

CHAPTER 6

Sensors for Measurement and Control

6.1. INTRODUCTION

No chemical plant can be operated unless it is adequately instrumented. The monitoring of flows, pressures, temperatures and levels is necessary in almost every process in order that the plant operator can see that all parts of the plant are functioning as required. Additionally, it may be necessary to record and display many other quantities which are more specific to the particular process in question, e.g. the composition of a process stream, the heat radiation produced in a crude oil heater or the humidity of a gas stream. In many instances, the sensor forms an essential part of a control system or strategy for a process. This may be quite complex and rely upon the performance and characteristics of a substantial number of different sensors. For example, a large catalytic cracking unit may contain upwards of a thousand instruments of various kinds. Each measurement has to be transmitted to a display unit or indicator or to a recording device which will generally have a visible indicator attached to it. The indicator or recorder may be situated locally with respect to the instrument or will, more commonly, be placed in the plant control room. This often requires the conversion of a measurement signal into a form which is suitable for transmission over what might be quite long distances. Such conversion is frequently called *signal conditioning* (Fig. 6.1) and the term *transducer* is used often in reference to a total sensor package containing both conditioning and sensing elements. Further modification, viz. *signal processing*, is generally necessary in order that the signal be changed to one which is suitable as an input to the next component in the system. This may simply take the form of an amplification or may be a conversion from a continuous (*analog*) to a discontinuous (*digital* or *discrete-time*) signal or vice versa. This can occur after direct transmission to the plant control room as illustrated in Fig. 6.1, or immediately after the signal conditioning stage where the data are to be supplied to a local indicator or to a *data hiway* as part of a *distributed control system* (Section 7.20). Hence, the topics of signal conditioning, signal transmission (*telemetry*) and signal processing are inevitably connected with the study of the sensors themselves.

Two of the most important considerations for a measurement system are accuracy and reliability. Clearly, a measurement is of little use if it is substantially inaccurate. It may be possible to allow for a consistent error in an instrument if it is known, but low frequency, randomly occurring errors will mean that incorrect actions may be taken by the operator as a result of reading that instrument, or by the control system employing it as a sensor. High frequency random variations in the measurement

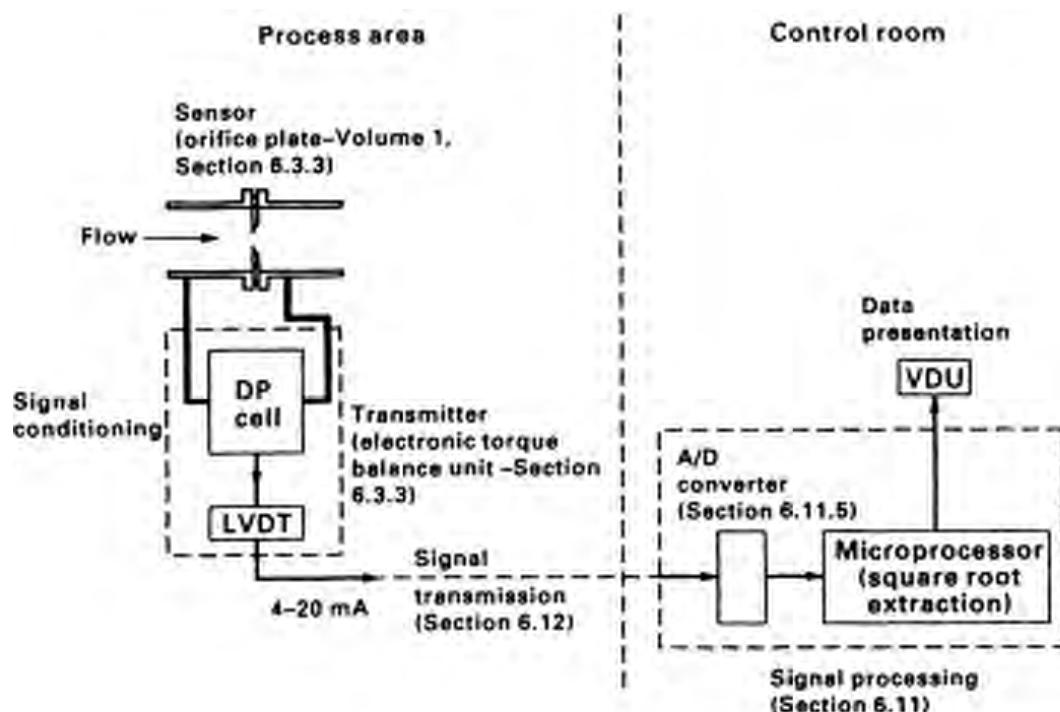


FIG. 6.1. Typical process measurement system showing the stages between sensor and presentation of the data to the process operator (DP—differential pressure cell, LVDT—linear variable differential transformer, A/D—analogue to digital, VDU—visual display unit)

signal (often termed *noise*) can be an equally serious problem. A measurement system should be reliable, i.e. produce consistent readings, in order that the process plant operator can be confident in the value of the particular process variable that it is indicating, and it is well to note that a control system (however sophisticated or complex) will not produce the desired result if the measurements employed are unreliable and/or incorrect.

Different types of sensor, together with the general static characteristics of measurement systems, are described in this chapter with the exception of those previously covered in Volumes 1 and 2. Because of their close connection, signal conditioning and signal processing elements are considered together in Section 6.11. The chapter concludes with a discussion of signal transmission (or telemetry) and a brief description of *smart* instruments and currently developing industry-based protocols. The dynamics of measuring elements are presented in Chapter 7.

6.2. THE MEASUREMENT OF FLOW

6.2.1. Methods Dependent on Relationship Between Pressure Drop and Flowrate

Instruments which are employed to measure flow often use the relation between rate of flow and pressure drop along a section of pipe, around some obstruction or across a restriction within the pipe. The more widely employed flow measuring devices (or *flowmeters*) are discussed in Volume 1, Chapter 6. These are as follows:

- (1) The pitot tube (Volume 1, Section 6.3.1).
- (2) The orifice meter (Volume 1, Section 6.3.3).
- (3) The nozzle (Volume 1, Section 6.3.4).
- (4) The venturi meter (Volume 1, Section 6.3.5).
- (5) The Dall tube (Volume 1, Section 6.3.6).

Other sensors which are described in Volume 1 (Sections 6.3.7–6.3.9) are the variable area meter, the notch or weir, the hot wire anemometer, the electromagnetic flowmeter and the positive displacement meter. Some of these flowmeters are relatively less suitable for producing signals which can be transmitted to the control room for display (e.g. weir, rotameter) and others are used in more specialist or limited applications (e.g. magnetic flowmeter, hot wire anemometer). The major characteristics of different types of flow sensor are summarised in Table 6.1. Brief descriptions follow of the principles underlying the more important types of flowmeter not described in Volume 1. In many instances such flow sensors are taking the place of those more traditional meters which rely upon pressure drop measurement. This is for reasons of versatility, energy conservation and convenience.

6.2.2. Further Methods of Measuring Volumetric Flow

The Averaging Pitot Tube

Because of its low pressure drop capability, the pitot tube is gaining popularity in the form of the *averaging pitot tube* or *Annubar* which is a variation of the standard pitot tube. This uses multiple sampling points across a pipe or duct in order to provide a representation of the full flow profile.

Vortex Flowmeters

The basic principle of vortex shedding is shown in Fig. 6.2a and is discussed in Volume 2, Section 3.2. A barrier (*bluff body*) is placed in the path of the fluid flow such that the fluid splits into two streams. The resulting instability of the boundary layer as it breaks away from the obstruction causes the fluid to *roll up* into a well-defined vortex. After the vortex is formed, it is *shed* from the body and a second vortex begins to form on the opposite side of the body. If the vortex shedding is stable, then the time taken for the formation of each vortex is proportional to the fluid velocity for a given bluff body geometry. This pattern is repeated producing a distinctive series of vortices known as the *von Karman vortex street*. The formation and shedding of these vortices results in regular pressure variations around and downstream of the bluff body. These can be measured by a suitably located pressure, thermal or ultrasonic detector (Fig. 6.2b). STROUHAL⁽¹⁾ showed that the free stream velocity u_{free} is related to the frequency ω of the changes in pressure by:

$$u_{\text{free}} = \frac{\omega B_f}{S} \quad (6.1)$$

where B_f is the width of the bluff body and S is the *Strouhal number* which is an experimentally determined quantity dependent only upon the geometry of the flowmeter.

TABLE 6.1. *Principal Characteristics of Common Flowmeters⁽²⁻⁵⁾*

Type of Flowmeter	Reference	Measures Volume or Mass Flow	Gases or Vapours		Steam		Liquids				Slurries		Operating Temperature of Sensor (K)
			Clean	Dirty	Yes	No	Yes	No	Usually	Usually	No	No	
Orifice-square edge	Volume I Section 6.3.3	Volume	Yes	No	Yes	Yes	Yes	No	Usually	Usually	No	No	< 800
Orifice-conic edge	Volume I Section 6.3.3	Volume	No	No	No	Yes	Yes	Yes	Usually	Usually	No	No	< 800
Venturi	Volume I Section 6.3.5	Volume	Yes	Usually	Yes	Yes	Yes	Usually	Usually	Usually	Usually	Usually	< 800
Flow Nozzle	Volume I Section 6.3.4	Volume	Yes	Usually	Yes	Yes	Yes	Usually	Usually	Usually	No	No	< 800
Annubar	Volume 3 Section 6.2.1	Volume	Yes	No	Yes	Yes	Yes	No	No	Usually	No	No	< 800
Electromagnetic	Volume I Section 6.3.9	Mass	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	230-450
Positive Displacement	Volume I Section 6.3.9	Volume	Yes	No	No	Yes	No	No	Usually	No	No	No	Gases < 400 Liquids < 580
Turbine	Volume I Section 6.3.9	Volume	Yes	No	No	Yes	No	No	Usually	No	No	No	10-530
Ultrasonic-time of flight	Volume 3 Section 6.2.1	Volume	No	No	No	Yes	Usually	No	Yes	No	No	No	100-530
Doppler	Volume 3 Section 6.2.1	Volume	No	No	No	No	Usually	Yes	Yes	Yes	Yes	Yes	100-400
Variable area	Volume I Section 6.3.7	Volume	Yes	No	No	Yes	Yes	No	Usually	No	No	No	Glass < 400 Metal < 800
Vortex	Volume 3 Section 6.2.1	Volume	Yes	Usually	Yes	Yes	No	Usually	Usually	No	No	No	80-680
Coriolis	Volume 3 Section 6.2.2	Mass	At high pressure only	At high pressure only	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	See comments
Thermal	Volume I Section 6.3.9	Mass	Yes	No	No	No	No	No	No	No	No	No	< 350

(a) FSD: full scale deflection.

(b) R: per cent of flowrate.

(c) See Section 6.10.1.

(d) All flow sensors based on pressure drop measurement become insensitive below about 10 per cent of their full scale deflection.

Maximum Operational Pressure (MPa)	$-\Delta P$ (Comparative)	Pipe Size (mm)	Minimum Re	Suitability for Very Low Flow Measurement	Maximum Accuracy (per cent FSD ^(a))	Maximum Turndown ^(c)	Comparative Cost (including transmitter)	Comments	Type of Flowmeter
< 40	High	> 40	2000	No	± 1 to ± 2	4:1	Medium	Inaccurate below 10 per cent of FSD ^(d)	Orifice-square edge
< 40	High	> 40	200	No	± 2	4:1	Medium	Inaccurate below 10 per cent of FSD ^(d)	Orifice-conic edge
< 40	80–90 per cent of energy recovered	> 50	7.5×10^4	No	± 1 to ± 2	4:1	High	Inaccurate below 10 per cent of FSD ^(d)	Venturi
< 40	High	> 50	10^4	No	± 1 to ± 2	4:1	Medium	Inaccurate below 10 per cent of FSD ^(d)	Flow Nozzle
< 40	Low	> 25	10^4	No	± 1.25	4:1	Low	Inaccurate below 10 per cent of FSD ^(d)	Annubar
< 10	Low	6–2000	(see Table 6.2)	Yes (Table 6.2)	$\pm 0.2R^{(b)}$ to ± 1	10:1	High	Conductive liquids only	Electromagnetic
< 10	Medium	< 300	$v < 8000$ (see Table 6.2)	Yes (Table 6.2)	Gases ± 1 Liquids $\pm 0.25R^{(b)}$	Better than 10:1	High	Insensitive to viscosity. Filter fluid to $10\mu\text{m}$	Positive Displacement
< 20	Medium	6–600	$v < 20$ (see Table 6.2)	Yes (Table 6.2)	$\pm 0.5R^{(b)}$	20:1	High	Mainly for small pipes. Accurate measurement	Turbine
Pipe rating	Low	> 12	Very small	No	$\pm 1R^{(b)}$ to ± 5	Better than 50:1	High	Also used in partly filled pipes and open channels	Ultrasonic-time of flight
Pipe rating	Low	> 12	Very small	No	$\pm 1R^{(b)}$ to ± 5	Better than 50:1	High	Also used in partly filled pipes and open channels	Doppler
Glass 2.4 Metal 5	Low	≤ 75	Very small	Yes (Table 6.2)	$\pm 0.5R^{(b)}$ to ± 1	10:1	Medium	Can be used to measure a highly viscous fluid	Variable area
< 10	Low	15–400	$> 10^4$	No	$\pm 0.5R^{(b)}$ to $\pm 1R^{(b)}$	20:1	High		Vortex
50	Low	10–100	(See Table 6.2)	Yes (Table 6.2)	± 1	20:1	High	Insensitive to temperature, pressure and viscosity	Coriolis
4	Low	10–100	(See Table 6.2)	Yes (Table 6.2)	± 1	100:1	Medium to high		Thermal

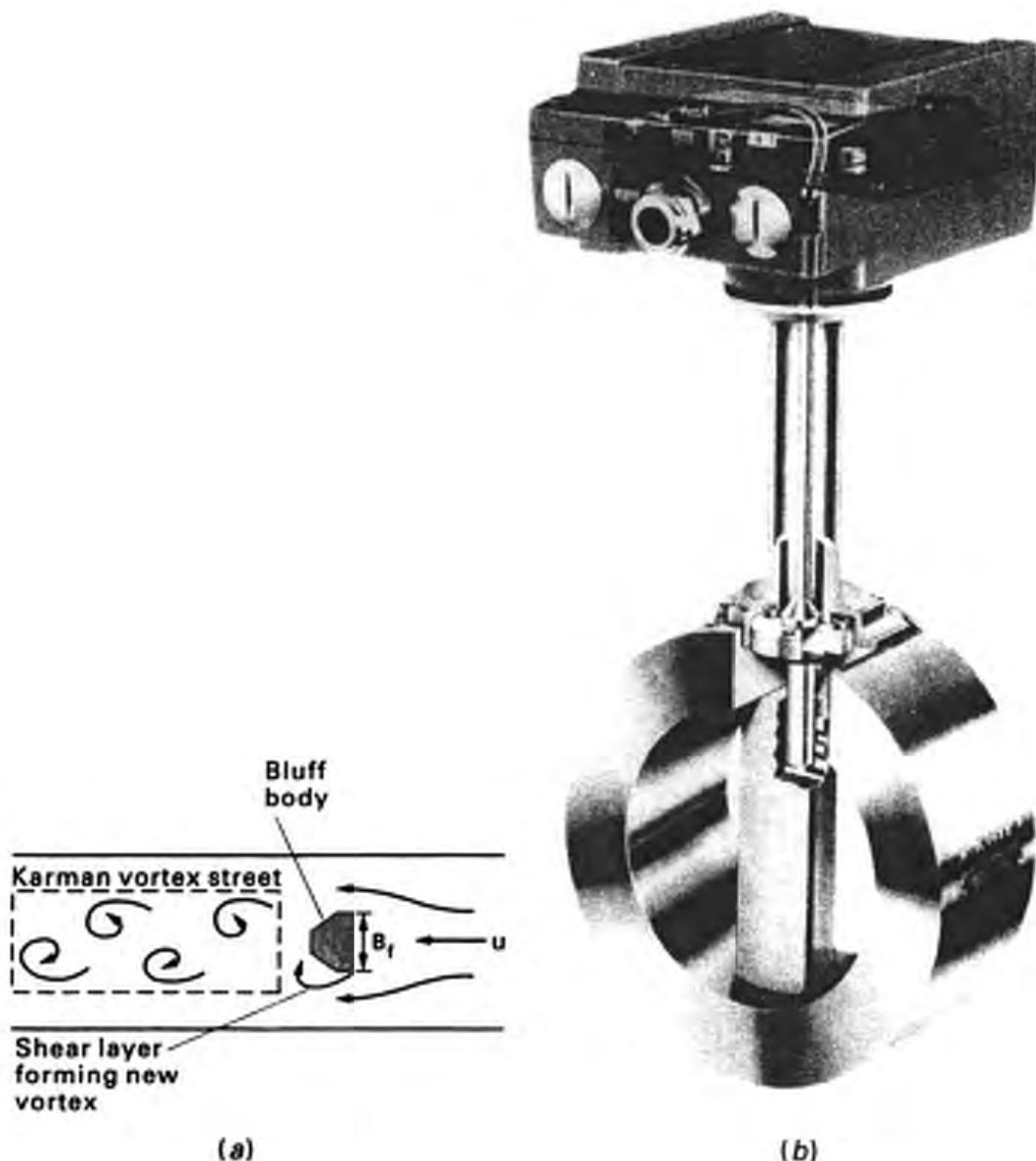


FIG. 6.2. Vortex-shedding flowmeter: (a) basic principle of meter; (b) general view

Vortex meters are being employed increasingly because of their accuracy, range, precision and relative insensitivity to fluid properties. They can be used for gases, saturated and superheated steam, low viscosity clean and dirty liquids, and cryogenic fluids⁽⁶⁾. They are not recommended for use when $Re < 10^4$.

Ultrasonic Methods⁽⁷⁾

Ultrasonic meters are finding increasing application because of their ability to measure clear and dirty liquids in difficult situations. They are usually non-intrusive and present little or no obstruction to the flow. They are effective also in measuring flow in open channels (Section 6.2.5) and in partially filled pipes. They are, however, highly sensitive to flow conditions and should be calibrated with care.

There are two principal types, viz. the *time-of-flight* instrument and the *Doppler* flowmeter.

The Time-of-Flight Meter

This instrument is used to measure the flow of clean liquids and involves the determination of the time required for an acutely angled, high frequency pressure wave to reach the opposite wall of a pipe. The elapsed time depends upon the velocity of the liquid u_ℓ , whether the pressure wave is moving with, or against the flow and upon the speed of sound in the liquid u_s . The most common time-of-flight meter is the *counter-propagating* type in which two transducers are placed on opposite sides of the liquid stream as shown in Fig. 6.3.

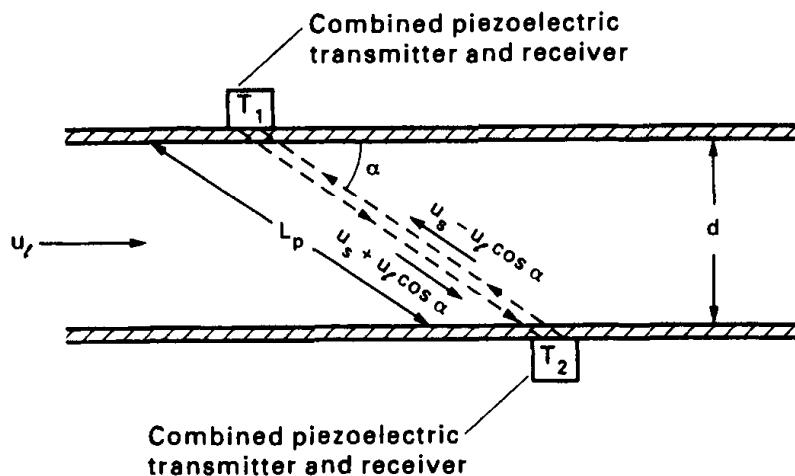


FIG. 6.3. Counter-propagating time-of-flight ultrasonic flowmeter

Both transducers are self-excited oscillating systems (usually piezoelectric crystals—see Section 6.3.1) which act alternately as transmitters and receivers, the receiving pulses being used to trigger the transmitted pulses in a feedback arrangement. A pulse from transmitter T_1 is directed downstream over a path length L_p to transducer T_2 (Fig. 6.3). The downstream elapsed time is:

$$t_{\text{down}} = \frac{L_p}{u_s + u_\ell \cos \alpha}$$

On receipt of the signal from T_1 , T_2 is triggered and transmits a pulse upstream to T_1 . The upstream elapsed time is:

$$t_{\text{up}} = \frac{L_p}{u_s - u_\ell \cos \alpha}$$

Hence:

$$\frac{1}{t_{\text{down}}} - \frac{1}{t_{\text{up}}} = \frac{2u_\ell \cos \alpha}{L_p}$$

Thus:

$$u_e = \frac{L_p}{2\cos\alpha} \left(\frac{t_{\text{up}} - t_{\text{down}}}{t_{\text{up}} t_{\text{down}}} \right) \quad (6.2)$$

and the average volumetric rate of flow is given by:

$$\begin{aligned} Q &= K_{vp} \left(\frac{\pi d^3 \tan \alpha}{8} \right) \left(\frac{t_{\text{up}} - t_{\text{down}}}{t_{\text{up}} t_{\text{down}}} \right) \\ &= K_{TF} \left(\frac{t_{\text{up}} - t_{\text{down}}}{t_{\text{up}} t_{\text{down}}} \right) \end{aligned} \quad (6.3)$$

where K_{vp} is a correction for the velocity profile and K_{TF} is normally a constant for a particular installation.

This type of meter can simply be clamped on the outside surface of the pipe which avoids the possibility of the transducer probes being affected by fouling. In this instance care must be taken to avoid *acoustic short-circuiting*, i.e. transducer signals being transmitted and received via the pipe wall. Both 'clamp-on' and wetted versions of the counter-propagating meter are sensitive to variations in the velocity profile of the measured liquid—but not to the velocity of sound in the medium (equation 6.3).

The Doppler Meter

Doppler ultrasonic flowmeters depend upon the reflection of a continuous ultrasonic wave (frequency 0.5–10 MHz) from particulate matter (*scatterers*) contained in the fluid. Hence they may be used to monitor the rate of flow of dirty liquids. The transducer involved can act both as transmitter and receiver and is generally of the clamp-on type (Fig. 6.4). If the scatterers can be assumed to be moving at the velocity of the liquid, then the volumetric rate of flow Q is related to the Doppler frequency shift $\Delta\omega_D$ by:

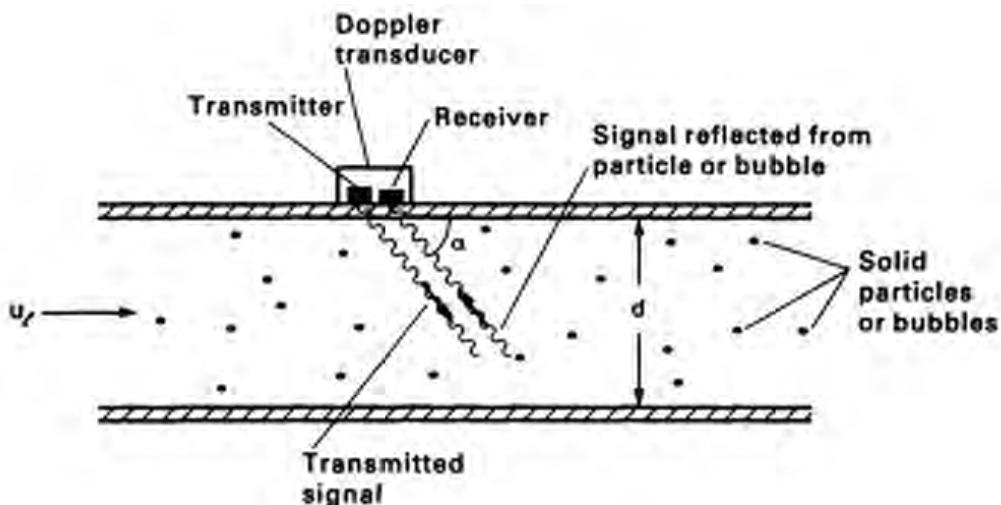


FIG. 6.4. Doppler flowmeter

$$Q = \left(\frac{\pi d^2}{4} \frac{u_s}{\cos\alpha} \right) \frac{\Delta\omega_D}{\omega} = K_D \Delta\omega_D \quad (6.4)$$

where K_D is a constant provided that u_s remains constant and ω is the transmitter frequency.

The Doppler flowmeter can be employed where other methods fail, e.g. for the measurement of two-phase systems such as slurries in the nuclear industry, of food products such as pickles and sauces and of gas-liquid mixtures.

6.2.3. The Measurement of Mass Flow

One class of flow measurement which is becoming of increasing importance (particularly in the form of sensors for control systems) is the monitoring of mass flow. This is rapidly superseding the measurement of volumetric flow—especially where it is required to determine accurately the transfer of large quantities of gas and liquid in the oil, gas and water industries. Two principal approaches are employed to measure mass flow. One is indirect and uses a combination of volumetric flow and density and the other is direct in that it involves the measurement of properties which are sensitive to variations in the mass rate of flow itself.

Indirect (Inferential) Methods

Any combination of flowmeter and suitable specific gravity (density) meter (Section 6.6) can in theory be employed to produce a mass rate of flow. However, these so-called *indirect meters* have a limited range and accuracy and require careful and frequent calibration and maintenance. An instrument based on the turbine flowmeter (Volume 1, Section 6.3.9) and acoustic density meter (Section 6.6.1) has been employed with good results⁽⁸⁾ (see Fig. 6.5).

The turbine meter produces a pulsed output of frequency ω_1 such that:

$$Q = K_1 \omega_1 \quad (6.5)$$

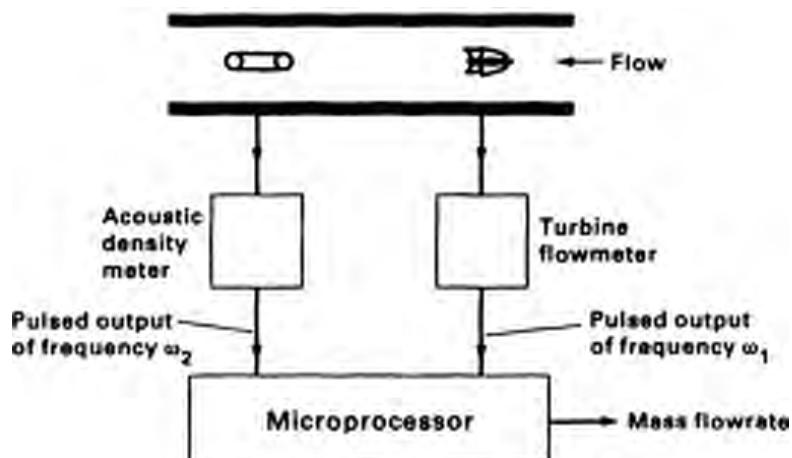


FIG. 6.5. Combination of sensors for determining the mass flow of fluid in a pipe

where Q is the volumetric rate of flow and K_1 is a constant characteristic of the flow measuring device. The density meter also gives a pulsed output of frequency ω_2 , which is related to the fluid density ρ by:

$$\rho = \frac{K_2}{\omega_2^2} + \frac{K_3}{\omega_2} \quad (6.6)$$

The microprocessor measures ω_1 and ω_2 by counting pulses over a fixed time period and calculates the mass m of fluid which has passed in time t from:

$$m = \delta t \sum_{j=1}^N \rho_j Q_j \quad (6.7)$$

where ρ_j and Q_j are the values of ρ and Q at the j th sampling instant, δt is the sampling interval and $N = t/\delta t$.

Direct Methods

These instruments can be divided into meters which employ thermal effects and those which are energised by variations in the momentum of the fluid passing through the meter. The former rely upon the rate of loss of heat from a heated wire immersed in a fluid and this rate of loss of heat is a function of the mass flowrate. This type of instrument is described in Volume 1, Section 6.3.9. A discussion of two of the more common types of momentum transfer meter follows.

The Axial Flow Transverse Momentum Flowmeter⁽⁹⁾

This consists of an impeller and turbine mounted adjacently within a pipeline. The impeller is rotated at a constant angular velocity ω which imparts the same angular velocity to the fluid as it flows past. On leaving the impeller, the fluid immediately enters the turbine where the angular momentum gained by the fluid is used to drive the turbine. If a mass of fluid dm enters the impeller during time dt , then:

$$dI = r_g^2 dm$$

where r_g and dI are the radius of gyration and the moment of inertia of the mass dm respectively. The transverse angular momentum of the fluid leaving the impeller is:

$$\omega dI = \omega r_g^2 dm$$

The deflecting torque on the turbine T is equal to the rate of change of angular momentum, i.e.:

$$T = \omega \frac{dI}{dt} = \omega r_g^2 \frac{dm}{dt}$$

Thus:

$$m = \frac{1}{\omega r_g^2} \int_0^t T dt \quad (6.8)$$

The turbine is linked to an integrator which computes the mass m passing in a given time t from T using equation 6.8.

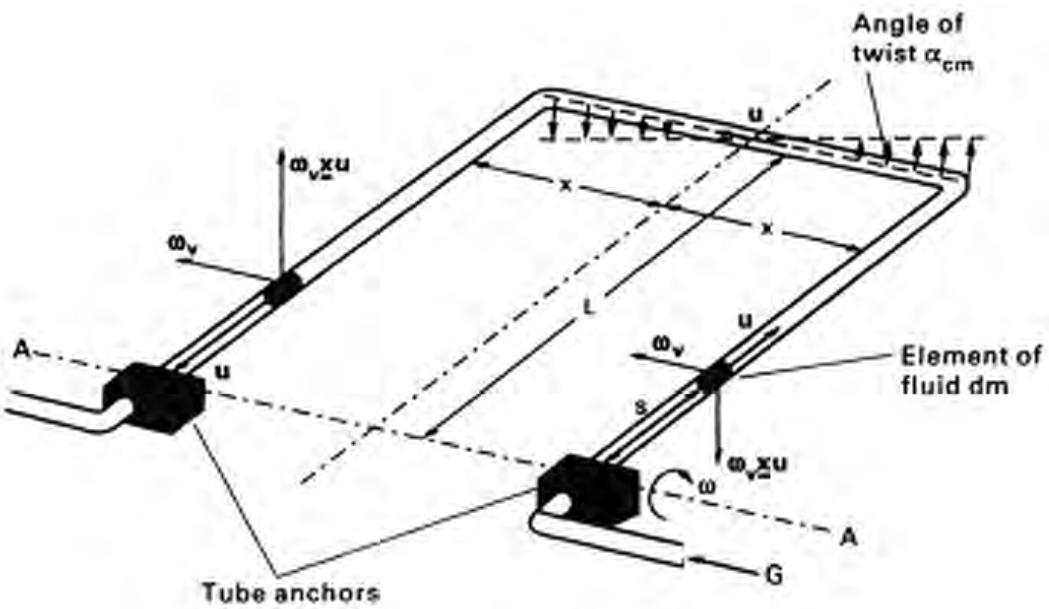


FIG. 6.6. Principle of the Coriolis meter

The Coriolis Meter

This class of meter depends upon the fluid attaining an angular velocity ω whose vector is perpendicular to the fluid velocity. A simplified representation is shown in Fig. 6.6⁽¹⁰⁾.

The rectangular pipe section is kept in constant oscillation in a vertical plane about AA at its resonant frequency (50–80 Hz) by an electromagnetic feedback system. As the fluid flows through the pipe, inertial forces cause changes in the shape of the rectangular section. Only those inertial forces which produce a twisting action in the direction opposite to $\omega_v \underline{x} \underline{u}$ (the *Coriolis acceleration*) are measured where \underline{u} is the fluid velocity vector, ω_v is the vector of the angular velocity experienced by the fluid perpendicular to \underline{u} , and \underline{x} represents the vector cross-product. An element of fluid of mass dm defined by s (where s is the magnitude of the position vector for dm relative to the origin) flowing in the direction indicated in Fig. 6.6 produces an inertia force of magnitude $dm(2\omega_v \underline{x} \underline{u})$. An equal and opposite force will be impressed upon the return leg of the rectangular section of the pipe. Hence, the torque vector on the element is:

$$\begin{aligned} dT &= 2(2\omega_v \underline{x} \underline{u})(dm)x \\ &= 2(2\omega_v \underline{x} \underline{u}) \left(\frac{G}{\underline{u}} ds \right) x \end{aligned}$$

where G is the mass rate of flow and $2x$ is the distance between the limbs of the rectangular section. Thus the total torque T has a magnitude:

$$K_{CM} \alpha_{CM} = 4\omega_v G x \int_0^L ds = 4\omega_v G x L \quad (6.9)$$

ω varies sinusoidally, hence T is sinusoidal also and acts as a driving torque which twists the rectangular section through an angle α_{CM} . K_{CM} is a constant for the meter. α_{CM} is obtained by measuring (optically or electrically) the difference in times at

which each limb of the beam passes sensing points during each cycle of the oscillation. Thus G can be computed as the output signal from the instrument. The total mass flow over any time interval can be obtained.

This type of meter does not restrict the flow of fluid, can be used for two-phase mixtures (e.g. foams, slurries, liquids containing entrained gases), and is insensitive to variations in temperature, pressure and viscosity. It responds quickly to flow variations and, although primarily a liquid flowmeter, it can be used to monitor gases where pressures are high enough to produce viscosities of sufficient magnitude to actuate the sensing tubes. In alternative versions of the instrument the fluid passes through two straight parallel pipes which are made to resonate. A phase shift occurs between inlet and outlet which is proportional to the mass rate of flow. The resonant frequency of the measuring pipes is a function of the oscillating mass and therefore of the density of the fluid. Most currently manufactured Coriolis meters have a double tube arrangement which produces a nominally balanced system and hence greater stability⁽¹¹⁾.

6.2.4. The Measurement of Low Flowrates

There are many applications where it is necessary to monitor very low rates of flow (e.g. addition of mercaptans to natural gas in the gas industry or of anti-foaming agents to fermentation processes in the pharmaceutical industry). A *low flow* is considered to be of the order of 100 mm³/s and an *ultra-low flow* of around 0.1 mm³/s for both liquids and gases. Table 6.2 includes commonly accepted minimum measurable rates of flow for types of flowmeter normally employed for this purpose⁽¹²⁾.

6.2.5. Open Channel Flow

Flow measurement in open unpressurised channels is a requirement generally associated with waste water systems and sewers. The use of a weir or notch to measure the flow of a liquid presenting a free surface is described in Volume 1, Section 6.3.8. The flow through a rectangular notch (Fig. 6.7a) is given by (Volume 1, equation 6.42):

$$Q = \frac{2}{3} C_D B \sqrt{2g} D^{1.5} \quad (6.10)$$

where B is the width of the notch and D is the depth of the liquid at the notch.

For a triangular notch (Volume 1, equation 6.45):

$$Q = \frac{8}{15} C_D \tan \alpha \sqrt{2g} D^{2.5} \quad (6.11)$$

where the notch is of angle 2α (Fig. 6.7b) and C_D is the coefficient of discharge.

Alternatively, a *flume* can be employed where the rate of fall of a stream is slight or where the stream contains a large quantity of solid material (silt or debris). The most widely used is the *venturi flume* (Fig. 6.7c) for which the volumetric flow can be determined from⁽¹³⁾:

$$Q = C_D B_2 D_2 \sqrt{\frac{2g(D_1 - D_2)}{1 - (B_2 D_2 / B_1 D_1)^2}} \quad (6.12)$$

TABLE 6.2. *Flowmeters that can be Used to Measure Low Flowrates*

Type of Flowmeter	Suitable for	Minimum Measurable Flowrate (mm ³ /s)	Principle of Operation	Typical Applications	Comments
Turbines, Pelton wheels	Liquids and gases	140	(See Volume 1, Section 6.3.9)	Fuel metering in aircraft	High repeatability. Can be used at high temperatures and pressures
Positive displacement	Liquids only	20	(See Volume 1, Section 6.3.9)	Hydrocarbon liquids, glues, food products (jams, chocolate, etc.)	Suitable for high viscosity fluids. High accuracy and wide range
Coriolis	Liquids. Gases at high pressure	20	(See Section 6.2.3)	Can be used for almost any liquid provided that the viscosity is not so great as to impose too high a pressure drop	(See Section 6.2.3)
Electro-magnetic	Liquids only	1.5	(See Volume 1, Section 6.3.9)	Additives in pharmaceuticals, paint, pulp and paper, water treatment using chlorine	Good chemical resistance. Hygenic and intrinsically safe. Wide range. Requires some conductivity
Thermal volumetric	Liquids only	1	Measures time taken for liquid to flow between two detectors by means of a heat pulse	High pressure liquid phase chromatography (Section 6.8.3 and Volume 2, Chapter 19)	No moving parts. Suitable for high pressures and temperatures

where B_1 and B_2 are the width of the channel and the venturi throat respectively, and D_1 and D_2 are the depths immediately upstream of the flume and the minimum depth within the throat of the flume respectively.

In each case, the volumetric rate of flow can be determined by measuring the liquid levels in the appropriate place. This is often achieved using an ultrasonic measuring system (Fig. 6.7d) in which the time taken for an ultrasonic wave to be reflected from the liquid surface is measured (see also Section 6.5.5). Accuracies of ± 2.5 mm/m distance between sensor and liquid surface are not uncommon. Standard designs of open channel restrictions can be found in BS 3680⁽¹⁴⁾.

6.2.6. Flow Profile Distortion

Pipe fittings such as elbows, tee-pieces, reducers, expanders, valves, etc. can all alter the symmetry of the flow profile. MILLER⁽²⁾ has listed the following effects:

- (a) Pure swirl (i.e. rotation of the fluid about the axis of the pipe caused by a succession of sharp elbows).
- (b) Secondary flows (e.g. vortices caused by pipe enlargement).

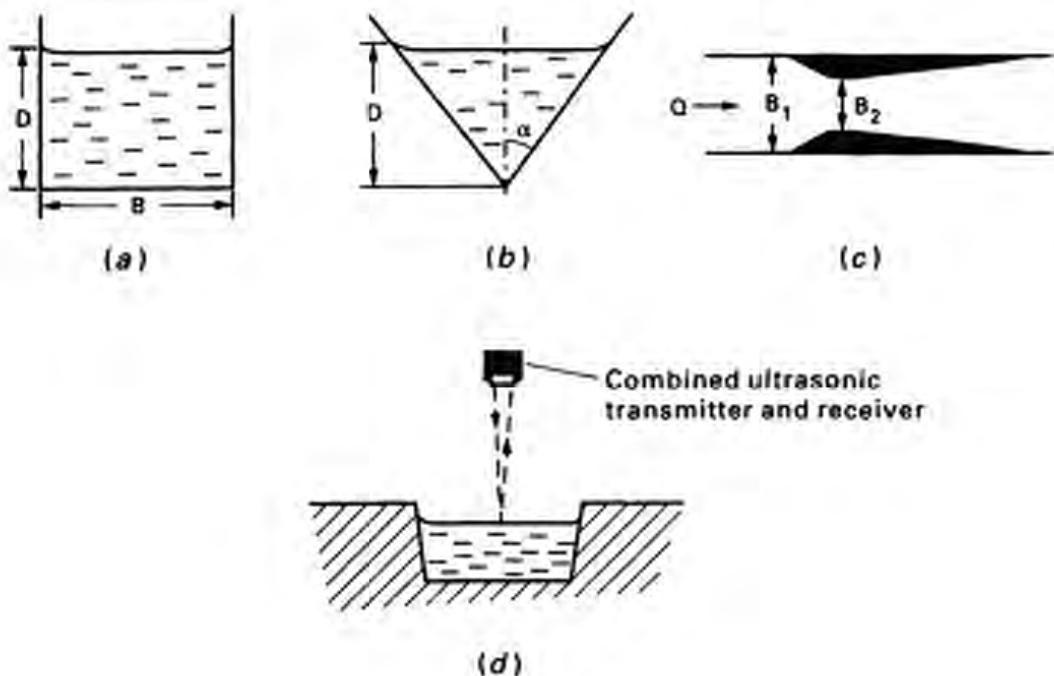


FIG. 6.7. Open channel flow measurement.

- (c) Symmetric profile with unusually high axial velocity (e.g. due to a large reduction in pipe diameter).
- (d) Asymmetric profile (e.g. due to a single elbow).

Two or more of these conditions can occur at the same time, resulting in asymmetric axial, radial and tangential velocity vectors. Some flowmeters are more sensitive than others to particular types of flow distortion, e.g. orifice meters are affected by pure swirl more than venturi meters are; magnetic flowmeters are unaffected by changes in the radial velocity component whereas ultrasonic time-of-flight meters are highly susceptible thereto; swirl and asymmetry have the least effect on positive displacement meters and the greatest effect on variable area meters.

Swirl is produced by the flow being made to change direction twice—each time in a different plane (Fig. 6.8b). This can be due to a combination of two successive 90° elbows or of a 90° elbow closely followed by a valve. The strongest swirl occurs when the two elbow planes are at 60° to each other⁽²⁾.

To avoid swirl, elbows should be well separated and have large radii of curvature. If this is not possible then the flowmeter should be sited at least 40 pipe diameters downstream of fittings causing asymmetric flow only and a minimum of 100 pipe diameters downstream when swirl is likely to occur⁽¹⁵⁾. There should also be at least 10 pipe diameters allowed downstream of the meter free of any obstruction or fitting. If the flow is laminar then these distances should be doubled.

Alternatively, a flow conditioning device can be fitted at least 15 pipe diameters upstream of the flowmeter. A large variety of these is available (a few are illustrated in Fig. 6.9) and the right one must be selected for the type of flow distortion occurring. In general the more complex flow conditioners produce the better velocity profiles but they are generally the more expensive and give higher pressure drops.

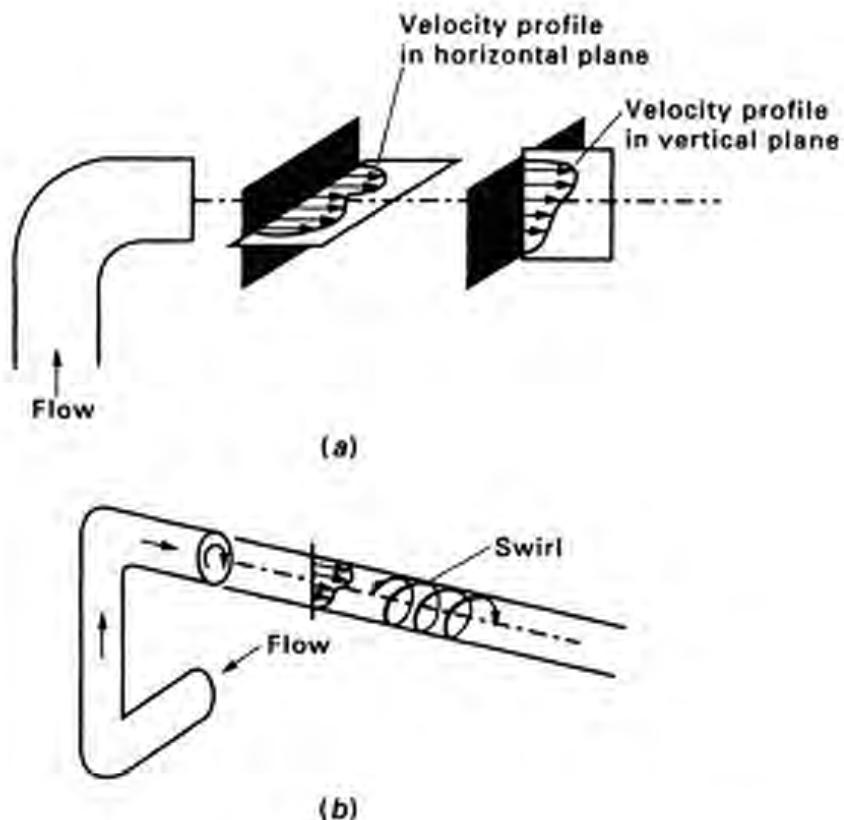


FIG. 6.8. Flow profile distortion: (a) velocity distribution after a single elbow; (b) velocity distribution and swirl following two 90° elbows in different planes

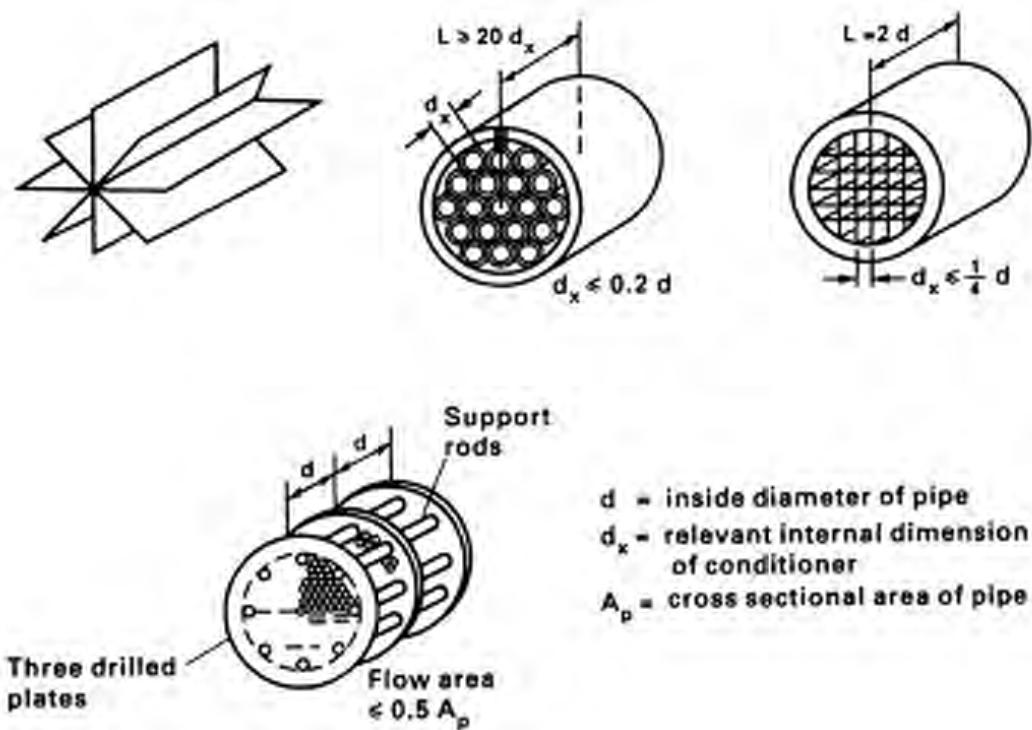


FIG. 6.9. Typical flow conditioners

6.3. THE MEASUREMENT OF PRESSURE

Pressure is measured extensively in the chemical processing industries and a wide variety of pressure measuring methods has been developed. Some of these have already been discussed in Volume 1, Section 6.2.2, viz. the manometer (which is an example of a gravity-balance type of meter), the Bourdon gauge (an example of an elastic transducer); and mention is made of the common first element in most pressure signal transmission systems—the differential pressure (DP) cell (Volume 1, Section 6.2.3). The latter also frequently forms part of a pneumatic transmission system and further discussion of this can be found in Section 6.3.4.

