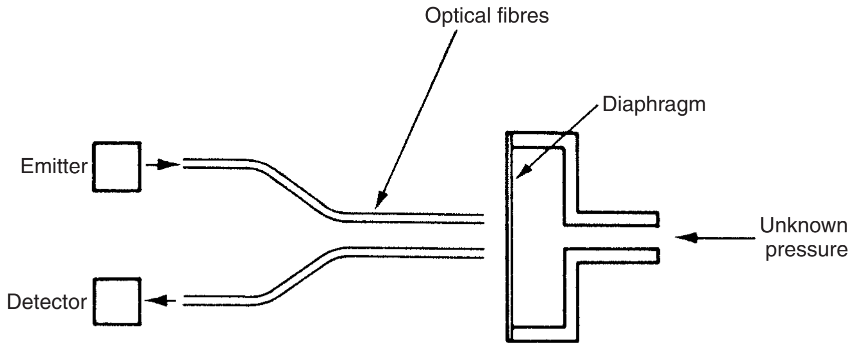

Fig. 15.2 Fotonic sensor.

their small size, low mass and immunity to electromagnetic noise are particularly advantageous.

Apart from the limited use above within diaphragm and Bourdon tube sensors, fibre-optic cables are also used in several other ways to measure pressure. A form of fibre-optic pressure sensor known as a *microbend sensor* is sketched in Figure 13.7(a). In this, the refractive index of the fibre (and hence of the intensity of light transmitted) varies according to the mechanical deformation of the fibre caused by pressure. The sensitivity of pressure measurement can be optimized by applying the pressure via a roller chain such that the bending is applied periodically (see Figure 13.7(b)). The optimal pitch for the chain varies according to the radius, refractive index and type of cable involved. Microbend sensors are typically used to measure the small pressure changes generated in vortex shedding flowmeters. When fibre-optic sensors are used in this flow-measurement role, the alternative arrangement shown in Figure 15.3 can be used, where a fibre-optic cable is merely stretched across the pipe. This often simplifies the detection of vortices.

Phase-modulating fibre-optic pressure sensors also exist. The mode of operation of these was discussed in Chapter 13.

15.4 Bellows

The bellows, schematically illustrated in Figure 15.4, is another elastic-element type of pressure sensor that operates on very similar principles to the diaphragm pressure sensor. Pressure changes within the bellows, which is typically fabricated as a seamless tube of either metal or metal alloy, produce translational motion of the end of the bellows that can be measured by capacitive, inductive (LVDT) or potentiometric transducers. Different versions can measure either absolute pressure (up to 2.5 bar) or gauge pressure (up to 150 bar). Double-bellows versions also exist that are designed to measure differential pressures of up to 30 bar.

Bellows have a typical measurement uncertainty of only ±0.5%, but they have a relatively high manufacturing cost and are prone to failure. Their principal attribute in the past has been their greater measurement sensitivity compared with diaphragm sensors. However, advances in electronics mean that the high-sensitivity requirement

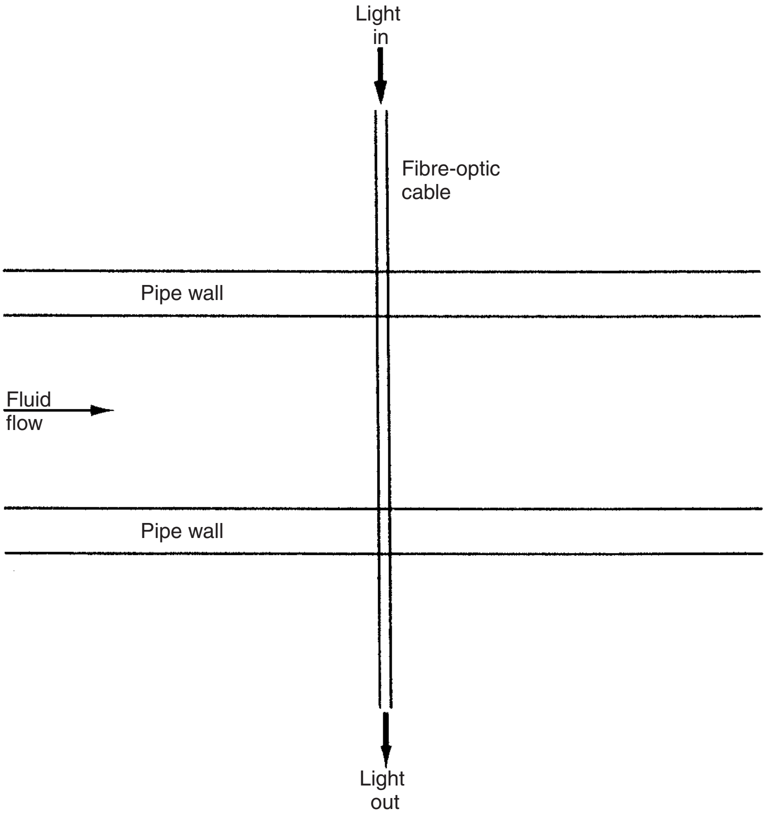

Fig. 15.3 Simple fibre-optic vortex detector.

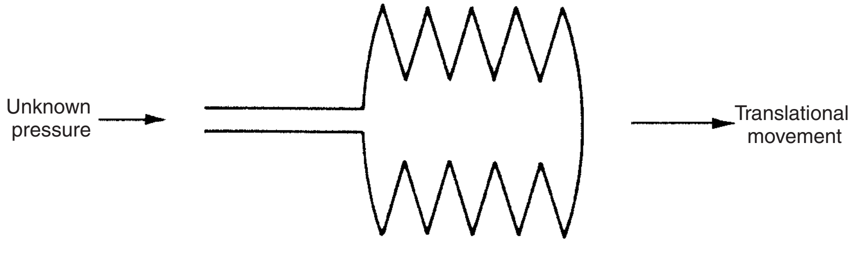

Fig. 15.4 Bellows.

can usually be satisfied now by diaphragm-type devices, and usage of bellows is therefore falling.

15.5 Bourdon tube

The Bourdon tube is also an elastic element type of pressure transducer. It is relatively cheap and is commonly used for measuring the gauge pressure of both gaseous and liquid fluids. It consists of a specially shaped piece of oval-section, flexible, metal tube that is fixed at one end and free to move at the other end. When pressure is applied at the open, fixed end of the tube, the oval cross-section becomes more circular. In consequence, there is a displacement of the free end of the tube. This displacement is measured by some form of displacement transducer, which is commonly a potentiometer or LVDT. Capacitive and optical sensors are also sometimes used to measure the displacement.

The three common shapes of Bourdon tube are shown in Figure 15.5. The maximum possible deflection of the free end of the tube is proportional to the angle subtended by the arc through which the tube is bent. For a C-type tube, the maximum value for this arc is somewhat less than 360°. Where greater measurement sensitivity and resolution are required, spiral and helical tubes are used. These both give a much greater deflection at the free end for a given applied pressure. However, this increased measurement performance is only gained at the expense of a substantial increase in manufacturing difficulty and cost compared with C-type tubes, and is also associated with a large decrease in the maximum pressure that can be measured. Spiral and helical types are sometimes provided with a rotating pointer that moves against a scale to give a visual indication of the measured pressure.

C-type tubes are available for measuring pressures up to 6000 bar. A typical C-type tube of 25 mm radius has a maximum displacement travel of 4 mm, giving a moderate level of measurement resolution. Measurement inaccuracy is typically quoted at ±1% of full-scale deflection. Similar accuracy is available from helical and spiral types, but whilst the measurement resolution is higher, the maximum pressure measurable is only 700 bar.