Reasons for pressure measurement in the process industries are three-fold. Firstly, any closed pipe or vessel will have a maximum safe operating pressure. Exceeding this can lead to the destruction of equipment and danger to personnel. In such cases, absolute and highly accurate readings of pressure are often less important than reliability, and it may be sufficient simply to install a high or low pressure limit alarm system. Secondly, the operating pressure of a process often has a significant effect upon other variables within the process and upon the specification of the product and, in such cases, it is usually necessary to have a consistent and accurate measurement including associated automatic control. Finally, pressure measurement can form part of the quality control procedures for a particular process. In this latter context care must be taken in the selection, installation and maintenance of the measuring equipment.

6.3.1. Classification of Pressure Sensors

SAUNDERS⁽¹⁶⁾ has suggested that pressure sensors may be divided into four categories, viz. utility, general industry, process control and precision and test. Utility instruments (gauges) are found on many small pressure-related items (regulators, valve positioners, small pumps, etc.) and should be considered as little more than indicators. General industrial instruments are required to have a reliable design with accuracies of 1 to 2 per cent of full scale deflection (see Section 6.10.1). It is necessary for gauges which are employed as sensors for control systems to be of good quality and reliability, and to have accuracies of the order of 0.5 to 1 per cent of full scale.

HIGHAM⁽¹⁷⁾ has listed three categories of pressure measurement, viz.:

- (a) *Absolute pressure* which is the difference between the measured pressure and a perfect vacuum.
- (b) *Gauge pressure* which is generally considered to be the difference between the measured pressure and local atmospheric pressure.
- (c) *Differential pressure* which is the difference between two measured pressures, neither of which is local atmospheric pressure.

Units of gauge pressure are frequently employed in the process industries and are typically expressed in terms of kN/m^2 *gauge* which is a unit not defined in the SI system. Care must be exercised in interpreting the recorded pressure when there is no indication of the meter reading being gauge or absolute. Some more recently manufactured pressure sensors reported as displaying gauge pressure compare

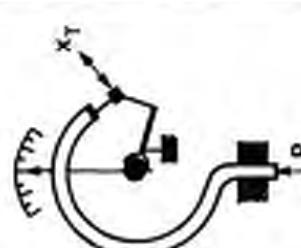
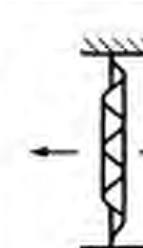
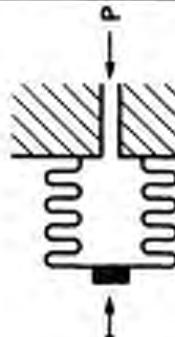
x_T = tip travel, i.e. direction in which tip of Bourdon tube moves				
Cross section of Bourdon tube	C-type Bourdon tube	Spiral Bourdon tube	Twisted Bourdon tube	Helical Bourdon tube
				
P	P	P	P_1 P_2	P
Flat diaphragm	Corrugated diaphragm	Capsule diaphragm	Differential pressure diaphragm	Bellows

FIG. 6.10. Some elastic pressure transducers^(4, 8, 18)

the measured pressure to a *fixed* pressure—usually the *standard atmosphere* (101.325 kN/m²).

6.3.2. Elastic Elements

Diaphragms and bellows used in the sensing of variations in pressure are illustrated in Fig. 6.10. Some common Bourdon gauge configurations are included for completeness. In each instance the elastic movement of the element is amplified by systems of linkages and/or gears or by conversion to an electrical signal. The principle of operation of the Bourdon tube lies in a property of its non-circular cross-section. Any increase in the pressure on the inside of the tube in comparison to the outside causes the tube to try to attain a circular cross-section which results in the tube attempting to untwist itself. The twisted and helical tubes are more sensitive than the C-type Bourdon element but are limited in terms of maximum pressure (Table 6.3). Increased sensitivity can also be achieved by linking a number of capsule diaphragms together.

TABLE 6.3. *Ranges of Some Basic Elastic Elements*⁽¹⁸⁾

Type of Element	Maximum Recommended Pressure (MPa)	Minimum Recommended Span ^(a) (kPa)
Bourdon C-type tube	700	30 ^(b)
Bourdon twisted tube	7	
Diaphragm	7	0.05 ^(c)
Bellows	6	1.2

^(a) See Section 6.10.1.

^(b) 100 kPa when measuring vacuum.

^(c) For single diaphragm or capsule.

6.3.3. Electric Transducers for Pressure Measurement

Electrical output transducers exist in many forms and consist simply of elastic elements coupled with suitable displacement transducers such as capacitance, inductance and reluctance pick-ups, certain types of strain gauge, piezoelectric elements, potentiometers and eddy current probes. A selection of these is described in the following paragraphs.

Capacitive Pressure Sensors

A typical capacitive sensor is illustrated diagrammatically in Fig. 6.11. The element consists of a gas filled parallel plate capacitor in which one plate is a flat circular diaphragm whilst the other is a fixed metal disc. When the pressure on the outside surface of the flexible diaphragm is increased by an amount δP compared with the pressure within the unit, the diaphragm is deflected by an amount w at a radius r_1 (assuming the distorted section to be smoothly curved) given by (Volume 6, Section 13.3.5):

$$w = \frac{3}{16} \frac{(1 - \nu^2)}{\varepsilon x_d^3} (r_2^2 - r_1^2)^2 \delta P \quad (6.13)$$

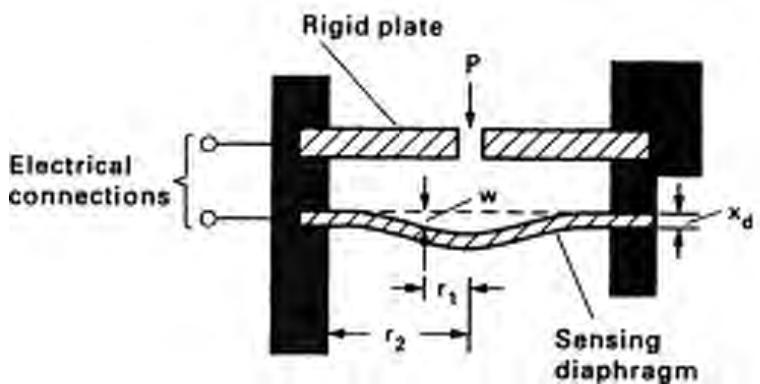


FIG. 6.11. Capacitive pressure sensor with flexible diaphragm

where r_2 is the radius of the diaphragm, ϵ is Young's modulus, x_d is the thickness of the diaphragm and ν is Poisson's ratio [$\nu = -$ (transverse strain in the diaphragm)/(longitudinal strain in the diaphragm)]. The resulting increase in capacitance is⁽¹⁹⁾:

$$\delta C = \frac{\epsilon_0 \epsilon_r \pi r_2^2 (1 - \nu^2)}{16 \epsilon x_d^3 \delta_c^2} \delta P \quad (6.14)$$

where δ_c is the initial separation of the plates of the capacitor. Usually air is used as the dielectric (i.e. $\epsilon_r \approx 1$). Capacitive sensing elements are employed in conjunction with either a.c. deflection bridges or with electrical oscillator circuits. Account should be taken of dielectric losses within the capacitor and any capacitance of the cable connecting the sensor to the measurement circuit. Alternative versions of this type of transducer either vary the area of the plates of the capacitor or the displacement of a solid dielectric section situated between the plates.

Capacitive pressure transducers are traditionally used for relatively low pressure ranges (up to about 800 kPa) and for vacuum measurement (Section 6.3.5).

Inductive Pressure Transducers

These employ a magnetically permeable member to increase and decrease respectively the inductances in the coils of a two coil inductance bridge. Changes in inductances are additive due to the way in which the coils are connected within the bridge circuit (Fig. 6.12).

It can be shown that, for such a transducer, the inductance \mathcal{L} of each coil is given by⁽⁸⁾:

$$\mathcal{L} = \frac{\mathcal{L}_0}{1 + k_s x_s} \quad (6.15)$$

where \mathcal{L}_0 is the reference inductance (at $x_s = 0$); x_s is a measure of the distance moved by the core of the inductor (the *stroke*) and k_s is a constant determined by the geometry of the transducer.

Such variable inductance transducers are available with strokes of 0.0025 to 0.5 m. The non-linearity of the element can range from 0.02 to 1 per cent with a sensitivity

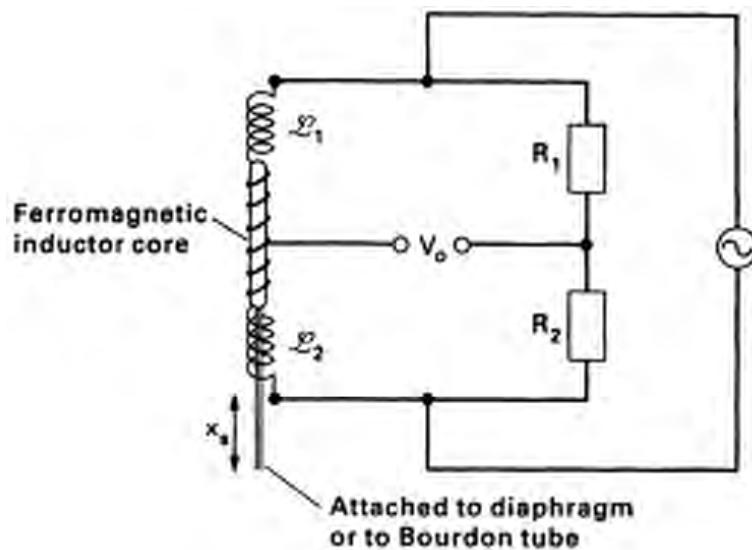


FIG. 6.12. Inductive pressure transducer

of between 200 and 1600 V/m. This type of transducer is normally coupled with a diaphragm or a Bourdon tube as the pressure sensor.

An associated type of transducer is the *Linear Variable Differential Transformer* (*LVDT*) which is essentially a transformer with a single primary winding and two identical secondary windings wound on a tubular ferromagnetic former. The primary winding is energised by an a.c. source (see Fig. 6.13).

The two secondary windings are connected in series opposition so that the output voltage is the difference of the voltages in the secondary windings (i.e. $V_o = V_1 - V_2$, $V_1 > V_2$). A ferromagnetic core moves inside the primary coil and thus varies the mutual inductance between the primary and secondary coils which in turn varies the secondary voltages. The displacement of the pressure sensor (capsule, bellows or

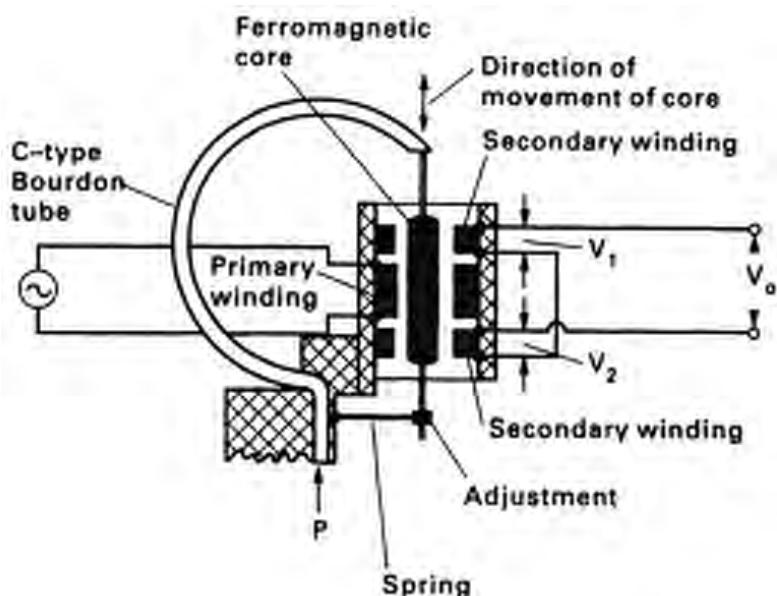


FIG. 6.13. Linear variable differential transformer (LVDT) using C-type Bourdon tube as the pressure sensor

Bourdon tube) is reflected in the position of the ferromagnetic core of the LVDT and is thus a function of the difference between the input and output voltages measured in terms of phase shift and amplitude ratio (see Section 7.8.4).

Commercial LVDTs have a full range stroke from 0.1 to 80 mm with a sensitivity of about 25 to 1250 V/m depending upon the frequency of excitation and size of stroke.

Reluctive Pressure Transducers

These are often associated with inductive transducers. However, in this instance the primary variable is the reluctance of a magnetic circuit. If a magnetic flux is induced in a magnetic circuit (e.g. a loop of ferromagnetic material) then, by analogy with the concept of an electromotive force driving a current through an electrical resistance, we can imagine a magnetomotive force F_{mm} driving a magnetic flux ϕ through a magnetic reluctance \mathcal{S} , where:

$$F_{mm} = \phi \mathcal{S} \quad (6.16)$$

If ϕ is induced by passing a current i through N_T turns of a coil wound on the ferromagnetic loop (Fig. 6.14a), then:

$$\phi = \frac{F_{mm}}{\mathcal{S}} = \frac{N_T i}{\mathcal{S}} \quad (6.17)$$

This is the flux linked by one turn of the coil. Hence, the total flux ϕ_T linked by N_T turns is:

$$\phi_T = N_T \phi = \frac{N_T^2 i}{\mathcal{S}} = \frac{N_T^2 i \mu_0 \mu_r A}{\ell} \quad (6.18)$$

where ℓ is the total length of the flux path, μ_r is the relative permeability of the loop material, μ_0 is the permeability of free space ($4\pi \times 10^{-7}$ Henry/m), A is the cross-sectional area of the flux path, and $\mathcal{S} = \ell / \mu_0 \mu_r A^{(20)}$.

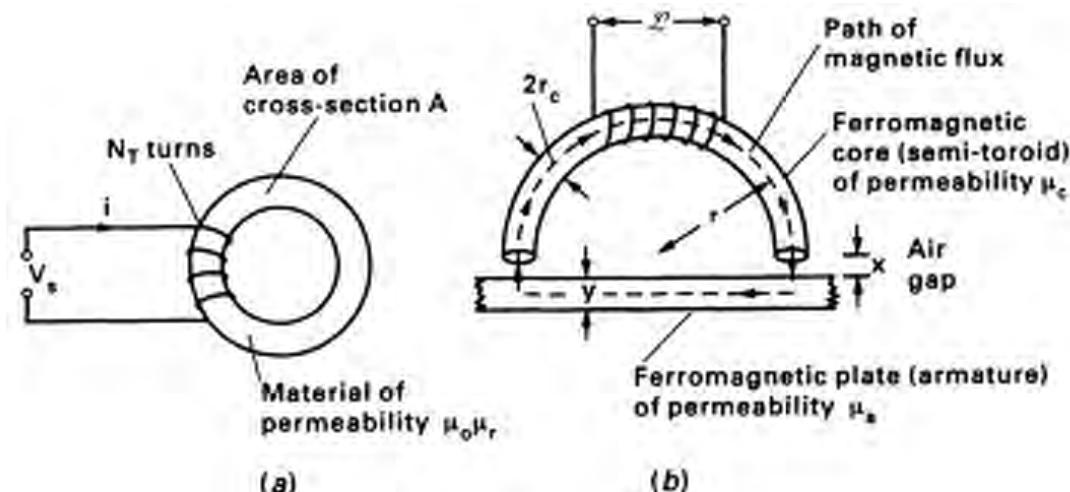


FIG. 6.14. Reluctive transducer: (a) basic circuit; (b) transducer with air gap and moveable armature

The principle of the reductive transducer is shown in Fig. 6.14b. The total reluctance in the magnetic circuit is:

$$\begin{aligned} \mathcal{S}_T &= \mathcal{S}_{\text{core}} + \mathcal{S}_{\text{air gap}} + \mathcal{S}_{\text{armature}} \\ &= \frac{\pi r}{\mu_0 \mu_c \pi r_c^2} + \frac{2x}{\mu_0 \pi r_c^2} + \frac{2r}{\mu_0 \mu_a (2ay)} \end{aligned} \quad (6.19)$$

where r is the radius of curvature of the semi-toroidal ferromagnetic core, r_c is the radius of the cross-section of the toroid, x is the width of the air gap and y is the thickness of the movable armature.

As $\mathcal{S}_{\text{air gap}} \gg \mathcal{S}_{\text{core}}$ or $\mathcal{S}_{\text{armature}}$, then a small change in x will produce a large variation in \mathcal{S}_T . The self-inductance \mathcal{L} of the coil in Fig. 6.14a is the total flux linked per unit current. Thus, from equation 6.18:

$$\mathcal{L} = \frac{\phi_T}{i} = \frac{N_T^2}{\mathcal{S}_T} \quad (6.20)$$

Consequently, a change in reluctance will produce a variation in \mathcal{L} , where, from equation 6.15:

$$\mathcal{L} = \frac{\mathcal{L}_0}{1 + k_i x} = \frac{N_T^2}{\mathcal{S}_T} \quad (6.21)$$

To overcome the non-linearity of equation 6.21, the transducer is generally designed on a push-pull basis and incorporated into an a.c. deflection bridge.

[Note the difference in operation of the inductive transducer (Fig. 6.12) where the core of an inductor is displaced linearly by a distance x , along the axis of the coil and the reductive sensor (Fig. 6.14) which responds to a small displacement x of the armature.]

Strain Gauges

The conversion of alterations in pressure into changes in resistance due to strain in two or four arms of a Wheatstone bridge network has been used in commercial pressure transducers for many years. Modern transducers generally employ *deposited metal film (thin film)* strain gauges applied either directly to the inside of a diaphragm pressure sensor (Fig. 6.15a) or to a secondary sensing member that is moved by a diaphragm via a mechanical linkage.

The principle of the resistance strain gauge⁽²¹⁾ is that the electrical resistance of a conductor will change when it is stretched or compressed due to the consequent variation in its physical dimensions. There is an additional effect called the *piezoresistance* which is the relation between the resistivity ρ' of the material and the mechanical strain. The resistance R of a conductor of area of cross-section A and length x is given by:

$$R = \rho' \frac{x}{A} \quad (6.22)$$

When R changes by an amount δR due to equivalent changes in ρ' , x and A (Fig. 6.15b), then:

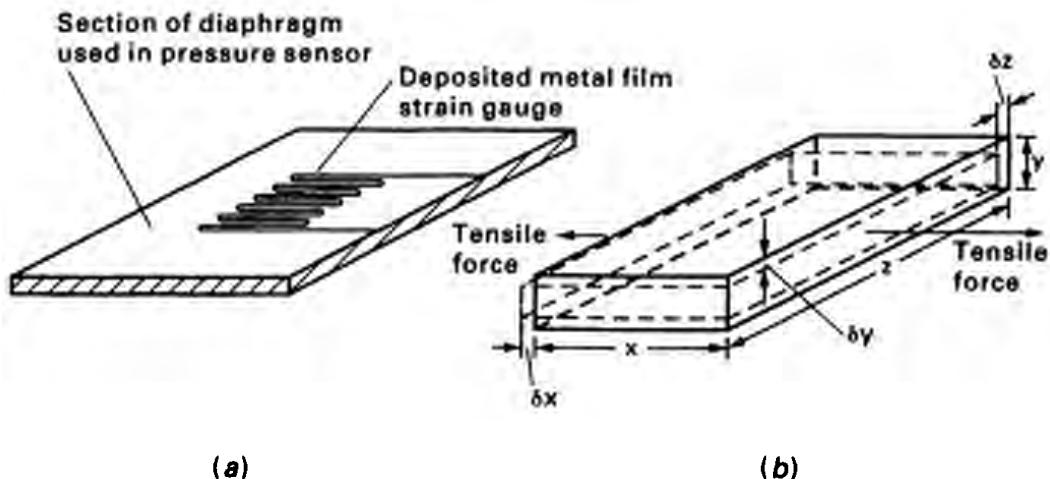


FIG. 6.15. Basis of strain gauge pressure transducer: (a) thin-film strain-gauge used as pressure sensor; (b) deformation of conductor under tensile stress

$$\begin{aligned}\delta R &= \left(\frac{\partial R}{\partial x} \right) (\delta x) + \left(\frac{\partial R}{\partial A} \right) (\delta A) + \left(\frac{\partial R}{\partial \rho'} \right) (\delta \rho') \\ &= \frac{\rho'}{A} (\delta x) - \frac{\rho' x}{A^2} (\delta A) + \frac{x}{A} (\delta \rho')\end{aligned}\quad (6.23)$$

Dividing through by $R = \rho' x / A$ gives:

$$\frac{\delta R}{R} = \frac{\delta x}{x} - \frac{\delta A}{A} + \frac{\delta \rho'}{\rho'} \quad (6.24)$$

$\frac{\delta x}{x}$ is the longitudinal strain e_x in the conductor and $A = zy$ for a rectangular cross-section (Fig. 6.15b).

Hence:

$$\delta A = z \delta y + y \delta z$$

Therefore:

$$\frac{\delta A}{A} = \frac{\delta y}{y} + \frac{\delta z}{z} = 2e_T \quad (6.25)$$

where δy , δz are the equivalent changes in y and z respectively and e_T is the transverse strain in the element.

Thus:

$$\begin{aligned}\frac{\delta R}{R} &= e_x - 2(-\nu e_x) + \frac{\delta \rho'}{\rho'} \\ &= (1 + 2\nu)e_x + \frac{\delta \rho'}{\rho'} \\ &= \mathcal{G}e_x\end{aligned}\quad (6.26)$$

with the gauge factor $\mathcal{G} = \frac{\delta R/R_0}{e_x}$.

$$\text{i.e.: } \mathcal{G} = \frac{\delta R/R_0}{\delta x/x} = 1 + 2\nu + \frac{1}{e_x} \frac{\delta \rho'}{\rho'} \quad (6.27)$$

Resistance change due to length change	Resistance change due to area change	Resistance change due to piezoresistance effect
--	--	--

A typical resistance strain gauge has a gauge factor of about 2, an unstrained resistance of 120Ω and a maximum change in resistance of approximately 7Ω between maximum compression and maximum tension. The strain gauge is placed in one arm of a Wheatstone bridge network—usually of the null-balance type so that the gauge carries no current. In order to compensate for temperature effects a second identical gauge in an unstressed diaphragm is attached to the other arm of the bridge. A more effective arrangement is to use all four arms of the Wheatstone bridge by placing a strain gauge in tension in one arm, an equivalent gauge in compression in a second arm, and unstressed gauges in the remaining two arms.

Semiconductor strain gauges have a much larger piezoresistance effect leading to gauge factors of between 100 and 175 for 'P' type material and between -100 and -140 for 'N' type material*. These consequently are much more sensitive to changes in strain than the metal resistance types. On the other hand, they are affected to a greater extent by variations in temperature.

Piezoelectric Sensing Elements

If a force is applied to a crystal, the atoms in the crystal lattice will be displaced by an amount which is proportional to the applied force.

A typical piezoelectric pressure transducer consists of a pressure sensing diaphragm acting against a stack of quartz discs which produces an output signal in the form of an electric charge (Fig. 6.16). This effect is reversible in that, if a charge is applied, then the material will mechanically deform. The discs form part of a capacitor constructed by attaching electrodes to selected faces of the material. Hence, any charge Q created will be reflected in terms of a voltage across the assembly according to $V = Q/C$ where C is the capacitance of the transducer. The charge does slowly leak away through the very high leakage resistance of the quartz. Thus the transducer is much better suited to measuring variations in pressure rather than static pressure. However, this type of sensor is gaining in popularity due to its very fast response (typically 10^{-6} s rise time and 15 per cent overshoot in response to a step change in pressure—see Section 7.11).

Potentiometric Transducers

These operate by sliding a movable contact or *wiper* over a resistance element. The contact motion can be translational, rotational or a combination of both depending upon the device providing the displacement (e.g. Bourdon tube, diaphragm, etc.). If no current is drawn from the meter then the output voltage V_0 will

* For an explanation of this difference between semiconductor materials see Ref. 20 or any good elementary text describing the basic principles of electronics.

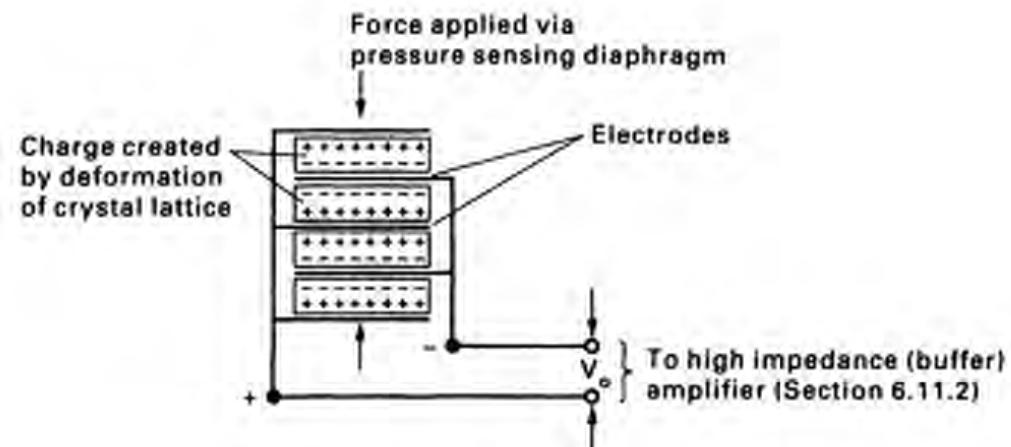


FIG. 6.16. Principle of the piezoelectric transducer

be directly proportional to the motion of the contact moving over the resistance element (provided that the distribution of resistance in the latter is uniform).

The usual situation, however, is that current is drawn from the element to operate a recorder and/or some further element within a control system. Under these conditions the relation between the displacement x of the contact (i.e. the change in process pressure) and V_o will be non-linear due to loading effects (Section 6.11.6) unless the resistance of the load R_L is much greater than that of the potentiometer R_{AB} .

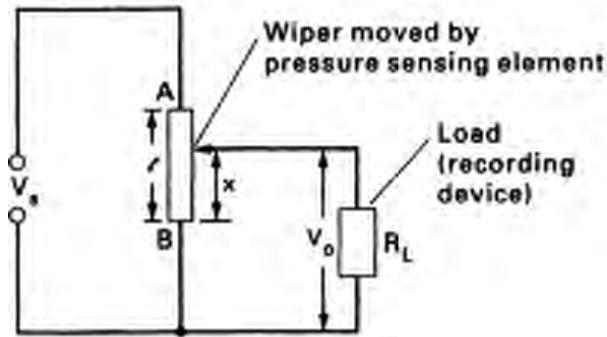


FIG. 6.17. Translational potentiometric transducer

From Fig. 6.17:

$$\frac{V_o}{V_s} = \frac{1}{\frac{x}{\ell} + \frac{R_{AB}}{R_L} \left(1 - \frac{x}{\ell}\right)} \quad (6.28)$$

where ℓ is the length of the potentiometer slide-wire. Hence, if $R_L \gg R_{AB}$, we have the linear relationship:

$$\frac{V_o}{V_s} \approx \frac{x}{\ell} \quad (6.29)$$

although under these conditions the sensitivity of the combination of sensor and recorder will be relatively low.

The resolution of potentiometric transducers is dependent upon the construction of the resistance element. In the case of a *wire-wound* resistance, in order to obtain a high resistance in a small space, the resistance wire is wound on to a *mandrel* or card which is straight or formed into a circle or helix depending upon the motion of the contact. This limits the resolution of the transducer as the wiper moves from one wire to the next on the mandrel. The best resolution that can be obtained is about 0.01 per cent (see Section 6.10.1). Typical wire-wound potentiometers have strokes of between 0.0025 m and 0.5 m and rotational versions from about 10° of arc to 50 turns. An alternative often employed is the *conductive plastic film* element. This provides a continuous resistance element and thus, a zero resolution, but such elements suffer from a higher temperature coefficient of resistance. A more recent development is a combination of earlier types in which a conductive plastic coating is sprayed on to a wire-wound resistor.

Vibrating Element Pressure Transducers

The principle upon which these are based is a change in the resonant frequency of a vibrating section—commonly a wire or a cylinder. A schematic diagram of the wire version is shown in Fig. 6.18.

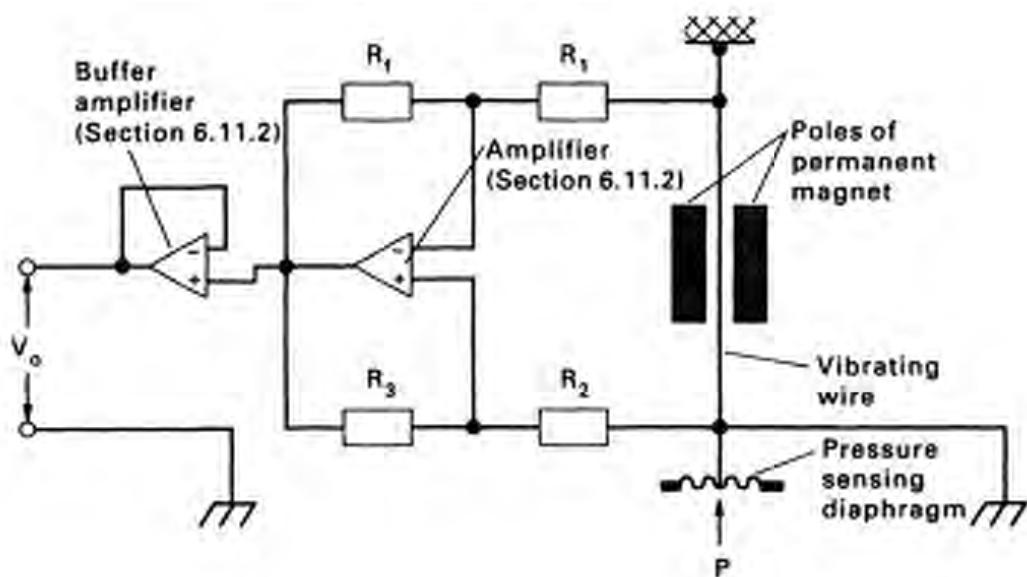


FIG. 6.18. Vibrating wire pressure transducer

A very thin wire (typically made of tungsten) is attached to the centre of a pressure sensing diaphragm. The fixed end of the wire is insulated and the whole is located within a magnetic field provided by a permanent magnet. When a current is passed through the wire it moves in this field sufficiently to induce an electro-motive force and an associated current within the wire. This induced emf is amplified and applied back across the wire in order to sustain its oscillation. The design is generally such that an increase of pressure produces a decrease in the tension in the wire and thus a reduction in its angular frequency of oscillation ω according to⁽²²⁾:

$$\omega = \frac{\pi}{\ell n} \sqrt{\frac{F}{A\rho}} \quad (6.30)$$

where n is the integer mode of frequency, ℓ is the length of the wire, A is the area of cross-section of the wire, ρ is the density of the material of the wire and F is the tensile force acting on the wire.

The vibrating cylinder version of this type of transducer employs a sensing element of the straight tube type and is similar to the vibrating cylinder density meter (Section 6.6.1). The cylinder is maintained in oscillation by a feedback amplifier/limiter combination and its frequency of oscillation varies with the pressure of the fluid within it, which alters the hoop stress on the cylinder. As with the vibrating wire, the frequency of oscillation increases with the fluid pressure. In order to be able to use the sensor for the measurement of absolute pressures, it is surrounded with a cylindrical housing and the annular space between the two is evacuated. Such sensors give excellent repeatability and have a relatively low temperature sensitivity.

6.3.4. Differential Pressure Cells

Differential pressure transmitters (or *DP cells*) are widely used in conjunction with any sensor that produces a measurement in the form of a pressure differential (e.g. orifice plate, venturi meter, flow nozzle, etc.). This pressure differential is converted by the DP cell into a signal suitable for transmission to a local controller and/or to the control room. DP cells are often required to sense small differences between large pressures and to interface with difficult process fluids. Devices are available that provide pneumatic, electrical or mechanical outputs.

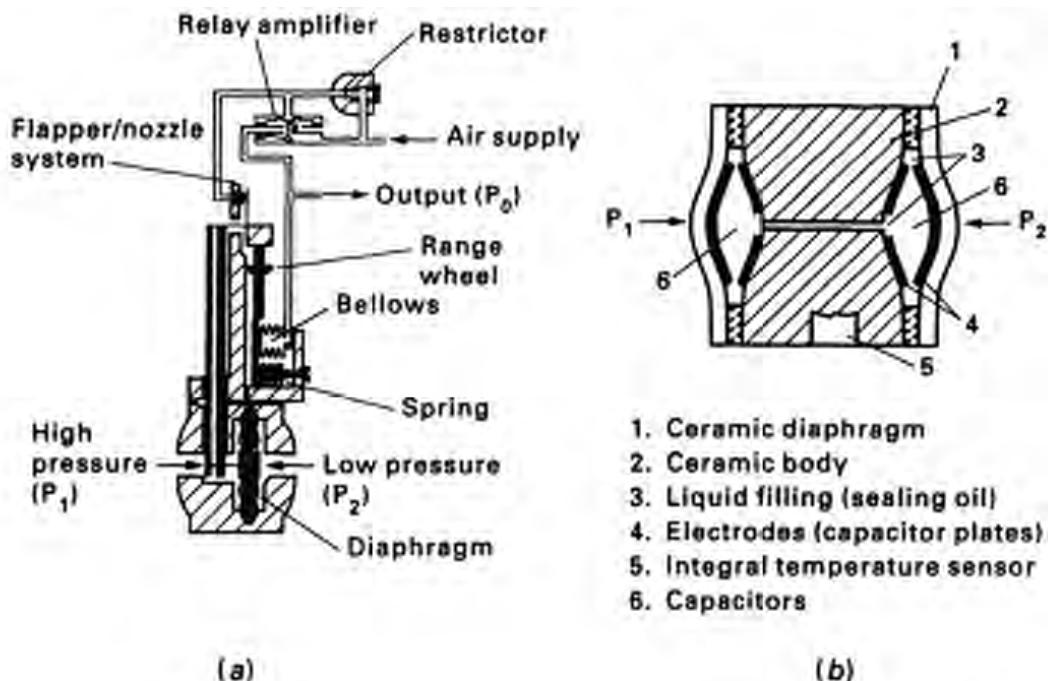


FIG. 6.19. Differential pressure cells (transmitters): (a) pneumatic cell; (b) capacitive ceramic cell

A typical DP cell is shown in Fig. 6.19a⁽²³⁾. The associated flapper/nozzle system works on a force-balance principle (see Volume 1, Section 6.2.3). The output pressure P_0 is linearly related to the difference in pressure ($P_1 - P_2$), thus:

$$P_0 = K(P_1 - P_2) \quad (6.31)$$

K is generally large and such systems exhibit good linearity and accuracy.

Figure 6.19b is an illustration of a DP cell which operates by varying the distance between the plates of two adjacent capacitors (see also Fig. 6.11)⁽²⁴⁾. The high and low pressure signals from the sensor are applied to ceramic diaphragms to which one plate of each capacitor is attached. The subsequent change in the separation of the capacitor plates produces a variation in capacitance which is detected by incorporating the cell into a capacitance bridge, as described in Section 6.5.3 (Fig. 6.31b).

The installation and positioning of the DP cell relative to the sensor is often dependent upon the nature of the fluid stream being measured. Some of the more common forms of installation are shown in Fig. 6.20.

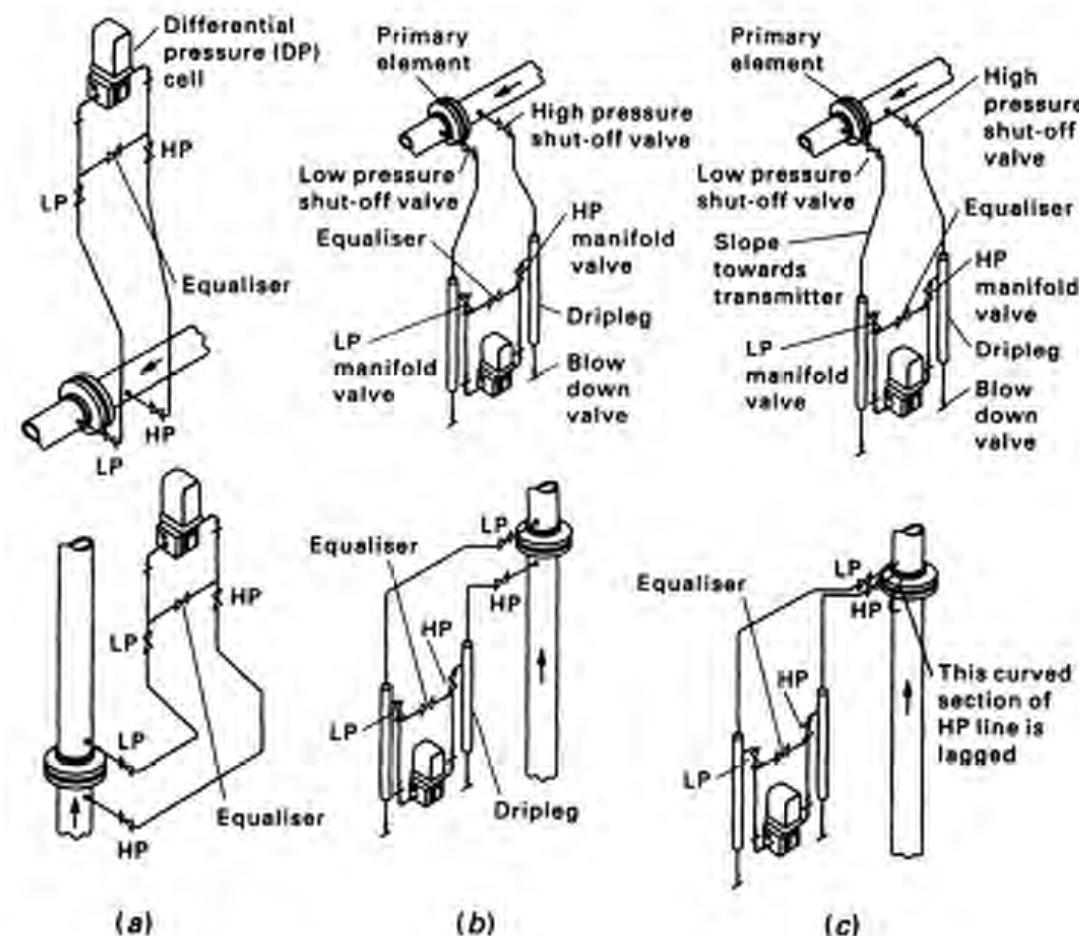


FIG. 6.20. Installation of differential pressure cells (transmitters): (a) arrangement for non-corrosive dry gas and non-corrosive liquid; (b) piping for wet gas (non-condensing) and liquids with solids in suspension; (c) arrangement for steam and condensable vapours

6.3.5. Vacuum Sensing Devices

These are considered separately as vacuum sensing devices differ substantially from other types of pressure sensor.

Two commonly used units of vacuum measurement are the *torr* and the *micrometer*. One torr is 1/760 of one atmosphere (or 1 mm Hg) at standard conditions and, hence, one torr = 133 N/m^2 and one micrometer = 10^{-3} torr = 0.133 N/m^2 . Ranges of vacuum are conventionally divided up as follows⁽²⁵⁾:

<i>Low vacuum:</i>	760 to 25 torr (100 to 3 kN/m^2)
<i>Medium vacuum:</i>	25 to 10^{-3} torr (3 to 10^{-4} kN/m^2)
<i>High vacuum:</i>	10^{-3} to 10^{-6} torr (10^{-4} to 10^{-7} kN/m^2)
<i>Very high vacuum:</i>	10^{-6} to 10^{-9} torr (10^{-7} to 10^{-10} kN/m^2)
<i>Ultra high vacuum:</i>	below 10^{-9} torr (below 10^{-10} kN/m^2).

Elastic elements such as diaphragms and capsules are used as sensing elements in combination with different displacement transducers (e.g. inductive, potentiometric, etc.) for low/medium vacuum measurements down to about 1 torr. Elastic elements have been employed in conjunction with capacitive transducers for the measurement of pressures as low as 10^{-5} torr.

Hot Wire or Thermal Conductivity Gauges

These measure the change in thermal conductivity of a gas due to variations in pressure—usually in the range 0.75 torr (100 N/m^2) to 7.5×10^{-4} torr (0.1 N/m^2). At low pressures the relation between pressure and thermal conductivity of a gas is linear and can be predicted from the kinetic theory of gases. A coiled wire filament is heated by a current and forms one arm of a Wheatstone bridge network (Fig. 6.21). Any increase in vacuum will reduce the conduction of heat away from the filament and thus the temperature of the filament will rise so altering its electrical resistance. Temperature variations in the filament are monitored by means of a thermocouple placed at the centre of the coil. A similar filament which is maintained at standard conditions is inserted in another arm of the bridge as a reference. This type of sensor is often termed a *Pirani gauge*.

Ionisation Gauges

There are two principal types of ionisation gauge, viz. the *hot cathode* type in which electrons are emitted by a heated filament, and the *cold cathode* type in which electrons are released from the cathode by the impact of ions. In both cases the vacuum is measured in terms of the ion current. The electrons are accelerated by a potential difference (usually about 2000 V) across the ionisation tube (see Fig. 6.22). Positively charged ions are formed by the electrons striking gas molecules. The number of positive ions produced is a function of the gas density (i.e. the pressure) and the electron current i_e which is normally held constant. The ions are collected at a negatively charged electrode and the resulting ion current i_i is a direct measure of the gas pressure. The hot cathode version is the most sensitive of the two and can be used to measure vacua down to about 10^{-10} torr ($\approx 10^{-8} \text{ N/m}^2$).

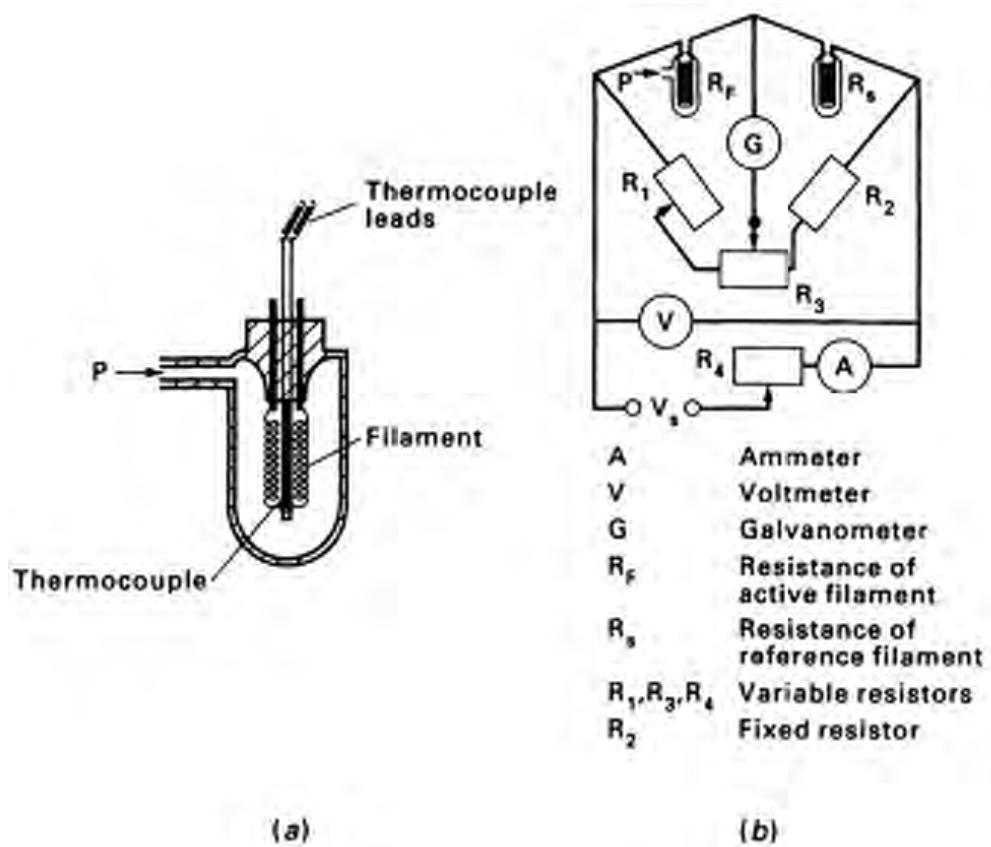


FIG. 6.21. Thermal conductivity vacuum-sensing (Pirani) gauge: (a) Pirani transducer; (b) typical bridge circuit for Pirani gauge

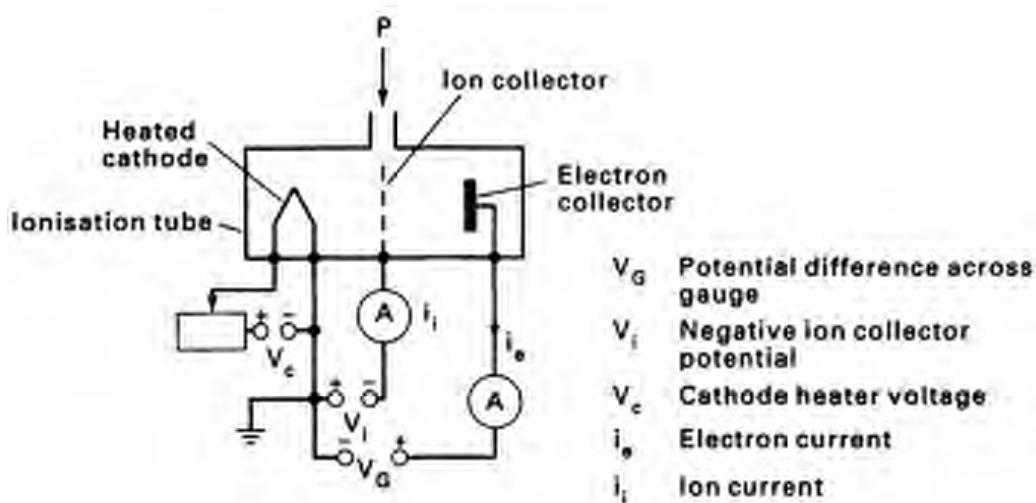


FIG. 6.22. Hot cathode ionisation gauge

6.4. THE MEASUREMENT OF TEMPERATURE

The fundamental meaning of temperature may be described in terms of the zeroth law of thermodynamics. This states that *when two bodies are each in thermal equilibrium with a third body they are then in thermal equilibrium with each other, i.e.*

all three bodies are said to be at the same temperature. Any temperature scale (and the numbers assigned to it) which is based upon one of the physical properties of materials which vary with temperature is, by nature, arbitrary and is, in principle, as good as any other scale based upon another of these properties. In practice, the properties employed will only be those which have easily observable thermometric characteristics, e.g. the pressure of a gas in a closed vessel, the length of a column of mercury in a capillary tube, or the resistance of a platinum wire. It is important that such a temperature scale should be *reproducible* (i.e. will give consistently the same values under the same conditions) and, in order that this should be so, the following must be specified:

- (i) the particular thermometric substance and property employed,
- (ii) the numbers to be attached to two fixed points, and
- (iii) the relation between the temperature and the thermometric property which is to be used for interpolating between the fixed points and extrapolating beyond them.

If the temperature is considered to be a linear function of the thermometric property, then:

$$\theta = a_\theta X + b_\theta \quad (6.32)$$

where θ is the temperature and X is the value of the thermometric property. The constants a_θ and b_θ are determined by the numbers assigned to the fixed points, e.g. on the Celsius scale, a_θ and b_θ can be determined by solving,

$$0 = a_\theta X_1 + b_\theta \quad \text{and} \quad 100 = a_\theta X_2 + b_\theta \quad (6.33)$$

where X_1 and X_2 are the values of the thermometric property at the ice and steam points. Hence from equations 6.32 and 6.33:

$$\theta(\text{°C}) = \frac{100(X - X_1)}{X_2 - X_1}. \quad (6.34)$$

A temperature measured on one scale can always be converted into a temperature measured on another scale (e.g. Fahrenheit) with mathematical *precision* (i.e. to as many significant figures as is required—see Section 6.10.1).

It is important to consider what happens when the substance or property employed is changed. For example, for a liquid in glass thermometer (using the Centigrade scale):

$$\theta(\text{°C}) = \frac{100(\ell - \ell_1)}{\ell_2 - \ell_1} \quad (6.35)$$

where ℓ is the length of the column of liquid at temperature θ °C. For a constant volume gas thermometer:

$$\theta(\text{°C}) = \frac{100(P - P_1)}{P_2 - P_1} \quad (6.36)$$

where P is the pressure at θ °C.

If linear interpolation is applied in this way then two thermometers using different thermometric properties brought into contact with the same heat reservoir will give identical readings only at the fixed points.

e.g. for the same heat source we may obtain:

Constant volume hydrogen thermometer	40°C
Mercury-in-glass thermometer	40.11°C
Platinum resistance thermometer	40.36°C.

An absolute scale of temperature can be designed by reference to the Second Law of Thermodynamics, viz. the *thermodynamic temperature scale*, and is independent of any material property. This is based on the Carnot cycle and defines a temperature ratio as:

$$\frac{T_1}{T_2} = \frac{Q_{H,1}}{Q_{H,2}} \quad (6.37)$$

where $Q_{H,1}$ and $Q_{H,2}$ are the quantities of heat absorbed and rejected respectively by a reversible engine operating between reservoirs at T_1 and T_2 . Hence, if a number is selected to describe the temperature of a chosen fixed point, then the temperature scale is completely defined. Currently, this fixed point is the *triple point* of water (273.16 K). The thermodynamic temperature scale is not, in fact, usable in practice as it is based on the ideal Carnot cycle. However, it can be shown that a temperature scale defined by a constant volume or constant pressure gas thermometer employing an ideal gas is identical to the thermodynamic scale. In practice, real gases have to be used in gas thermometers, and the readings must be corrected for deviations from ideal gas behaviour. The determination of a temperature on any thermodynamic scale is a tedious and time-consuming procedure and the International Practical Temperature Scale (IPTS) has been developed to conform as closely as possible to the thermodynamic scale. For this, apart from the triple point of water (at which the two scales are in precise agreement), five other primary fixed points are specified, viz:

Boiling point of liquid oxygen	-182.96°C (90.17 K)
Boiling point of water	100.00°C (373.13 K)
Freezing point of zinc	419.58°C (629.71 K)
Freezing point of silver	961.93°C (1235.06 K)
Freezing point of gold	1064.43°C (1337.56 K).

For interpolation between these points, the IPTS specifies the use of specific measuring instruments, equations and procedures⁽²⁶⁾. The highest reproducibility of the IPTS is at the triple point of water. The accuracy falls at lower or higher temperatures than the triple point.

6.4.1. Thermoelectric Sensors

The Thermocouple

In 1821 Seebeck discovered that, in an electric circuit consisting of two different materials X and Y in the form of wires, when the two junctions are at different temperatures θ_1 and θ_2 a potential exists at the terminals on open circuit and, if the circuit is closed, a current flows⁽²⁷⁾. At each junction there exists a *contact potential* E_{XY}^θ and E_{YX}^θ respectively which depends on the type of metal employed and the temperature of the junction. When the system is on closed circuit the electromotive force (emf) is given by:

$$E_{XY}^{\theta_1, \theta_2} = E_{XY}^{\theta_1} - E_{XY}^{\theta_2} = \beta_1(\theta_1 - \theta_2) + \beta_2(\theta_1^2 - \theta_2^2) + \dots \quad (6.38)$$

where β_1 and β_2 etc. are coefficients determined by the types of metal employed to construct the junctions.

DOEBELIN⁽⁴⁾ lists five laws of thermocouple behaviour:

- (i) The emf of a given thermocouple depends only upon the temperatures of the junctions and is independent of the temperatures of the wires connecting the junctions.
- (ii) If a third metal Z is inserted between X and Y then, provided that the two new junctions are at the same temperature (θ_3), the emf is unchanged.
- (iii) If a third metal Z is inserted between X and Y then, provided that the two new junctions XZ and ZY are both at the same temperature (θ_1 or θ_2), the emf is unchanged.
- (iv) If the emf obtained using the metals X and Y is E_{XY} and that using metals Y and Z is E_{YZ} then the emf obtained employing X and Z will be:

$$E_{XZ} = E_{XY} + E_{YZ} \quad (6.39)$$

(the junction temperature being θ_1 and θ_2 in each case). This is called the *Law of Intermediate Metals*.

- (v) If a thermocouple produces an emf $E_{XY}^{\theta_1, \theta_2}$ when its junctions are at θ_1 and θ_2 respectively and $E_{XY}^{\theta_2, \theta_3}$ when its junctions are at θ_2 and θ_3 then it will produce an emf:

$$E_{XY}^{\theta_1, \theta_3} = E_{XY}^{\theta_1, \theta_2} + E_{XY}^{\theta_2, \theta_3} \quad (6.40)$$

when the junctions are at θ_1 and θ_3 . This is termed the *Law of Intermediate Temperatures*.

Law (i) is important in industrial applications where the leads joining measurement and reference junctions may well experience large changes in ambient temperature. Law (ii) means that there will be no change in emf when a voltmeter is placed in the circuit. Law (iii) allows the brazing or soldering of the wires at the measurement junctions without affecting the emf. The use of law (v) is illustrated in the following example.

Example 6.1

The temperature of a gas oil product flowing through a pipe is monitored using a chromel/alumel thermocouple. The measurement junction is inserted into the pipe and the reference junction is placed in the plant control room where the temperature is 20°C. The emf at the thermocouple junction is found to be 6.2 mV by means of a potentiometer connected into the thermocouple circuit adjacent to the reference junction. Find the measured temperature of the gas oil.

Solution

Standard thermocouple tables (BS 4937)⁽²⁸⁾ can be employed to find the measured temperature, but these require a reference temperature of 0°C. However, using equation 6.40:

$$E^{\theta_1, \theta_3} = E^{\theta_1, \theta_2} + E^{\theta_2, \theta_3}$$

Thus we can write:

$$E^{\theta_1, 0} = E^{\theta_1, \theta_2} + E^{\theta_2, 0}$$

From tables, for a chromel/alumel junction at 20°C, $E^{\theta_2, 0} = 0.8$ mV.

$$E^{\theta_1, 0} = 6.2 + 0.8 = 7.0 \text{ mV.}$$

Hence, from tables:

$$\theta_1 = \underline{177^\circ\text{C.}}$$

Thermojunctions may be formed by welding, soldering or pressing the materials together. Such junctions give identical emfs (by law (iii)), but may well produce different currents as the contact resistance will differ depending on the joining process utilised. Whilst many materials exhibit thermoelectric effects, only a small number are employed in practice. The characteristics of the more common thermocouple materials are listed in Table 6.4.

A typical thermocouple installation for an industrial application is shown in Fig. 6.23. Instead of placing the reference junction in a temperature controlled environment (which is often inconvenient), an *automatic reference junction compensation circuit* is fitted. This provides a second source of emf $E^{\theta_2, 0}$ in series with the thermocouple emf E^{θ_1, θ_2} . The meter thus measures $E^{\theta_1, \theta_2} + E^{\theta_2, 0} = E^{\theta_1, 0}$ where $E^{\theta_2, 0}$ varies with temperature according to:

$$E^{\theta_2, 0} = \beta_1 \theta_2 + \beta_2 \theta_2^2 + \beta_3 \theta_2^3 + \dots$$

$$\approx \beta_1 \theta_2 \quad (\text{as } \theta_2 \text{ is generally small}).$$

In order to protect the thermocouple against chemical or mechanical damage, it is normally enclosed in a sheath of mineral packing or within a *thermowell* (Fig. 6.24). Any material which contains the junction should be a good conductor of heat on the one hand, but an electrical insulator on the other. A potentiometric converter is frequently employed to convert the thermocouple signal to the standard 4–20 mA current range prior to further processing and control room presentation. The *extension wires* which connect the thermocouple element to the control room should have similar thermoelectric properties to those of the thermocouple junction wires.

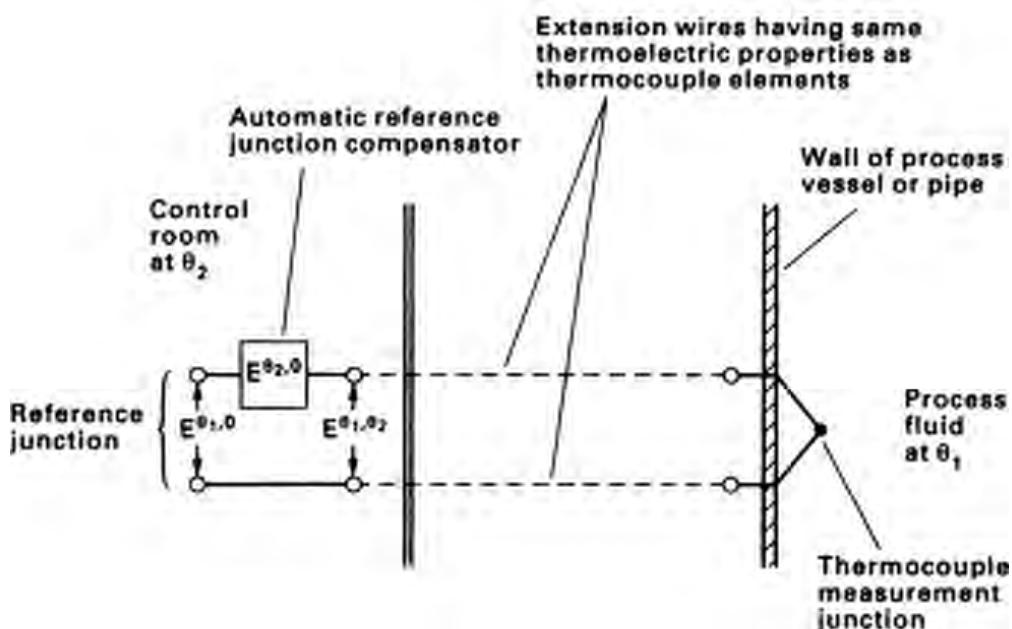


FIG. 6.23. Thermocouple installation with automatic reference junction compensation circuit

TABLE 6.4. Standard Thermocouple Data and Characteristics^(8, 29, 30, 31)

Thermocouple Type	Operating Range (K)	Best Tolerance	Output Emf (μV) ^(a)				Some Typical Applications	Comments
			600K	800K	1000K	1000K		
B Platinum-30%Rhodium/ Platinum-6%Rhodium	273-2000	$\begin{cases} 900-1100\text{K}: tol = +4\text{K} \\ 1100-2000\text{K}: \\ tol = \pm 0.005 T-273 \text{K} \end{cases}$	517	1381	2618	Wherever high stability and long life is required.	Very stable. Poisoned by reducing atmospheres and metal vapours. Use non-metallic sheath.	
E Chrome/Constantan	100-1100	$\begin{cases} 230-650\text{K}: tol = \pm 1.5\text{K} \\ 650-1100\text{K}: \\ tol = \pm 0.004 T-273 \text{K} \end{cases}$	23147	39184	55259	Annealing furnaces, acid production (acetic acid, nitric acid, etc.).	High output emf—useful for low temperature sensitivity. Requires good sheath protection in sulphur-bearing or reducing atmospheres.	
J Iron/Constantan	100-1100	$\begin{cases} 230-650\text{K}: tol = \pm 1.5\text{K} \\ 650-1050\text{K}: \\ tol = \pm 0.004 T-273 \text{K} \end{cases}$	17818	28906	40823	Polyethylene manufacture, paper making, tar stills, annealing and reheat furnaces, chemical reactors.	Good oxidation resistance. Requires good sheath protection in sulphur-bearing atmospheres above 800K, also in oxygen and in humid surroundings.	
K Chromel/Alumel	100-1300	$\begin{cases} 230-650\text{K}: tol = \pm 1.5\text{K} \\ 650-1300\text{K}: \\ tol = \pm 0.004 T-273 \text{K} \end{cases}$	13331	21791	30257	Blast furnace gases, brick kilns, annealing furnaces, boilers, acid production, reactors, superheater tubes, nuclear pile instrumentation, soaking pits, glass tank flues.	Stable and very linear. Recommended for oxidising and neutral conditions. Requires good sheath protection for sulphur-bearing or reducing atmospheres.	
N Nickel-Chromium-Silicon (<i>Nicrosil</i>)/ Nickel-Silicon (<i>Nisil</i>)	100-1300	$\begin{cases} 230-650\text{K}: tol = \pm 1.5\text{K} \\ 650-1300\text{K}: \\ tol = \pm 0.004 T-273 \text{K} \end{cases}$	10303	17780	25587	Blast furnace gases, heat treatment, semiconductor manufacturing, nuclear pile instrumentation, power station boilers, brick kilns.	Very low drift. Particularly good at extreme temperatures and nuclear applications.	
R Platinum-13%Rhodium/ Platinum	273-1850	$\begin{cases} 273-1400\text{K}: tol = \pm 1\text{K} \\ 1400-1900\text{K}: \\ tol = \pm [1 + 0.003(T-1400)]\text{K} \end{cases}$	2666	4766	7063	As for type B.	As for type B.	
S Platinum-10%Rhodium/ Platinum	273-1850	$\begin{cases} 273-1400\text{K}: tol = \pm 1\text{K} \\ 1400-1900\text{K}: \\ tol = \pm [1 + 0.003(T-1400)]\text{K} \end{cases}$	2571	4502	6560	As for type B.	As for type B.	
T Copper/Constantan	30-700	$\begin{cases} 230-400\text{K}: tol = \pm 0.5\text{K} \\ 400-620\text{K}: \\ tol = \pm 0.004 T-273 \text{K} \end{cases}$	300K	400K	500K	Sulphuric acid manufacture, food processing, stack gases, plastic moulding, lubricating oils, producer gas plants.	Recommended for low temperatures. Requires protection from acid fumes. Suitable for oxidising and reducing atmospheres < 600K.	

^(a) Referred to 273.16 K.

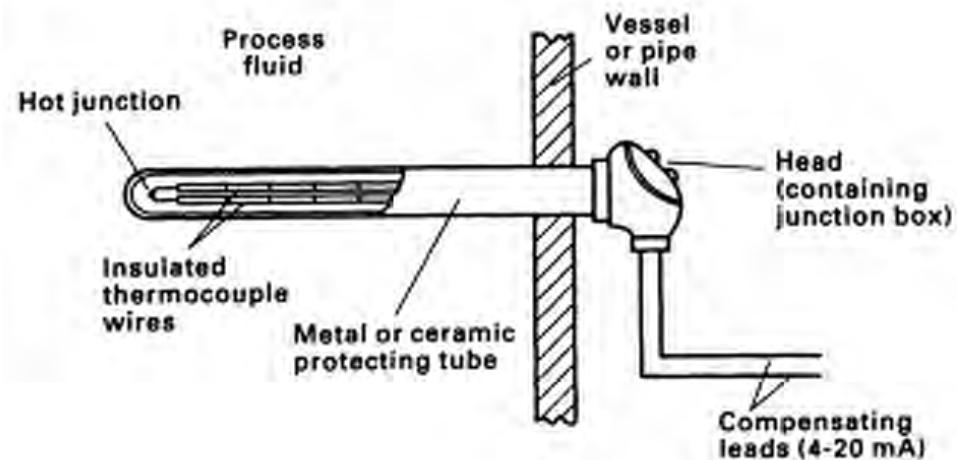


FIG. 6.24. Typical industrial thermocouple arrangement

The dynamics of thermocouple junctions are discussed in Section 7.5.2.

Several thermocouples may be connected in series in order to increase the sensitivity of the instrument. This arrangement is called a *thermopile* and, for n identical thermocouples, gives an output which is n times greater than that from a single thermocouple. Thermopiles are frequently used to detect and measure heat radiation (Section 6.4.2). In this case the surface of the detector is blackened to maximise the absorption of the incoming radiation.

Electrical Resistance Sensors

There are two principal classes of this type of sensor, viz. (i) resistance thermometers (resistance temperature detectors)—which are constructed from normal metallic conducting materials, and (ii) thermistors—which are bulk semiconductor sensors.

The Resistance Temperature Detector (RTD) or Resistance Thermometer

The variation of resistance with temperature θ for metals can be expressed by:

$$R_\theta = R_0(1 + \beta_{\theta,1}\theta + \beta_{\theta,2}\theta^2 + \dots + \beta_{\theta,N}\theta^N) \quad (6.41)$$

where R_0 is the resistance at $\theta = 0^\circ\text{C}$ and $\beta_{\theta,1}, \beta_{\theta,2}, \dots$ are the temperature coefficients of resistance. The RTD is usually constructed from copper, nickel or platinum and, over limited ranges, responds with reasonable linearity (i.e. putting $\beta_{\theta,2} = \beta_{\theta,3} = \dots = \beta_{\theta,N} = 0$ in equation 6.41). More common RTDs are listed in Table 6.5, and a well-type element together with its associated bridge configuration is shown in Fig. 6.25.

A balance over the bridge circuit gives⁽⁸⁾:

$$\theta = \frac{100V_o(R_0 + 2R_{CL})}{R_0 V_s \beta_{\theta,1}} \quad (6.42)$$

Temperature variations in the instrument are a source of error and electrical power dissipation is limited to avoid the effects of self-heating. This is achieved by means of the four lead system shown in Fig 6.25b. This minimises any effects of variations in temperature on the resistance R_{CL} of the connections between the RTD and the bridge and is used normally with digital thermometers and data acquisition systems where the sensor non-linearity is corrected within the computer software.

TABLE 6.5. *Typical RTDs and Thermistors⁽³²⁻³⁵⁾*

Resistance Temperature Detector (RTD) Type	Normal Operating Range (K)	Accuracy (K)	Comments
Platinum 100Ω	70 to 870	±0.4	Resistance increases with temperature (i.e. temperature coefficient always positive).
Platinum 200Ω	70 to 870	±0.4	Good stability. Special types are available
Platinum 500Ω	70 to 870	±0.2	which extend the range of temperatures able to be monitored from a minimum of 10K to a maximum of 1120K.
Copper 10Ω	170 to 370	±2.4	
Copper 25Ω	170 to 370	±1.0	
Nickel 500Ω	200 to 450	±0.1	
Thermistor Type	Normal Operating Range (K)	Accuracy (K)	Comments
Mixed Metallic Oxides	170 to 470	±0.1 to ±0.2	Temperature coefficient large and negative. Much higher sensitivity and resistance than RTDs so less affected by interconnecting resistances.
Silicon	100 to 430	±0.1 to ±0.2	

The Thermistor

Whereas the RTD exhibits a small positive temperature coefficient, the thermistor has a large negative temperature coefficient and the resistance/temperature relationship is highly non-linear. The latter is typically:

$$R = R_0 \exp \left[\beta_\theta \left(\frac{1}{\theta} - \frac{1}{\theta_0} \right) \right] \quad (6.43)$$

where R and R_0 are the resistances at temperatures θ K and θ_0 K respectively, and β_θ is a constant which is characteristic of the material of the semiconductor. Usually θ_0 is set at 298 K. The maximum range of temperatures over which thermistors can be employed is between 70 and 1300 K (standard ranges are shown in Table 6.5). Commercial thermistor probes are generally more sensitive than RTDs or thermocouples, and the severely non-linear characteristics involved can be accommodated by employing a suitable computerised data monitoring system.

6.4.2. Thermal Radiation Detection

Thermal radiation has a frequency range principally between $7.5 \times 10^{12} \text{ s}^{-1}$ and $1 \times 10^{15} \text{ s}^{-1}$ and, as such, covers most of the visible and infra-red sections of the electromagnetic spectrum (EMS). The relation between thermal radiant energy and temperature is discussed in Volume 1 (Section 9.5.3).

The applications of *thermal radiation detectors* (TRDs) now have become more comprehensive in the process industries as they can be employed anywhere it is

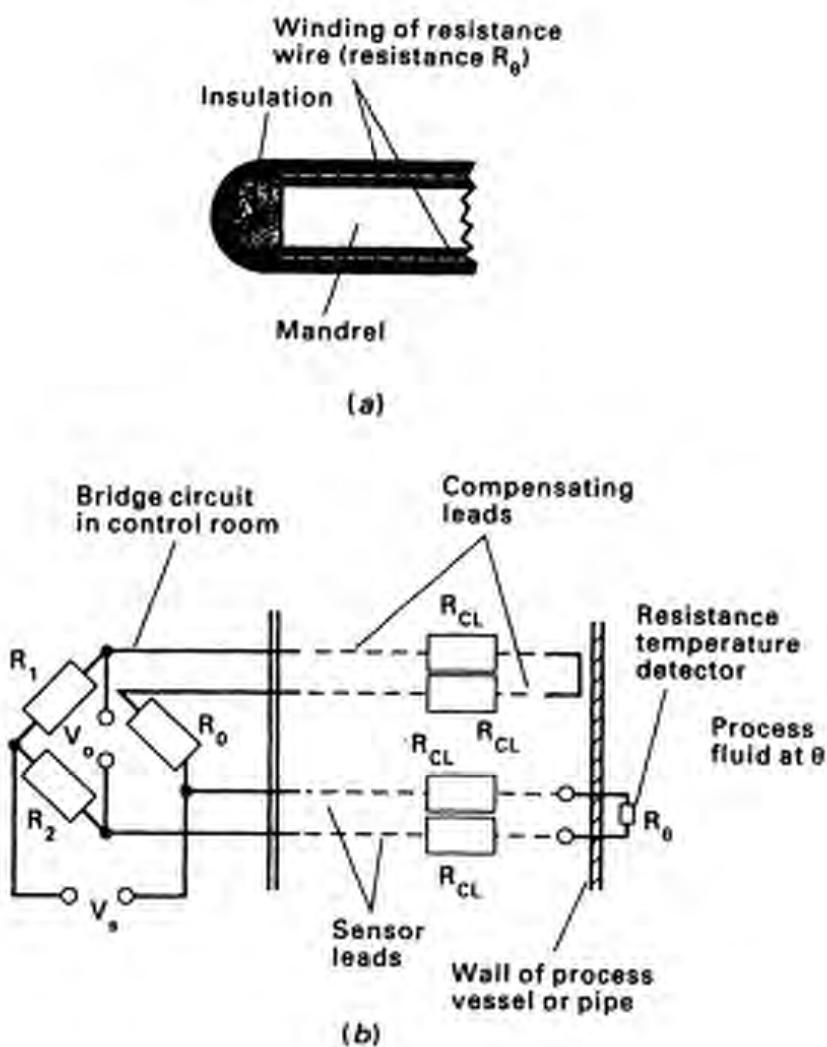


FIG. 6.25. Typical resistance temperature detector element of circular cross-section:
 (a) well-type RTD element of circular cross-section; (b) four lead compensation system
 and associated bridge circuit

desirable that there should be no contact between the process fluid, solid or vessel and the temperature measuring device. Originally this type of sensor was used to measure the heat energy radiated from a *hot* body (> 600 K) but modern detectors are able to measure temperatures as low as 220 K⁽³⁶⁾. Typical applications for TRDs are^(8, 36):

- (i) Measurement of temperature under the following conditions:
 - (a) High temperatures at which a normal sensor would melt or decompose (e.g. process heaters, high temperature gas phase reactors).
 - (b) Of a moving body.
 - (c) Detailed measurement of the temperature distribution over a surface where the number of conventional sensors required would be prohibitive.
 - (d) Other applications where contact with the process material is not possible or is undesirable (e.g. in the food industry, frozen foods).
- (ii) Measurement of radiant heat flux.
- (iii) Measurement of gas composition (Table 6.16).

The total energy emitted per unit area per unit time (i.e. the total power) for a black body at temperature T is given by the *Stefan–Boltzmann law* (see also Volume 1, Section 9.5.3), viz.:

$$E = \sigma T^4 = \int_0^\infty W_\lambda d\lambda = \int_0^\infty \frac{J_1}{\lambda^5 [\exp(J_2/\lambda T) - 1]} d\lambda \quad (6.44)$$

where W_λ is the power spectral density for a black body radiator (i.e. the quantity of radiation emitted from a flat surface into a hemisphere, per unit wavelength, at the wavelength λ), σ is the *Stefan–Boltzmann constant*, and J_1 and J_2 are constants. (If E is measured in W/m^2 , W_λ in W/m^3 , λ in m and T in K, then $\sigma = 5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$, $J_1 = 3.74 \times 10^{-16} \text{ Wm}^2$ and $J_2 = 0.0144 \text{ mK}$.) The wavelength λ_{\max} at which W_λ has a maximum value decreases as T increases and:

$$\lambda_{\max} = \frac{J_3}{T} \quad (6.45)$$

where J_3 is a constant. (If T is measured in K and λ_{\max} in m, then $J_3 = 2.89 \times 10^{-3} \text{ mK}$.) Hence, at higher temperatures there is more power in the visible light region of the EMS, and at lower temperatures there is more power in the infra-red section.

Equation 6.44 gives the total power emitted by a black body. However, materials and bodies whose temperatures are measured with radiation-type instruments often deviate considerably from ideal black body behaviour. This deviation is expressed generally in terms of the *emissivity* e of the measured body (see also Volume 1, Section 9.5.4), and the energy emitted by the body per unit area per unit time is:

$$E_g = \sigma e T^4 \quad (6.46)$$

Emissivities are functions of λ , T and properties of the system which are difficult to quantify or measure, such as size, shape, surface roughness, angle of viewing, etc. This often leads to uncertainties in the estimation of the temperature of a body from the measurement of the thermal radiation it emits. The emissivity of a black body is 1, and a body which has an emissivity which is independent of λ and T is termed a *grey body*. A further source of error is the loss of energy in transmitting radiation from the source to the radiation detector. Such losses may occur by absorption in glass lenses and mirrors used to focus the energy and/or in absorptive gases such as H_2O , CO_2 and O_2 .

Thermal Radiation Measurement Systems

The Broadband Radiation Thermometer (Total Radiation Pyrometer)

This instrument (Fig. 6.26) is the most common type used in day-to-day industrial applications and is sensitive to all wavelengths present in the incoming radiation⁽³⁷⁾. The total power detected can be obtained from equations 6.44 and 6.46,

i.e.:

$$E_g = J_{RT}e \int_0^{\infty} \frac{J_1}{\lambda^5 [\exp(J_2/\lambda T) - 1]} d\lambda = J_{RT}e\sigma T^4 \quad (6.47)$$

assuming that the emissivity e is independent of λ and T . J_{RT} is a factor dependent upon the source lens/detector geometry.

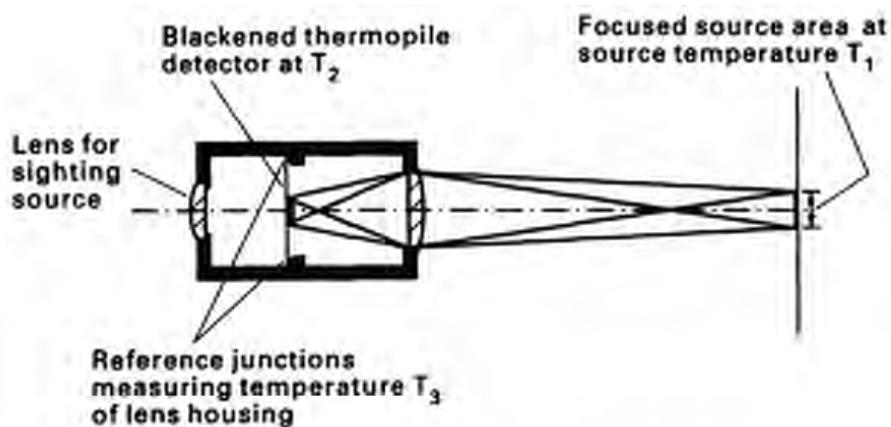


FIG. 6.26. Lens-type broadband radiation thermometer

These instruments employ a blackened thermopile as a detector and focus the radiation using lenses or mirrors. For a given source temperature T_1 , the incoming radiation heats the measuring junction until losses due to conduction, convection and radiation just balance the heat input, i.e.

$$h_{RT}(T_2 - T_3) \approx J_{RT}e\sigma T_1^4 \quad (6.48)$$

Heat loss	Radiant heat input
-----------	--------------------

where h_{RT} may be considered as a heat transfer coefficient for combined conduction, convection and radiation and T_2 and T_3 are the temperatures of the detector and the lens housing respectively (Fig. 6.26). T_1 and T_3 are both influenced by ambient conditions and suitable compensation must be provided for any variations in the latter—particularly when low temperatures are being monitored. The thermopiles can have from 1 to 30 junctions. A smaller number of junctions will give a faster response (due to the smaller mass) but will have a lower sensitivity.

Narrow-Band Radiation Thermometer

These instruments use photon detectors which are semiconductor devices that are responsive only to a narrow band of wavelengths. Many narrow-band thermometers further restrict the wavelength bandwidth by means of a narrow pass filter. In this case the total power detected is⁽⁴⁾:

$$E_g = J_{RT}e \int_b^a \frac{J_1}{\lambda^5 [\exp(J_2/\lambda T) - 1]} d\lambda$$

(where $a = \lambda_0 + \delta\lambda/2$, $b = \lambda_0 - \delta\lambda/2$ and λ_0 is the mean wavelength detected)

i.e.:
$$E_g \approx J_1 J_{RT} e \frac{\delta\lambda}{\lambda_0^5} \exp\left(-\frac{J_2}{\lambda_0 T}\right) \quad (6.49)$$

where $\delta\lambda \ll \lambda_0$ and $J_2/\lambda T \gg 1$.

Chopped Radiation Thermometers

With several different types of instrument a technique is employed in which the radiation between the source and the detector is chopped (i.e. periodically interrupted) at a controlled frequency. This enables high gain a.c. amplifiers to be employed, leading to greater instrument sensitivity as well as good temperature compensation. Thermal detectors employing this method include the blackened chopper radiometer (Fig. 6.27) in which a mirror focuses the radiation on to a square thermistor detector. The motion of the chopper enables the detector to "see" radiation from the source and radiation reflected from the black surface of the chopper. The instrument then compares the two. A typical temperature range for this instrument is ambient to 1600 K with a time constant of about 0.01 s and a chopping frequency of 200 Hz. If a faster response is required then a photon detector can be substituted for the thermal detector.

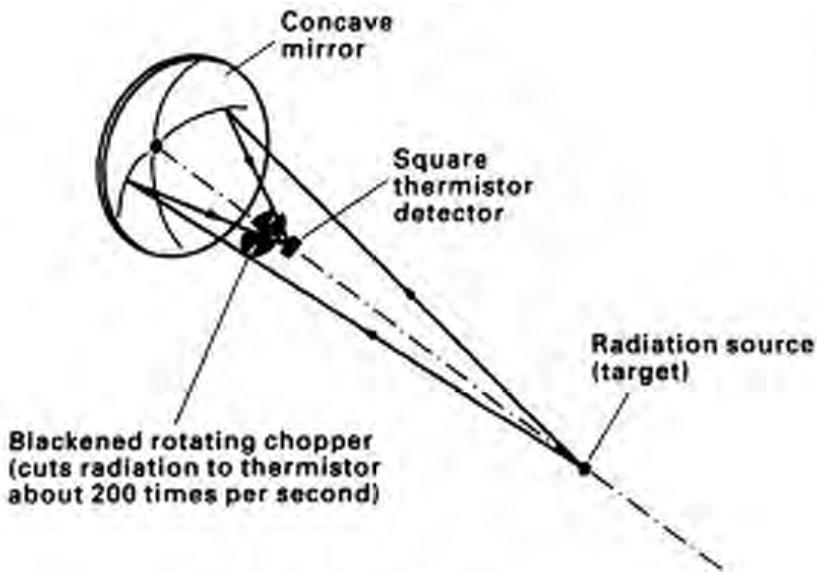


FIG. 6.27. Blackened chopper radiometer

Optical Pyrometers

The most accurate of all radiation thermometers is the disappearing filament optical pyrometer which is employed in setting the IPTS above 1336 K. An image of the source is superimposed on the filament of a previously calibrated tungsten lamp. The calibration enables the brightness temperature of the filament to be related to the current through the filament. A red narrow-band filter is placed between the tungsten lamp (which itself lies between the observer and the source) and the eye of the observer. The current through the lamp filament is varied until the image of the filament disappears in the superimposed image of the source. At this point it is

considered that the brightness of the filament (at temperature T_f) and of the source (at temperature T_s) are equal. For these conditions, from equations 6.44 and 6.46:

$$\frac{\frac{J_1 e_{\lambda s}}{\lambda^5 [\exp(J_2/\lambda T_s) - 1]}}{\text{Source}} = \frac{\frac{J_1 e_{\lambda f}}{\lambda^5 [\exp(J_2/\lambda T_f) - 1]}}{\text{Filament}}$$

where $e_{\lambda s}$ is the emissivity of the source at wavelength λ and the emissivity of the filament $e_{\lambda f}$ can be considered as 1 at the same wavelength. If SI units are employed, then $\exp(J_2/\lambda T) \gg 1$ for $T < 4000$ K, and:

$$\frac{e_{\lambda s}}{\exp(J_2/\lambda T_s)} = \frac{1}{\exp(J_2/\lambda T_f)}$$

Hence:

$$\frac{1}{T_s} - \frac{1}{T_f} = \frac{\lambda}{J_2} \ln(e_{\lambda s}) \quad (6.50)$$

For $e_{\lambda s} \neq 1$, equation 6.50 gives the required temperature correction. The system is not very sensitive to errors in $e_{\lambda s}$; e.g. for a source at 1000°C, an error of 10 per cent in $e_{\lambda s}$ results in an error of 0.45 per cent in $T_s^{(4)}$.

Difficult Applications

The use of TRDs has been facilitated by the use of fibre-optic cable assemblies (Section 6.12.4). This permits sensing in confined spaces as well as enabling the sensor to 'see round corners' and into regions containing nuclear or electromagnetic radiation⁽³⁶⁾. Low levels of source visibility can be overcome by employing *two-colour* or *ratio* sensors which measure radiation at two different wavelengths simultaneously. Such instruments can be used where dust or dirt obscures the source from the sensor.

Lower temperature applications commonly occur in the food industry (e.g. the monitoring of frozen foods). This is particularly important over a frequency range of $2 \times 10^{13} \text{ s}^{-1}$ to $4 \times 10^{13} \text{ s}^{-1}$ within which most organic materials emit infra-red radiation of significant power. An additional advantage is that the infra-red absorption bands for CO₂ and water vapour (the presence of which can cause errors because they attenuate the radiation emitted from the source material) are outside this range of wavelengths.

6.5. THE MEASUREMENT OF LEVEL

Liquid level measurement is of considerable importance in the process industries and methods range from a simple dip stick or sight glass to sophisticated computerised systems giving the total mass of liquid in a large storage tank to accuracies of ± 0.1 per cent. A number of the methods described in this section can be applied also to level measurement of such materials as slurries, powders and granular solids and this is indicated where appropriate. Often a level measuring device is not required to give a continuous measurement but simply an indication of whether the material inside the vessel has risen or fallen to a certain limiting height. Such devices simply initiate *high* and *low level limit alarms* respectively and are termed *float switches*.

6.5.1. Simple Float Systems

Floats are independent of the static pressure and are of either the *buoyant* or the *displacement* type (Fig. 6.28)⁽³⁸⁾. The former is less dense than the liquid in which it is partially immersed and the latter is slightly denser than the liquid. Consequently, the buoyant or *moving* float has a constant immersion and will rise and fall precisely the same distance as the liquid level. Its position at any instant is measured via a potentiometric or retractive transducer (Section 6.3.3) to give an output which is directly proportional to the level. The displacement or *static* type has a variable immersion and a variable upthrust upon it. The level is then measured in terms of the net weight of the float. In this case the buoyant force exerted on the float is converted into an output signal by a strain gauge or force-balance transducer (Section 6.3.3). Both types of float are used to give a continuous measurement of level. In the case of corrosive liquids, the number of parts immersed is reduced to a minimum by coupling the float magnetically with the transducer which is sealed from the contents of the vessel. If the liquid surface is likely to be turbulent (e.g. when the liquid is boiling, as in the base of a distillation column), then the float is placed in a float chamber or side arm where calmer conditions will prevail (Fig. 6.29).

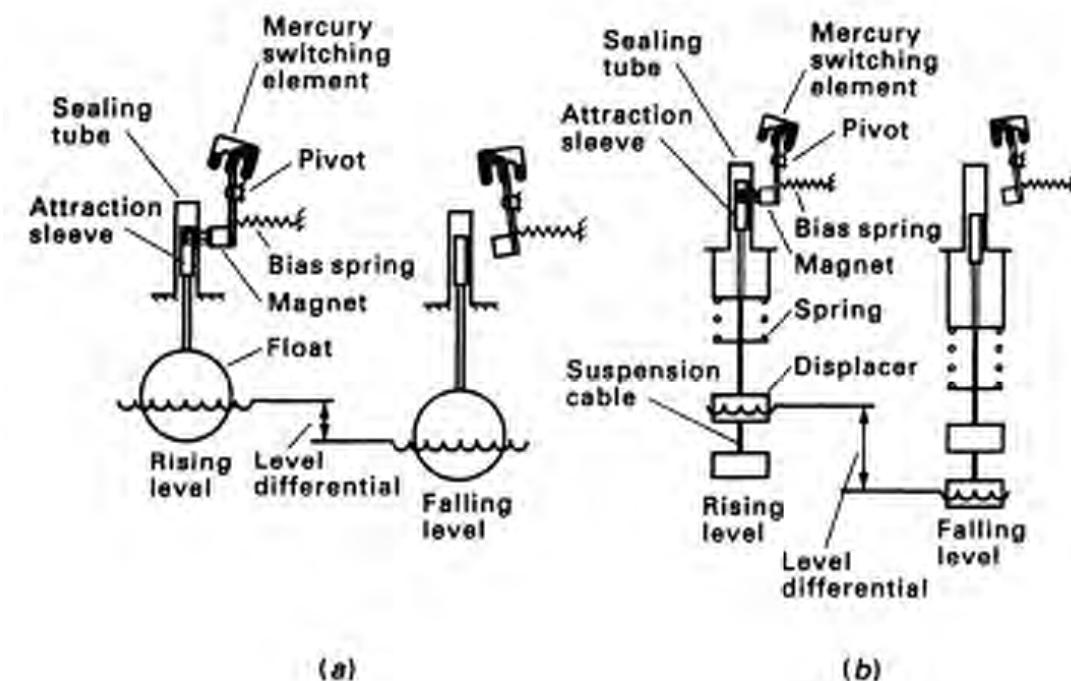


FIG. 6.28. Simple float switches: (a) buoyant type; (b) displacement type

Floats are simple, reliable and rugged. They are suitable for use at high pressures and temperatures and in the presence of foams. If constructed of suitable materials, they can be employed in aggressive environments and for liquids with densities as low as 300 kg/m^3 . When used in the level limit alarm mode, float switches can detect variations in level down to about 2 mm. However, as they are mechanical devices, floats can suffer from jamming, fouling by the material being measured, and general wear and tear.

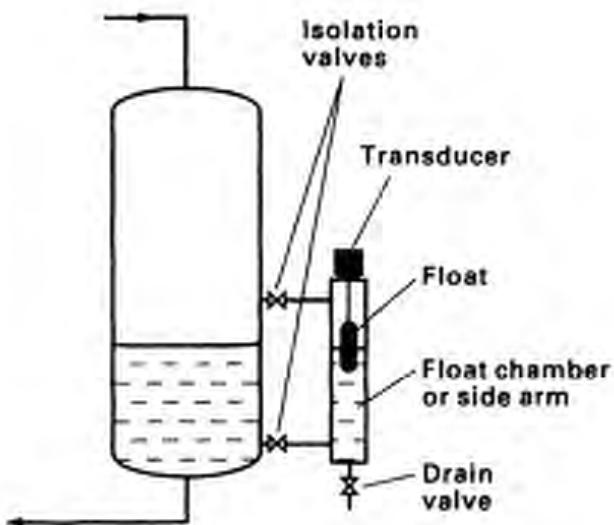


FIG. 6.29. Use of float chamber to measure liquid level

6.5.2. Techniques Using Hydrostatic Head

Several techniques of varying complexity are used for directly measuring the hydrostatic head exerted by a liquid in a vessel. These include:

- Flush-mounting a pressure transducer (Section 6.3) close to the base of the vessel. This is appropriate for an open vessel and gives a direct measure of the liquid head. This technique can be employed also for slurries, powders, highly viscous media such as toothpaste, etc. However, it is not suitable for applications where the measured material can solidify or crystallise over the transducer diaphragm. Careful consideration should also be given to the constancy of the specific gravity of the material with variations in temperature or composition.
- If the vessel is closed, then the difference in pressure between that in the vapour space and that near the base is measured using a differential pressure (DP) cell (Section 6.3.4). Generally the latter will not be flush with the vessel wall and a typical arrangement for a volatile liquid is illustrated in Fig. 6.30.