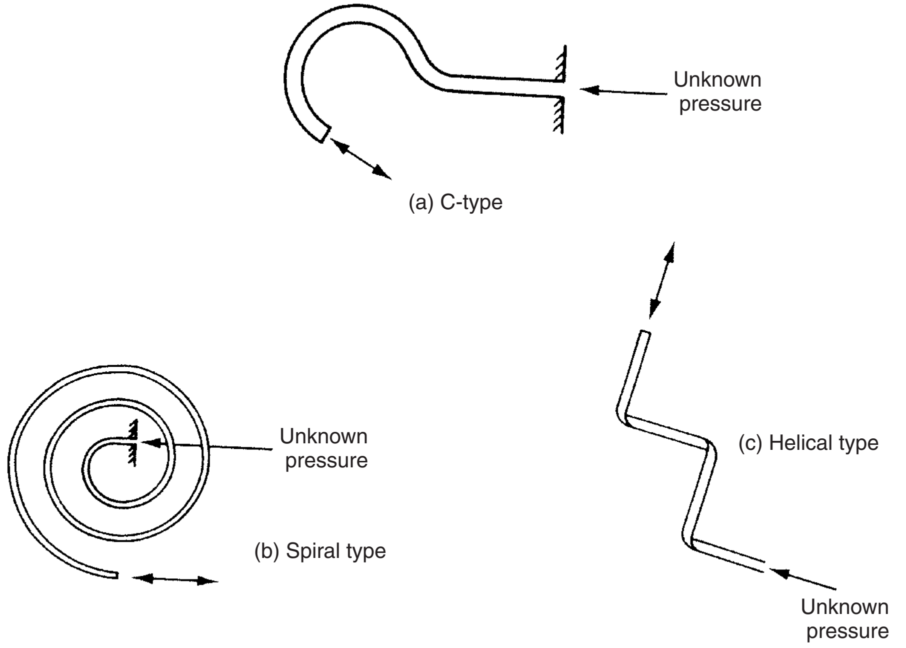

Fig. 15.5 Bourdon tubes.

The existence of one potentially major source of error in Bourdon tube pressure measurement has not been widely documented, and few manufacturers of Bourdon tubes make any attempt to warn users of their products appropriately. The problem is concerned with the relationship between the fluid being measured and the fluid used for calibration. The pointer of Bourdon tubes is normally set at zero during manufacture, using air as the calibration medium. However, if a different fluid, especially a liquid, is subsequently used with a Bourdon tube, the fluid in the tube will cause a non-zero deflection according to its weight compared with air, resulting in a reading error of up to 6%. This can be avoided by calibrating the Bourdon tube with the fluid to be measured instead of with air, assuming of course that the user is aware of the problem. Alternatively, correction can be made according to the calculated weight of the fluid in the tube. Unfortunately, difficulties arise with both of these solutions if air is trapped in the tube, since this will prevent the tube being filled completely by the fluid. Then, the amount of fluid actually in the tube, and its weight, will be unknown.

In conclusion, therefore, Bourdon tubes only have guaranteed accuracy limits when measuring gaseous pressures. Their use for accurate measurement of liquid pressures poses great difficulty unless the gauge can be totally filled with liquid during both calibration and measurement, a condition that is very difficult to fulfil practically.

15.6 Manometers

Manometers are passive instruments that give a visual indication of pressure values. Various types exist.

The *U-tube manometer*, shown in Figure 15.6(a), is the most common form of manometer. Applied pressure causes a displacement of liquid inside the U-shaped glass tube, and the output pressure reading P is made by observing the difference h between the level of liquid in the two halves of the tube A and B, according to the equation $P = h\rho g$, where ρ is the specific gravity of the fluid. If an unknown pressure is applied to side A, and side B is open to the atmosphere, the output reading is gauge pressure. Alternatively, if side B of the tube is sealed and evacuated, the output reading is absolute pressure. The U-tube manometer also measures the differential pressure $(p_1 - p_2)$, according to the expression $(p_1 - p_2) = h\rho g$, if two unknown pressures p_1 and p_2 are applied respectively to sides A and B of the tube.

Output readings from U-tube manometers are subject to error, principally because it is very difficult to judge exactly where the meniscus levels of the liquid are in the two halves of the tube. In absolute pressure measurement, an addition error occurs because it is impossible to totally evacuate the closed end of the tube.

U-tube manometers are typically used to measure gauge and differential pressures up to about 2 bar. The type of liquid used in the instrument depends on the pressure and characteristics of the fluid being measured. Water is a cheap and convenient choice, but it evaporates easily and is difficult to see. Nevertheless, it is used extensively, with the major obstacles to its use being overcome by using coloured water and by regularly topping up the tube to counteract evaporation. However, water is definitely not used when measuring the pressure of fluids that react with or dissolve in water. Water is also unsuitable when high-pressure measurements are required. In such circumstances, liquids such as aniline, carbon tetrachloride, bromoform, mercury or transformer oil are used instead.