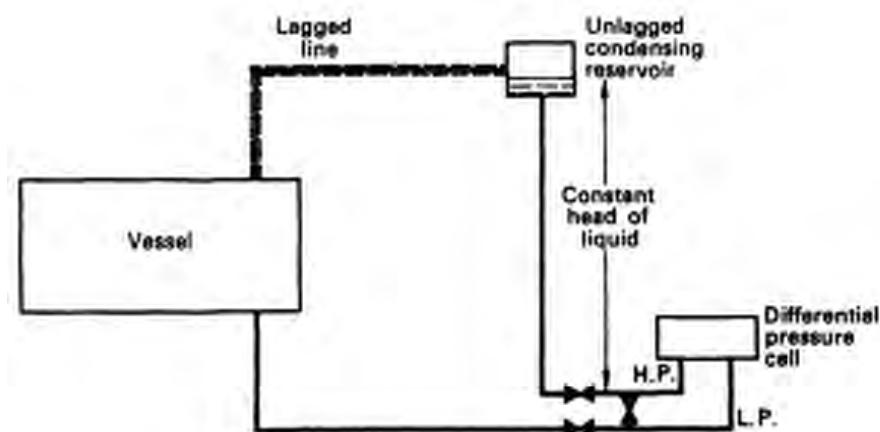


FIG. 6.30. Measurement of the level of a volatile liquid using a differential pressure cell

If the liquid is not volatile, the condensing reservoir shown is not required and the high and low pressure connections on the DP cell are reversed. The DP cell is normally located *below* the lower measuring point (or *tapping*) in the vessel. Any lines connected to the DP cell which are liquid filled should be bled through the DP cell *bleed port* to make sure that there is no trapped vapour present.

Hydrostatic head sensors are easily installed, contain no moving parts, and have good accuracy (approaching ± 0.5 per cent of full scale) and repeatability.

6.5.3. Capacitive Sensing Elements

A common method of level measurement is to use a capacitance bridge. A typical arrangement is shown in Fig. 6.31a in which the sensor consists of two concentric metal cylinders. In the case of a circular tank, the wall of the tank can be employed as the outer cylinder of the sensor. The capacitance of the sensor is:

$$C_0 = \frac{2\pi\epsilon_0[\ell_c + (\epsilon_r - 1)z]}{\ln\left(\frac{r_2}{r_1}\right)} \quad (6.51)$$

where the cylinders are of height ℓ_c and contain liquid up to depth z within the annulus. ϵ_0 is the *permittivity of free space* (8.85×10^{-12} farads/metre), ϵ_r is the *relative permittivity* of the liquid involved, and r_2 and r_1 are the radii of the cylinders ($r_2 > r_1$). (Note that frequent reference is made to the *dielectric constant* of a material. This is identical to the material's permittivity ϵ , where $\epsilon = \epsilon_0\epsilon_r$.)

Capacitive sensing elements are incorporated into either electrical oscillator circuits or into a.c. deflection bridge circuits. An example of the latter is shown in Fig. 6.31b. In this the output voltage is:

$$V_o = V_s \left(\frac{1}{1 + C_0/C} - \frac{1}{1 + R/R_0} \right) \quad (6.52)$$

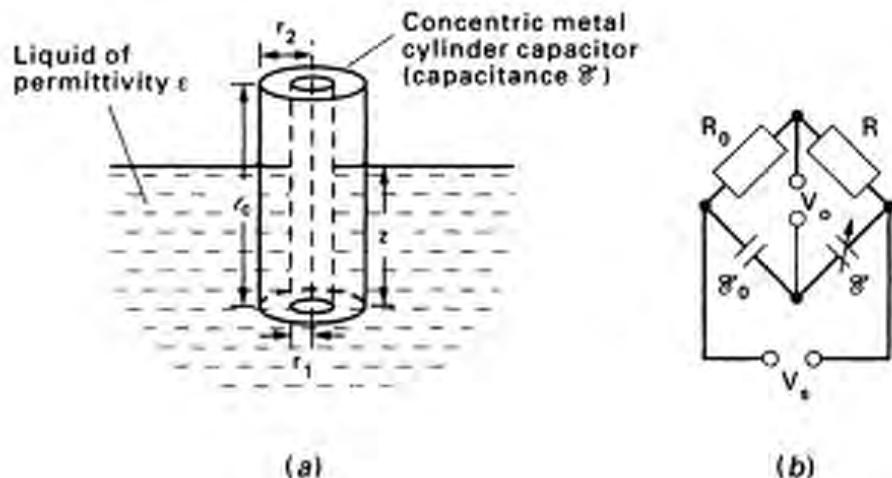


FIG. 6.31. Level-sensing capacitor and associated bridge network: (a) concentric cylinder capacitor; (b) capacitance bridge

If $\epsilon = \epsilon_{\min}$ when $V_o = 0$, then $\epsilon_0/\epsilon_{\min} = R/R_0$, i.e. $\epsilon_0 = \epsilon_{\min}R/R_0$.

Hence:

$$V_o = V_s \left(\frac{1}{1 + \frac{\epsilon_{\min}R}{\epsilon R_0}} - \frac{1}{1 + \frac{R}{R_0}} \right)$$

If R/R_0 is made $>> 1$:

$$V_o \approx V_s \frac{R_0}{R} \left(\frac{\epsilon}{\epsilon_{\min}} - 1 \right) \quad (6.53)$$

The level in the tank can then be determined from equations 6.51 and 6.53.

If the material is non-conducting then a bare capacitance probe can be employed—otherwise the probe must be insulated. Difficulties can arise due to unexpected variations in the dielectric constant of the material being measured (e.g. in the case of a powder which is prone to absorb water vapour).

6.5.4. Radioactive Methods (Nucleonic Level Sensing)

A γ -ray source (e.g. ^{137}Cs , ^{60}Co , ^{226}Ra) is frequently used for liquid level *measurement* and for liquid and solid level *detection*. The absorption of the γ radiation varies with the thickness x and nature of the absorbing material between the source and the detector according to the Beer–Lambert law, viz:

$$\phi = \phi_0 \exp(-\xi \rho x) \quad (6.54)$$

where ϕ and ϕ_0 are the intensities of the radiation received at the detector with and without the presence of the absorbing material respectively, ξ is the mass absorption coefficient (constant for a given source and absorbing material) and ρ is the density of the absorbing material. If two phases are present between the source and the detector (e.g. gas and liquid or gas and solid), then:

$$\phi = \phi_0 \exp(-\xi_1 \rho_1 x_1 - \xi_2 \rho_2 x_2) \quad (6.55)$$

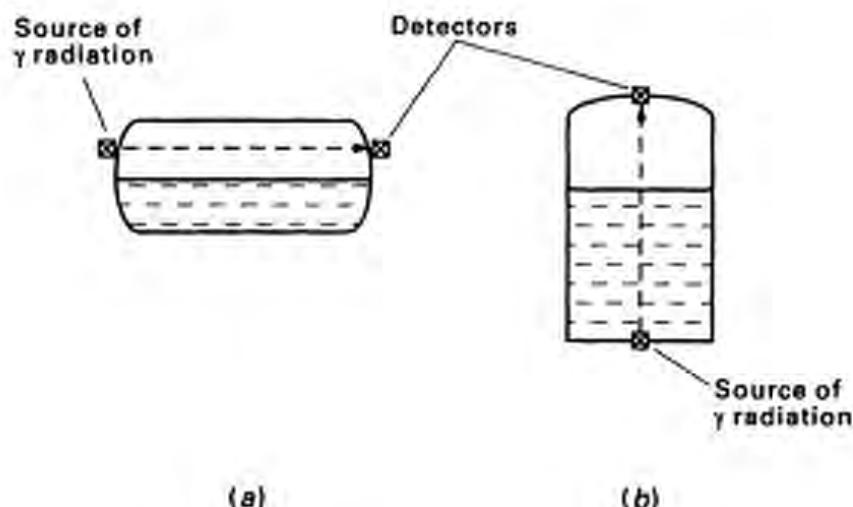


FIG. 6.32. Nucleonic level-sensing

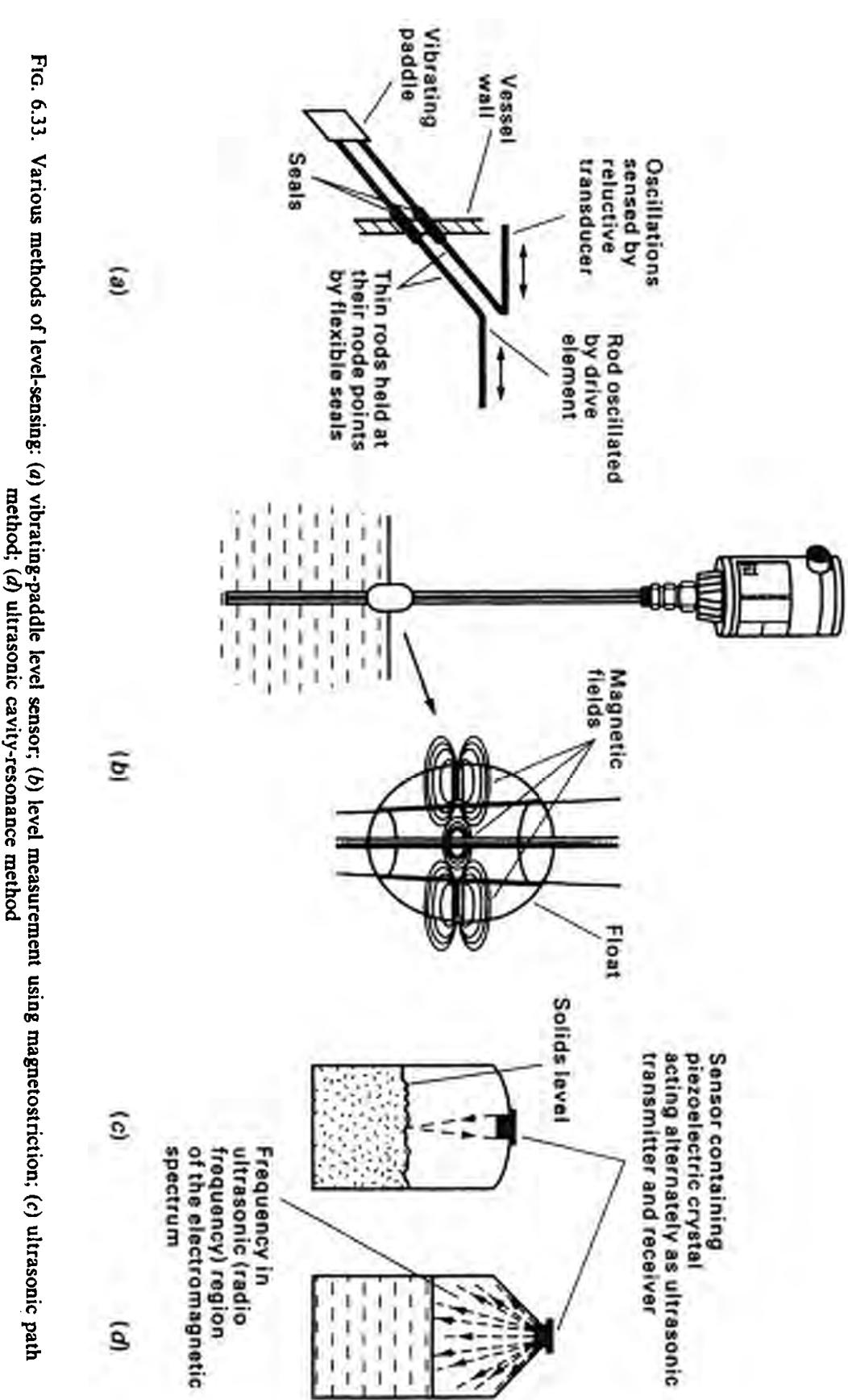


FIG. 6.33. Various methods of level-sensing: (a) vibrating-paddle level sensor; (b) level measurement using magnetostriction; (c) ultrasonic path; (d) ultrasonic cavity-resonance method

Two different arrangements are illustrated in Fig. 6.32. Figure 6.32a shows a typical installation where a high level limit alarm is required. In this case the intensity of the radiation ϕ reaching the detector would be determined by equation 6.54. If a continuous measurement of level is necessary, then the radioactive source and detector would be positioned as in Fig. 6.32b and ϕ is then given by equation 6.55.

6.5.5. Other Methods of Level Measurement

These are summarised in Table 6.6.

6.6. THE MEASUREMENT OF DENSITY (SPECIFIC GRAVITY)

Instruments are available for the continuous measurement of the density and relative density (specific gravity) of both liquids and gases. When specific gravity is a sufficiently sensitive function of composition for a particular process stream, sensors employed to monitor density can also be employed as composition analysers.

6.6.1. Liquids

The Use of Level Measuring Devices

Certain instruments which have been designed to measure liquid level (Section 6.5) can be modified easily to record variations in liquid density. Such instruments are those that measure the pressure P exerted by a given depth of liquid z in a vessel, i.e. $P = \rho g z$. If z is fixed then:

$$\rho = \frac{1}{gz} P \quad (6.56)$$

Typical are the pressure transducer (Section 6.3.2) and the DP cell (Section 6.3.4). In these cases, of course, the level must be maintained constant.

Weighing Meters

These are generally in the form of a U-tube attached by flexible connectors to the inlet and outlet lines of the instrument (Fig. 6.34). The instrument has a substantial volume ($ID \approx 0.025\text{ m}$) and, where flows are small (recommended minimum velocity $\approx 1\text{ m/s}$), it is probable that the whole process fluid stream, rather than simply a sample, will be sent through the instrument.

The operation of the instrument is a typical and useful example of pneumatic feedback⁽³⁹⁾. Initially the counterbalance weight is so positioned that balance is achieved. When the weight of the U-tube increases, due to an increase in the density of the process liquid, the weighing beam tends to turn in a clockwise direction, raising the flapper and thus allowing more air to escape from the nozzle. The resulting decrease in pressure on top of the diaphragm in the relay allows the valve spool to rise and this enlarges the pressure in the feedback bellows. The latter increases until sufficient extra force is applied to the U-tube through the pivoted transmitter arm to restore the original balance. The U-tube is thus continuously

TABLE 6.6. *Other Methods of Level Measurement*^(25, 40, 41, 42, 43)

Sensing by	Continuous Measurement	Discrete Measurement	Suitable for	Comments
Conductivity	yes	yes	liquids	Tank wall can be used as one electrode if metallic. Liquid must be electrically conductive. Electrodes form part of a conductivity bridge network.
Weight	yes	no	liquids, powders, granular solids.	Generally uses load cells positioned beneath the vessel. Typical accuracy—about 0.1 per cent of FSD ^(a) .
Heat transfer	no	yes	liquids	Uses resistive element in which a current produces a self-heating effect. Element cools when liquid comes into contact with it. The resulting change in resistance is measured.
Photo-electric effect	no	yes	liquids, powders, granular solids.	Electromagnetic signal in visible light or infra-red region of electromagnetic spectrum is sensed by photo-electric cell. Beam is attenuated by liquids and cut off by solids. Liquids can transmit or reflect the beam.
Damped oscillations	no	yes	liquids and some dry products.	Employs oscillating element which is normally a vibrating fork or paddle driven mechanically (Fig. 6.33a) or by a piezoelectric crystal vibrating at its resonant frequency. When immersed in the material there is a frequency or amplitude shift due to viscous damping which is sensed usually by a reductive transducer (Section 6.3.3).
Damped oscillations (magnetostriuctive type)	no	yes	liquids, powders, granular solids.	When a ferromagnetic rod is exposed to a longitudinal magnetic field it increases slightly in length. The field is created and oscillated by drive and feedback coils wound on the rod—the end of which is in contact with the inside surface of the tip of a sealed probe sheath. The oscillator circuit is set so as to maintain the oscillation in the rod when the tip of the probe is in contact with any compressible fluid (e.g. gas, froth, foam, etc.). When the end of the probe touches an incompressible fluid (viz. a liquid) the vibration is damped, the oscillation ceases and a signal is generated. This type of instrument is used increasingly—particularly with difficult systems. The probe should not be immersed in any material which may harden on the probe tip (Fig. 6.33b).
Ultrasonic type—cavity resonance method	yes	no	liquids, powders, granular solids.	Volume sensing technique in which electromagnetic oscillations at ultrasonic or radio frequencies are projected from a transmitter placed at the top of the vessel into the space above the material (the ullage). As the level rises the volume of the ullage decreases and the resonant frequency of the oscillation changes. This method is not recommended where the density of the vapour above the material varies significantly (e.g. when measuring the level of solvents) or in the presence of foams. Typical accuracies are of the order of 1 per cent of FSD ^(e) . (Fig. 6.33d.)
Ultrasonic type—ultrasonic path method	yes	yes	liquids, powders, granular solids.	For continuous level sensing the sensor uses a reflected pulsed ultrasonic signal. The travel time of a pulse reflected back from the surface is measured. For discrete level sensing a directly transmitted continuous signal is employed. The solid or liquid being measured intervenes in the sonic path and either cuts the signal (solids) or attenuates it (liquids). Unsuitable where the density of the vapour varies and in the presence of foams. Suitable for vessels, flumes, weirs and open channels. Typical accuracies are of the order of 1 per cent of FSD ^(e) (Fig. 6.33c.)
Microwaves and Radar	yes	yes	liquids, powders, granular solids.	Action very similar to ultrasonic signals. Has been employed for discrete sensing. Pulsed energy used in transmitted or reflected modes. Transmitter and receiver can be mounted outside the vessel. Very useful for determining mean levels in closed vessels under difficult conditions, e.g. in cases of high turbulence, in the presence of vapour or condensate, or where there is encrustation of surfaces with deposits. Typical accuracies are of the order of 0.2 per cent FSD ^(e) .

(a) FSD: full scale deflection (see Section 6.10.1).

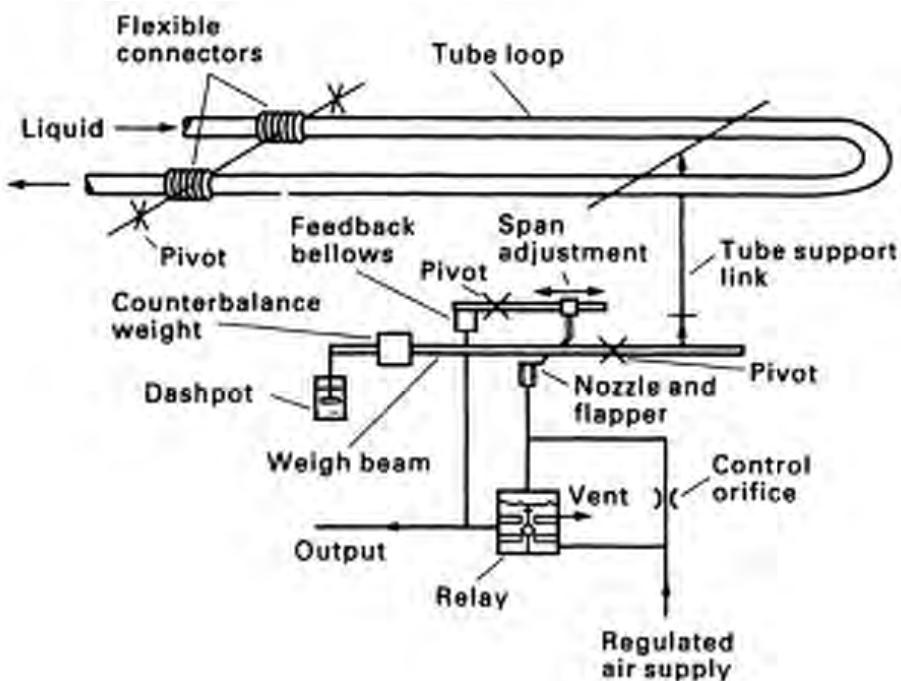


FIG. 6.34. U-Tube specific gravity (density) meter and pneumatic transmitter

balanced and its movement, which is damped, is no greater than a few seconds of arc. Since the area of the feedback bellows and lever lengths are fixed, the increase in pressure required to restore balance is directly proportional to the density of the fluid flowing in the U-tube. The output air pressure (usually in the range 20–100 kN/m²) is a measure of the density of the fluid.

This type of meter is used generally to measure liquid densities ranging from 500 kg/m³ to 1600 kg/m³ with an accuracy of about ± 0.5 per cent of FSD. The effects of variations in ambient temperature are negligible, but mechanical vibration (e.g. from pumps, etc.) can create substantial errors.

Buoyancy Meters

These are typically based on the principle of the hydrometer. For automatic measurement and control an inductance bridge may be employed to detect the position of the hydrometer. The level of the liquid in which the hydrometer is floating must be maintained constant. The float or *displacer* may be partially or totally immersed in the liquid (similar to the float systems used to measure level—Section 6.5.1 and Fig. 6.28). A schematic diagram of an instrument using a totally immersed displacer is shown in Fig. 6.35.

As the density of the liquid increases the float also rises and lifts the chain. The float continues to ascend until the additional weight of the chain raised equals the additional buoyancy due to the increased density. The reverse occurs when the density of the liquid is reduced. The position of the float is detected by a linear variable differential transformer (LVDT) in which the movement of the ferromagnetic core of the displacer changes the inductance between the primary and secondary windings of a differential transformer (see also Fig. 6.13). Such meters

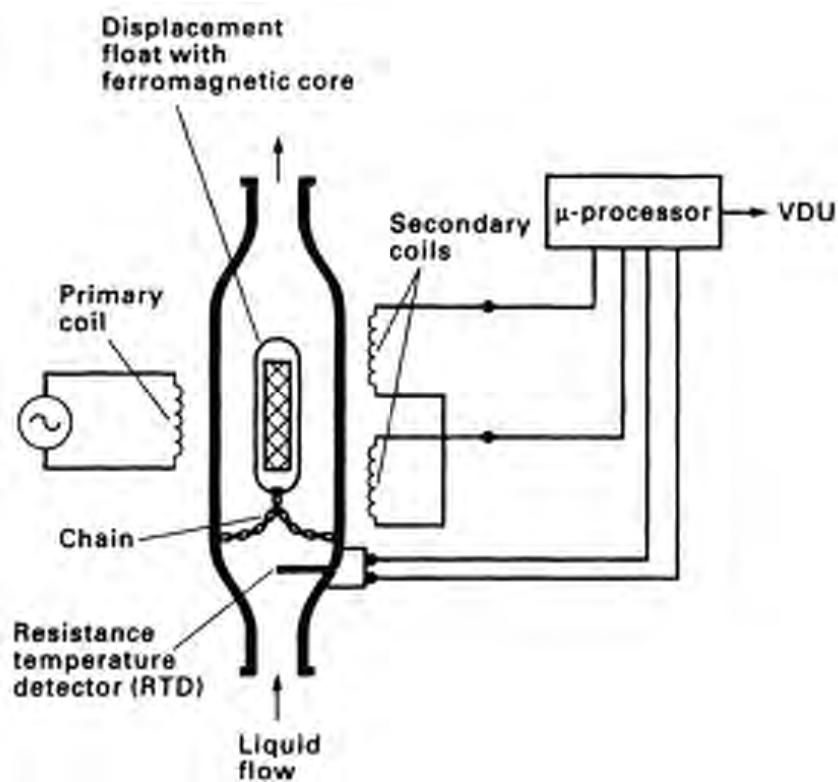


FIG. 6.35. Buoyancy meter with totally immersed float and LVDT sensing-element

are used generally to measure densities in the range 500–3500 kg/m³ with spans of between 5 kg/m³ and 200 kg/m³. Accuracies of ± 3 per cent of span or ± 0.2 kg/m³ (whichever is the greater) have been reported⁽³⁹⁾. A resistance thermometer is provided to record changes in temperature and to modify the output accordingly.

Acoustic Meters

These operate on the basis of the measurement of the resonant frequency of an oscillating system. The oscillation is impressed on the system, either via a cylinder immersed in the liquid, or via a tube through which the liquid flows. A typical arrangement is shown in Fig. 6.36 in which the sensing element consists of a single pipe through which the process fluid flows⁽⁴⁴⁾. Heavy masses are fixed to each end of the pipe and the whole is attached to the pipe flanges and outer casing of the instrument by bellows and ligaments which allow the pipe to oscillate freely. Positioned along the pipe is an electromagnetic drive and a pick-up coil assembly. Any variation in the mass per unit length of the oscillating section (due to a change in the density of the fluid flowing through it) produces a change in the resonant angular frequency ω of the system. This is transmitted by magnetically coupling the oscillating system with a suitable amplifier. The latter provides both a frequency modulated output signal and the excitation to produce the required oscillation. The output is automatically compensated for any change in the length of the tube due to variations in temperature and is expressed in terms of the density ρ of the sample liquid by:

$$\rho = K_{LAM} \left[\left(\frac{\omega_0}{\omega} \right)^2 - 1 \right] \quad (6.57)$$

where ω_0 is the resonant angular frequency obtained with the pipe empty and K_{LAM} is the transducer constant. Although equation 6.57 is non-linear, linearity can be assumed with little error for changes in density up to about 20 per cent. Meters of this kind are very robust and give excellent results. Any range of densities can be monitored and accuracies better than 0.01 kg/m^3 have been reported⁽¹⁷⁾.

6.6.2. Gases

The principle of the acoustic meter can be equally applied to the monitoring of gas densities. A high sensitivity is required as the variations in density involved are

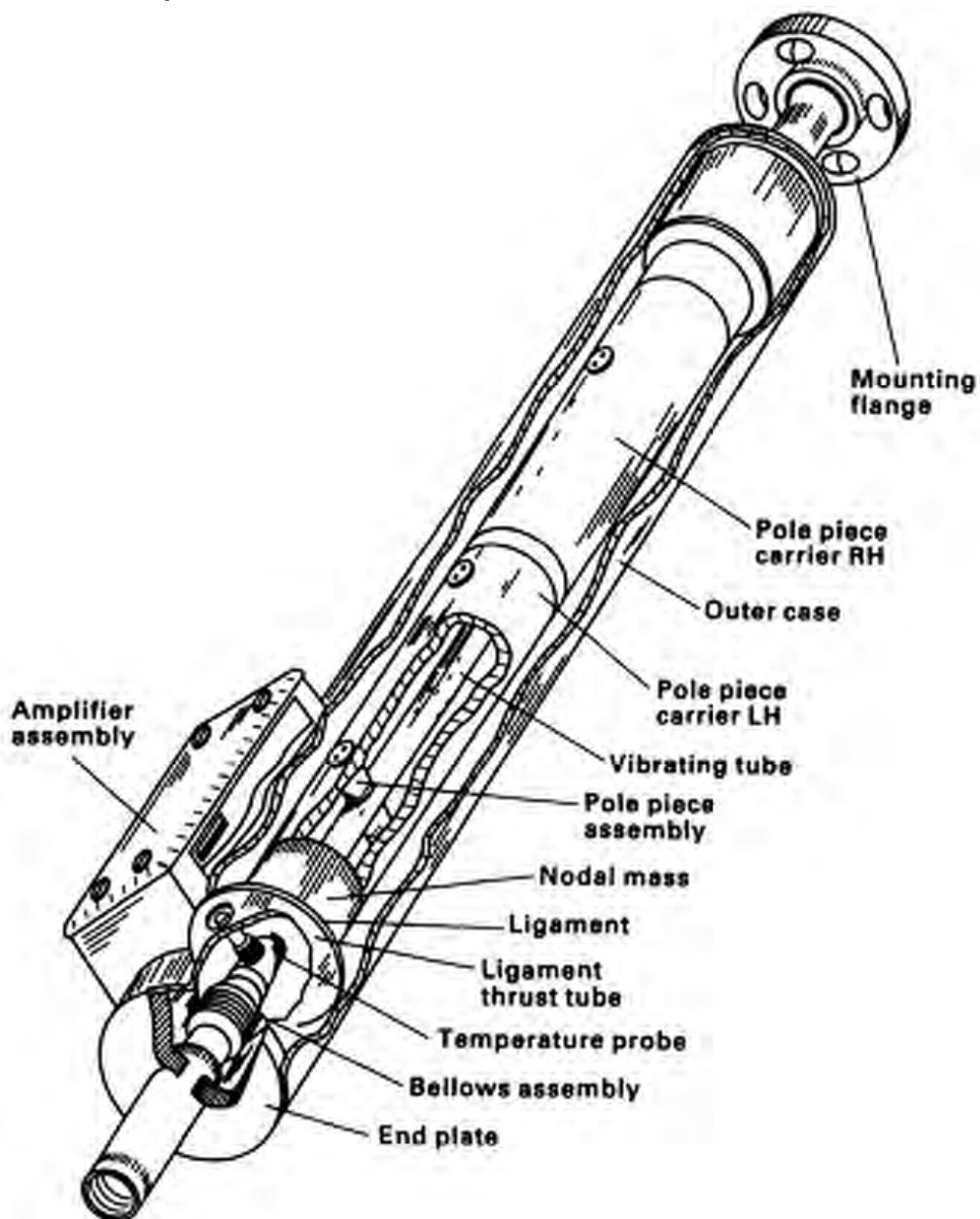


FIG. 6.36. Acoustic liquid-density meter

much smaller than for liquids. One method is to induce a resonant frequency in a thin-walled cylinder immersed in the sample gas. This causes the gas surrounding the cylinder to oscillate at the same frequency. The total mass of the vibrating system is thus increased. This reduces the resonant angular frequency and the change in frequency is related to the density of the gas by:

$$\rho = K_{GAM} \frac{\omega_0 - \omega}{\omega_0^2 \omega} \left[1 - K'_{GAM} \left(\frac{\omega_0 - \omega}{\omega_0^2 \omega} \right) \right] \quad (6.58)$$

where ω_0 is the resonant angular frequency under vacuum conditions and K_{GAM} and K'_{GAM} are calibration constants. The output of the instrument is automatically compensated for variations in gas temperature. Densities from 0 to 400 kg/m³ can be monitored with accuracies of 0.1 per cent of the meter reading⁽¹⁷⁾.

There are several instruments which employ highly sensitive weighing techniques. One particular meter is based upon the measurement of the upthrust on a float⁽⁴⁵⁾. Any displacement of the float due to a change in the gas density (and consequently buoyancy) is counterbalanced by a magnetic field produced by an electromagnet. The float is thus maintained in the null position by the force generated by the flow of a *direct* current in the coil of the electromagnet. This current is directly proportional to the density of the gas. A temperature correction is applied to the readout and densities up to 500 kg/m³ at pressures up to 17 MN/m² can be measured.

6.7. THE MEASUREMENT OF VISCOSITY

The concept of viscosity as a physical property of a fluid is considered in Volume 1, first for Newtonian fluids (Section 3.3) and secondly for the non-Newtonian case (Section 3.7). A further discussion of viscosity on the molecular scale in terms of the momentum transfer occurring in a gas flowing over a flat surface appears in Volume 1, Section 12.2.4. Methods for estimating viscosities are described in Volume 6, Section 8.7.

There are a substantial number of ways in which the viscosity of a fluid can be measured. Not all of these can be adapted easily to on-line process measurement. It is convenient to classify viscometers according to the type of physical measurement made.

6.7.1. Off-line Measurement of Viscosity

Measurement of the Rate of Flow of Fluid in a Capillary

The Ostwald U-tube instrument is the most common type of viscometer based upon this principle (Fig. 6.37a and Table 6.7). The viscometer is filled with liquid until the liquid level is such that the bottom of the meniscus in the right-hand limb coincides with the mark C. The fluid is drawn up the left-hand limb to a level about 5 mm above A and then released. The time t taken for the bottom of the meniscus to fall from A to B is recorded. The dynamic viscosity μ is determined from Poiseuille's law (Volume 1, equation 3.30 and Section 9.4.3) which under the

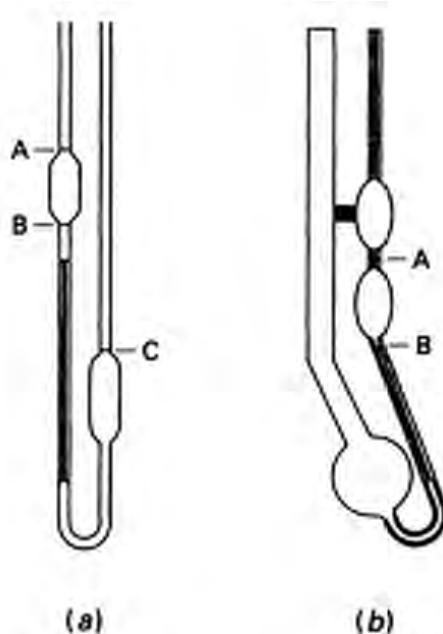


FIG. 6.37. Common capillary viscometers: (a) simple Ostwald type; (b) Cannon-Fenske type

conditions applied (viz. the driving force remaining nearly constant throughout) gives:

$$\mu = K_v \rho t \quad (6.59)$$

or:

$$\nu = K_v t \quad (6.60)$$

where K_v is the viscometer constant (not dimensionless), ρ is the density of the liquid and ν is the kinematic viscosity ($= \mu/\rho$). Capillary viscometers with different dimensions are employed for different viscosity ranges. For fluids having kinematic viscosities below $10^{-5} \text{ m}^2/\text{s}$ (fast flow, giving small values of t), it may be necessary to apply a correction to equation 6.60 for kinetic energy effects, thus:

$$\nu = K_v t - K'_v / t. \quad (6.61)$$

Many modifications of the basic Ostwald geometry are employed in different situations. One example is the Cannon-Fenske routine viscometer (Fig. 6.37b) which is used in the oil industry for measuring kinematic viscosities of $0.02 \text{ m}^2/\text{s}$ and less⁽⁴⁶⁾. As viscosity is sensitive to variations in temperature, these types of viscometer are always immersed in a constant temperature bath. They are not normally suitable for non-Newtonian fluids although FAROOQI and RICHARDSON⁽⁴⁷⁾ have employed a capillary viscometer to characterise a power-law fluid.

Measurement of the Time Taken for a Body to Fall Freely Through a Fluid

The falling sphere instrument is representative of this class of viscometer and is employed with higher viscosity liquids. A stainless steel ball is allowed to sink through a column of the liquid under test, and the time taken to fall from one designated level to another at its terminal falling velocity is recorded. In order that the terminal

falling velocity u_0 is attained, the upper timing mark is positioned at a distance of at least six diameters of the ball below the point at which the ball is released. The conditions of the test should be such that Stokes' law can be applied (i.e. at $Re'_0 < ca. 0.2$, where $Re'_0 = u_0 d' \rho / \mu$ is the particle Reynolds number and d' is the diameter of the ball (Volume 2, Section 3.2)), and the ratio of the ball to tube diameter should not exceed 1/10 to minimise the drag effects of the tube wall on the terminal falling velocity (Volume 2, Section 3.3.3). British Standard BS 188⁽⁴⁸⁾ makes recommendations regarding suitable ball diameters and rates of fall for kinematic viscosities in the range $5 \times 10^{-4} - 0.25 \text{ m}^2/\text{s}$. The viscosity is generally determined from⁽⁴⁸⁾:

$$\nu = \frac{K_v(\rho_s - \rho)}{\rho} t \quad (6.62)$$

where K_v is the viscometer constant (not dimensionless), ρ_s and ρ are the densities of the ball material and the liquid respectively and t is the time taken for the ball to travel between the two timing marks.

Measurement of the Torque Exerted on a Stationary Surface by an Adjacent Moving Surface

Typical of this class of viscometer is the coaxial or Couette type of instrument described in Volume 1, Section 3.7.4. The sample fluid is contained within the annular space between two coaxial cylinders, either of which may be rotated by a motor with the remaining cylinder suspended elastically in such a way that the torsional couple exerted on the latter can be measured. If the outer cylinder of radius r_2 rotates with an angular velocity ω_v and the inner cylinder of radius r_1 is stationary, and the torque (or viscous drag) per unit length of cylinder exerted on the inner cylinder is T' , then, for a Newtonian fluid⁽⁴⁹⁾:

$$\mu = \frac{(r_2^2 - r_1^2)}{4\pi\omega_v r_1^2 r_2^2} T' \quad (6.63)$$

Hence μ can be determined by measuring T' at given values of ω_v (Table 6.7).

Major difficulties which arise with such viscometers are end effects due to the drag exerted on the ends of the rotating section, viscous heating due to the work done on the test fluid, and possible misalignment of the axes of the rotating and stationary

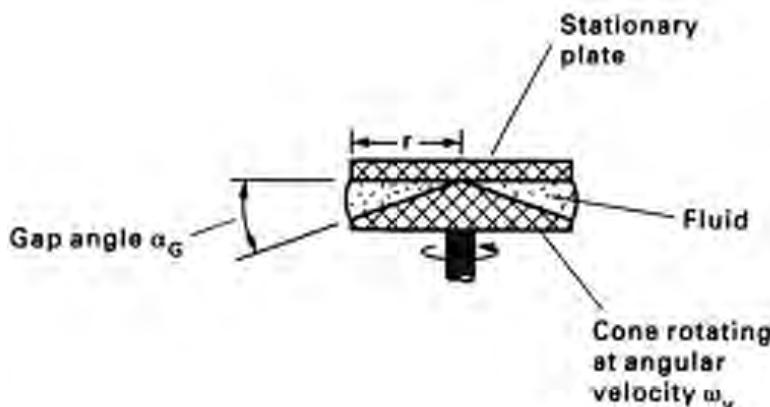


FIG. 6.38. Basis of the cone-and-plate viscometer

sections⁽⁵⁰⁾. Equation 6.63 is established assuming negligible end effects, i.e. that the concentric cylinders are of effectively infinite length. Non-Newtonian behaviour of the test liquid can be taken into account by the use of suitable correction factors⁽⁴⁹⁾.

Another frequently employed viscometer of this type involves the cone and plate arrangement shown in Fig. 6.38. If T is the torque required to maintain the plate of radius r in a stationary position, then, for Newtonian liquids⁽⁵¹⁾:

$$\mu = \frac{3}{2\pi\dot{\gamma}r^3} T \quad (6.64)$$

where edge effects are neglected and $\dot{\gamma}$ is the rate of shear ($= \omega_v/\alpha_G$, where ω_v is the angular velocity of the cone and the angle α_G between the cone and the plate is sufficiently small that $\sin \alpha_G \approx \alpha_G$). Equation 6.64 can also be applied in the case of non-Newtonian fluids provided that $\dot{\gamma}$ is reasonably constant throughout the measurement⁽⁴⁹⁾.

TABLE 6.7. Ranges of Common Viscometers

Viscometer type	Lowest viscosity (Ns/m ²)	Highest viscosity (Ns/m ²)	Shear rate range (s ⁻¹)
<i>Off-Line (Laboratory) Instruments</i>			
Capillary (Fig. 6.37)	2×10^{-4}	100	$1 - 1.5 \times 10^4$
Falling ball	1	200	indeterminate
Couette	5×10^{-4}	4×10^6	$10^{-2} - 10^4$
Cone and plate (Fig. 6.38)	10^{-4}	10^9	$10^{-3} - 10^4$
Oscillating cylinder (Weissenberg rheogoniometer)	$10^{-4}(b)$	$5 \times 10^6(b)$	$7 \times 10^{-3} - 9 \times 10^3$
<i>On-Line Instruments</i>			
Applications			
Capillary (Fig. 6.39)	2×10^{-3}	4	Newtonian fluids (e.g. lubricating oils, fuel oils). Repeatability ± 0.5 per cent of FSD ^(a) .
Couette type (Fig. 6.40)	10^{-3}	5×10^3	In-line or in-tank. Suitable for Newtonian and non-Newtonian fluids. Repeatability ± 0.2 per cent of FSD ^(a) .
Vibrating rod or cylinder (Fig. 6.41)	$10^{-4}(b)$	$2 \times 10^3(b)$	In-line or in-tank. Suitable for Newtonian and non-Newtonian fluids. Can be used for mineral slurries. Repeatability ± 0.25 per cent of FSD ^(a) .

(a) Repeatability and FSD (full scale deflection)—see Section 6.10.1.

(b) This is the *dynamic viscosity in small amplitude oscillatory shear* which is the *real component* of the *complex shear viscosity* which is a function of the angular frequency of oscillation.

By the Reaction of a Vibrating Element Immersed in the Liquid

This instrument employs an oscillating sphere, cylinder, paddle or reed. The range of a typical instrument (Weissenberg Rheogoniometer) is given in Table 6.7. The

amplitude of the oscillation varies with the viscosity of the liquid under test and this variation in amplitude is detected by a suitable transducer. Such devices are sensitive to changes in density as well as viscosity and, in order to minimise variations in density, the temperature of the measured fluid and the transducer is carefully controlled. This procedure is also suitable for the characterisation of fluids exhibiting non-Newtonian properties⁽⁴⁹⁾.

6.7.2. Continuous On-line Measurement of Viscosity

The on-line measurement of viscosity under plant conditions poses particular difficulties. This is due to the wide range of viscosities that can occur within a process plant, to the difficulty of obtaining reliable measurements (particularly for non-Newtonian fluids) and to the accuracy that is often required (e.g. better than within ± 1 per cent for lubricating oils). Variables which can affect the measured viscosity are the temperature, pressure and rate of flow of the sampled stream—quite apart from the normal errors that can occur in any similar instrument (e.g. due to variations in supply voltage and frequency, sample contamination, sample not being representative of the bulk fluid, etc.). Automatic temperature compensation is always required and, in the case of multiphase systems, the difficulty of obtaining a representative sample is considerable (see Section 6.9). In this instance

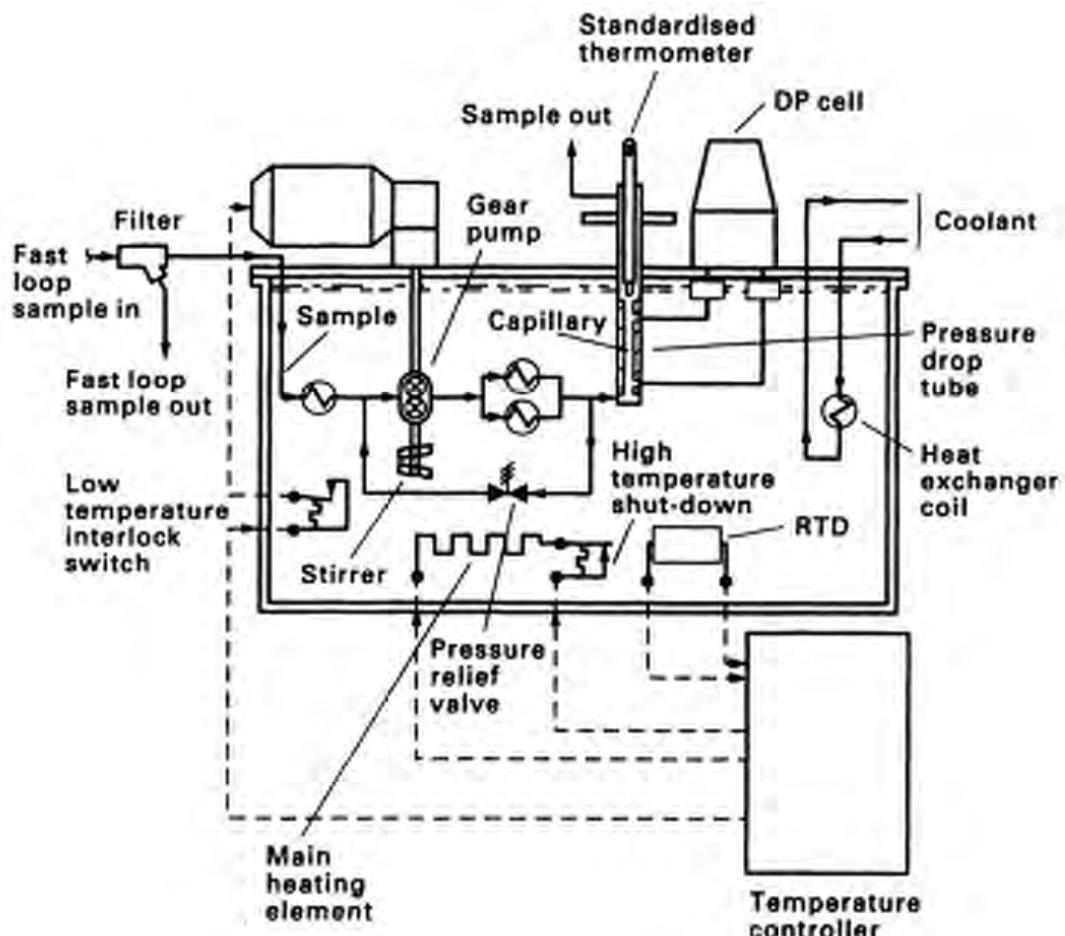


FIG. 6.39. On-line capillary viscometer

it is advisable to pass the whole of the process stream through the instrument where possible.

Some instruments are available for process on-line application (Table 6.7). Capillary types give good results with Newtonian fluids and are based upon Poiseuille's law (Volume 1, equation 3.30). The pressure drop across the capillary

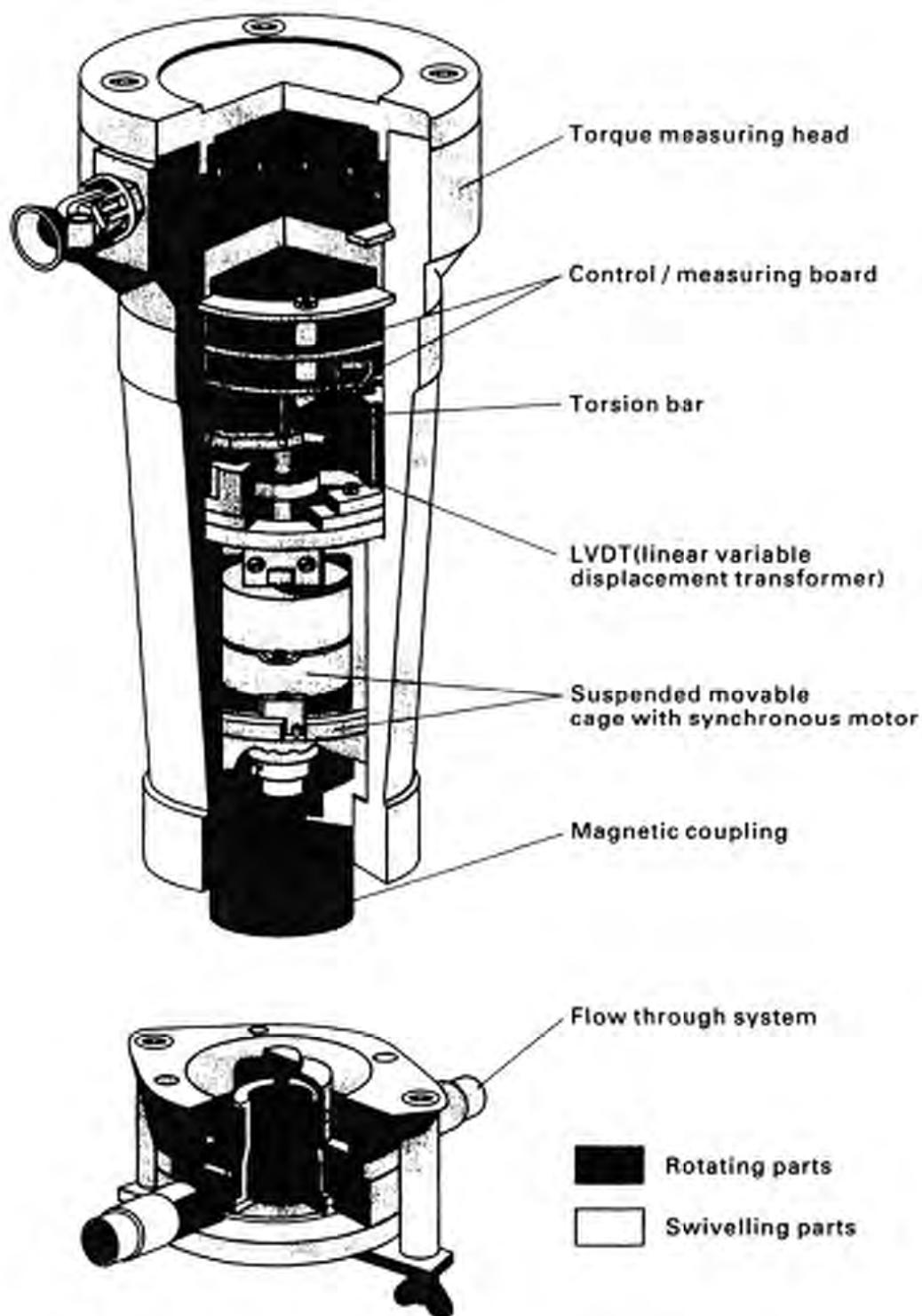


FIG. 6.40. Continuous process viscometer based upon the Couette principle

section and the temperature of the sample stream are carefully controlled (Fig. 6.39)⁽⁵²⁾. A fast loop sampling system (Section 6.9) is often provided as a means of reducing the total response time of the instrument (usually about 3 min).

Continuous viscometers based upon the Couette principle are able to measure the viscosity of both Newtonian and non-Newtonian fluids over a wide range (Table 6.7). A typical instrument of this type is illustrated in Fig. 6.40⁽⁵³⁾.

A cylinder is rotated within the fluid by means of a magnetic coupling with a rotating magnet driven by a synchronous motor. The latter is suspended by a torsion bar and the torque reaction of the motor caused by the viscous drag on the rotating cylinder is balanced by the resistance of the torsion bar. The angle of deflection of the bar (which is a function of the viscosity) is measured and converted into a 4–20 mA output signal. At small rates of flow ($< 7 \times 10^{-4} \text{ m}^3/\text{s}$) the whole stream can be passed through the instrument—otherwise a sampling system is necessary.

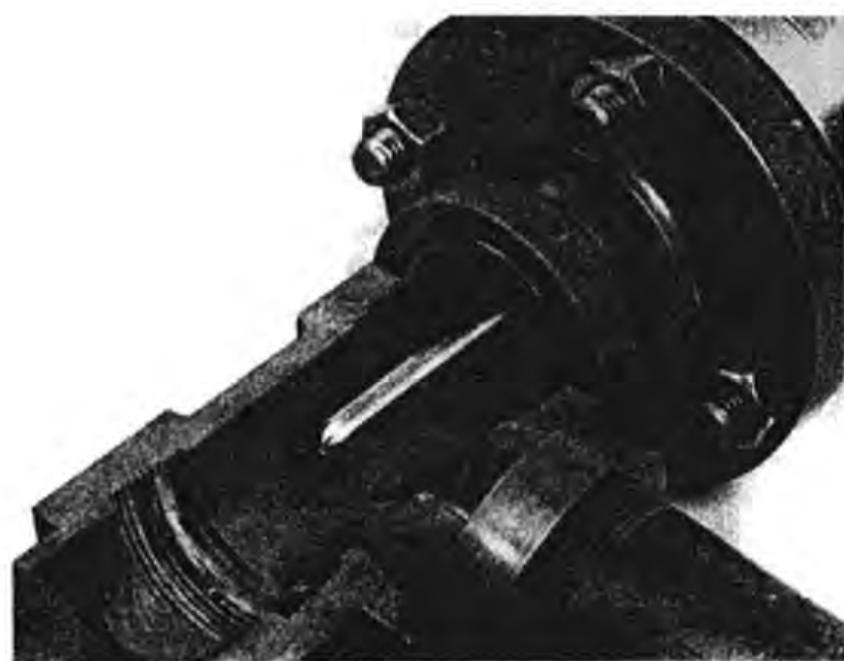
Direct in-line measurement of viscosity can also be achieved by employing an oscillating sensor. The latter may be driven by an electromechanical system (Fig. 6.41)⁽⁵⁴⁾ or by a pulse of current through a piece of magnetostrictive alloy⁽⁵⁵⁾. The electromechanical type is the more complex, but also the more rugged, and can cover a much wider range of viscosities (as listed in Table 6.7)—oscillating sphere versions being used over lower viscosity ranges and oscillating rods for higher ranges. A temperature sensor is inserted within the sphere or at the tip of the rod. The less expensive pulsed current viscometer produces ultrasonic oscillations within a thin blade sensor. The blade protrudes through a metal diaphragm and, once energised, oscillates longitudinally at its natural frequency which is determined by its length. The amplitude of the oscillation is less than $5 \times 10^{-7} \text{ m}$ and is damped by the flowing liquid. The degree of damping depends upon the viscoelastic properties of the material being tested. When the amplitude has been damped to a predetermined level, a further drive pulse is initiated. Hence, as the viscosity increases, the frequency N_p of the drive pulse also increases such that, for Newtonian materials:

$$\mu = K_v'' \left(\frac{N_p^2}{\rho} \right) \quad (6.65)$$

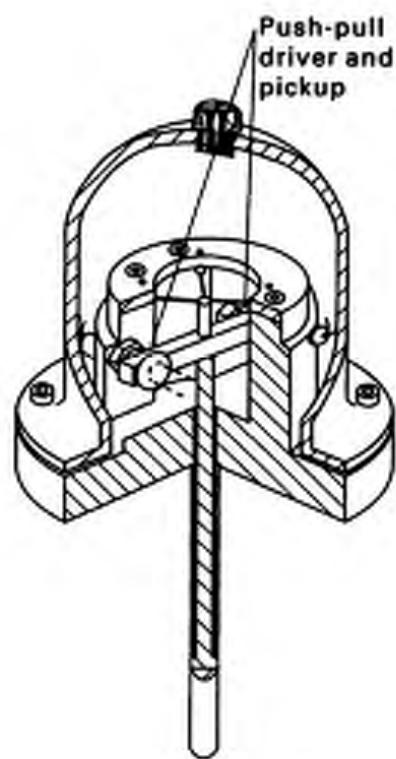
where K_v'' is the sensor constant (not dimensionless). Temperature compensation is provided and the technique can be applied to non-Newtonian fluids. Care must be taken when positioning oscillation viscometers on a plant as they are sensitive to plant vibration.

6.8. THE MEASUREMENT OF COMPOSITION

A knowledge of the composition of a process stream is often of major importance. Such information may be necessary to determine whether a particular product has the required specification or whether the composition of a particular stream is changing. Frequently, variations in either will require some kind of control action to maintain the planned operational strategy of the plant. Direct measurement of composition is, at first sight, the obvious method of determining the nature of the materials entering, leaving or passing from point to point within a process. In practice, however, there are many difficulties. In the first instance, it is necessary to



(a)



(b)

FIG. 6.41. Electromechanically-driven rod viscometer

decide what property of the material can be employed as a suitable measure of its composition. This property may be physical or chemical and should be a quantity that differs widely between the various components of the material stream being analysed. It is also important to ascertain whether off-line or on-line analysis is required. The latter is necessary if the analyser is to be the measuring element for an automatic control system (see Chapter 7) in which case the response time (i.e. time constant) of the analyser must be substantially smaller than that of the plant it is being used to control. If off-line analysis is sufficient, then such considerations are of less importance.

There are numerous properties of materials which can be used as measures of composition, e.g. preferential adsorption of components (as in chromatography), absorption of electromagnetic waves (infra-red, ultra-violet, etc.), refractive index, pH, density, etc. In many cases, however, the property will not give a unique result if there are more than two components, e.g. there may be a number of different compositions of a particular ternary liquid mixture which will have the same refractive index or will exhibit the same infra-red radiation absorption characteristics. Other difficulties can make a particular physical property unsuitable as a measure of composition for a particular system, e.g. the dielectric constant cannot be used if water is present as the dielectric constant of water is very much greater than that of most other liquids. Instruments containing optical systems (e.g. refractometers) and/or electromechanical feedback systems (e.g. some infra-red analysers) can be sensitive to mechanical vibration. In cases where it is not practicable to measure composition directly, then indirect or *inferential* means of obtaining a measurement which itself is a function of composition may be employed (e.g. the use of boiling temperature in a distillation column as a measure of the liquid composition—see Section 7.3.1).

The composition analysers having the widest application are those which separate the components within a mixture as part of the analysis. The most common examples of this are the chromatograph and the mass spectrometer. Mass spectrometers are expensive and on-line chromatographic analysis can suffer from substantial time lapses (regarded as distance-velocity lags for control purposes—Section 7.6) before the result of the analysis is known. A further limitation of these two methods is that they are suitable generally for volatile liquids only, although liquid phase chromatographs are available (Volume 2, Section 19.4.3).

In the following account, the more common means of composition analysis are presented. The descriptions are not intended to be exhaustive as many methods of analysis are specific to particular processes. Reference should be made to manufacturers' literature for further information.

6.8.1. Photometric Analysers

These include such instruments as opacity monitors, turbidimeters, colorimeters, refractometers and spectrophotometers. A selection of these is described—particularly where the instrument has a more general application as an on-line process analyser and/or to illustrate a general principle of operation. It is likely that development of fibre-optic techniques (Section 6.12.4) will extend the use of this type of sensor in the future⁽⁵⁶⁾.

Spectrophotometers

These instruments constitute a class of *spectroradiometric* analysers generally encountered in the chemical process industries and employed to monitor wavelengths between the middle infra-red (MIR) and ultra-violet (UV) regions of the electromagnetic spectrum (Table 6.8).

TABLE 6.8. *Regions of the Electromagnetic Spectrum*

Region	Wavelength range
FIR (far infra-red)	15–800 μm
MIR (middle infra-red)	3–15 μm
NIR (near infra-red)	780–3000 nm
VIS (visible light)	380–780 nm
UV (ultra-violet)	200–380 nm
XUV (extreme ultra-violet)	10–200 nm

The radiation may be due to emissions from a hot source, or to the luminescence, fluorescence or phosphorescence of the sample. An *emission spectrum* consists of a number of generally very narrow peaks (called *spectral lines*) occurring at certain wavelengths which are characteristic of the materials contained within the source. The amplitudes of the peaks are related to the *abundance* or concentration of the materials present. Alternatively, radiation from a source is passed through a sample. In this case the quantity absorbed by the sample at a particular wavelength is again characteristic of the materials present in the sample. This is termed *absorption spectrometry* and produces spectral transmission lines in the form of equally narrow valleys—or peaks (Fig. 6.42) where the information is expressed in terms of *absorbance* (A) rather than *transmittance* (T)⁽⁵⁷⁾, and:

$$A = \log\left(\frac{1}{T}\right) \quad (6.66)$$

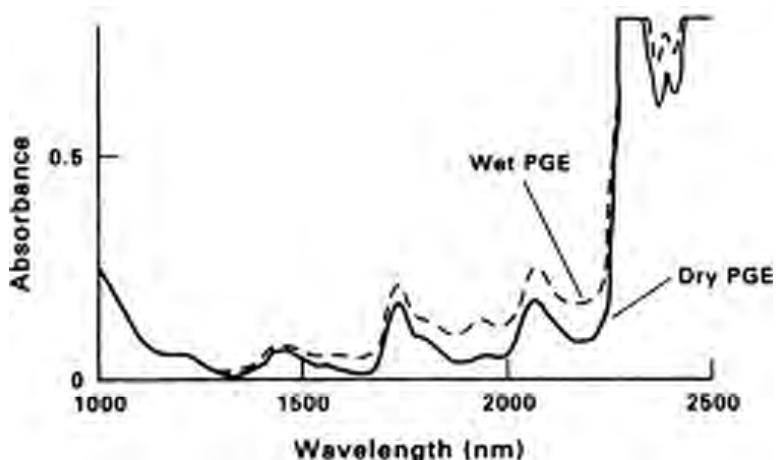


FIG. 6.42. Absorbance spectra of wet and dry polyalkylene glycol ether (brake fluid) in the near infra-red region of the electromagnetic spectrum⁽⁵⁷⁾

Dispersive Photometers

These are distinguished from non-dispersive instruments by the presence of a wavelength dispersing device or *monochromator*. This receives a wide band of wavelengths and transfers a selection of these (i.e. a narrow band of wavelengths) via an exit slit to a suitable detector. Photometers using visible light employ interference filters, prisms or diffraction gratings as monochromators, the latter being the most common. The grating is rotated by a suitable drive and the band of wavelengths of interest is scanned by sweeping the diffracted beam over a very narrow exit slit so that the detector senses one wavelength at a time. The wavelength sensed is dependent upon the characteristics of the grating and its angular displacement. Similar diffraction-grating monochromators are used in photometers operating in the infra-red, visible light and ultra-violet regions and can give resolutions better than 0.01 nm for wavelengths from 30 nm to 50 μm ⁽²⁵⁾.

Non-Dispersive Photometers

These differ from dispersive instruments in that the monochromator is replaced by a *narrow-band-pass* filter which is selected for the wavelength of maximum emission (or maximum absorption) of a specific material whose relative abundance is to be determined. The instrument of this type most commonly employed in the process industries to measure concentrations of gases in flowing gas mixtures is the *non-dispersive infra-red (NDIR) analyser*. This instrument works on the basis of the absorption of infra-red radiation at specific wavelengths (generally in the NIR region) peculiar to particular gases. A simplified diagram of a typical arrangement is shown in Fig. 6.43⁽⁵⁸⁾.

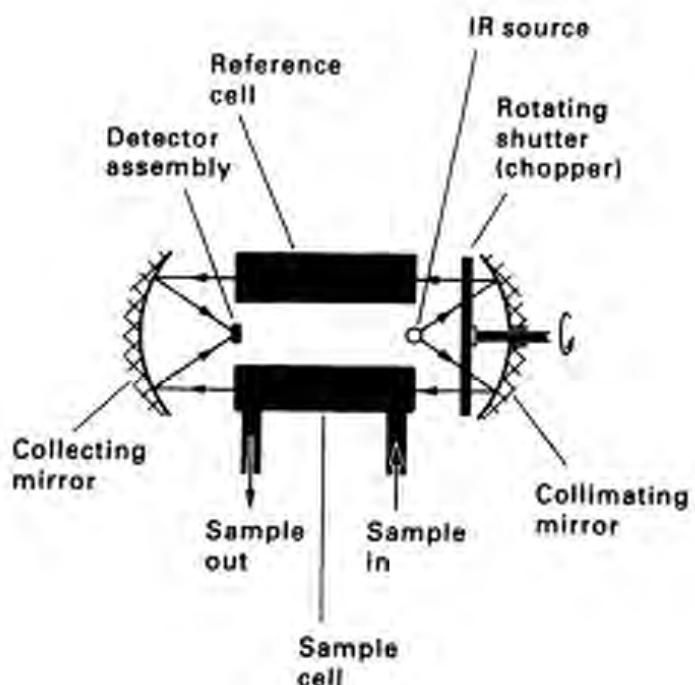


FIG. 6.43. Schematic diagram of a dual-beam NDIR analyser

Two beams of infra-red radiation of equal energy (see also Section 6.4.2) are chopped by a rotating shutter which allows the beams to pass simultaneously but intermittently through a sample cell which contains the flowing sample and a reference cell. The latter is filled with a non-absorbing gas. The detector assembly consists of two sealed absorption chambers separated by a thin metal diaphragm which acts as one plate of a parallel-plate capacitor. The quantity of infra-red radiation at a particular wavelength passing through the sample cell is a direct function of the concentration of absorbing gas in the sample. This is compared with the equivalent radiation passing through the non-absorbent gas in the reference cell.

Absorbent gases which can be monitored using this type of detector include CO, CO₂, N₂O, SO₂, H₂O, CH₄, C₂H₅OH, CH₃COCH₃, C₆H₆ and other hydrocarbons. Common non-absorbing gases are O₂, N₂, Cl₂, Ar and He. Relative sensitivities to various absorbing gases are given in Table 6.4.

TABLE 6.9. *Sensitivities of a Typical Infra-red Analyser to Various Absorbing Gases Expressed as a Comparison to that for Water Vapour^(58, 59)*

Gas	Sensitivity
H ₂ O	1.0
CO	0.5
CO ₂	0.1
CH ₄	0.5
C ₂ H ₄	1.0
N ₂ O	0.1
NO ₂	1.0
SO ₂	0.2
HCN	1.0
CH ₃ COCH ₃	2.5
C ₆ H ₆	2.5

The length of the absorption tube depends upon the gas being sampled and the concentration range to be covered. The energy absorbed E_{abs} by a column of gas of path length ℓ_p is:

$$E_{\text{abs}} = E_{\text{inc}} \{ 1 - \exp(-k_{\text{abs}} C \ell_p) \} \quad (6.67)$$

where E_{inc} is the incident energy, C is the concentration of the gas being measured and k_{abs} is an absorption constant. When $k_{\text{abs}} C \ell_p \ll 1$, i.e. at low concentrations, the relation between E_{abs} and C is approximately linear. The instrument is relatively insensitive to variations in temperature. For water vapour a figure of 3 per cent variation in sensitivity per 1 K change in temperature has been reported⁽⁶⁰⁾.

The conventional dual beam instrument is now being superseded by totally solid-state devices based upon single beam, multi-wavelength technology⁽⁶¹⁾. Advantages claimed for the latter are improved stability, resistance to shock and vibration, and insensitivity to the effects of sample cell contamination—which is a common problem when using IR absorption techniques to analyse dirty gases (e.g. flue gases).

The Interaction of Light with Materials

Refractometry

This involves the measurement of the *refractive index* of an optically transparent material. When light passes between two optical media of differing density, it will be refracted and Snell's law applies, viz:

$$\frac{\eta_1}{\eta_2} = \frac{\sin \alpha_2}{\sin \alpha_1} \quad (6.68)$$

where α_1 and α_2 are the *angles of incidence* and η_1 and η_2 are the *refractive indices* for the two media respectively.

If the composition of an optically transparent sample changes, then its refractive index will also change. The *continuous process refractometer* generally measures the effect that this change in refractive index has on the *critical angle* occurring at the interface between a glass prism and the sample. When the angle of incidence within the prism α_c becomes so large that the light cannot emerge, then the ray is totally internally reflected (Fig. 6.44). The minimum value of α_c at which this occurs is called the critical angle α_c , where:

$$\frac{\eta_2}{\eta_1} = \frac{1}{\sin \alpha_c} \quad (6.69)$$

Thus, if η_2 (the refractive index of the glass of the prism) is known, then η_1 (the refractive index of the sample) can be determined by measuring α_c .

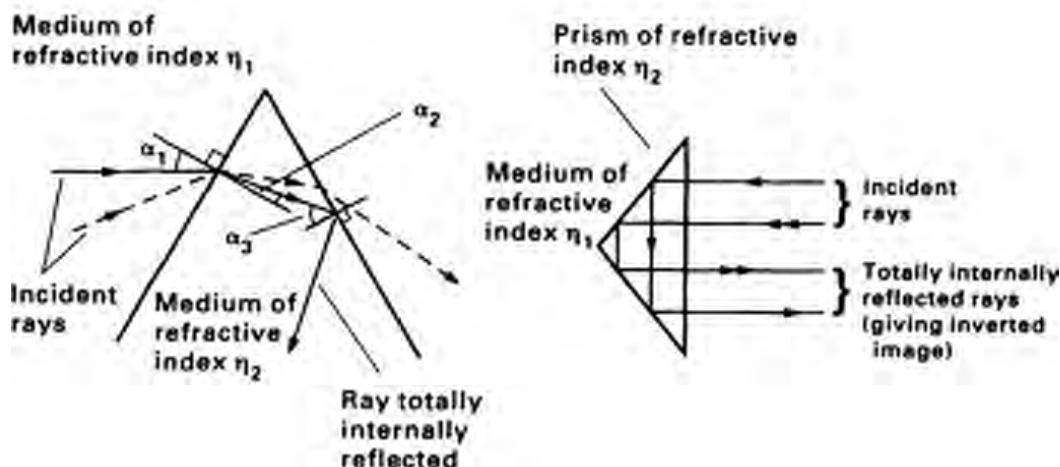


FIG. 6.44. Examples of total internal reflection

A typical arrangement for an on-line process refractometer is shown in Fig. 6.45. Besides the prism, which is in contact with the process liquid, there is commonly a light source, a beam collimator and a photo-conductive sensor. As the nature or concentration of the process liquid varies, the critical angle changes, so moving the internally reflected collimated beam of light across the photo-detector. The latter is divided into two sections, one of which is arranged to receive a constant amount of

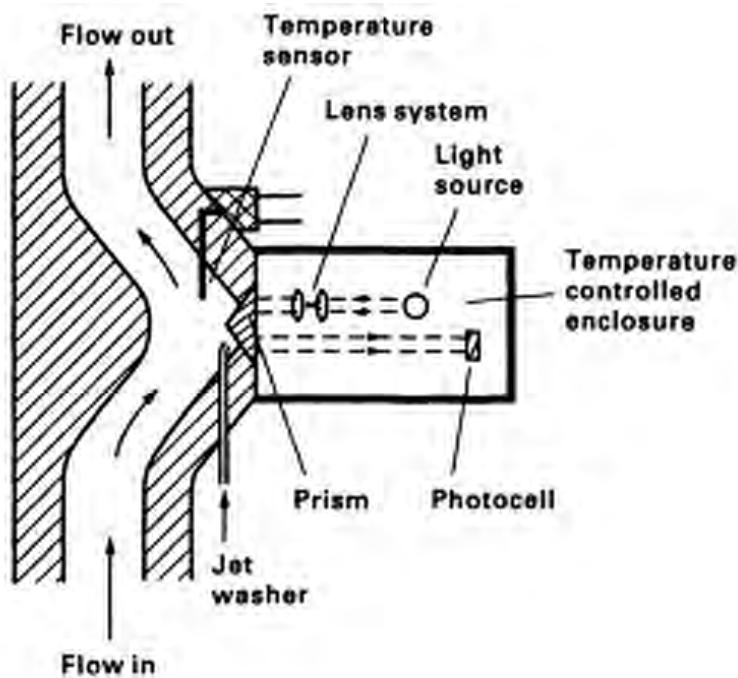


FIG. 6.45. Continuous valve-body type refractometer suitable for measuring concentration of dissolved solids

light (as a reference) and the other which responds to light which varies in intensity as the critical angle changes. Such instruments can be used also for measuring concentrations of solids in liquids but, in this application, fouling of the optical surface can be a problem.

Turbidimeters

These measure *turbidity*, usually by sensing light scattered at 90° to the direction of the incident light beam. This type of turbidimeter is frequently termed a *nephelometer* or *nephelometric turbidimeter*. A typical arrangement is shown in Fig. 6.46. The nephelometer is commonly used for detecting solid particles present in water (e.g. waste water) or in air (e.g. smoke). The instrument requires periodic cleaning due to fouling of the optical system.

Opacity Monitors

These are similar to nephelometers, except that they measure the attenuation of a light beam due to the combined effects of absorption and scattering by the sample. The instrument consists of a light source, a collimator and a photo-detector. The most common application is the measurement of smoke density in chimney stacks. In this case the optical surfaces exposed to the smoke are kept clean by flows of clean air. The density of the smoke is expressed in terms of *per cent opacity*, *per cent transmittance* or *optical density*, where:

$$\text{per cent opacity} = 100 \times \text{opacity} = 100 - \text{per cent transmittance} \quad (6.70)$$

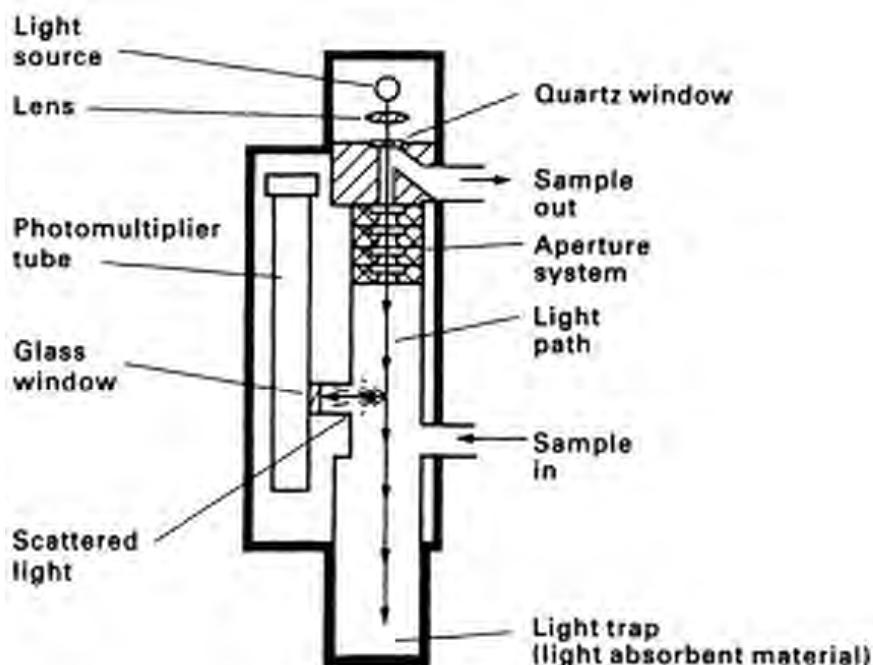


FIG. 6.46. Continuous nephelometric turbidimeter

and:

$$\text{optical density} = -\log(1 - \text{opacity}) \quad (6.71)$$

More modern instruments employ lasers as the light source.

6.8.2. Electrometric Analysers

These instruments use electrochemical methods to determine composition.

Conductivity Cells

The conductivity of a conducting liquid is very sensitive to the presence of small quantities of electrolytes. Dilution not only increases the proportion of dissolved electrolyte which forms ions in solution, but also reduces generally the number of ions per unit volume. To negate the latter effect, a *molar conductivity* Λ is defined as:

$$\Lambda = \frac{\kappa}{C} \quad (6.72)$$

where κ is the conductivity (i.e. conductance per metre) and C is the concentration. Conductance is measured in *Siemens* (S) and is the reciprocal of the electrical resistance measured in ohms. (Hence, if C is measured in kmol/m^3 and κ in S/m then the units of Λ will be Sm^2/kmol .)

The molar conductivity of an electrolyte at infinite dilution Λ^0 is given by Kohlrausch's law, i.e.:

$$\Lambda^0 = \lambda_a^0 + \lambda_c^0 \quad (6.73)$$

where λ_a^0 , λ_c^0 are the ionic conductivities per unit charge of the anions and the cations, respectively, of the dissolved electrolyte at infinite dilution (see Table 6.10).

Kohlrausch's law can be assumed to apply at concentrations up to about 10^{-4} kmol/m³. For a fully dissociated electrolyte at these concentrations, from equations 6.72 and 6.73:

$$\kappa = (n_a Z_a \lambda_a^0 + n_c Z_c \lambda_c^0) C \quad (6.74)$$

where n_a , n_c represent respectively the numbers of anions and cations produced by the dissociation of one molecule of the electrolyte and Z_a , Z_c are the respective charges on each ion. Values of λ_a^0 and λ_c^0 vary greatly with temperature (e.g. for Na⁺, $\lambda_c^0(298\text{K}) = 5.01 \text{ Sm}^2/\text{kmol}$ and $\lambda_c^0(373\text{K}) = 14.50 \text{ Sm}^2/\text{kmol}$) and approximate values can be calculated from:

$$\lambda_T^0 = \lambda_{298}^0 [1 + \beta_c(T - 298)] \quad (6.75)$$

where β_c is a temperature coefficient for a specific ion and T is in K.

TABLE 6.10. *Some Ionic Conductivities at Infinite Dilution at 298 K ($\lambda_{298}^0 \text{ Sm}^2/\text{kmol}$)⁽⁶²⁾*

Anion	λ_a^0	Cation	λ_c^0
OH ⁻	19.91	H ⁺	34.98
½ SO ₄ ²⁻	8.00	NH ₄ ⁺	7.36
Cl ⁻	7.64	½ Ca ²⁺	5.95
NO ₃ ⁻	7.15	½ Cu ²⁺	5.36
½ CO ₃ ²⁻	6.93	½ Mg ²⁺	5.31
CH ₃ COO ⁻	4.09	Na ⁺	5.01

Many different types of conductivity cell are available but the principle of operation is the same in the great majority of cases. A small current is passed through the sample liquid between two electrodes using a square wave voltage source (this type of excitation minimises the effects of polarisation)⁽⁶³⁾. If the electrodes are of fixed area A_e and constant distance x_e apart, then the conductance is:

$$\kappa' = \frac{\kappa A_e}{x_e} = \frac{1}{R_c} \quad (6.76)$$

assuming that the liquid between the electrodes maintains a uniform cross-section. Thus, if the resistance R_c is measured (usually by means of a Wheatstone bridge network), the concentration of the electrolyte can be determined from equation 6.74. Often equation 6.76 is expressed in terms of a cell constant k_c such that $\kappa = k_c/R_c$. The cell constant employed depends upon the conductivity of the solution being measured. Conductivities of between 5 $\mu\text{S}/\text{m}$ and 1000 S/m can be monitored using corresponding cell constants of between 1 m^{-1} and 5000 m^{-1} respectively. Cell constants can be affected by the polarisation of the sample material. The extent of the polarisation depends largely upon the frequency of the excitation current used and the nature of the electrode surfaces. This is particularly so at higher values of conductivity ($>0.1 \text{ S}/\text{m}$) when it is necessary to treat or coat the electrodes. Increasing the frequency of the current reduces polarisation but increases errors due to capacitance effects.

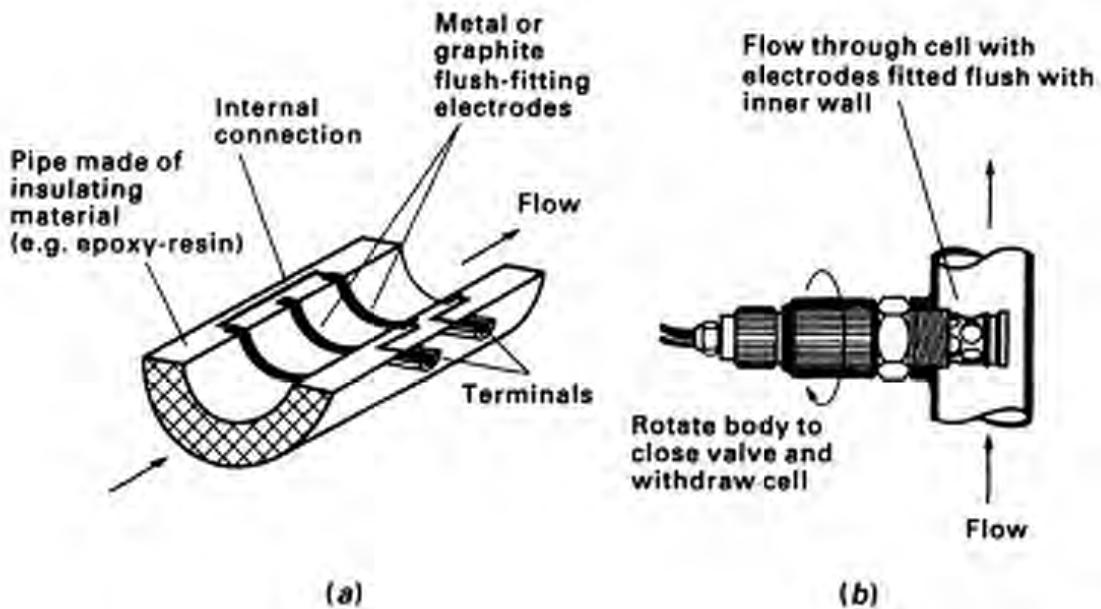


FIG. 6.47. Electrical conductivity cell: (a) section through flow-through conductivity cell showing arrangement of electrodes; (b) screw-in cell inserted in pipeline

Flow-through conductivity sensors suitable for insertion in pipelines (see Fig. 6.47a) are now available for use at temperatures up to 480 K and pressures up to 1700 kN/m²⁽⁶⁴⁾. As conductivity is temperature sensitive, a thermistor is usually included in the detector circuit as part of a temperature compensator. Screw-in cells (Fig. 6.47b) will withstand higher pressures. More recently, electrodeless methods of measuring conductivity have become available. In this case the solution is placed between two energised toroids. The output voltage of the instrument (from the output toroid circuit) is proportional to the conductivity of the solution provided that the input voltage remains constant. This type of conductivity meter can be used under much more severe conditions, e.g. with highly corrosive or dirty systems⁽⁶³⁾.

pH Measurement and Other Ion Selective Electrodes

pH is defined as:

$$\text{pH} = \log\left(\frac{1}{[\text{H}^+]}\right) \quad (6.77)$$

where [H⁺] is the concentration of hydrogen ions in solution in appropriate units. Thus pH varies between 0 for solutions having a hydrogen ion concentration of 1 kmol/m³ (strong acid) and 14 when the hydrogen ion concentration is 10⁻¹⁴ kmol/m³ (strong alkali) with the neutral point (pure water) having a pH of 7. pH values of some common materials are listed in Table 6.11. A pH sensor enables the degree of acidity or alkalinity of a liquid to be determined and is of particular use in monitoring effluent and discharges from chemical works, refineries, etc.

pH as described by equation 6.77 is difficult to measure and an operational definition of pH (BS 1647⁽⁶⁵⁾) is obtained by specifying the EMFs E_A and E_B of two standard cells, where:

E_A is the EMF of the cell: Pt-H₂/solution A/concentrated KCl solution/reference electrode.

E_B is the EMF of the cell: Pt-H₂/solution B/concentrated KCl solution/reference electrode.

Both cells are at the same temperature and the reference and bridge solutions are identical in the two cells. Then:

$$\text{pH}_A - \text{pH}_B = \frac{E_A - E_B}{2.303 \frac{RT}{F}} \quad (6.78)$$

where R is the universal gas constant, T is the temperature in K and F is the Faraday Number, i.e. 9.6490×10^7 coulombs/kmol (96,490 coulombs/mole).

TABLE 6.11. pH Values of some Common Materials at 298K⁽⁶²⁾

Material	Concentration (kmol/m ³)	pH
Acids		
Hydrochloric acid	1.0	0.1
Sulphuric acid	1.0	0.3
Hydrochloric acid	0.1	1.1
Sulphuric acid	0.1	1.2
Sulphurous acid	0.1	1.5
Oxalic acid	0.1	1.6
Acetic acid	1.0	2.4
Benzoic acid	saturated	2.8
Acetic acid	0.1	2.9
Carbonic acid	saturated	3.8
Hydrogen sulphide	0.1	4.1
Ammonium sulphate	0.1	5.5
Alkalies		
Sodium bicarbonate	0.1	8.4
Calcium carbonate	saturated	9.4
Magnesium hydroxide	saturated	10.5
Ammonia	0.1	11.1
Ammonia	1.0	11.6
Sodium carbonate	0.1	11.6
Calcium hydroxide	saturated	12.4
Sodium hydroxide	0.1	13.0
Sodium hydroxide	1.0	14.0

It is not easy to set up a hydrogen electrode, hence subsidiary reference electrodes are used where the potentials of these relative to the standard hydrogen electrode have been determined previously. Practical considerations limit such electrodes to those consisting of a metal in contact with a solution which is saturated with a sparingly soluble salt of the metal and which contains also an additional salt with a common anion. Examples of commonly used electrodes are the silver/silver chloride electrode, i.e. Ag/AgCl(s)KCl(aq), and the mercury/mercurous chloride electrode (known as the calomel electrode), i.e. Hg/Hg₂Cl₂(s)KCl(aq). In each case the potential of the reference electrode is governed by the activity of the anion in solution, which can be shown to be constant at a given temperature.

A typical pH measuring circuit consists of two electrodes, viz. the *pH sensing electrode* and the *reference electrode*, immersed in the fluid to be measured together with a high-impedance voltage measuring system (see Fig. 6.48a and Section 6.11.6). The most commonly employed pH electrode is the glass electrode (Fig. 6.48b) which consists of a glass body and an electrode wire. The latter connects an external coaxial cable to the internal reference electrode which is immersed in a solution of constant pH. This solution wets a specially constructed glass membrane which is selective to H⁺ ions (i.e. to pH). The exterior of this membrane is immersed in the solution to be measured. Figure 6.48c is a diagrammatic representation of the reference electrode which is similar to the pH sensing electrode, except that the glass membrane is replaced by a porous plug allowing a liquid/liquid interface to exist between the salt solution and the sample. The Ag/AgCl(s)KCl(aq) reference electrode is a silver wire coated with solid silver chloride and the salt solution is 3 molar KCl (3 kmol/m³).

The measured potential across the system (Fig. 6.48a) is:

$$E = E_{ir} + E_m + E_j - E_{er} \quad (6.79)$$

where E_{ir} , E_m , E_j and E_{er} are the EMFs generated at the internal reference electrode, the membrane, the liquid junction and the external reference electrode, respectively. Under normal conditions, E_j is negligible and E_{ir} and E_{er} are constant. Hence, equation 6.79 becomes:

$$E = E_0 + E_m \quad (6.80)$$

where E_0 is a constant.

A typical half-cell reaction may be written:



where α , β , etc. are the numbers of the respective ions denoted by A, B, etc. Then the electrode potential can be expressed in terms of the *Nernst Equation*⁽⁶⁶⁾.

i.e.:
$$E = E_0 + \frac{RT}{nF} \ln \left(\frac{[A]^\alpha [B]^\beta \dots}{[C]^\gamma [D]^\delta \dots} \right) \quad (6.81)$$

where [A] is the ionic concentration of component A, etc., and n is the net number of negative charges transferred in the reaction.

For any ion-selective electrode, equation 6.81 reduces to:

$$E = E_0 + \frac{RT}{nF} \ln a \quad (6.82)$$

where a is the activity of the particular ions involved (i.e. of H⁺ ions for a pH meter). Thus, it should be noted that pH measuring devices actually measure the effective concentration (or activity) of the H⁺ ions and not the actual concentration. Hence, defining pH in terms of the H⁺ activity a_{H^+} (i.e. pH = $-\log(a_{H^+})$ where $a_{H^+} = (\gamma_{H^+})[H^+]$ and γ_{H^+} is the activity coefficient), then from equation 6.82 (assuming that the electrode is entirely selective to H⁺ ions):

$$\text{pH} = \frac{F(E_0 - E)}{2.303RT} \quad (6.83)$$

and for any positive ion carrying one elementary charge (e.g. H⁺) at 298 K:

$$E - E_0 = 59.2 \times 10^{-3} \log a \quad (6.84)$$

where E , E_0 and the coefficient (59.2×10^{-3}) are expressed in V. Thus the nominal output of a pH electrode is 59.2 mV/pH at 298K. The actual output can vary from

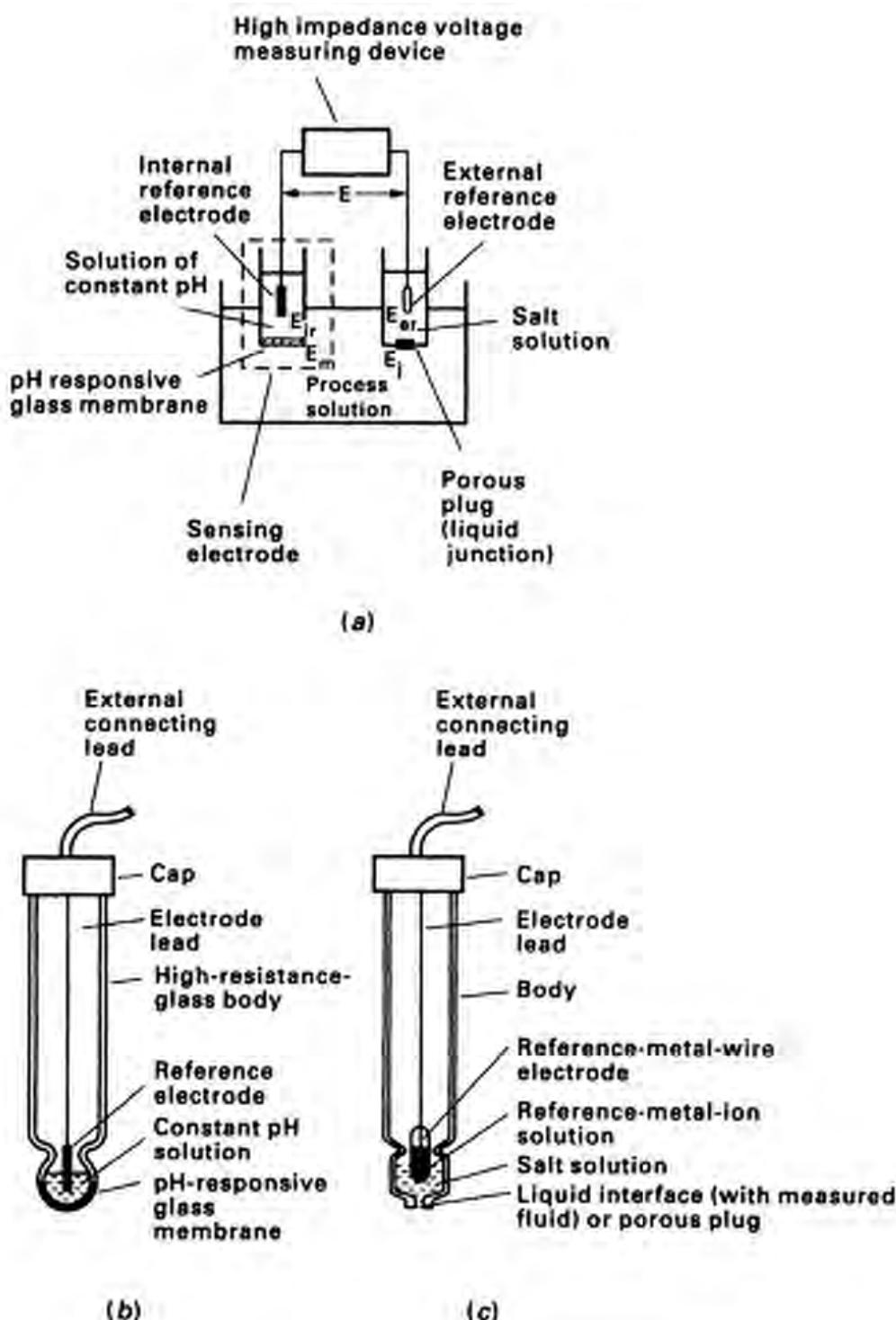


FIG. 6.48. Schematic diagrams of pH sensing electrodes: (a) pH measurement system; (b) pH electrode; (c) reference electrode

this value and a means of adjustment is provided to correct for this against a solution of known pH.

Electrodes which are selective to ions other than H⁺ are commonly available. These are called *specific ion* or *pIon* sensors and are listed in Table 6.12. Major difficulties with pH and pIon sensors are non-linearity, noise and sensitivity. Fouling of the probe can also be troublesome and many industrial instruments employing these principles are provided with the means of cleaning electrode surfaces ultrasonically.