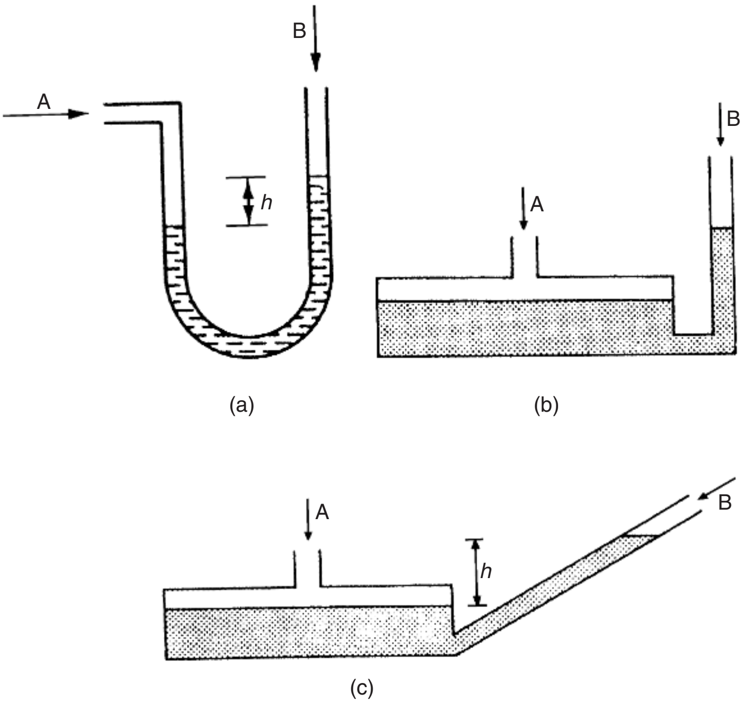

Fig. 15.6 Manometers: (a) U-tube; (b) well type; (c) inclined type.

The *well-type or cistern manometer*, shown in Figure 15.6(b), is similar to a U-tube manometer but one half of the tube is made very large so that it forms a well. The change in the level of the well as the measured pressure varies is negligible. Therefore, the liquid level in only one tube has to be measured, which makes the instrument much easier to use than the U-tube manometer. If an unknown pressure p_1 is applied to port A, and port B is open to the atmosphere, the gauge pressure is given by $p_1 = h\rho$. It might appear that the instrument would give a better measurement accuracy than the U-tube manometer because the need to subtract two liquid level measurements in order to arrive at the pressure value is avoided. However, this benefit is swamped by errors that arise due to the typical cross-sectional area variations in the glass used to make the tube. Such variations do not affect the accuracy of the U-tube manometer to the same extent.

The *inclined manometer* or *draft gauge*, shown in Figure 15.6(c), is a variation on the well-type manometer in which one leg of the tube is inclined to increase measurement sensitivity. However, similar comments to those above apply about accuracy.

15.7 Resonant-wire devices

A typical resonant-wire device is shown schematically in Figure 15.7. Wire is stretched across a chamber containing fluid at unknown pressure subjected to a magnetic field.

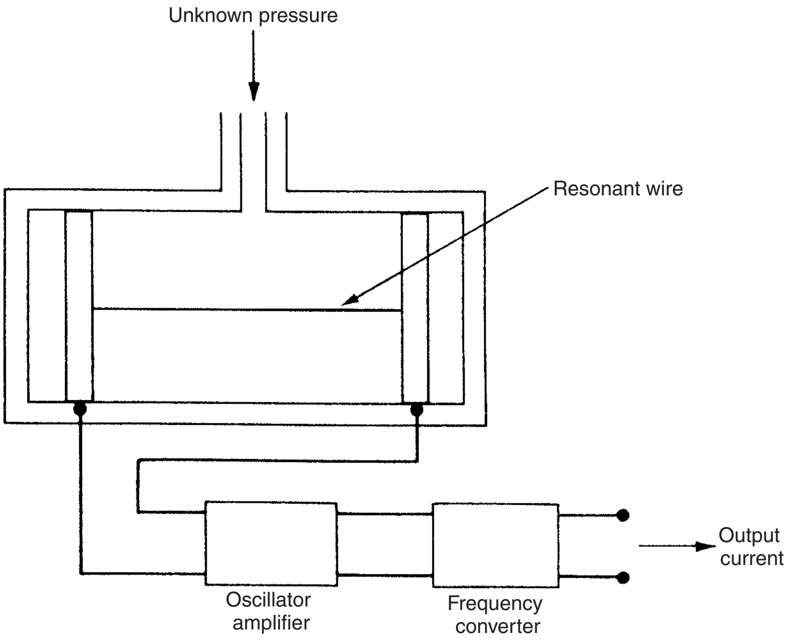

Fig. 15.7 Resonant-wire device.