TABLE 6.12. *Some Commonly Available Specific Ion (pIon) Electrodes*^(58, 67)

Type of Electrode	Type of Construction	Selective to Ions
Glass	As for H ⁺ and pH.	Na ⁺ , K ⁺ , NH ⁺ , Ag ⁺ and other univalent cations
Solid state	Membrane consists of compacted disc or single crystal of active material.	F ⁻ , Cl ⁻ , Br ⁻ , I ⁻ , S ²⁻ , Ag ⁺ , Cu ²⁺ , Pb ²⁺ , Cd ²⁺
Heterogeneous membrane	Similar to solid-state type but active material dispersed in inert matrix.	Cl ⁻ , Br ⁻ , I ⁻ , S ²⁻ , Ag ⁺
Liquid ion exchange	Internal reference solution and measured solution are separated by a porous layer holding liquid of low water solubility in which is dissolved large molecules containing the ions of interest.	Ca ²⁺ , Cu ²⁺ , Pb ²⁺ , Cl ⁻ , ClO ₄ ⁻ , NO ₃ ⁻ , BF ₄ ⁻
Gas sensing membrane	Not true membrane electrodes as no current passes across the membrane. The ion being determined diffuses through the membrane into an electrochemical cell. The consequent change in the chemistry of the cell is monitored by an ion sensitive electrode.	NH ₃ , SO ₂ , CO ₂

ORP (Redox) Sensors

When a suitable electrode is immersed in a solution containing ions of a material in two different states of oxidation (e.g. Cu⁺ and Cu²⁺, Fe²⁺ and Fe³⁺) the electrode acquires a potential which depends upon whether the ions tend to move towards the higher or towards the lower oxidation state. If the tendency is towards the higher oxidation state then the solution has reducing properties and the ions will preferentially discharge electrons to the electrode which will become negatively charged relative to the solution. If, on the other hand, the ions in solution tend to move towards the lower oxidation state (i.e. if the solution has oxidising properties) then the ions will take electrons from the electrode which will then become positively charged with respect to the solution. Hence, the electrode potential (*oxidation-reduction* potential, ORP, or *redox* potential) is a measure of the oxidising or reducing power of the solution in which it is immersed. The ORP (E_{orp}) can be calculated from the activities of the ion in the oxidation states using equation 6.82:

$$E_{orp} = E_0 + \frac{RT}{nF} \ln \left(\frac{\text{activity of ion in higher oxidised state}}{\text{activity of ion in lower oxidised state}} \right) \quad (6.85)$$

The ORP electrode is similar to the pH electrode except that it is made from platinum, gold or silver on a platinum base. A reference electrode is required which may be either the Ag/AgCl or the calomel electrode used in pH determination. Combined pH/ORP instruments are also available and the user can switch to whichever facility is required.

Polarographic Sensors

When two dissimilar metals are immersed in an electrolyte and connected together, a current will flow due to the build-up of electrons on the more electropositive electrode. This current soon stops due to the polarisation of the cell. If a suitable depolarising agent is added, then current will continue to flow. In the polarographic sensor the sample is arranged as the depolarising agent and the magnitude of the current produced is a function of the concentration of the material to be detected in the sample. In some polarographic instruments the reaction and the current in the cell are maintained by applying an external voltage (≈ 0.7 V) across the cell. This type of sensor is used to measure pollutants such as Cl_2 , HCl , HBr and HF in air; for determining the concentration of O_2 in flue gas (up to about 25 per cent); and for measuring quantities of inert gases. Accuracies of ± 1 per cent of full scale deflection have been reported⁽⁶³⁾.

High Temperature Ceramic Sensors (Zirconia Cells)

Zirconium oxide (*zirconia*— ZrO_2) doped with small quantities of yttria (Y_2O_3) has a stable lattice structure which permits oxygen ion conduction at high temperatures. The sensor is constructed by placing a heated section of the doped ZrO_2 in contact with the sample gas containing O_2 and a reference gas (usually air). Figure 6.49a shows a particular arrangement in which two porous platinum electrodes are attached to the opposite sides of a disc of the zirconia electrolyte which is heated electrically to about 1000 K⁽⁶⁸⁾. A potential difference E_{Zr} is set up between the two electrodes which is a function of the partial pressures of the concentrations of O_2 in the sample and in the reference. From equation 6.82:

$$E_{\text{Zr}} = E - E_0 = 0.0496T \log \left(\frac{P'_0}{P'} \right) + k_{\text{Zr}} \quad (6.86)$$

where E , P' and E_0 , P'_0 are the potentials and partial pressures of the sample and reference respectively and k_{Zr} is the cell constant (V). The constant 0.0496 has the units V/K in the SI system. Equation 6.86 should not be used with any other system of units.

Zirconia cells are specific to O_2 and are employed generally to monitor the O_2 content of flue gases. They can be used for concentrations of O_2 from about 0.1 to 20 mole per cent with accuracies of ± 0.1 per cent up to 10 per cent O_2 and of ± 2.5 per cent between 10 and 20 per cent O_2 ⁽⁶⁹⁾. The sensor can be inserted directly into the flue or can employ a sampling system (Fig. 6.49b). The response time is short (≈ 7 s for 90 per cent of the response to take place—depending on the application) but because of the high temperature of operation the instrument is not suitable for measuring the O_2 content of flammable gases.

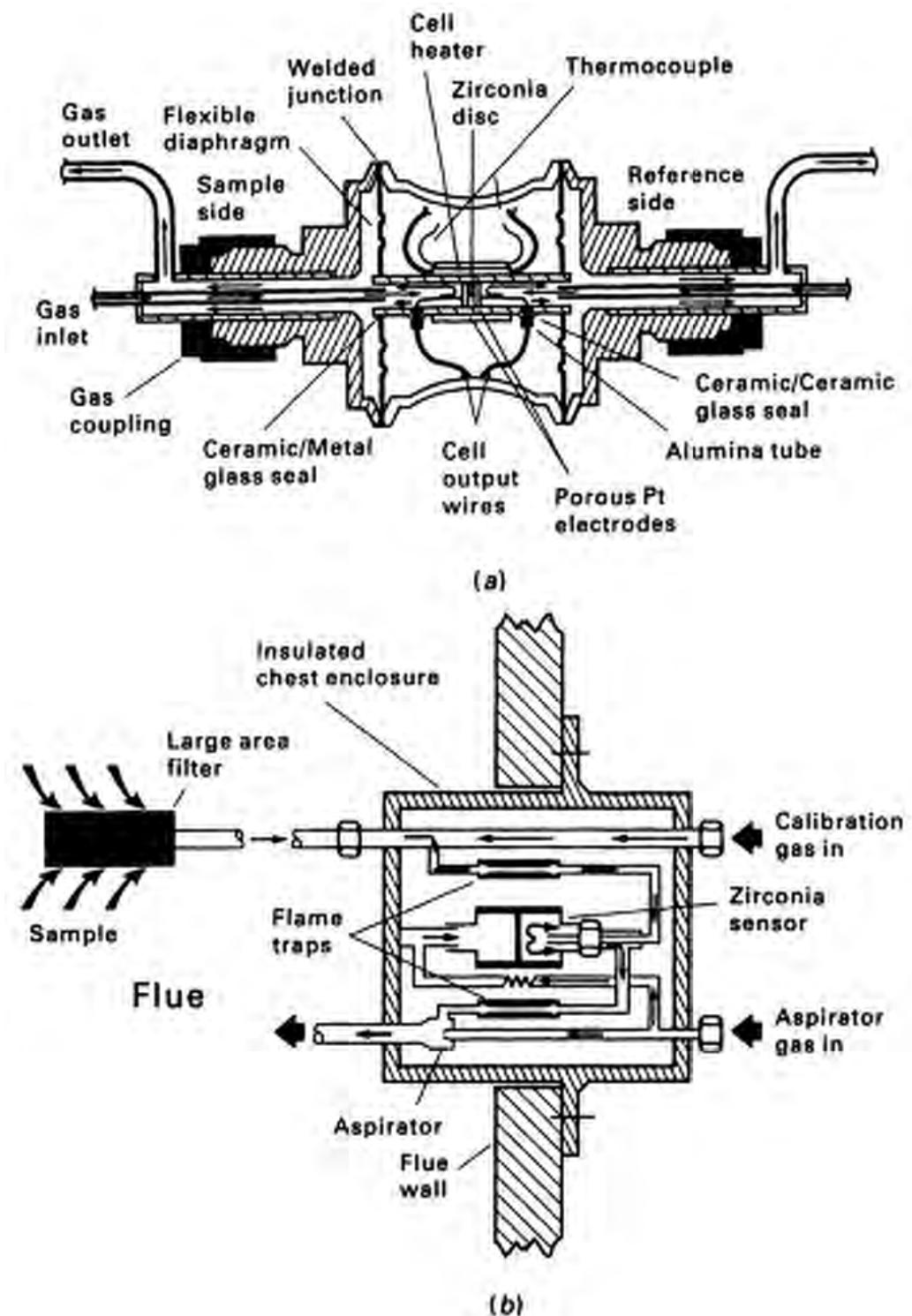


FIG. 6.49. Zirconia oxygen-analyser: (a) details of typical analyser; (b) analyser used in the extractive mode for measuring the oxygen concentration in flue gas

6.8.3. The Chromatograph as an On-Line Process Analyser

One of the most widely employed instruments for the on-line analysis of samples of multicomponent gases or volatile liquids is the gas-liquid or gas-solid chromatograph (GLC or GSC). This is an instrument which analyses discrete samples of

material, and the total time taken between the extraction of the sample from the process stream and the production of a result in the form of a signal to a relevant control system can be considerable. This constitutes one of the major difficulties in using such instruments for on-line control purposes (Section 7.17).

The principles underlying the operation of the chromatograph and its use in a commercial separation process are discussed in Volume 2, Chapter 19. In this section emphasis is placed on its function as an on-line process analyser in which form it consists of three major subdivisions (apart from any electronic readout system), viz. the sampling assembly, the chromatograph column and the detector. All three are generally contained within the same temperature-controlled environment (Fig. 6.50).

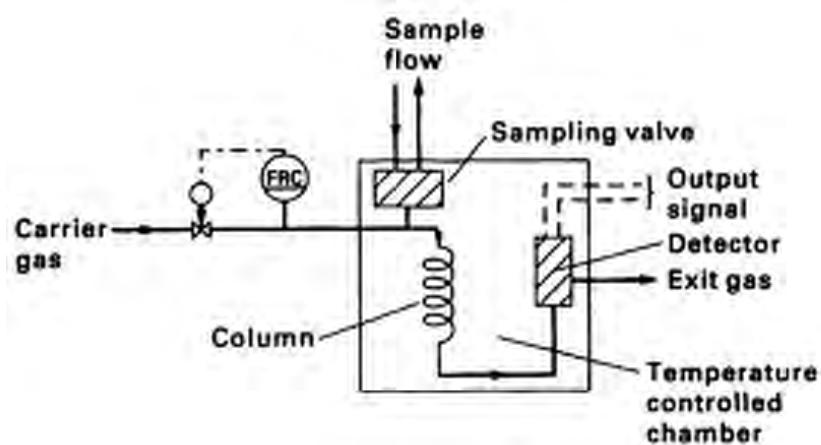


FIG. 6.50. Schematic diagram of gas chromatograph

The Sampling Assembly

This is of major importance and must send to the chromatograph representative and homogeneous samples of the material in vapour or gaseous form such that they can be analysed at the required intervals of time. A typical sampling valve is illustrated in Fig. 6.51. A continuous flow of sample passes through the sampling valve and the *sample loop* to minimise sample dead-time (Fig. 6.51a). The sample loop provides the correct volume of sample for analysis. The sample must be vaporised where necessary and filtered to ensure that it is clean and dry. Sample flowrates are usually of the order of 10^{-7} - $10^{-6} \text{ m}^3/\text{s}$ (6–60 ml/min) (see Section 6.2.3). More complex sampling systems are often required either when more than one column is used in the analysis, or where one installation is employed to analyse a number of different streams (Fig. 6.52)⁽⁷⁰⁾. In the latter case, *back-flushing* is necessary to prevent inter-sample contamination.

The Chromatograph Column

This typically consists of a 2–10 mm OD stainless steel tube of 1–2 m length wound into a single or double helix or shaped into a U-tube. Many different packings (*solid supports*) are available (e.g. glass beads, activated charcoal, activated alumina, etc.) which are coated with a selected solvent (*stationary phase*). There are many of the

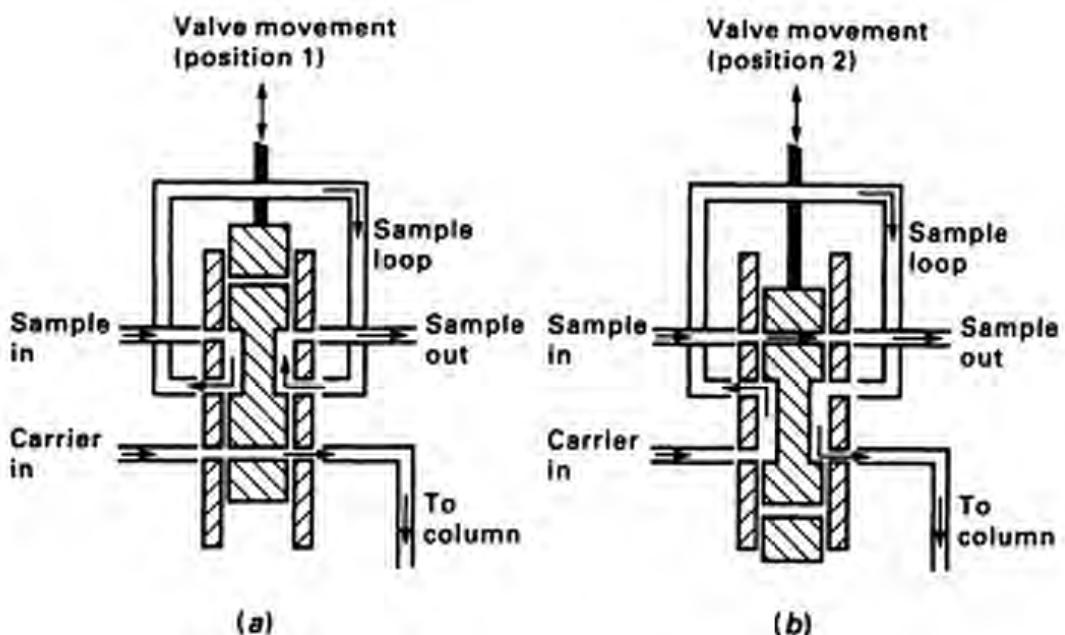


FIG. 6.51. Typical gas chromatograph sampling assembly: (a) sample flow by-passing column; (b) sample conveyed into column by carrier gas

latter and they are generally identified by trade names. The choice of stationary phase is dependent upon its thermal stability, upon the components present in the sample and upon the degree of separation required within the column. This process is called *gas-liquid chromatography* (GLC) and is now being superseded by *gas-solid chromatography* (GSC) which uses columns packed with molecular sieves and other porous polymeric materials which give the required component separations⁽⁷¹⁾. No liquid stationary phase is required and, hence, no difficulties can occur due to either its loss or its thermal instability.

The Detector

Ideally, this should exhibit a fast response, a high sensitivity and reproducibility, give a linear output over a wide range of compositions, be suitable for different carrier gases and be sufficiently rugged for use in the field. Two kinds of detector generally meet these requirements, viz. the flame ionisation detector (FID) (Table 6.16) and the thermal conductivity detector (TCD) (Section 6.8.5). Other detectors that can be used in special applications are described in Table 6.16. Generally, the detector and the carrier gas are chosen together such that the components eluted from the column generate large signals, e.g. helium is used with TCDs because of its high thermal conductivity (Table 6.13) and because it is safer to use than hydrogen. TCDs are more suitable for the analysis of permanent gases whereas FIDs are generally employed for the detection of organic compounds.

The Liquid Phase Chromatograph (LC)

Liquid Phase Chromatography is employed to analyse liquids of low volatility (Volume 2, Section 19.4.3). No carrier gas is used and the sampling valve (Fig. 6.51)

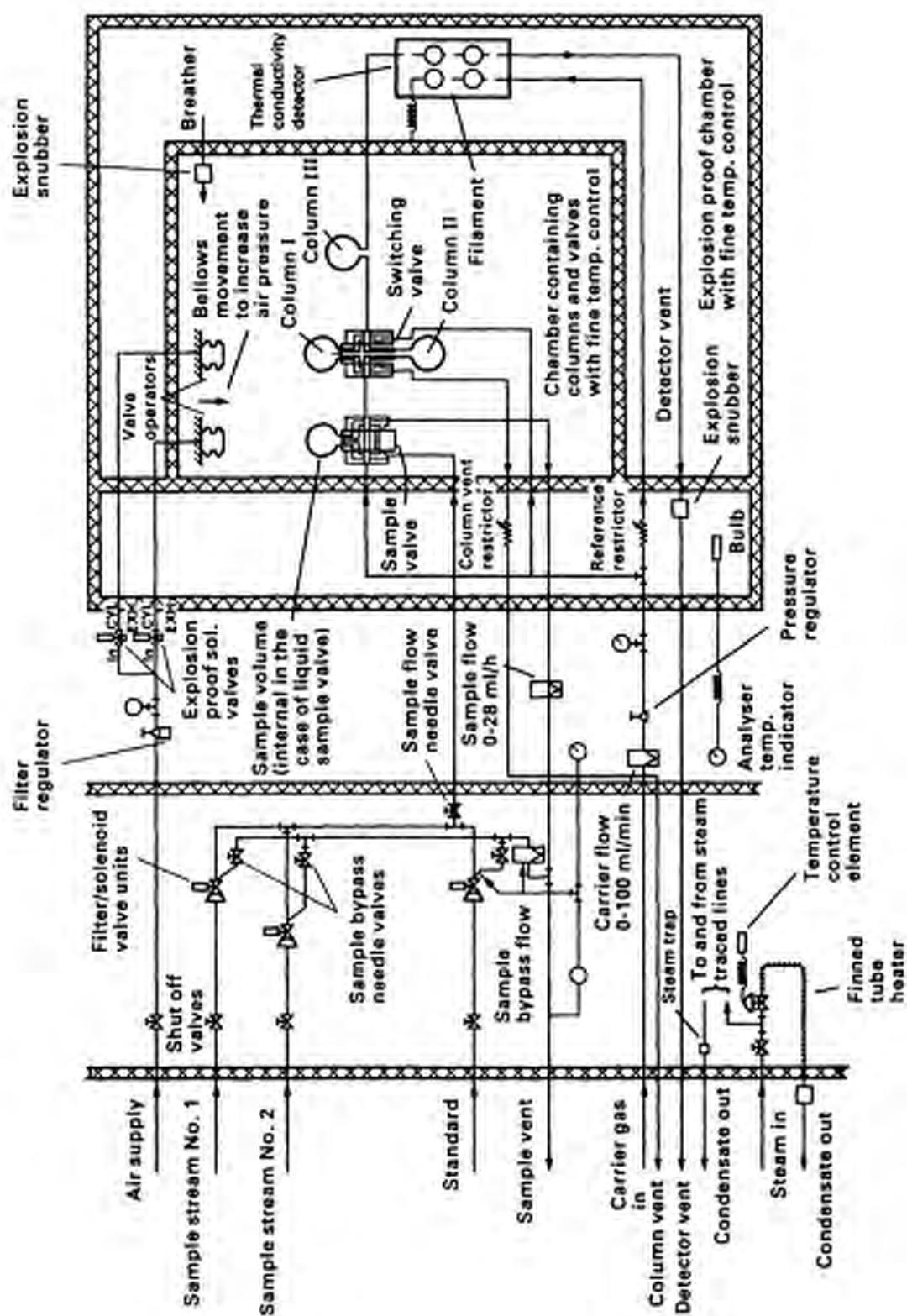


FIG. 6.52. Flow diagram of multi-stream chromatograph with thermal conductivity detector

does not require a sample loop (as a smaller sample suffices—Fig. 6.51). LC columns may simply contain solid particles or use a support and stationary phase as in the GLC. The most widely employed detectors for LCs are UV photometric and refractive index sensors (Section 6.8.1).

6.8.4. The Mass Spectrometer

This instrument is able to make a quick and accurate analysis of a wide range of materials either on or off line. Many different configurations of the instrument are available. Figure 6.53 is a schematic diagram of the *double focusing* type which has the advantage of providing a much more uniform range of ion energies than the *single focusing* version. Analysis times as low as 1 s to 3 s can be obtained although cycle times experienced under on-line process conditions (which include the DV lag in the sampling system) are of the order of 10 s to 15 s⁽⁷²⁾. When used in combination with the gas chromatograph (Section 6.8.3) the mass spectrometer is able to identify and quantify very small traces of substances (of the order of 1 in 10^9). Sensitivities of 1 to 5 ppm can be achieved with standard process instruments with repeatabilities of ± 1 per cent—although these figures are very much dependent upon the stream compositions and the particular application⁽⁷³⁾. It is a highly specific instrument but unfortunately too expensive for many process applications.

The basic principle of the instrument is that positive ions are produced from the various components in the sample to be analysed by subjecting the sample material to a series of electric sparks or by bombarding it with high energy photons. These ions are passed through a magnetic or electric field (or a combination of both) which resolves them into their component ions according to their charge/mass ratio. The deflecting field is arranged to focus ions of a given mass on to an electron multiplier or scintillation counter. By arranging the deflecting field to vary in a predetermined manner, a range of masses can be scanned and the abundance of ions of each particular mass recorded. This *mass spectrum* can be analysed automatically

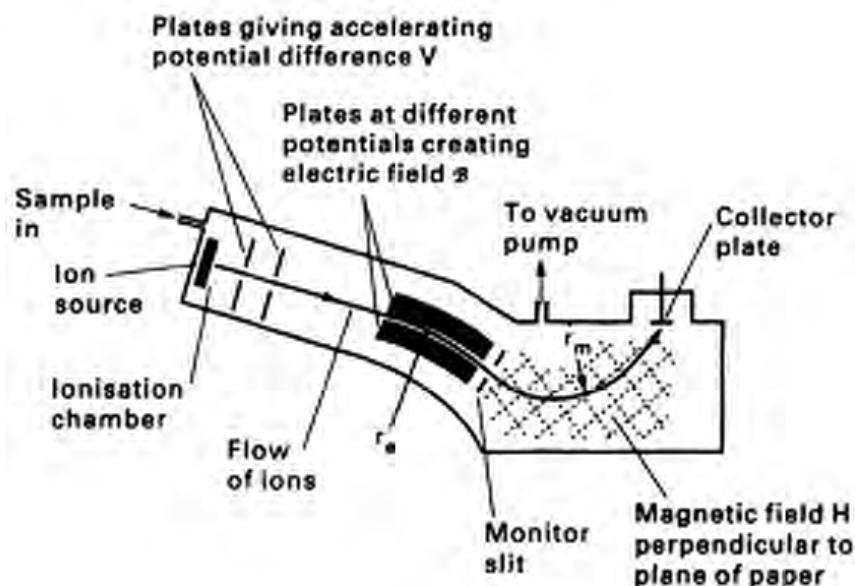


FIG. 6.53. Schematic diagram of double-focusing mass spectrometer

using a computer-based analysis system and compared with mass spectra of known materials held in a data bank. Thus the identity and concentration of the various components within the sample are derived on a continuous basis. A simplified treatment of the underlying principle of the mass spectrometer follows.

Consider an ion of mass m_i and charge e accelerated through a controlled potential difference of V . The work done on the ion as a result of the potential difference V will accelerate it from rest to a velocity u_i , thus:

$$\frac{1}{2}m_i u_i^2 = eV \quad (6.87)$$

Suppose the ion now enters a deflecting electric field \mathcal{F} at right angles to the direction of the field (Fig. 6.53). The ion will then move in a circular path of radius r_e and the consequent reaction to the centripetal force will be:

$$\frac{m_i u_i^2}{2r_e} = e\mathcal{F} \quad (6.88)$$

Hence, from equations 6.87 and 6.88:

$$r_e = \frac{m_i u_i^2}{e\mathcal{F}} = \frac{2V}{\mathcal{F}} \quad (6.89)$$

Thus the radius of the path of the ion in the field depends on the accelerating and deflecting fields only and is independent of e/m_i . Consequently, if \mathcal{F} is maintained constant, the electrostatic analyser will focus the ions at the monitor slit in accordance with their translational energies imparted by the potential difference V . The monitor slit can be arranged to intercept a given portion of the beam. This passes to the electromagnetic analyser in which a magnetic field of magnetic flux density \mathcal{B} is applied at right angles to the direction of the beam. The force F_i exerted on the ions is:

$$F_i = \mathcal{B}eu_i \quad (6.90)$$

which is at right angles to their motion (Fleming's left hand rule), and thus the ions once more follow a circular path of radius r_m described by:

$$\frac{m_i u_i^2}{r_m} = \mathcal{B}eu_i \quad (6.91)$$

From equations 6.87 and 6.91:

$$\frac{e}{m_i} = \frac{2V}{\mathcal{B}^2 r_m^2} \quad (6.92)$$

Hence, if the electric and electromagnetic fields are kept constant then all ions having the same e/m_i ratio will have the same value of r_m .

6.8.5. Thermal Conductivity Sensors for Gases

Gas thermal conductivity sensors are used to detect variations in the composition of mixtures of gases by monitoring changes in the thermal conductivity of the mixture. Such instruments are used (a) as detectors for gas chromatographs (Section

6.8.3), and (b) as stand-alone instruments for gas analysis. In some applications the pressure exerted by a pure gas is determined directly from its thermal conductivity (Section 6.3.5).

Several forms of gas sensor based upon thermal conductivity are available. The most common type of detector (the *katharometer*) consists of a number of hot-wire sensors arranged in a Wheatstone Bridge circuit (Fig. 6.54)⁽⁸⁾. A small current i is supplied to heat each arm of the bridge. The heat transfer coefficient h for

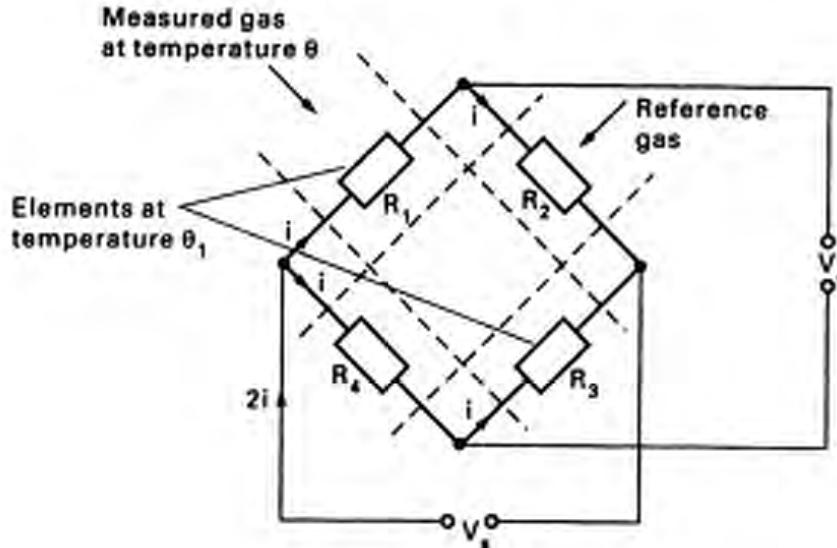


FIG. 6.54. Katharometer deflection bridge

convection from the wire to the gas (under the conditions applied within the instrument) is dependent largely upon the velocity of the gas and its thermal conductivity k (see also Volume 1, Section 9.4). If the gas velocity is maintained constant and small then h will be predominantly a function of k , and from a steady-state heat balance over the resistance R_1 :

$$i^2 R_1 = h_{\text{mix}} A_R (\theta_1 - \theta) \quad (6.93)$$

where A_R is the surface area of R_1 and θ_1 and θ are the temperatures of R_1 and the gas respectively ($\theta_1 > \theta$).

$$\text{But: } R_1 = R_0(1 + \beta_\theta \theta_1) \quad \text{and} \quad R_\theta = R_0(1 + \beta_\theta \theta) \quad (6.94)$$

where β_θ is a temperature coefficient and R_0 is the resistance of R_1 at the temperature of the gas.

$$\text{Hence: } \frac{R_1}{R_\theta} = \frac{1 + \beta_\theta \theta_1}{1 + \beta_\theta \theta} \approx 1 + \beta_\theta (\theta_1 - \theta) \quad (6.95)$$

assuming that $(\theta_1 - \theta)$ is small. Thus, from equations 6.93 and 6.95:

$$i^2 R_1 = \frac{h_{\text{mix}}}{\beta_\theta} \left(\frac{R_1}{R_\theta} - 1 \right) \quad (6.96)$$

$$\therefore R_1 = \frac{R_\theta h_{\text{mix}}}{h_{\text{mix}} - \chi} = R_3 \quad (6.97)$$

as the sample flows over both R_1 and R_3 (Fig. 6.54) and where $\chi = i^2 \beta_\theta R_\theta / A_R$ is a constant if θ is maintained constant. Similarly, for the reference gas:

$$R_2 = R_4 = \frac{R_\theta h_{\text{ref}}}{h_{\text{ref}} - \chi} \quad (6.98)$$

Hence:

$$\begin{aligned} V_o &= i(R_1 - R_4) = \frac{i R_\theta \chi (1/h_{\text{mix}} - 1/h_{\text{ref}})}{(1 - \chi/h_{\text{mix}})(1 - \chi/h_{\text{ref}})} \\ &= i R_\theta \chi (1/h_{\text{mix}} - 1/h_{\text{ref}}) \text{ as } \chi/h_{\text{mix}} \text{ and } \chi/h_{\text{ref}} \text{ are generally } \ll 1 \\ &= \frac{i^3 R_\theta^2 \beta_\theta}{A_R} \left(\frac{1}{h_{\text{mix}}} - \frac{1}{h_{\text{ref}}} \right) \end{aligned} \quad (6.99)$$

Consequently, the output voltage varies as the cube of the sensor current and is a non-linear function of the heat transfer coefficient, i.e. of the thermal conductivities, provided that the velocities of the gases passing through the detector are small. Equation 6.99 indicates that the katharometer has a maximum sensitivity (≈ 1000 ppm) when the bridge current is high and when it is used to measure composition changes in binary or pseudo-binary mixtures of gases whose components have thermal conductivities which differ widely (Table 6.13).

TABLE 6.13. *Relative Thermal Conductivities of Some Common Gases at 298K (Air = 100)^(74, 75)*

Gas	Thermal conductivity	Gas	Thermal conductivity
Cl ₂	34	CO	96
SO ₂	36	Air	100
C ₆ H ₆	40	N ₂	100
CO ₂	64	O ₂	103
H ₂ O	68	CH ₄	132
C ₂ H ₄	80	He	577
NH ₃	94	H ₂	700

(Thermal conductivity of air at 298 K is 0.026 W/mK.)

Example 6.2

A katharometer is employed to determine the concentration of H₂ in a H₂/CH₄ mixture. The proportion of H₂ can vary from 0 to 60 mole per cent. The katharometer is constructed as shown in Fig. 6.54 from four identical tungsten hot-wire sensors for which the temperature coefficient of resistance β_θ is 0.005 K⁻¹. The gas mixture is passed over sensors R₁ and R₃ whilst the reference gas (pure CH₄) is passed over sensors R₂ and R₄. The total current supplied to the bridge is 220 mA and it is known that the resistance at 25°C and surface area of each sensor are 8 Ω and 10 mm² respectively. Assuming the heat transfer coefficient h between gas and sensor filaments to be a function of gas thermal conductivity k only under the conditions existing in the katharometer and that in this case $h = k \times 10^4$ (h in W/m²K and k in W/mK), draw a graph of the output voltage V_o of the bridge network as a function of mole per cent H₂.

Solution

From Table 6.13, at 298 K:

$$k_{H_2} = 700 \times 0.026/100 = 0.182 \text{ W/mK}$$

$$k_{CH_4} = 132 \times 0.026/100 = 0.034 \text{ W/mK.}$$

Consider one particular gas composition, e.g. 50 mole per cent H₂. This is equivalent to $(100/(100 + 800)) \times 100 = 11.1$ mass per cent H₂. From Volume 6, Section 8.8.4, the thermal conductivity of the mixture k_{mix} can be considered as a simple weighted average, i.e.:

$$k_{\text{mix}} = 0.111 \times 0.182 + 0.889 \times 0.034 \approx 0.050 \text{ W/mK.}$$

Hence:

$$\text{Heat transfer coefficient for the gas mixture } h_{\text{mix}} = k_{\text{mix}} \times 10^4 = 0.050 \times 10^4 \text{ W/m}^2\text{K}$$

$$\text{and for the pure reference gas } h_{CH_4} = k_{CH_4} \times 10^4 = 0.034 \times 10^4 \text{ W/m}^2\text{K.}$$

From equations 6.96 and 6.97 and noting that the current i in each arm of the bridge is $220/2 = 110 \text{ mA} = 0.11 \text{ A}$, then $\chi/h_{\text{mix}} = i^2 \beta_o R_o / (A_R h_{\text{mix}}) = 0.11^2 \times 0.005 \times 8 / (10^{-5} \times 0.050 \times 10^4) \approx 0.10$ which is sufficiently smaller than unity for equation 6.99 to be applicable. Hence, from equation 6.99:

$$V_o = \frac{i^3 R_o^2 \beta_o}{A_R} \left(\frac{1}{h_{\text{mix}}} - \frac{1}{h_{CH_4}} \right) = \frac{0.11^3 \times 8^2 \times 0.005}{10^{-5}} \left(\frac{1}{0.050 \times 10^4} - \frac{1}{0.034 \times 10^4} \right)$$

$$\approx (-)40 \text{ mV.}$$

(The negative sign is not significant.)

Thus a range of output voltages can be calculated for different gas mixture compositions. These are shown in Fig. 6.55.

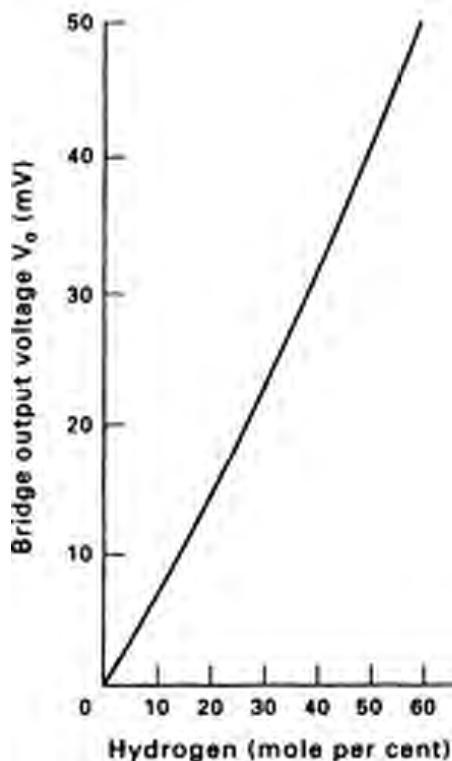


FIG. 6.55. Katharometer output voltage as a function of hydrogen concentration in sample

6.8.6. The Detection of Water

The Measurement of Water in Gases—Humidity Sensors

Methods of determining humidity by physical or chemical absorption or adsorption or using wet and dry bulb thermometry and associated psychrometry can be

TABLE 6.14. Techniques Suitable for the On-line Monitoring of Moisture⁽¹⁶⁻¹⁷⁾

Type of Sensor	Principle of Operation	Accuracy, Range, etc.	Comments
Resistive hygrometer elements	Used in both wafer and cylindrical form. Wire electrodes are inserted into a thin flat section of suitable insulation (e.g. polytetraene) or are wound round a cylinder of the same material. This is covered with a film of hygroscopic salt and thus the resistance of the element changes with the quantity of water vapour absorbed. The latter is a function of the concentration of water vapour in the gas to which the hygrometer surface is exposed.	Reasonably accurate if calibrated regularly.	Other resistive hygrometers employ a humidity sensitive substrate only, e.g. SiO_2 , CrO_2 , Al_2O_3 , and various polymers. These materials often exhibit a change in capacitance as well as resistance and, in such cases, the change in total impedance is measured. They can be used at high moisture concentrations and have a wide response range. They have a rapid response, are simple to use and are cheap. They are prone to contamination. The salt can be etched away and the sensor requires frequent recalibration due to the resulting drift. Very limited on-line use.
Electrolytic (coulometric) hygrometers	The quantity of electricity required to carry out a chemical reaction is measured. The principle is based upon Faraday's law of electrolysis. Water is absorbed on to a thin film of desiccant (e.g. P_2O_5) and electrolysed. The current required for the electrolysis varies according to the amount of water vapour absorbed. The current depends also upon the flowrate.	Capable of high precision. Used in the range 1000 to 3000 ppm of water by volume.	Somewhat complicated procedure. Recombination of products to water is necessary after electrolysis. Density, pressure and flowrates have to be maintained precisely. Contamination can poison the cell. It is ideal for binary mixtures but is of limited range. Suitable for on-line operation.
Aluminium oxide sensor	Consists of a strip of aluminium anodised with a porous oxide layer and coated with a thin layer of gold. The aluminium and gold form two electrodes of what is effectively an Al_2O_3 capacitor. Water vapour rapidly transports through the gold layer and absorbs on to the oxide layer. This equalises in a manner which can be related to the vapour pressure by the change in electrical impedance.	Capable of high precision. Limited operating range—generally between 200 K and 300 K.	Sample has to be clean to avoid poisoning the sensor. Sensor has to be dried if oversaturated, then recalibrated. Has fast response and is ideal for binary mixtures. Relatively cheap. Suitable for on-line use.
Electrolytic type sensors	Uses thick film techniques, e.g. capacitor coated in glass bonded on to a ceramic disc mounted on a thermoelectric (Peltier effect) cooler. Control is by a platinum resistance thermometer which adjusts the temperature of the cooler to regain equilibrium after a change in capacitance due to moisture deposit.	Range depends on technique. Capable of high precision.	Limitations are similar to those for Al_2O_3 sensor. Capable of being direct mounted. Relatively cheap. Suitable for on-line use.
Piezoelectric hygrometers (Fig. 6.56)	These consist of a quartz crystal with a hygroscopic coating (Fig. 6.56a and Section 6.3.3). Two crystals are usually employed and the wet gas (sample) and dry gas (reference) are passed over them alternately (normally every 30 s—Fig. 6.56b). The crystals absorb and desorb. The difference in angular frequency $\Delta\omega$ is proportional to the concentration of water vapour by volume.	Capable of high precision. Can monitor moisture contents of the order of 1 to 3000 ppm by volume. Usually measures up to dewpoint of 310 K.	Fast response but expensive. Sample must be clean to avoid contamination of the crystals. Complex sampling system. Suitable for on-line use.
Optical dewpoint sensors	The humidity of a gas is equal to the humidity of that gas in its saturated state at its dew point. A typical dewpoint sensor uses a plate with a mirror surface in close contact with a thermoelectric (Peltier effect) cooler. A beam of light is directed at the mirror and the reflected ray is detected with a photocell. The amount of condensation occurring on the mirror during cooling affects directly the quantity of light reaching the photocell.	High precision. Maximum range from 220 K to 350 K. Typical accuracy ± 0.2 K and typical resolution ± 0.01 K.	Can be used as a standard instrument for calibration purposes. Ideal for laboratories. Control has to be very precise. Mirror contamination can occur in dirty gases. Cannot be employed in presence of other gases which condense at similar temperatures to the moisture. Some instruments fitted with heated mirror to boil off contaminants—does not necessarily eliminate the problem. Suitable for on-line use—can have continuous or semi-continuous operation.
Photometric methods (non-dispersive infra-red techniques) (Figs 6.57 and 6.43)	Narrow bands of infra-red energy at both reference and measurement wavelengths (in the 1 to $2 \mu\text{m}$ range) are passed alternately through a sample cell and a reference cell (Fig. 6.57), the remaining energy is collected by a solid-state detector and suitable hardware is used to calculate the ratio of these energy levels. The latter is a direct measure of the concentration of water vapour in the sample. Simpler dual-beam instruments are also available (Fig. 6.43).	Single-beam version gives good selectivity with complex mixtures—dual-beam type much less selective. Less sensitive than conventional hygrometers. Higher cost than conventional hygrometers. Suitable for on-line use. Both resistant to contamination—however, single-beam instruments are less affected by deposits on the cell—give better calibration stability in polluted gases.	

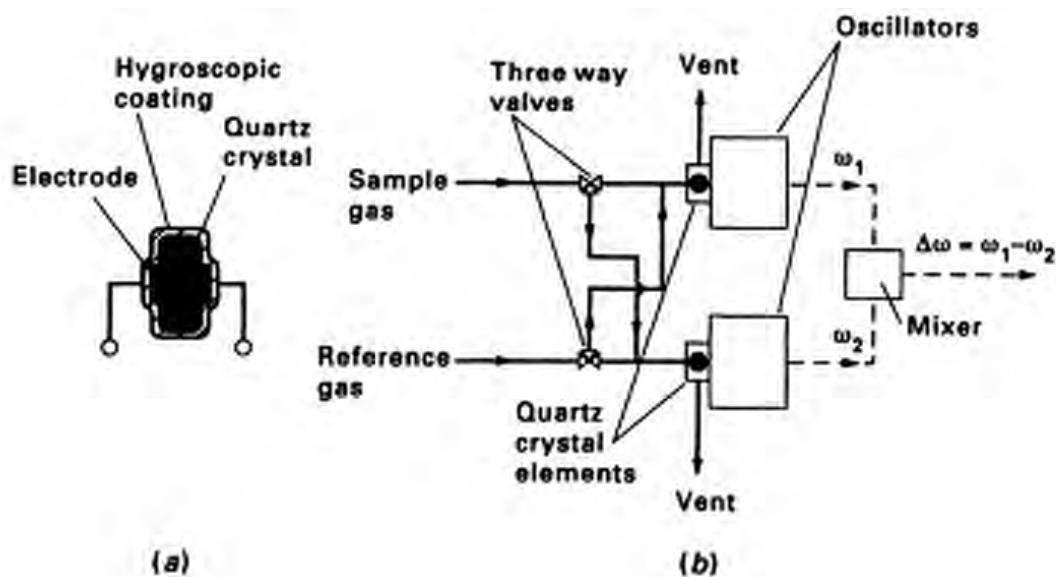
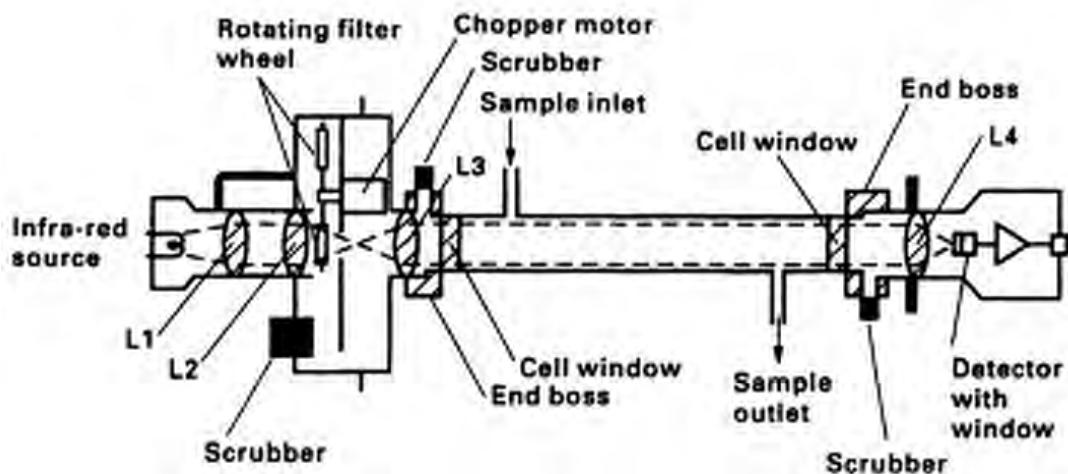


FIG. 6.56. Quartz-oscillator moisture-meter

found in Volume 1, Sections 13.2 and 13.3. These methods of determining the moisture content of process gases are however being superseded by more direct means. A brief resumé of the more common on-line humidity sensors (*hygrometers*) is given in Table 6.14.

Most common moisture probes are prone to contamination. The most serious causes of the latter are exposure to Cl_2 , NH_3 , or wet acids. Common causes of errors in hygrometer readings are too infrequent calibration and the use of the wrong materials for sampling pipework. The allowable concentration of water vapour is so small in some processes that diffusion of water vapour through the walls of

FIG. 6.57. Single-beam infra-red analyser suitable for the detection of water in liquids
(L1-L4: lenses)

sampling tubes can cause significant errors. In general, plastics are quite unsuitable as sample pipe material—stainless steel or copper being the best choice⁽⁷⁹⁾.

The Detection of Water in Liquids and Solids (The Measurement of Moisture Content)

The detection of water in some organic liquids is of considerable importance, e.g. both 'antifreeze' (ethylene glycol) and aviation fuel (kerosene) should contain as little water as possible. Such materials can be monitored for water content by the use of non-dispersive infra-red techniques or turbidimeters (Section 6.8.1).

TABLE 6.15. *Typical Industrial Methods for the Measurement of Moisture in Solids⁽⁸⁰⁾*

Method	Approximate practical range (per cent by mass)	Limitations
Conductance	0 to 25	Affected by other conductive substances in the sample.
Capacitance	0 to 30	The conductivity of the material and variations in the density will affect the measurement.
Near infra-red	0 to 90	By surface measurement. Highly reflective surfaces, crystalline materials and very dark coloured materials can cause difficulty.
Microwave absorption	By sample—0 to 100 In-line—3 to 45	Sensitive to changes in the density of the material.
Nuclear magnetic resonance	0 to 100	Relatively small sample. Affected by any other hydrogen atoms present in the sample other than water, e.g. oils and fats.