The wire resonates at its natural frequency according to its tension, which varies with pressure. Thus pressure is calculated by measuring the frequency of vibration of the wire. Such frequency measurement is normally carried out by electronics integrated into the cell. These devices are highly accurate, with a typical inaccuracy figure being ±0.2% full-scale reading. They are also particularly insensitive to ambient condition changes and can measure pressures between 5 mbar and 2 bar.

15.8 Dead-weight gauge

The dead-weight gauge, as shown in Figure 2.3, is a null-reading type of measuring instrument in which weights are added to the piston platform until the piston is adjacent to a fixed reference mark, at which time the downward force of the weights on top of the piston is balanced by the pressure exerted by the fluid beneath the piston. The fluid pressure is therefore calculated in terms of the weight added to the platform and the known area of the piston. The instrument offers the ability to measure pressures to a high degree of accuracy but is inconvenient to use. Its major application is as a reference instrument against which other pressure-measuring devices are calibrated. Various versions are available that allow measurement of gauge pressures up to 7000 bar.

15.9 Special measurement devices for low pressures

A number of special devices have been developed for measurement of pressures in the vacuum range below atmospheric pressure (<1.013 bar). These special devices include the thermocouple gauge, the Pirani gauge, the thermistor gauge, the McLeod gauge and the ionization gauge, and they are covered in more detail below. Unfortunately, all of these specialized instruments are quite expensive.

The *thermocouple gauge* is one of a group of gauges working on the thermal conductivity principal. The paranoia and thermistor gauges also belong to this group. At low pressure, the kinematic theory of gases predicts a linear relationship between pressure and thermal conductivity. Thus measurement of thermal conductivity gives an indication of pressure. Figure 15.8 shows a sketch of a thermocouple gauge. Operation of the gauge depends on the thermal conduction of heat between a thin hot metal strip in the centre and the cold outer surface of a glass tube (that is normally at room temperature). The metal strip is heated by passing a current through it and its temperature is measured by a thermocouple. The temperature measured depends on the thermal conductivity of the gas in the tube and hence on its pressure. A source of error in this instrument is the fact that heat is also transferred by radiation as well as conduction. This error is of a constant magnitude, independent of pressure. Hence, it can be measured, and thus correction can be made for it. However, it is usually more convenient to design for low radiation loss by choosing a heated element with low emissivity. Thermocouple gauges are typically used to measure pressures in the range 10^{-4} mbar up to 1 mbar.

A typical form of *Pirani gauge* is shown in Figure 15.9(a). This is similar to a thermocouple gauge but has a heated element that consists of four coiled tungsten wires connected in parallel. Two identical tubes are normally used, connected in a bridge circuit as shown in Figure 15.9(b), with one containing the gas at unknown pressure and the other evacuated to a very low pressure. Current is passed through the tungsten element, which attains a certain temperature according to the thermal conductivity of the gas. The resistance of the element changes with temperature and causes an imbalance of the measurement bridge. Thus, the Pirani gauge avoids the use

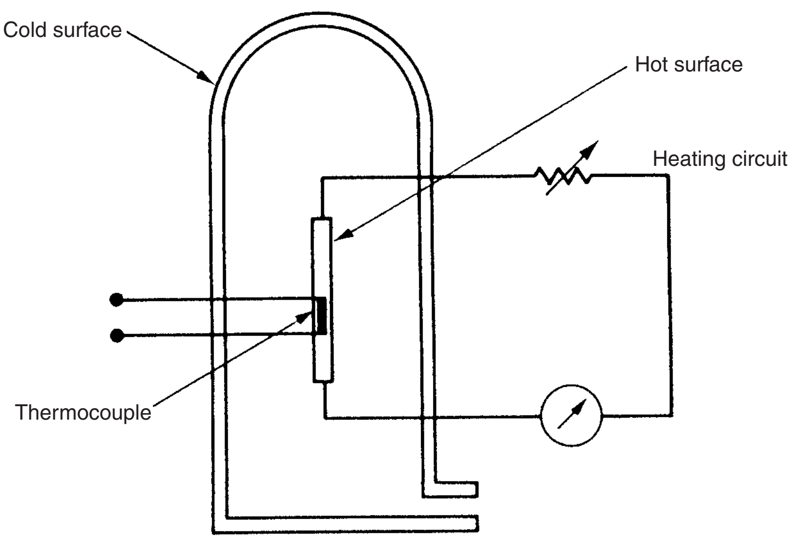

Fig. 15.8 Thermocouple gauge.

of a thermocouple to measure temperature (as in the thermocouple gauge) by effectively using a resistance thermometer as the heated element. Such gauges cover the pressure range 10^{-5} mbar to 1 mbar.

The *thermistor gauge* operates on identical principles to the Pirani gauge but uses semiconductor materials for the heated elements instead of metals. The normal pressure range covered is 10^{-4} mbar to 1 mbar.

Figure 15.10(a) shows the general form of a *McLeod gauge*, in which low-pressure fluid is compressed to a higher pressure that is then read by manometer techniques. In

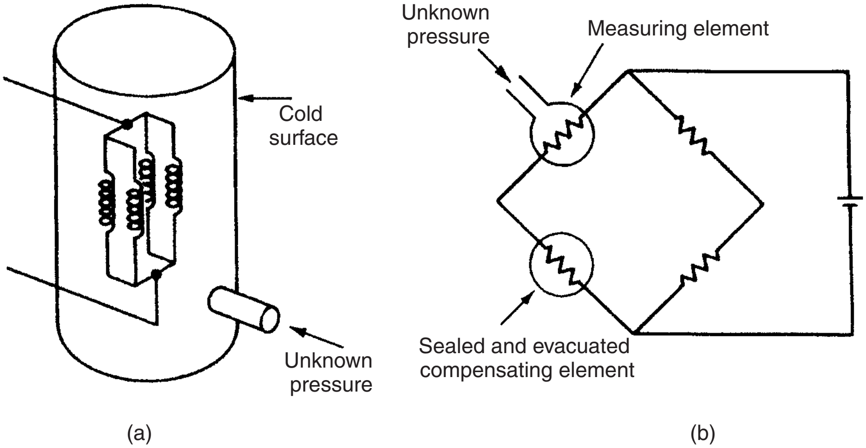

Fig. 15.9 (a) Pirani gauge; (b) Wheatstone bridge circuit to measure output.

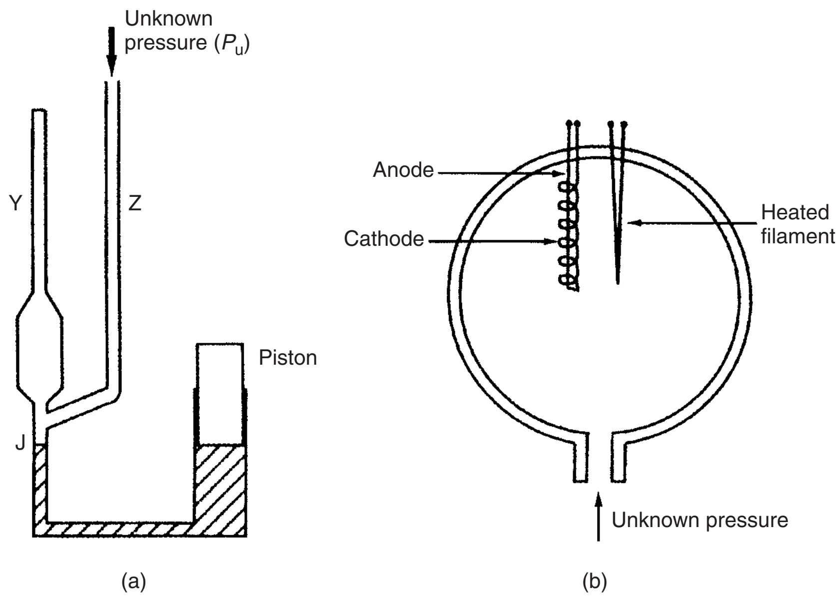

Fig. 15.10 Other low-pressure gauges: (a) McLeod gauge; (b) ionization gauge.