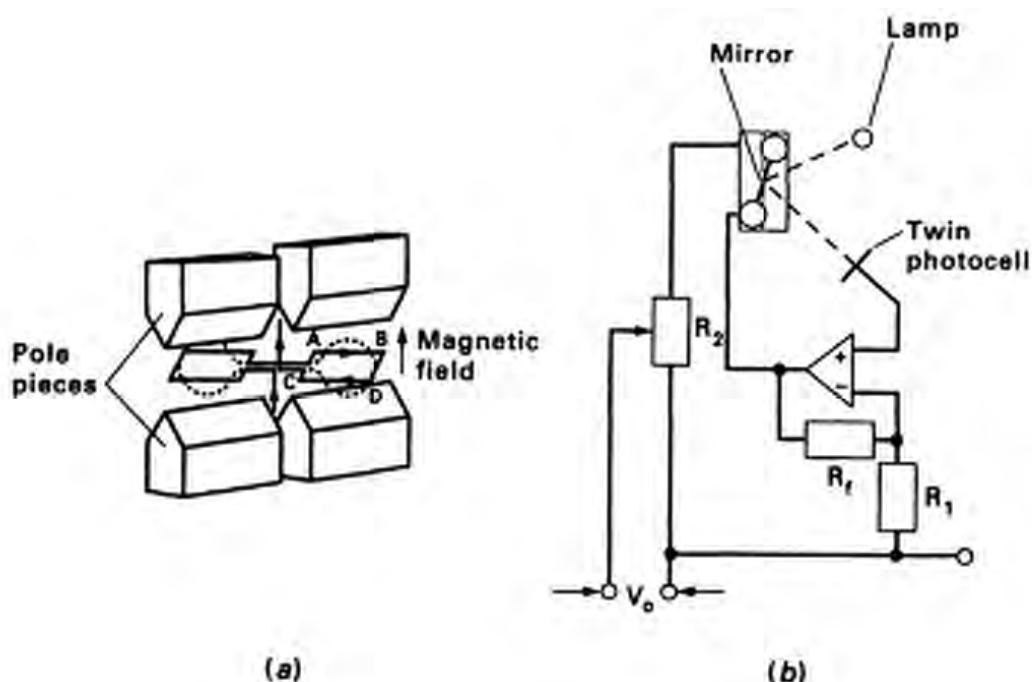


FIG. 6.58. Dumbbell-type paramagnetic oxygen analyser: (a) arrangement of dumbbell and magnetic poles; (b) principle of operation

There are many solid materials where the control of moisture content is essential, e.g. in manufactured foodstuffs, animal feed, pharmaceuticals, paper and board, tobacco, sand and cement, and a wide range of chemicals and plastics. It has to be considered whether the total moisture content is required or whether it is sufficient simply to measure surface moisture—although generally a relationship can be established between the two. Table 6.15 lists typical industrial methods for the measurement of the water content of solid materials.

6.8.7. Other Methods of Gas Composition Measurement

There are numerous instruments available for the measurement of the compositions of (or simply for the detection of) gases. These sensors employ a wide variety of physical and chemical methods and many can also be used for analysing liquids by vaporising the liquid sample before it is passed through the instrument. A selection is described in Table 6.16.

6.9. PROCESS SAMPLING SYSTEMS

6.9.1. The Sampling of Single-Phase Systems

The importance of a well designed sampling system cannot be overemphasised and poor sampling techniques will lead to erroneous results even with the most sophisticated instruments. Sampling systems vary widely and are often unique to a particular situation and application. However, certain guidelines are common to many fluid sampling arrangements and the objective in all cases is to obtain a truly representative sample of the material to be analysed⁽⁸¹⁾. Procedures applied to solids are very specialised and are not considered here.

Fluid sampling systems generally consist of four main sections, viz. the probe, the sample line, sample treatment and sample disposal.

The Probe

The probe is used to remove the sample from the main stream of material and it is important to ensure that the material to be sampled is well mixed prior to the sampling point so that the probe is able to extract a representative sample. Figure 6.59a shows a simple probe which is suitable for sampling liquids and gases at low pressures and is generally made from 11.7 mm ID stainless steel tubing. The fluid is sampled at the centre of the main stream unless this requires the probe to be of such a length that the stream velocity conditions create unacceptable vibrational stress within the probe. The maximum permissible length of any probe from its support required to avoid such stresses can be determined from⁽⁸²⁾

$$L_{\max} = K_x \left(\frac{\mathcal{E} d_0^2 (d_0^2 + d^2)}{u_{\max}^2 \rho} \right)^{0.25} \quad (6.100)$$

where \mathcal{E} and ρ are the modulus of elasticity and density of the probe material respectively, d_0 and d are the OD and ID of the probe tube, u_{\max} is the maximum

TABLE 6.16. *Further Methods of Gas Measurement and Detection*^(74, 83)

Type of Gas Detector	Used to Detect	Bulk Gas (or Carrier Gas where Appropriate)	Principle of Operation	Relative Sensitivity (a)	Application
Magnetodynamic O ₂ (magnetic susceptibility) (Fig. 6.58)	Various		The magnetic susceptibility of O ₂ is very large compared with that of other gases (except NO, NO ₂ and ClO ₂). Such gases are called paramagnetic. Two quartz spheres are attached to the ends of a bar to form a dumb-bell which is suspended in an atmosphere of N ₂ between the poles of a powerful magnet. The sample is fed into the chamber containing the dumb-bell. The magnetic field is disturbed and the dumb-bell is deflected. This deflection is detected by an optical system. The dumb-bell is returned to its null position by passing a current through a coil surrounding it. This current is proportional to the concentration of O ₂ .	0.01	Measurement of O ₂ from 0 to 100 per cent in various streams. Can be used with flammable gas mixtures
Ultrasonic	Mainly gases of low molar mass	H ₂ , N ₂ , CO ₂ , He, Ar.	A quartz crystal transducer transmits a sound wave through a sample of gas with a similar crystal used as the receiver. The velocity of the sound wave is proportional to the square root of the molar mass of the sample. The phase shift of the sound signal is measured by comparison with a reference signal. Precise temperature control is required.	1-10	Gas chromatography
Catalytic (Pellistor)	Flammable gases	Air	Measures the heat output due to the catalytic oxidation of flammable gas molecules. A stream of the sample is passed over the sensor which is usually a ceramic bead impregnated with Pt or Pd. The temperature variations in the sensor due to reaction are monitored.	Dependent on individual design.	Flammable gas detector. Usually portable
Semiconductor	Flammable and other gases	Air	Two small coils of platinum wire are fused side by side within a bead of semiconductor material of diameter 2-3 mm. The sample gas flows over the bead and molecules of gas are adsorbed on the surface of the semiconductor—thereby changing the resistance of the semiconductor as measured between the two coils. One coil is also employed as a heater to ensure that the adsorption is reversible. The device is sensitive but has poor selectivity.	Dependent on individual design.	Flammable gas detector. Inexpensive
Flame photometric (FPD)	Compounds of S, P, and halogens	N ₂ , He	The sample is mixed with a H ₂ /O ₂ or H ₂ /air mixture and ignited. The resulting flame produces simple molecular species and excites them to higher electronic states. The excited species subsequently return to their ground states—at the same time producing characteristic molecular band-spectra. These emissions are monitored by a photomultiplier via a suitable filter, thus making the detector highly selective. The instrument is very sensitive but suffers from a highly non-linear response.	100	Sulphur analysers; gas chromatography
Flame ionisation (FID)	Organic compounds	N ₂	The sample is fed to a H ₂ /air flame. The latter contains relatively few ions but does contain atoms of high kinetic energy. The flame produces large numbers of positive ions and secondary electrons from the trace organic materials in the sample gas. A potential is applied across the detector chamber and the ions and electrons move towards the electrodes thus forming an <i>ionisation current</i> which is suitably amplified. The FID is mass rather than concentration sensitive and the sensitivity is thus the minimum detectable mass of carbon passing through the flame per second. The FID has a high sensitivity and a linear response.	100 ^(b)	Hydrocarbon analysers; gas chromatography
Photo ionisation (PID)	Organic compounds (except low molar mass)	N ₂	Uses monochromatic UV radiation to ionise molecules of organic compounds. The ions formed are driven to a collector electrode by applying an electric field across the ionisation chamber. The resulting ion current is measured by means of an electrometer. The instrument can be made selective by using UV sources of different wavelengths. The instrument is highly sensitive and has a wide linear range.	100-1000	Gas chromatography
Helium ionisation	Traces of permanent gases	He	Helium gas containing the trace materials is passed through a small chamber where it is exposed to β radiation from a tritium source. The helium atoms are excited by collision with the high energy β electrons. The excited helium atoms lose their energy by collision with atoms or molecules of the trace gases. The resulting ionisation is measured by application of an electric field so producing an <i>ionisation current</i> . The performance of this detector is highly dependent upon its geometry.	100	Gas chromatography
Electron capture	Oxygen and halogen compounds	Ar, N ₂	This detector employs a source of β radiation (usually ^{63}Ni —cf. helium ionisation detector). The velocities of the high energy electrons are reduced to thermal velocities by collision with atoms of inert gas with which the detector chamber is purged. When a sample of a gas with a greater electron affinity than the inert gas is introduced into the cell, some of the electrons are captured and form negative ions. Hence the current across the cell (produced by an appropriate electric field) is reduced. This instrument is extremely sensitive to electronegative species, particularly halogenated and oxygenated compounds. Carrier gas, detector current and detector temperature are selected for maximum sensitivity.	10000-10,000	Trace gas and explosive detector; gas chromatography

^(a) Rough guide only—highly dependent upon design and application—unity represents one part in 10^{12} , etc.^(b) In terms of mass—not concentration.

possible velocity of the process fluid in the pipe and K_x is a dimensionless constant (≈ 3.4).

High Pressure Probes

If the fluid to be sampled is liquid which is to be vaporised, or is a gas at high pressure, then a narrow bore pipe (typically 2 mm ID) is inserted through the original low pressure probe (Fig. 6.59b).

Probes for Fluids at High Temperatures

Figure 6.59c is an illustration of a typical furnace gas probe suitable for temperatures up to 700 K. For higher temperatures (up to 1900 K) it is necessary to provide water cooling.

Probes for Dirty Gases

To sample dirty gases the sample probe should be turned downstream as solid particles have a much greater inertia than gas molecules and are much less likely to change direction and enter the probe⁽³⁹⁾. Alternatively the end of the probe may be covered with an unglazed porcelain filter. Often a water spray is provided at the inlet to the probe in order to wash solids out of the gas as it enters the sampling system (Fig. 6.59d). The gas and the water vapour are separated in a water trap and care should be taken to avoid any water entering the measuring instrument. This type of probe is unsuitable for water soluble gases (e.g. CO₂, SO₂, H₂S, etc.).

Probes for Corrosive Gases

If the gas is particularly corrosive the steam ejector system shown in Fig. 6.59e may be employed to sample gases at temperatures of up to 450 K (e.g. flue gases). The possibility of corrosion occurring in the sample lines when the steam/gas sample cools to the dew point is much reduced due to the dilution of the corrosive condensate by the condensed steam.

Probes for Large Diameter Pipes

In large gas ducts or large diameter pipes carrying liquids it may be necessary to use multiple probes (Fig. 6.59f) or long probes with multiple inlets. ASTM Standard D4177⁽⁸²⁾ specifies sampling procedures required to obtain representative samples of petroleum and petroleum products and similar methods can be employed in sampling most non-corrosive liquid industrial chemicals.

The Sample Line

The second part of the system consists of the sample line or pipe which transports the sample to the analyser. The distance between the analyser and the sample point

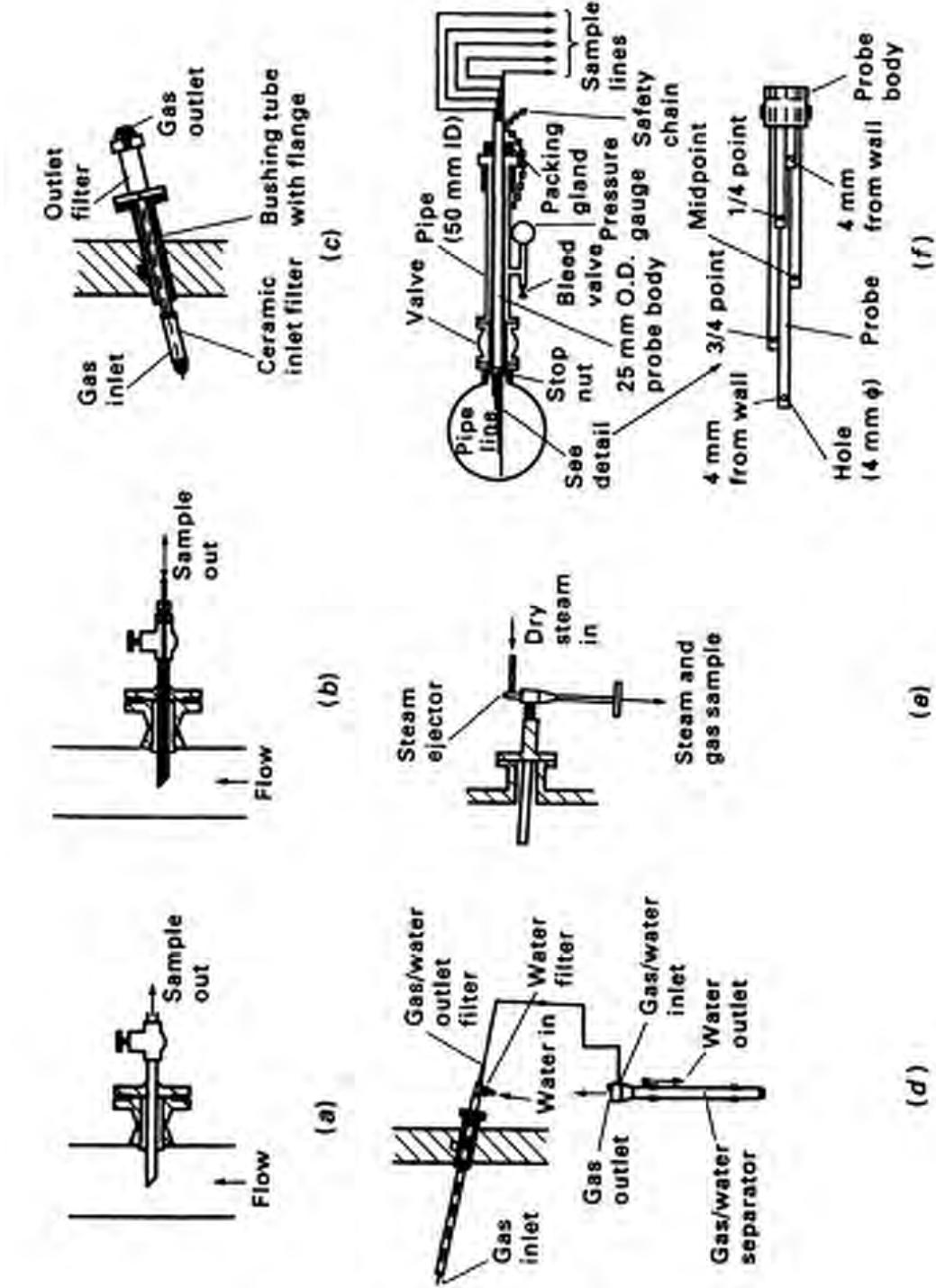


FIG. 6.59. Fluid sampling probes: (a) normal sample probe; (b) small volume probe; (c) gas-sampling probe; (d) water-wash probe for furnace gases; (e) probe for flue gas, using steam ejector; (f) multipoint pipeline probe

should be kept to a minimum so that the dead time in the sample line is as small as possible. In any event the dead time should not exceed 30 s⁽³⁹⁾. If a long sample line is unavoidable, then a *fast loop* should be installed (Fig. 6.60) which operates at a substantially higher rate of flow than that required by the analyser.

Other techniques can also be used for reducing the sample line dead time, e.g. allowing volatile liquids under pressure (such as propane or butane) to vaporise within the probe as gases flow at much higher velocities than liquids under the same conditions. The material from which the sample line is constructed should not change the characteristics of the sample. In some instances (e.g. when sampling low concentrations of H₂S or water vapour through copper tubing) processes of adsorption/desorption can affect the response of the measuring instrument quite severely⁽⁷⁹⁾. Errors can also arise due to the permeability of the walls of sample tubing made of various plastics to certain gases (e.g. PTFE tubing is permeable to O₂ and to water vapour (Section 6.8.6) and PVC tubing is permeable to the smaller hydrocarbon molecules such as CH₄).

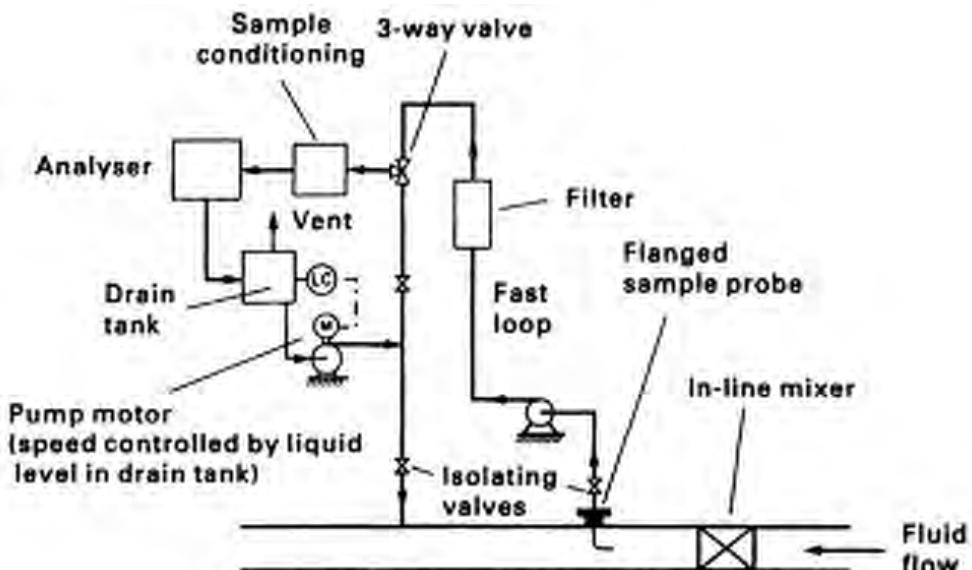


FIG. 6.60. Typical liquid-sampling system with fast loop

Sample Treatment

It is necessary to treat the sample so that it is in a suitable state for analysis. This can involve the adjustment of the temperature, pressure and/or rate of flow of the sample. It is often necessary to monitor carefully the rate of flow of sample through the measuring instrument itself. Such flowrates are generally small and any of the techniques listed in Table 6.2 can be employed. Most commercial analysers are designed to operate at or near atmospheric pressure. All solid material should be filtered from the sample as soon as possible and corrosive and deposit-forming materials should be removed using suitable chemical absorbants. Condensation should be avoided in vapour sample lines by keeping the sample above its dew point. This may require lagging and/or heating of the line. Facilities for washing out should always be provided.

Sample Disposal

Finally, a means must be available for the disposal of the sample after it leaves the analyser. Direct discharge to atmosphere or to drain is possible only where it is safe to do so. In some cases this is done after suitable treatment and in others the sample is pumped back to the process.

6.9.2. The Sampling of Multiphase Systems (Isokinetic Sampling)

Sampling of materials consisting of more than one phase at the sampling point is particularly difficult. Common examples are the sampling of liquid or vapour from a plate absorber or distillation column or from a packed column, or the sampling of a multiphase mixture flowing in a pipe or duct. In such cases it is not always known whether the liquid or vapour has been sampled or some combination of both.

When sampling process gases, either to determine dust concentration or to obtain a representative dust sample, it is necessary to take special precautions to avoid segregation through inertial effects. For this purpose the gas duct is traversed by the nozzle of the sampling tube and samples are taken at predetermined points across the traverse. The nozzle is pointed directly into the gas stream and the gas velocity at the mouth of the nozzle must be the same as the local gas velocity at that point. This procedure is termed *isokinetic sampling*. If the sampling velocity is too high, the dust sample will contain a lower concentration of dust particles than the stream being sampled with a greater proportion of fine particles. If the sampling velocity is too low, then the dust sample may contain a higher concentration of dust with a greater percentage of coarse particles.

6.10. THE STATIC CHARACTERISTICS OF SENSORS

The selection of the most suitable instrument for a required measurement from a range of commercially available instruments necessitates the knowledge of certain important factors. These can be divided into the *static* and *dynamic* characteristics of the instrument. The dynamic properties of instruments are fundamentally no different from those of any other system or process and are described, therefore, by the analysis of system dynamics presented in Chapter 7. Static properties, which are specific to instrumentation, are discussed in this section.

6.10.1. Definitions

There is a wide variety of important static terms and properties related to instrumentation which require careful definition and understanding. Some of these are frequently used in a misleading or even incorrect context. Expressions such as the *accuracy* of an instrument or its *precision* or its *sensitivity* are often employed by manufacturers in a casual or imprecise manner. A brief description of the more common terms follows.

Range

The *range* of an instrument is the region over which a quantity may be measured or received (input range) or transmitted (output range) and is defined by stating the

lower and upper range values, e.g. a thermocouple may be quoted as having an input range of 100–250°C and an output range of 4–10 mV. The lowest and the highest quantities to which a device can be adjusted are termed the *lower and upper range limits*, respectively.

Span

This is often termed the *full scale deflection* (FSD) and is the magnitude of the range of the instrument. In the above example, the input span of the thermocouple is 150°C and the output span is 6 mV.

Turndown

The *turndown* is a direct function of the range of an instrument and is the *ratio of the upper range value of the instrument to the lower range value*. For example, if an instrument is required to measure pressures which range from 100 kN/m² to 1000 kN/m² then it is said to have a turndown of 10:1. Care must be taken in specifying a suitable turndown for an instrument when it is only occasionally exposed to a very high value of the measured variable. Suppose that a mass flowmeter is specified to measure a process stream which has a normal rate of flow of about 1 kg/s but very intermittently produces flows of the order of 50 kg/s. In this case the important characteristic of the instrument is that it should have a good *over-range capability* rather than a turndown of 50 to 100 since the latter may be unattainable or may require a much more expensive transducer (see Table 6.1).

Sensitivity

This may be defined as the ratio of the change in magnitude of the output signal corresponding to the change in the magnitude of the input after a steady state has been reached. In the limit this becomes the rate of change of the output with respect to the input. For example, consider a thermocouple for which the output E in mV is given by:

$$E = -3.275 \times 10^{-6}(T - 273.15)^2 + 0.04153(T - 273.15) - 0.03043$$

where T is the temperature in K and the reference junction is held at 273.15 K. Then the sensitivity (mV/K) will be:

$$\frac{dE}{dT} = -6.55 \times 10^{-6}(T - 273.15) + 0.04153.$$

Note that, in this case, the sensitivity is a function of T , e.g. at 300 K, $\frac{dE}{dT} = 0.04135$ mV/K and at 500 K, $\frac{dE}{dT} = 0.04004$ mV/K.

Resolution

This is defined as the minimum difference in the values of a quantity that can be discriminated by a device. In essence this is the largest change in input that can

occur without the output changing. Strictly this is a function of elements that have a discrete output and an analog input, e.g. the analog to digital converter (Section 6.11.5) for which the resolution is the change in input voltage required to make the output change by the least significant bit.

Example 6.3

A stepper motor having a resolution of 1/256 of a revolution is used as direct drive for a gate valve controlling a liquid flow. The mass rate of flow G kg/s is given by:

$$G = \alpha(2.7 + 0.2\alpha)$$

where α is the angular rotation of the shaft of the stepper motor in radians. Calculate the rate of flow of the liquid and its resolution when the stepper motor shaft has rotated 0.15 radians.

Solution

$$\begin{aligned} G &= \alpha(2.7 + 0.2\alpha) = 0.15[2.7 + 0.2(0.15)] \\ &= \underline{\underline{0.410 \text{ kg/s}}}. \end{aligned}$$

$$\frac{dG}{d\alpha} = 2.7 + 0.4\alpha = 2.7 + 0.4(0.15) = 2.76 \text{ kg/s per unit angular rotation of the shaft}$$

$$\begin{aligned} \text{resolution} &= \delta G = 2.76 \delta\alpha = \frac{2.76 \times 2\pi}{256} \\ &\approx \underline{\underline{0.068 \text{ kg/s}}}. \end{aligned}$$

Repeatability

This may be defined as the closeness of agreement among a number of consecutive outputs from the given device for the same value of the device input under the same operating conditions when approached from the same direction over a full range sweep of readings. It is necessary to specify the direction of approach because of the possibility of *hysteresis* in the instrument where hysteresis is the difference between the output of a device for a given value of the input depending on whether the output is increasing or decreasing.

The most common reason for a lack of repeatability is the existence of random fluctuations in the environment surrounding the instrument x_1 , possibly in its power supply x_2 , and also in its input signal x_3 , due to random variations in the operation of a device upstream of the instrument in question. These random fluctuations frequently display a normal or Gaussian distribution. The output of a device in response to such random fluctuations may then be expressed as:

$$y = k_0 + k_{x_1}x_1 + k_{x_2}x_2 + k_{x_3}x_3 + f(x_1, x_2, x_3) \quad (6.101)$$

where $f(x_1, x_2, x_3)$ contains any non-linear contributions and k_0, k_{x_1}, k_{x_2} and k_{x_3} are constants. If δy is a small variation in y due to small deviations in x_1, x_2 and x_3 , (viz. $\delta x_1, \delta x_2$ and δx_3 , respectively) then:

$$\delta y = \left(\frac{\delta y}{\delta x_1} \right) \delta x_1 + \left(\frac{\delta y}{\delta x_2} \right) \delta x_2 + \left(\frac{\delta y}{\delta x_3} \right) \delta x_3 \quad (6.102)$$

and $\frac{\delta y}{\delta x_i}$, etc. can be determined from equation 6.101.

It can be shown⁽⁸⁴⁾ that if y is a linear function of x_1 , x_2 and x_3 , i.e. $f(x_1, x_2, x_3)$ in equation 6.101 is zero, then:

$$\sigma_y = \sqrt{k_{x_1}^2 \sigma_{x_1}^2 + k_{x_2}^2 \sigma_{x_2}^2 + k_{x_3}^2 \sigma_{x_3}^2} \quad (6.103)$$

where σ_y , σ_{x_1} , etc. are the standard deviations of y , x_1 , etc., respectively. Hence the standard deviation of δy , i.e. that of y about the mean of y , is:

$$\sigma_{\delta y} = \left(\left(\frac{\partial y}{\partial x_1} \right)^2 \sigma_{x_1}^2 + \left(\frac{\partial y}{\partial x_2} \right)^2 \sigma_{x_2}^2 + \left(\frac{\partial y}{\partial x_3} \right)^2 \sigma_{x_3}^2 \right)^{1/2} \quad (6.104)$$

The corresponding mean value y' of the element output will be obtained from equation 6.101, viz.

$$y' = k_0 + k_{x_1} x'_1 + k_{x_2} x'_2 + k_{x_3} x'_3 + f(x_1, x_2, x_3) \quad (6.105)$$

Accuracy (Precision), Bias and Measurement Error

There is often confusion concerning the distinction between *accuracy* and *precision*. The term *precision* is frequently used to describe the *reproducibility* or *repeatability* of results⁽⁸⁵⁾ (see previous section). Accuracy denotes the nearness of a measurement to its accepted value and should be expressed in terms of *error* (see below). Thus, accuracy involves a comparison with respect to a true or accepted value, and precision compares a result with the best value of several measurements made in the same way. An alternative (but less carefully worded) distinction⁽⁸⁶⁾ is to describe precision as the number of digits employed in a calculation (which may not all be correct) and accuracy as the number of digits to which the result of that calculation is correct.

The *error* in the reading of an instrument is accepted generally as being the difference between the actual measurement and the corresponding *true* value of the measurement where:

$$\text{positive error} = \text{actual measurement} - \text{true value}. \quad (6.106)$$

The true value or true reading is the value that would be obtained if the quantity were measured by an *exemplar* method, i.e. a method agreed upon by experts as being sufficiently accurate for the purpose to which the data will be put. However, it is important to distinguish between the error in a single measurement as defined in this way and the error intrinsic within the measurement process associated with the relevant instrument. In the latter instance, a single reading will constitute a sample from a statistical population generated by the measurement process. If the characteristics of that measurement process are known, then it is possible to determine the limits of the error in the single measurement, although the error itself is not known as this would presume knowledge of the corresponding true value. In order to achieve this, a statistical testing of the instrument is required in which a large number of readings (outputs) is recorded under the same apparent process conditions and with the same input to the instrument. However, as previously pointed out, these readings will differ due to random fluctuations in the

environment in which the instrument is placed. Generally, such fluctuations and the instrument outputs corresponding to them are assumed to exhibit a normal or Gaussian distribution. This may not be so in practice, and the closeness of the data to a Gaussian distribution can be ascertained by application of appropriate statistical tests⁽⁸⁷⁾.

When instruments are calibrated, in practice it is usual to vary the input to the instrument incrementally over a particular range of true values and to record the corresponding measured values. Often there is no multiple repetition of the test at any one true value of the input. The resulting set of input/output data provides an *average calibration curve* for that instrument. Frequently (and often simply for convenience), this is assumed to be a straight line and the well-known least squares procedure is employed to fit a straight line to the data. It is then possible to estimate such quantities as the *instrument bias* and the *uncertainty* of the instrument reading, as outlined in the following example.

Example 6.4

A certain mass flowmeter (see Section 6.2.3) was tested (calibrated) by comparing the readings given by the instrument G_R with true (known) values G_T of the flow of a gas as measured by the instrument in a 0.15 m ID pipeline. True and measured values are compared in Fig. 6.61 and Table 6.17. Estimate the errors in the flowmeter due to bias and imprecision. Assume that variations in the input and output of the instrument are normally distributed.

TABLE 6.17. *True and Measured Mass Rate of Flow*

True flowrate G_T (kg/min)	Measured flowrate G_R (kg/min)	True flowrate G_T (kg/min)	Measured flowrate G_R (kg/min)	True flowrate G_T (kg/min)	Measured flowrate G_R (kg/min)
0.00	0.75	3.50	3.98	7.00	7.25
0.50	1.16	4.00	4.40	7.50	7.76
1.00	1.34	4.50	4.73	8.00	7.79
1.50	1.94	5.00	5.28	8.50	8.33
2.00	2.24	5.50	5.67	9.00	8.67
2.50	3.12	6.00	6.16		
3.00	3.26	6.50	6.70		

Solution

A straight line was fitted to these data using the method of least squares⁽⁸⁷⁾. The equation obtained was:

$$G_R = m G_T + k$$

where:

$$m = \frac{N \sum_{j=1}^N (G_T)_j (G_R)_j - \sum_{j=1}^N (G_T)_j \sum_{j=1}^N (G_R)_j}{N \sum_{j=1}^N (G_T)_j^2 - \left(\sum_{j=1}^N (G_T)_j \right)^2}$$

$$= \frac{19 \times 537.9 - 85.5 \times 90.53}{19 \times 527.3 - 7310}$$

$$= \underline{\underline{0.916}}$$

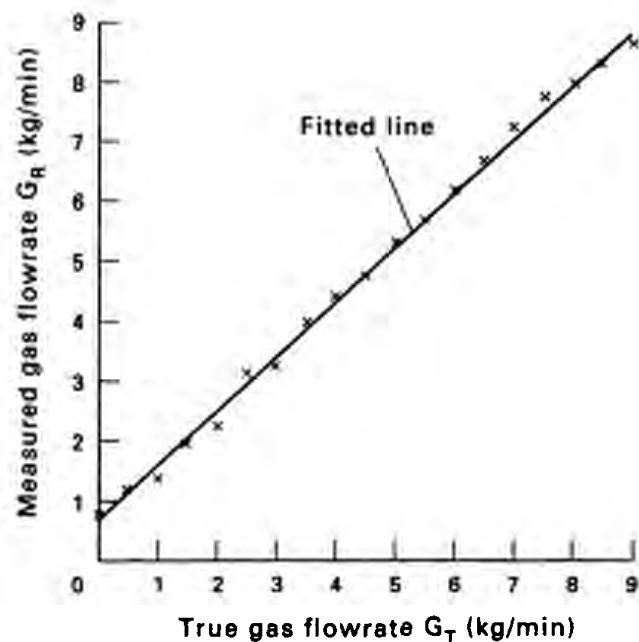


FIG. 6.61. Measured gas flowrate as a function of true flowrate

and:

$$\begin{aligned}
 k &= \frac{N \sum_{j=1}^N (G_R)_j \sum_{j=1}^N (G_T)_j^2 - \sum_{j=1}^N (G_T)_j (G_R)_j \sum_{j=1}^N (G_T)_j}{N \sum_{j=1}^N (G_T)_j^2 - \left(\sum_{j=1}^N (G_T)_j \right)^2} \\
 &= \frac{90.53 \times 527.3 - 537.9 \times 85.5}{19 \times 527.3 - 7310} \\
 &= \underline{\underline{0.643}}
 \end{aligned}$$

The fitted line is shown in Fig. 6.61. In order to estimate the scatter of the data it is necessary to compute the relevant standard deviations.

$$\begin{aligned}
 \text{The variance of the measured values } \sigma_{G_R}^2 &= \frac{1}{N} \sum_{j=1}^N (m G_T + k - G_R)^2 \\
 &= 0.0214
 \end{aligned}$$

Thus the standard deviation of the measurements

$$= \sigma_{G_R} = \sqrt{0.0214} = \underline{\underline{0.146}}$$

$$\begin{aligned}
 \text{The variance of the gradient } \sigma_m^2 &= \frac{N \sigma_{G_R}^2}{N \sum_{j=1}^N (G_T)_j^2 - \left(\sum_{j=1}^N (G_T)_j \right)^2} \\
 &= 1.50 \times 10^{-4}
 \end{aligned}$$

Thus:

$$\sigma_m = \underline{\underline{0.0123}}$$

$$\text{The variance of the intercept } \sigma_k^2 = \frac{\sigma_{G_R}^2 \sum_{j=1}^N (G_T)_j^2}{N \sum_{j=1}^N (G_T)_j^2 - \left(\sum_{j=1}^N (G_R)_j \right)^2}$$

$$= 0.00417$$

Hence: $\sigma_k = \underline{0.0645}$

In this calculation it has been assumed that the value of σ_{G_R} is sufficiently nearly the same for all values of G_T so that all the data points in the table can be used, thus making it unnecessary to repeat the experiments many times. Furthermore, if the distribution is considered to be Gaussian, then the *confidence limits* for the estimates of the gradient and intercept of the fitted line can be determined. For this type of distribution it can be shown⁽⁶⁷⁾ that 95 per cent of the readings will lie within $\pm 2\sigma$ of the mean. Hence it is possible to say with 95 per cent certainty (or with 95 per cent confidence limits) that the equation of the fitted line is:

$$G_R = m G_T + k$$

where $m = 0.916 \pm 2\sigma_m = \underline{0.916 \pm 0.02}$ and $k = 0.643 \pm 2\sigma_k = \underline{0.643 \pm 0.13}$.

Corresponding values are $\pm 3\sigma$ for 99.7 per cent confidence limits and $\pm \sigma$ for 68 per cent confidence limits for a Gaussian distribution. The true values G_T of the process variables must also contain some positive or negative errors. These can be determined from σ_{G_T} where:

$$\sigma_{G_T}^2 = \frac{1}{N} \sum_{j=1}^N \left(\frac{G_R - k}{m} - G_T \right)^2 = \frac{\sigma_{G_R}^2}{m^2}$$

Hence:

$$\sigma_{G_T} = \frac{\sigma_{G_R}}{m}$$

$$\approx \underline{0.16}$$

Thus, if the instrument output records a reading of $G_R = 5.50 \text{ kg/min}$ then the estimate of the true value of the rate of flow will be the corresponding value of $G_T \pm 2\sigma_{G_T}$, i.e. $5.68 \pm 0.32 \text{ kg/min}$, with 95 per cent confidence limits. The total error obtained in the calibration may be split into two parts, viz. the *bias* (or *systematic error*), i.e. $5.50 - 5.68 = -0.18 \text{ kg/min}$, and the *error due to imprecision* (*random error* or *non-repeatability*), i.e. $\pm 0.32 \text{ kg/min}$. The bias is assumed to be the same each time this reading is obtained and consequently can be corrected for, whereas the random error is generally different each time and thus cannot be removed—although the limits of this error can be estimated as above. The *total inaccuracy* of the measuring element is the sum of the bias and the random error. A better method of estimating uncertainty when the number of samples is small (such as in this example) is to use *Student's t-Test*⁽⁸⁷⁾.

Care must be taken in evaluating instrument error from manufacturers' literature. Frequently the accuracy of an instrument is specified without any explanation as to what the precise meaning of the number is. The error quoted is often simply the largest horizontal deviation from the fitted line of any data point. In Fig. 6.61, this is 0.25 kg/min and occurs at a number of points. This would therefore be quoted as an error of *2.8 per cent of full scale* (full scale being 9 units). This is reasonable if the bias is known to be zero. The form of the specification for an instrument quoted by manufacturers is generally in terms of a percentage of the full scale reading of that instrument. Thus, if a thermocouple is quoted as having an inaccuracy of $\pm 0.5 \text{ per cent of full scale}$ and covers a range of 100 K to 1000 K , then this can be

taken to mean that no error greater than 5 K will occur anywhere in the range. Of course, at 100 K, this would constitute a maximum error of ± 5 per cent.

Threshold

This is defined as the minimum value of the input below which no output from the instrument can be detected (*cf.* resolution).

Dead Band, Dead Space, Dead Zone

When applied to the performance of an instrument these terms signify the range over which an input can be varied without the instrument output responding in any way. They are usually expressed in terms of the percentage of span of the instrument and should not be confused with the concept of dead time (Section 7.6).

Scale Readability

This is dependent upon the accuracy to which a human observer can read an analog record of the output of the instrument in question, or how closely an indicator marking a particular position on a scale can be read. For example, can a particular pressure gauge be read to the nearest 0.1 kPa, to the nearest 1 kPa, or to the nearest 10 kPa? It is important to consider this carefully when presented with data from an instrument with a digital output where the readability will be the same over the whole range of the instrument. In many cases the data obtained are only as precise as those indicated in the analog form.

Zero Shift (Zero Error)

It is important to check the zero setting (or the setting of the lower range value) for an instrument as a zero error will cause the whole of the instrument span to be displaced. The zero setting may drift or change over a period of time (*zero shift*). Such drifting is frequently due to variations in ambient conditions—most commonly temperature. In addition to zero shift, point values of the measured variable in different regions of the span may drift by different amounts.

6.11. SIGNAL CONDITIONING

Data produced by any basic measuring device commonly have to pass through two further stages before being presented to the process operator and/or used in a process control system (see Fig. 6.1). First, an individual signal may require some form of conditioning before it can be transmitted to the control room (e.g. amplification, conversion to a variable more suitable for transmission) and, secondly, it has to be transmitted—often simultaneously with other suitably conditioned signals. Further conditioning (e.g. noise reduction, further variable conversion, amplification, etc.) will frequently take place in the control room prior to the quantity being indicated or recorded, and/or employed as the measured variable of a given control scheme.

6.11.1. Bridge Circuits

Primary variables such as pressure, flow, temperature, etc., are frequently converted into resistance, capacitance or inductance by the use of a suitable transducer (Sections 6.2–6.4). These latter quantities are generally measured using a variety of bridge circuits. Both null and deflection bridges are employed with facilities such as the provision of sensitivity adjustment, calibration, and zeroing of the output voltage when the measured physical quantity is itself zero. Literature concerning bridge circuits is commonplace and the reader is referred to NEUBERT⁽¹⁹⁾.

6.11.2. Amplifiers

Most electrical signals produced by transducers via bridges or otherwise are of low voltage (0–100 mV) or low power. Such signal levels are not generally suitable for data transmission, analog or digital processing, energising (deflection of) an indicator or for remote recording; hence they require amplification. The basis of most amplifier circuits, filters, converters and much other data processing equipment is the *operational amplifier (op-amp)*. There are many types and makes, and a typical simplified version of a voltage amplifying op-amp circuit is illustrated in Fig. 6.62a.

It is easy to show that this configuration gives:

$$V_o = \left(\frac{R_f}{R} + 1 \right) V_i \quad (6.107)$$

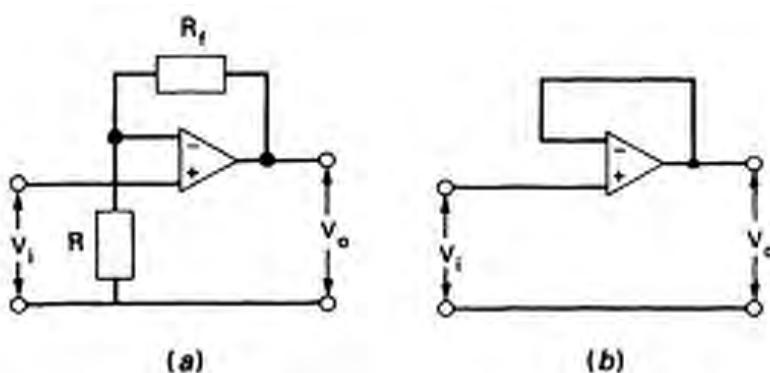


FIG. 6.62. Typical operational amplifiers: (a) non-inverting amplifier; (b) buffer amplifier

Thus, the *signal gain* depends upon the ratio R_f/R . Figure 6.62b represents a *buffer amplifier* or *voltage follower* in which $V_o = V_i$. This has the high input and low output impedances necessary to obviate the kind of inter-element loading problems illustrated in Section 6.11.6. For a more detailed treatment the reader is referred to SMITH⁽⁸⁸⁾.

The *instrumentation amplifier* is a high-performance differential amplifier consisting of a number of closed-loop op-amps. An ideal instrumentation amplifier gives an output voltage which is proportional only to the difference between two input voltages V_{i_2} and V_{i_1} , viz.:

$$V_o = K_{\text{amp}}(V_{i_2} - V_{i_1}) \quad (6.108)$$

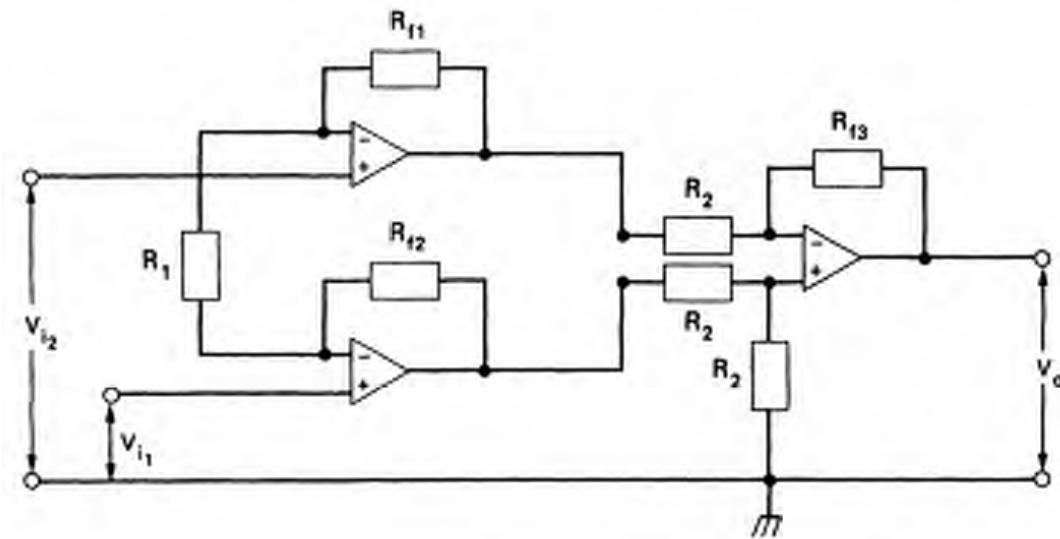


FIG. 6.63. Typical instrumentation amplifier

where K_{amp} is the amplification factor which can be varied over a wide range by manipulating the values of the resistors in the network⁽⁸⁸⁾.

The *isolation amplifier* is an instrumentation amplifier which is used in more difficult applications, e.g. where low level signals are superimposed upon high common-mode voltages, where processing circuitry has to be protected from faults and power transients, or where interference from motors etc. is severe. "Ordinary" instrumentation amplifiers require a return path for the bias current. If this is not provided then the bias current will charge stray capacitances which, in turn, produce large drifts in the output. Thus, when "floating" sources such as thermocouples are amplified, a connection to amplifier ground must be provided (Fig. 6.63) and this can produce excessive noise. An isolation amplifier does not need a ground connection of this type as the signal is *isolated* from ground and interfering noise is largely rejected⁽⁴⁾.