essence, the gauge can be visualized as a U-tube manometer that is sealed at one end, and where the bottom of the U can be blocked at will. To operate the gauge, the piston is first withdrawn. This causes the level of mercury in the lower part of the gauge to fall below the level of the junction J between the two tubes marked Y and Z in the gauge. Fluid at unknown pressure P_u is then introduced via the tube marked Z, from where it also flows into the tube of cross-sectional area A marked Y. Next, the piston is pushed in, moving the mercury level up to block the junction J. At the stage where J is just blocked, the fluid in tube Y is at pressure P_u and is contained in a known volume V_u. Further movement of the piston compresses the fluid in tube Y and this process continues until the mercury level in tube Z reaches a zero mark. Measurement of the height (h) above the mercury column in tube Y then allows calculation of the compressed volume of the fluid V_c as $V_c = hA$.
Then, by Boyle's law:

$$P_u V_u = P_c V_c$$

Also, applying the normal manometer equation:

$$P_c = P_u + h\rho g$$

where ρ is the mass density of mercury, the pressure P_u can be calculated as:

$$P_u = \frac{Ah^2 \rho g}{V_u - Ah} \tag{15.1}$$

The compressed volume V_c is often very much smaller than the original volume, in which case equation (15.1) approximates to:

$$P_u = \frac{Ah^2 \rho g}{V_u} \quad \text{for} \quad Ah \ll V_u \tag{15.2}$$

Although the smallest inaccuracy achievable with McLeod gauges is $\pm 1\%$, this is still better than that which is achievable with most other gauges that are available for measuring pressures in this range. Therefore, the McLeod gauge is often used as a standard against which other gauges are calibrated. The minimum pressure normally measurable is 10^{-4} bar, although lower pressures can be measured if pressure-dividing techniques are applied.

The *ionization gauge* is a special type of instrument used for measuring very low pressures in the range 10^{-13} to 10^{-3} bar. Gas of unknown pressure is introduced into a glass vessel containing free electrons discharged from a heated filament, as shown in Figure 15.10(b). Gas pressure is determined by measuring the current flowing between an anode and cathode within the vessel. This current is proportional to the number of ions per unit volume, which in turn is proportional to the gas pressure. Ionization gauges are normally only used in laboratory conditions.

15.10 High-pressure measurement (greater than 7000 bar)

Measurement of pressures above 7000 bar is normally carried out electrically by monitoring the change of resistance of wires of special materials. Materials having

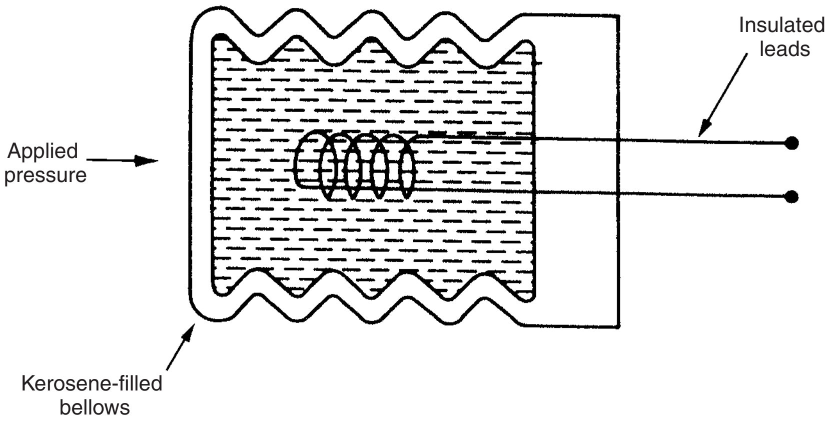

Fig. 15.11 High-pressure measurement–wire coil in bellows.

resistance-pressure characteristics that are suitably linear and sensitive include manganin and gold–chromium alloys. A coil of such wire is enclosed in a sealed, kerosene filled, flexible bellows, as shown in Figure 15.11. The unknown pressure is applied to one end of the bellows, which transmits the pressure to the coil. The magnitude of the applied pressure is then determined by measuring the coil resistance. Pressures up to 30 000 bar can be measured by devices like the manganin-wire pressure sensor, with a typical inaccuracy of ±0.5%.

15.11 Intelligent pressure transducers

Adding microprocessor power to pressure transducers brings about substantial improvements in their characteristics. Measurement sensitivity improvement, extended measurement range, compensation for hysteresis and other non-linearities, and correction for ambient temperature and pressure changes are just some of the facilities offered by intelligent pressure transducers. For example, inaccuracy figures as low as ±0.1% can be achieved with silicon piezoresistive-bridge devices.

Inclusion of microprocessors has also enabled the use of novel techniques of displacement measurement, for example the optical method of displacement measurement shown in Figure 15.12. In this, the motion is transmitted to a vane that progressively shades one of two monolithic photodiodes that are exposed to infrared radiation. The second photodiode acts as a reference, enabling the microprocessor to compute a ratio signal that is linearized and is available as either an analogue or digital measurement of pressure. The typical measurement inaccuracy is ±0.1%. Versions of both diaphragms and Bourdon tubes that use this technique are available.

15.12 Selection of pressure sensors

Choice between the various types of instrument available for measuring mid-range pressures (1.013–7000 bar) is usually strongly influenced by the intended application.

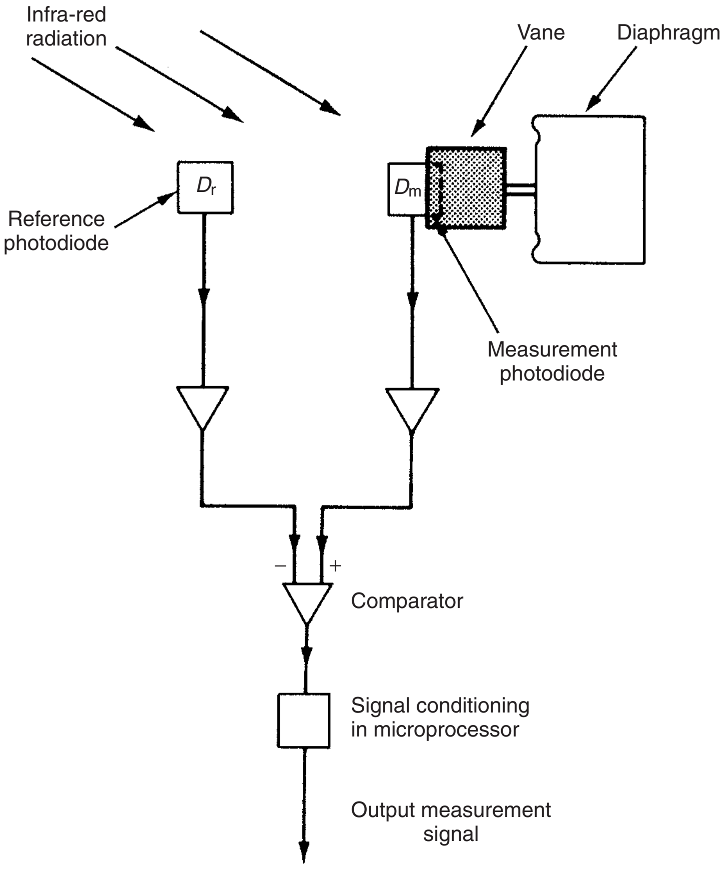

Fig. 15.12 Example of intelligent pressure-measuring instrument.

Manometers are commonly used when just a visual indication of pressure level is required, and deadweight gauges, because of their superior accuracy, are used in calibration procedures of other pressure-measuring devices. When an electrical form of output is required, the choice is usually either one of the several types of diaphragm sensor (strain gauge, capacitive or fibre optic) or, less commonly, a Bourdon tube. Bellows-type instruments are also sometimes used for this purpose, but much less frequently. If very high measurement accuracy is required, the resonant-wire device is a popular choice.

In the case of pressure measurement in the vacuum range (less than atmospheric pressure, i.e. below 1.013 bar), adaptations of most of the types of pressure transducer described earlier can be used. Special forms of Bourdon tubes measure pressures down to 10 mbar, manometers and bellows-type instruments measure pressures down to 0.1 mbar, and diaphragms can be designed to measure pressures down to 0.001 mbar. However, a number of more specialized instruments have also been developed to measure vacuum pressures, as discussed in section 15.9. These generally give better measurement accuracy and sensitivity compared with instruments that are primarily designed for measuring mid-range pressures. This improved accuracy is particularly evident at low pressures. Therefore, only the special instruments described in section 15.9 are used to measure pressures below 10^{-4} mbar.

At high pressures ($>$7000 bar), the only devices in common use are the manganin-wire sensor and similar devices based on alternative alloys to manganin.

For differential pressure measurement, diaphragm-type sensors are the preferred option, with double-bellows sensors being used occasionally. Manometers are also sometimes used to give visual indication of differential pressure values (especially in liquid flow-rate indicators). These are passive instruments that have the advantage of not needing a power supply.