6.11.3. Signals and Noise

Noise occurs for many reasons in signals that are transmitted between elements of a control loop or in data transmission systems. Sources of noise may be internal or external. Internal sources are those such as random temperature-induced motion of electrons or other charge carriers leading to a corresponding random voltage variation (*Johnson noise*). Transistors produce a similar type of noise (*shot noise*) due to random fluctuations in the way in which carriers diffuse across a junction. External sources of noise are most commonly near a.c. power circuits. This latter form of noise is frequently termed *mains pick-up* or *mains hum*. Heavy generators and turbines can also cause severe disturbances. Other electrical sources of interference are high voltage power lines, fluorescent lighting, and the switching on and off of electric motors. These external sources cause interference by inductive and/or capacitive coupling with the signal (in Fig. 6.64 this coupling effect is indicated in lumped form whereas, in practice, it will be distributed along the entire length of

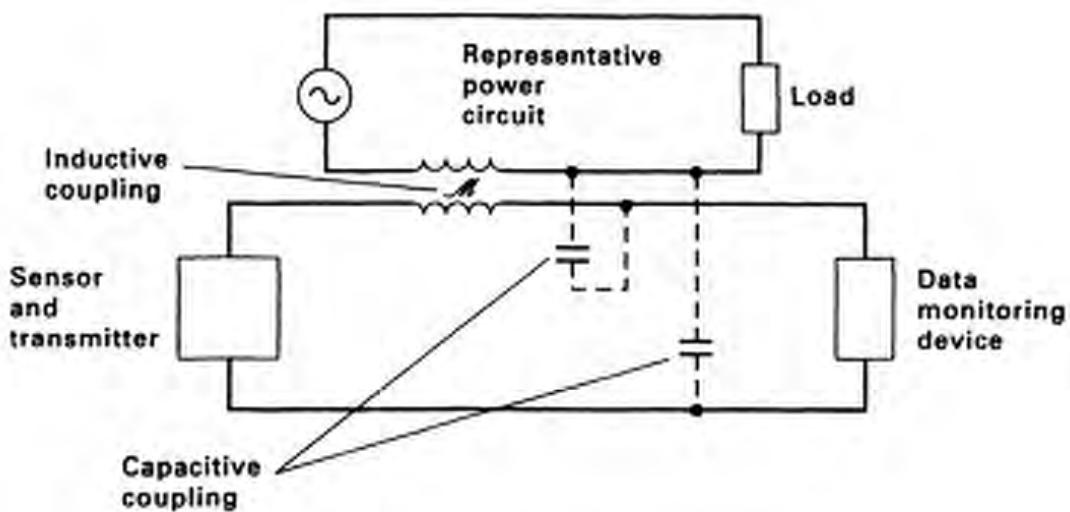


FIG. 6.64. Interference from external sources due to inductive and capacitive coupling

the circuit). For example, if there is inductive coupling present, then an alternating current i in a power circuit will induce an interference signal V_{int} in the measuring element circuit, where:

$$V_{\text{int}} = \mathcal{M} \frac{di}{dt} \quad (6.109)$$

where \mathcal{M} is the mutual inductance. Inductive coupling will occur even if the measuring element circuit is isolated from earth.

Heavy electrical equipment can cause interference through the creation of *multiple earths* where there are leakages to earth at different points of the measuring device circuit. These earth points will be at different potentials due to the existence of the ground current which produces *common* and *series mode* interference voltages in the measurement circuit.

Clearly, such interference can be reduced by increasing the distance between the source and the measurement circuit—mutual inductance and capacitance both being inversely proportional to the distance. Inductive coupling can also be much reduced by the use of twisted pair cable (Fig. 6.65). If adjacent loops in the circuit have the same area (e.g. loops 1 and 2) and are coupled with the same magnetic field, then the induced voltages between points A and B and between B and C will cancel each other out, and this will be repeated along the whole section of twisted pairs.

Capacitive coupling can be suppressed by enclosing the entire measurement circuit within an earthed metal screen which provides a low impedance path to earth for the interfering currents. This is called *electrostatic screening*.

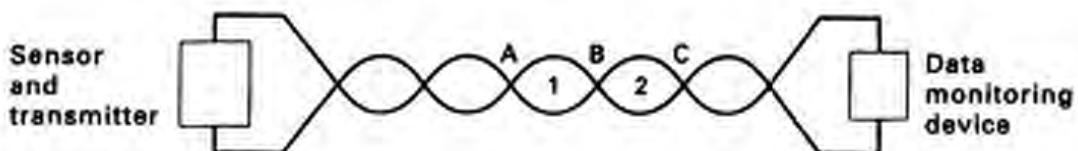


FIG. 6.65. The twisted-pairs technique for reducing inductive coupling

6.11.4. Filters

Filters are devices which transmit a specific range of the frequency spectrum of a signal and which reject the remainder. They can take many physical forms—but the most highly developed and convenient types are electrical. The latter can be divided into *analog filters* and *digital filters*. Analog filters are electrical networks of resistors, capacitors and amplifiers used to condition continuous signals. Digital filters consist of software within a microcomputer which processes sampled data signals. If the power spectrum of a measurement signal occupies a different frequency range from that of any noise or interference, then a filter will substantially improve the signal to noise ratio of that measurement signal. A large variety of such filters is available. The one having the required characteristics should be selected in terms of the ranges of frequencies required to be transmitted and rejected. The effects of employing the four most common types of filter are illustrated in Fig. 6.66. Of course, if the power spectrum of the measurement signal and that of the interfering noise overlap, then filtering will be of limited use and other procedures have to be considered.

6.11.5. Converters^(89, 90)

Analog to Digital (A/D) Conversion

A/D conversion is of increasing importance as, in many instances, the analog outputs of various measuring elements are now frequently connected to microcom-

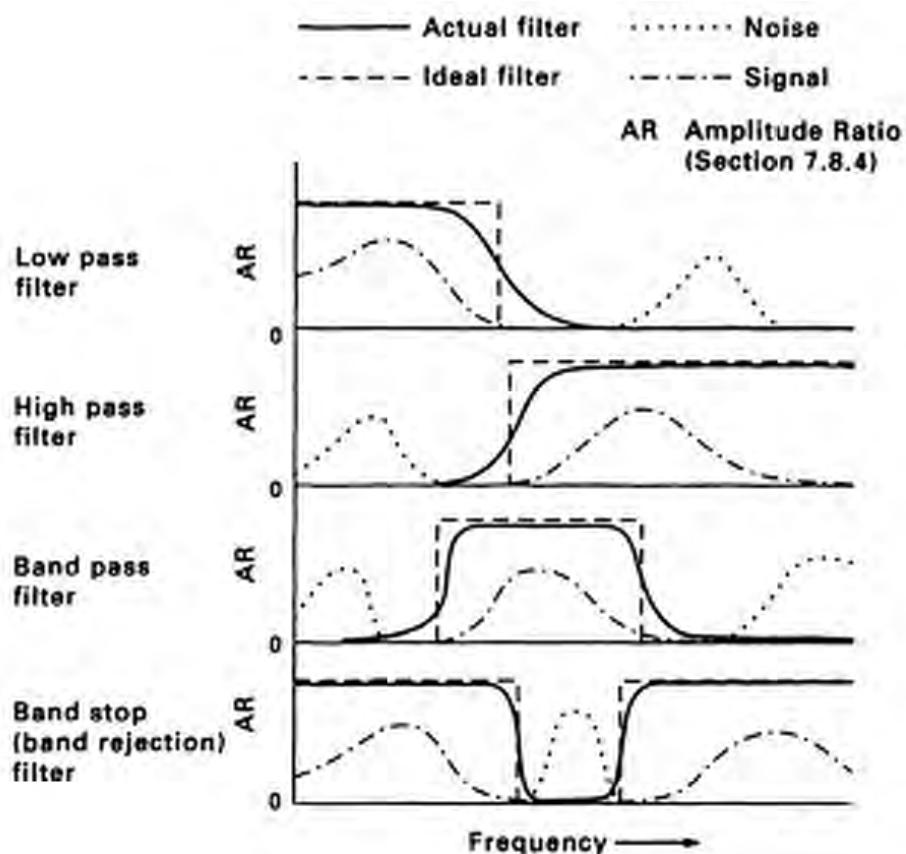


FIG. 6.66. Basic filter characteristics

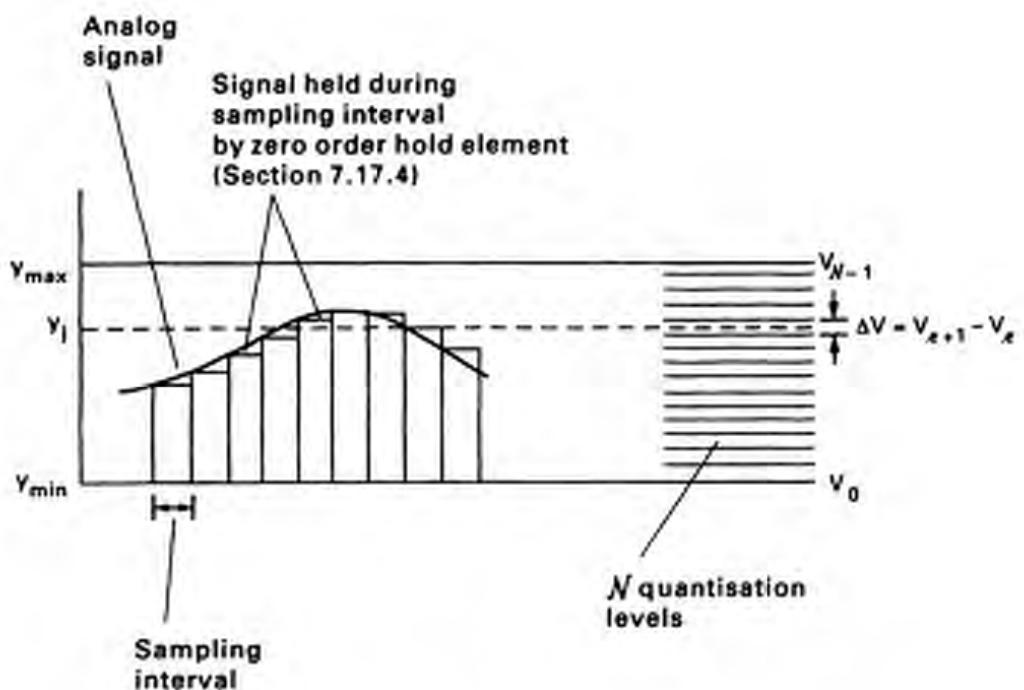


FIG. 6.67. Sample, hold and quantisation of an analog signal

puter installations which operate on the basis of discrete information. The function of an A/D converter can be divided up into three stages, viz. *sampling*, *quantisation* and *encoding*. Sampling (i.e. *sample* and *hold* in this context) is discussed in Section 7.17. Figure 6.67 illustrates the basic operations of the sample and hold process. This element is necessary as the A/D conversion requires a finite time to operate (up to a few ms). The signal from the hold element y_j is rounded to the nearest of N quantisation levels, i.e. V_z where $z = 0, 1, 2, \dots, N - 1$. The *quantisation interval* can then be written as:

$$\Delta V = \frac{y_{\max} - y_{\min}}{N - 1} \quad (6.110)$$

where $y_{\max} - y_{\min}$ is the span (Section 6.10.1) allowed for y_j with $y_{\max} = V_{N-1}$ and $y_{\min} = V_0$.

The maximum *quantisation error* expressed as a percentage of the span is:

$$\Xi_{\max} = \pm \frac{100 \Delta V}{2(y_{\max} - y_{\min})} \text{ per cent} = \pm \frac{50}{N - 1} \text{ per cent} \quad (6.111)$$

and the resolution (Section 6.10.1) of the converter due to the quantisation step is:

$$\mathcal{R} = \frac{100 \Delta V}{V_{N-1} - V_0} \text{ per cent of the full-scale deflection.} \quad (6.112)$$

The encoder converts V_z into a *parallel digital signal* corresponding to a binary coded version of the denary numbers $0, 1, 2, \dots, N - 1$, where the number of binary digits (*bits*) required to encode a decimal number x is:

$$n \geq \frac{\log x}{\log 2} \quad (6.113)$$

and n wires in parallel will be required to produce an n -bit parallel electrical signal corresponding to the n -bit binary number.

TABLE 6.18. Operation of a Successive Approximation A/D Converter

Input voltage = 1.843 V

Clock Pulse	D/A Converter Input	D/A Converter Output (V_{dac} Volts)	Comparator Output (V_{comp} Volts)	Bit Value
1 (clear register)	00000000	0	0	—
2 (first guess)	01111111	1.27	0 (LO)	$b_7 = 1$ (MSB)
3 (second guess)	10111111	1.91	1 (HI)	$b_6 = 0$
4	10011111	1.59	0 (LO)	$b_5 = 1$
5	10101111	1.75	0 (LO)	$b_4 = 1$
6	10110111	1.83	0 (LO)	$b_3 = 1$
7	10111011	1.87	1 (HI)	$b_2 = 1$
8	10111001	1.85	1 (HI)	$b_1 = 0$
9 (final guess)	10111000	1.84	0 (LO)	$b_0 = 1$ (LSB)

Output digital signal = 10111001, i.e. 1.85 V

Equivalent serial digital signal:
(see also Fig. 6.75)

1 0 0 1 1 1 0 1

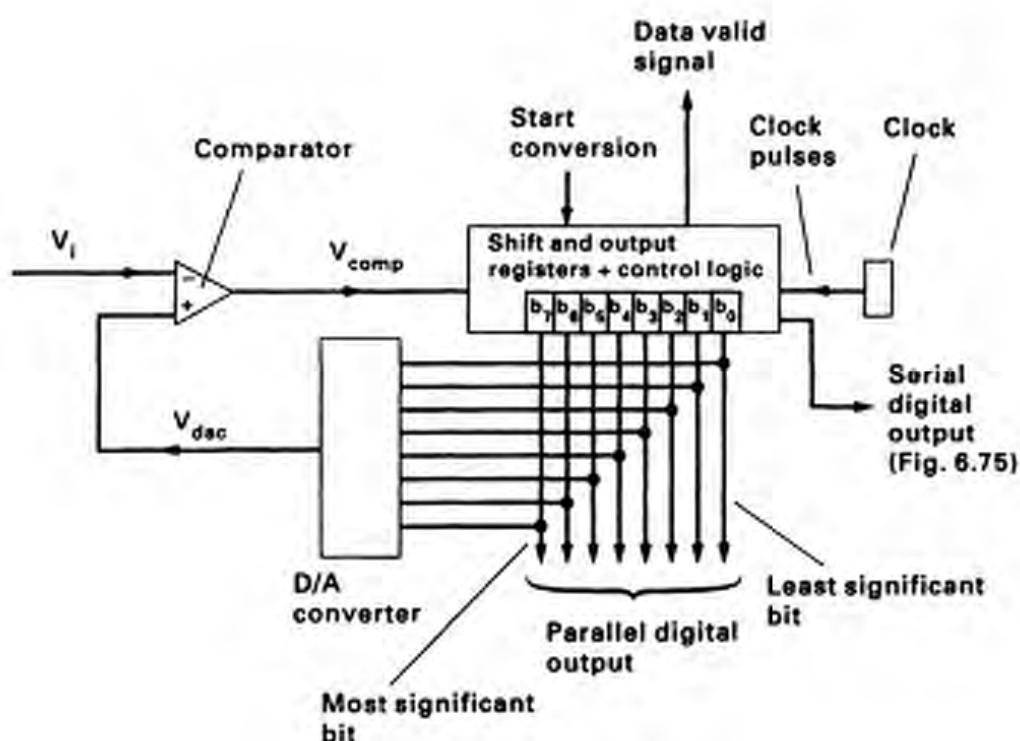


FIG. 6.68. Successive approximation 8-bit binary A/D converter (Table 6.18)

Another commonly employed encoding scheme is that of *binary coded decimal (bcd)*. In this case each decade of the denary (decimal) number is coded separately into its binary equivalent and each denary digit has a maximum of four bits. The number of bits required in this case to encode a decimal number x is:

$$n_{bcd} \geq 4 \log x \quad (6.114)$$

There are many types of commercial A/D converter. The most common is the *successive approximation* type (shown in Fig. 6.68) which employs a D/A converter (see below) in a closed-loop arrangement. Converters of this type are available with resolutions of up to 16 bits and conversion times of $30\ \mu s$ or less. As an example of the way in which such a converter operates—consider an analog input voltage of $V_i = 1.843\ V$ supplied to the A/D converter shown in Fig. 6.68. At each successive clock-pulse after the conversion is initiated, one bit of the digitally encoded output will be produced, the most significant bit (MSB) being first, and the least significant bit (LSB) being last. The operation of the converter is represented in Table 6.18.

The *dual slope* converter is superior to the successive approximation type in many respects, e.g. in having an automatic zero capability, good noise suppression, and accuracy which is not affected by capacitor rating or clock frequency. However, the use of the latter type of converter is limited because of its slow conversion time (about 30 ms).

Digital to Analog (D/A) Conversion

This is required when a digital signal (e.g. the output from a microcomputer) is used to drive an analog device (e.g. a control valve). Most D/A converters utilise the so-called *R-2R ladder network*. The accuracy of these devices is dependent upon the stability of the reference voltage and of the resistors employed. Figure 6.69 illustrates a simple 3 bit D/A circuit using an R-2R ladder network. The *current steering* switches are connected to ground whether they are at 0 ("off") or 1 ("on"). This is because the op-amp negative input is a *virtual ground*⁽⁹⁰⁾. The op-amp sums the currents "steered" to it by the switches and produces an output voltage which is proportional to this sum. Devices giving 8–12 bits of resolution and 4–20 mA current output are the most commonly employed in process control applications.

6.11.6. Loading Effects

When devices are connected together, the action of one device may affect the performance of the device immediately preceding it. This is termed *inter-element loading*. If a total measurement system is constructed out of basic building blocks (e.g. sensor, amplifier, transmitter, receiver, recorder), then loading problems must be considered carefully if the measurement system is to work satisfactorily. Not only has inter-element loading to be taken into account, but also the effect of placing the measuring element within the process itself. For example, the insertion of the thermocouple into a flowing fluid will change the flow pattern in the vicinity of the thermocouple and the temperature distribution at the end of the thermocouple will not then be the same as when the thermocouple was not present⁽⁹¹⁾. This is called *process loading*. On the whole, errors due to the latter are of less importance than

those caused by inter-element loading. These effects are additional to any random instrument error as described in Section 6.10.1. The extent of the error that can occur through inter-element loading can easily be illustrated in Example 6.5.

MSB: Most Significant Bit

$$i_1 = \frac{V_i}{2R}$$

LSB: Least Significant Bit

$$i_2 = \frac{V_i}{4R}$$

$$i_3 = \frac{V_i}{8R}$$

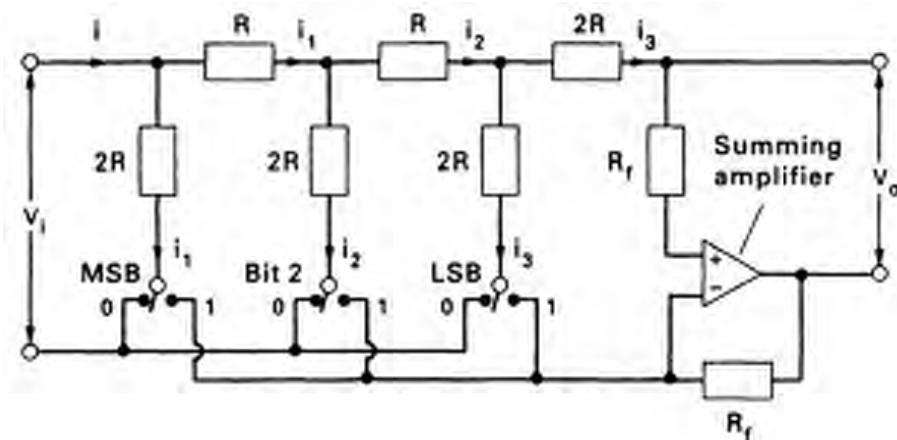


FIG. 6.69. An R-2R ladder-network 3-bit D/A converter

Example 6.5

A pH glass electrode (Section 6.8.2) having a sensitivity of 50 mV per unit pH and a resistance of 250 MΩ is connected directly to a recording device which has a sensitivity of 0.02 pH scale reading per mV and a resistive load of 100 kΩ (Fig. 6.70). If the electrode is immersed in a solution of pH = 5, determine the pH reading displayed by the recorder.

Solution

$$\text{e.m.f. due to pH meter} = 50 \times 5 = 250 \text{ mV}$$

$$\text{Total resistance of circuit} = 250 \text{ M}\Omega + 100 \text{ k}\Omega \approx 250 \text{ M}\Omega$$

$$\text{Current in circuit} = \frac{0.25}{2.5 \times 10^8} = 10^{-9} \text{ amps.}$$

$$\text{Hence, potential difference across recorder} = V_L = 10^{-9} \times 10^5 = 10^{-4} \text{ V.}$$

$$\begin{aligned} \text{Meter reading in pH units} &= 10^{-4} \times 20 \\ &= \underline{\underline{2 \times 10^{-3}}} \end{aligned}$$

which is clearly nonsense. This result is due to inter-element loading.

Suppose now that a buffer amplifier (Section 6.11.2) is inserted between the pH sensor and the recorder. A buffer amplifier has a large input impedance (of the order of $10^{12} \Omega$), a low output impedance (about 10Ω) and a voltage gain of unity. The circuit is now represented by Fig. 6.71. Thus:

$$V_i = \frac{0.25 \times 10^{12}}{2.5 \times 10^8 + 10^{12}} = 0.25 \text{ V}$$

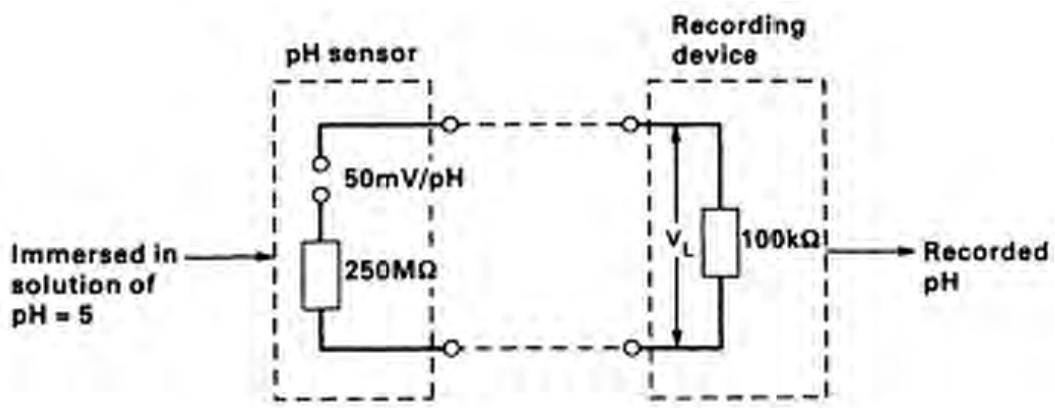


FIG. 6.70. An example of inter-element loading with a pH sensor

For a buffer amplifier:

$$V_o = V_i$$

Thus:

$$V_L = \frac{0.25 \times 10^5}{10 + 10^5} = 0.25 \text{ V}$$

Hence the reading of the pH meter will be 0.25×20

$$= \underline{\underline{5 \text{ pH units.}}}$$

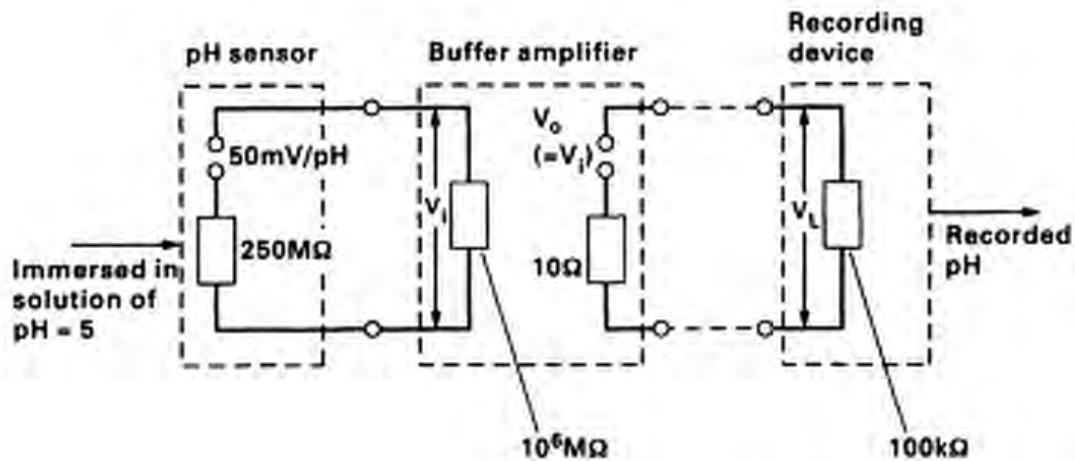


FIG. 6.71. Avoidance of inter-element loading by the use of a buffer amplifier

Example 6.5 shows that the insertion of a buffer amplifier reduces the error due to inter-element loading to negligible proportions (about 0.1 per cent in terms of pH). As a general guide, the impedance of the recording device should be much greater than that of the sensor where there is direct voltage transfer from sensor (source) to recording element (load). The relationship between the load voltage and source in a complex circuit is much simplified by the application of *Thévenin's theorem*⁽²⁰⁾ which states that any linear network of impedances and voltage sources can be substituted by an equivalent circuit containing a single voltage source E_{Th} .

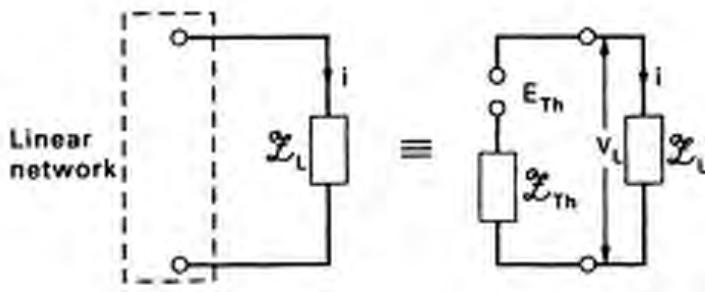


FIG. 6.72. Thévenin equivalent circuit

and an impedance Z_{Th} in series with it, where E_{Th} is the open-circuit voltage of the network across its output terminals and Z_{Th} is the network impedance with all source voltages put equal to zero and replaced by their respective internal impedances.

An *equivalent Thévenin circuit* is shown in Fig. 6.72. If V_L is the potential difference across the impedance of the load Z_L (e.g. the recorder in the above example), then:

$$V_L = i Z_L = \left(\frac{E_{Th}}{Z_{Th} + Z_L} \right) Z_L. \quad (6.115)$$

Hence, to reduce the effect of inter-element loading to a minimum, Z_L must be much greater than Z_{Th} , i.e. $V_L \approx E_{Th}$ (as in the second part of Example 6.5 where Z_{Th} is effectively 10Ω and Z_L is $100\text{k}\Omega$).

If the sensor or transmitter is a current source rather than a voltage source, then a converse approach is required. This can be illustrated by a further example.

Example 6.6

An electronic torque balance transmitter incorporating an LVTD (Fig. 6.13) has a sensitivity of 1 mA output current per 1 kN/m^2 change in measured differential pressure, where the current is measured across an output impedance of $100\text{k}\Omega$. This transmitter is connected to a recorder which has an input impedance of $10\text{k}\Omega$ and a sensitivity of 1 kN/m^2 per mA change in current from the transmitter (Fig. 6.73). If the pressure sensor is measuring a true pressure differential of 5 kN/m^2 , what will be the corresponding reading on the recorder?

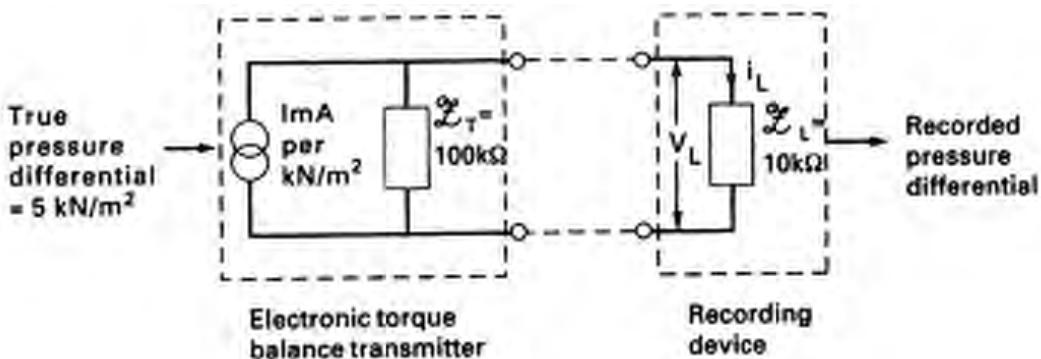


FIG. 6.73. The recording of a transmitter signal when the transmitter is acting as a current source

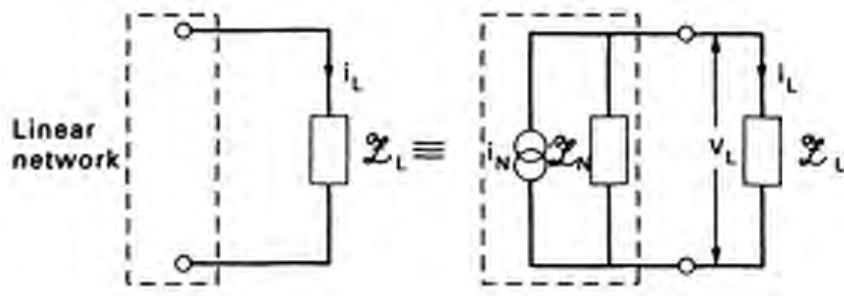


FIG. 6.74. Norton equivalent circuit

Solution

From the transmitter sensitivity, for a true pressure differential of 5 kN/m^2 , the transmitter output current i_T is 5 mA. Neglecting any resistance in the cables connecting the transmitter and the recorder, the total impedance of the circuit is:

$$\mathfrak{Z}_x = \frac{\mathfrak{Z}_T \mathfrak{Z}_L}{\mathfrak{Z}_T + \mathfrak{Z}_L} = \frac{100 \times 10}{100 + 10} = \frac{100}{11} \text{ k}\Omega$$

Thus:

$$V_L = i_T \mathfrak{Z}_x = \frac{500}{11} \text{ V}$$

and:

$$i_L = V_L / \mathfrak{Z}_L = 4.5 \text{ mA}$$

Hence, the recorded pressure differential = 4.5 kN/m^2 which represents an error of about 10 per cent.

If, however, \mathfrak{Z}_T is increased to $1 \text{ M}\Omega$ and \mathfrak{Z}_L is reduced to $1 \text{ k}\Omega$, then, for a transmitter output of 5 mA, $\mathfrak{Z}_x = 1000/1001 \text{ k}\Omega$ and $V_L = 5 \times 1000/1001 \text{ V}$.

Hence: $i_L = \frac{5 \times 1000 \times 1000}{1001 \times 1000} = 4.995 \text{ mA.}$

In this case the recorded pressure differential is 4.995 kN/m^2 , i.e. an error of 0.1 per cent.

For more complex current sources, it is necessary to employ *Norton's theorem*⁽²⁰⁾ which states that any linear network of impedances and voltage sources can be substituted by an equivalent circuit containing a current source i_N in parallel with an impedance \mathfrak{Z}_N , where i_N is the current which flows when the output terminals of the network are short-circuited and \mathfrak{Z}_N is the network impedance with all source voltages put equal to zero and replaced by their internal impedances.

From the *equivalent Norton circuit* (Fig. 6.74):

$$V_L = \frac{i_N \mathfrak{Z}_N \mathfrak{Z}_L}{\mathfrak{Z}_N + \mathfrak{Z}_L} \quad (6.116)$$

Hence, it is necessary to make $\mathfrak{Z}_L \ll \mathfrak{Z}_N$ in order to minimise the effect of inter-element loading (i.e. to make $V_L \approx i_N \mathfrak{Z}_L$) when the sensor or transmitter is a current source.

6.12. SIGNAL TRANSMISSION (TELEMETRY)

Some type of signal transmission is required for all measuring systems that have a display (indicator, recorder) remote from the measuring element and transmitter. In many instances, measurements may be required of temperatures, flows, pressures,

compositions, etc. from a plant in a particular preset order, or upon demand from a central point (e.g. in a distributed computer control system (Section 7.20)). In such cases a *multi-input, multi-output (MIMO) data acquisition* system using *time division multiplexing* may be employed. Instruments may be connected together in the form of *local area networks (LANs)* as part of a distributed control system. The way in which the instruments (termed *nodes* in this context) are connected together is known as the *topology* of the system. Various topologies are in common use and the particular topology of the LAN specifies the way in which each instrument or device within the LAN supplies information (i.e. *talks*) to the other instruments or devices in the LAN.

The term *telemetry* is reserved, generally, for multiple data systems which use a modulated high frequency carrier to transmit information concerning required sets of measurements from one point to another. This is necessary where plant items are located in remote areas at considerable distances from each other (e.g. pumping stations for the transfer of fluids through long pipelines in the oil, gas and water industries). A typical telemetry system comprises a *master station* acting as a central control point, with several *out-stations* placed at strategic positions. It must be capable of transmitting large quantities of information in both directions between master station and out-station and, as such, it involves the principles of *serial digital signalling*, *error detection* and *frequency shift keying*⁽⁹²⁾.

6.12.1. Multiplexers (Time Division Multiplexing)

A multiplexer is essentially a device which switches between a number of different inputs (*channels*) and is constructed of solid-state switches⁽⁹³⁾. Channels are addressed usually in a fixed order (*sequential addressing*) with a parallel channel address to specify the order in which the input channels are to be connected to the output channel. *Random addressing* is also possible, in which the operator can select a channel as required. A sample and hold device (Section 7.17.4) is attached which maintains the value of a particular signal until it is sampled again. The final output is generally encoded either as a *serial digital binary* signal or as a *bcd* signal (Section 6.11.5). Different measured variables often have frequency spectra with different maximum frequencies, i.e. the rates of change of different process variables can vary widely. Thus, it may be necessary to sample a flow measurement much more often than (say) a temperature measurement, or a composition measurement more often (if possible) than a pressure measurement.

6.12.2. Serial Digital Signals

Where large quantities of information have to be transmitted between control room, measuring devices, local controllers, etc., parallel analog signalling systems (in which individual devices are connected separately to the control room) are being replaced rapidly by two wire serial digital connections⁽⁹⁴⁾. The latter have a number of advantages, the two major ones being the cost of wiring and the ability to withstand corruption by noise. Generally, the analog signal is changed to digital form prior to transmission using an A/D converter. The latter produces a parallel

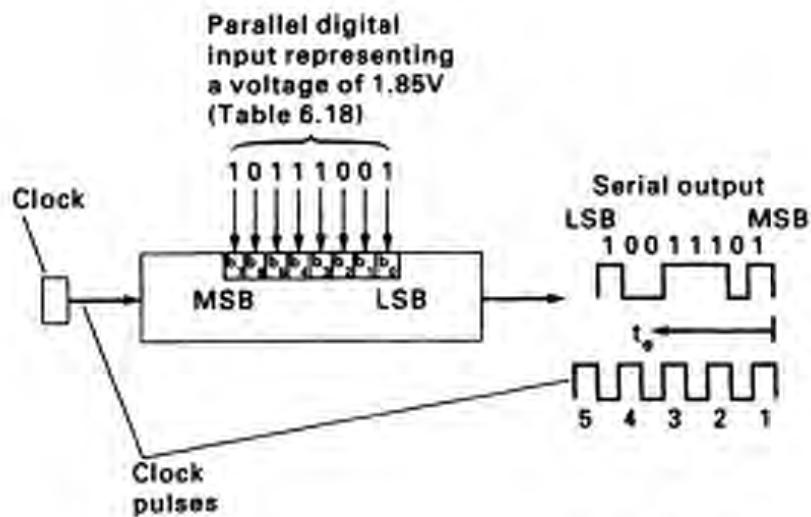


FIG. 6.75. Parallel-to-serial conversion of digital signals (t_s = time elapsed after initial clock pulse)

digital signal which requires conversion to serial form. Figure 6.75 illustrates diagrammatically how this can be achieved.

On receipt of the first clock pulse, the contents of the 8-stage shift register are shifted one place to the right, and hence b_0 (the least significant bit—LSB) is transmitted first. The second clock pulse causes the next bit b_1 to be transmitted, and so on until the register is empty. This type of data transmission is frequently termed *pulse code modulation (PCM)*. It is resistant to considerable noise levels as the final receiver has only to decide whether a 1 or a 0 has been transmitted (i.e. whether there is a pulse or not) and the length of the pulse. The transmission link over which the PCM is sent may be a cable, an optical fibre, or a radio link. Such links have a variety of speeds of data transmission which are expressed in terms of *baud* (or *baud rate*) where 1 baud = 1 bit/s. A single signal encoded into an n -bit code and sampled f times per second requires a transmission bit rate of⁽⁸⁾:

$$\mathcal{R}_b = nf \text{ baud.} \quad (6.117)$$

If there are k_m multiplexed signals in the PCM transmission then:

$$\mathcal{R}_b = nk_m f \text{ baud} \quad (6.118)$$

and the bandwidth of the PCM for a single or multiplexed signal is:

$$\psi = 0 \text{ to } \mathcal{R}_b/2 \quad (6.119)$$

It is important that any errors occurring during the decoding of a noise-affected PCM are detected. This is achieved by the addition of extra *check digits* to the *information digits* containing the measurement data. Hence, each complete *code word* transmitted of n digits will consist of k' information digits and $(n - k')$ check digits. This is termed an (n, k') code and is described as having a *redundancy* of $\frac{100(n - k')}{n}$ per cent.

In industrial telemetry systems, the quantity of random noise is generally small and, consequently, there is a low probability of errors occurring. Occasionally, large errors extending over short time periods do occur (e.g. due to the switching of pumps, etc.). In such cases no attempt is made to correct the signal and the receiver, having detected an error, simply requests that the information be transmitted again or ignored for that time period.

High transmission rates can be achieved, if necessary, over the relatively short distances required in a process plant. The PCM equivalent of the 4–20 mA analog transmission system shown in Fig. 6.1 can operate at up to 9,600 baud for distances up to 3000 m. The standard RS-232C transmission link is limited to about 15 m at rates up to 20,000 baud. Higher speed interfaces (such as versions of the IEEE-488 connection) used for computer control systems can handle up to 20,000 bytes/s (which for an 8-bit system is about 1.6×10^5 baud). However, in this case, the distance between devices is limited to about 2 m⁽⁴⁾. The more recent RS-422A standard allows the transmission of data rates of 10^7 baud over distances not exceeding 16.4 m and 10^5 baud over distances not exceeding 1220 m⁽⁵⁾.

In many telemetry systems the PCM signal is frequency modulated on to a *carrier wave*. This is termed *frequency shift keying (FSK)*. In other arrangements, the output of the transducer is converted into fixed step changes of the phase of the modulating signal. A device for this purpose is termed a modulator/demodulator or *modem*.

6.12.3. The Transmission of Analog Signals

This is the traditional mode of transmitting data between plant and control room and is being steadily superseded by serial digital links (Section 6.12.2). Such hard-wire connections are prone to the effects of noise and exhibit inductance and capacitance effects which may be serious if the frequency of the transmitted signal is high. This has not generally been the case in the process industries and the frequency response of such analog data links is quite adequate. A common hard-wired analog transmission link widely used in the process industries is the 4–20 mA two-wire current loop. The 4–20 mA current is known as an *offset zero* or *live zero* signal. The advantage of employing a live zero is that it allows instrument or line faults to be detected. This system transmits both power and signal. The voltage appearing across the transmitter output terminals (which varies as the output current changes) forms the transmitter power supply, but the transmitter operation is insensitive to changes in this voltage as long as it stays above a given minimum value. In this case the transmitter is a true current source which makes the system relatively insensitive to induced noise voltages and line resistance changes.

6.12.4. Non-electrical Signal Transmission

Optical Fibres^{(6), (7)}

The role of fibre-optics in high speed telemetry systems is increasing rapidly. Necessary components are an electrically controllable light source (e.g. a *light emitting diode (LED)*), an optical fibre, and a photo detector as the receiver. Very high data rates with wide bandwidths can be achieved. Optical fibres have the following advantages:

- (a) They are immune from common electromagnetic interference sources such as power switching.
- (b) They exhibit a high degree of safety in hazardous environments.
- (c) They provide considerable data security and minimal fibre-to-fibre leakage (or cross-talk).
- (d) Data can be transmitted at much higher frequencies (up to 10 MHz) with much lower losses than in equivalent electrical systems. Hence, many more signals can be multiplexed into one cable and these can travel much greater distances (at present up to 30 km) without further amplification.
- (e) The fibres are highly resistant to corrosion.
- (f) The fibres are lighter and of smaller diameter than metal conductors of the same information carrying capacity.
- (g) Earth loop difficulties are reduced or eliminated.

One area where further development of fibre-optic transmission systems is required is in the design of suitable interfaces or converters to provide sufficient mechanical force to drive control valve actuators (Section 7.22.3)⁽⁹⁸⁾.

Pneumatic Transmission

Pneumatic transmission lines have been used in the process industries for many years and, although increasingly being superseded by hard-wired, optical fibre and even radio telemetry systems, they are still employed in flammable environments and where signals are conveyed over distances of up to 100 m—particularly in older plants. The essential components of a pneumatic transmission system are a supply of clean, dry air (usually at a pressure of 125–200 kN/m² gauge—see Section 6.3.1); a suitable transmitter which produces an output pressure generally in the range 20–100 kN/m² gauge; a receiver; and the necessary pipework. Pneumatic transmitters

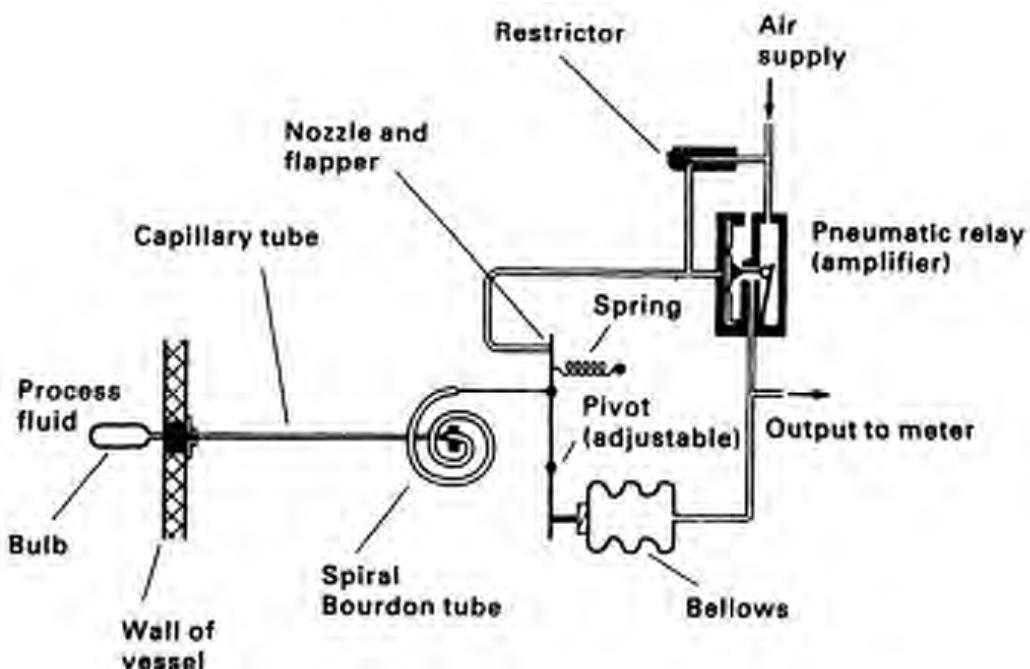


FIG. 6.76. Temperature-sensing bulb and associated pneumatic transmitter

consist of three main elements, viz. a sensing element such as a bellows, diaphragm or Bourdon tube; a sensor such as a flapper/nozzle system; and a feedback element which is usually another bellows. A typical pneumatic transmitter linked to a temperature sensing bulb is shown in Fig. 6.76.

The distance over which pneumatic signals can be transmitted is limited by the volume of the tubing and the resistance to flow. The dynamics of pneumatic systems can generally be approximated by a first order lag plus a dead time (Sections 7.5 and 7.6). Tubing may be made of copper, aluminium or plastic, and is normally of 5 mm ID. Pneumatic receivers can be in the form of indicators, recording devices and/or controllers.

Electropneumatic (E/P) Converters

One important application of pneumatic transmission is in the operation of diaphragm actuators. These are the elements generally employed to drive the spindles of control valves (Section 7.22.3) and, if hard-wired transmission systems are employed, require devices which convert electric current into air pressure or air flowrate, i.e. *electropneumatic (E/P) converters*. The basic construction of a typical E/P converter is illustrated in Fig. 6.77. A coil is suspended in a magnetic field in such a way that when a current is passed through the coil it rotates. This rotation is sensed by a flapper/nozzle system (Section 7.22.1). The nozzle is supplied with air via a restrictor and its back pressure actuates a pneumatic relay. The output from the latter is applied to the feedback bellows and also acts as output from the E/P converter. Electropneumatic valve positioners employ the same principle of operation.

Force-Balance Transducers

These elements also operate on the flapper/nozzle principle and are similar in construction to the pneumatic differential pressure (DP) cell (Section 6.3.4 and Figs 6.19a and 6.34) and the pneumatic controller (Section 7.22.1).

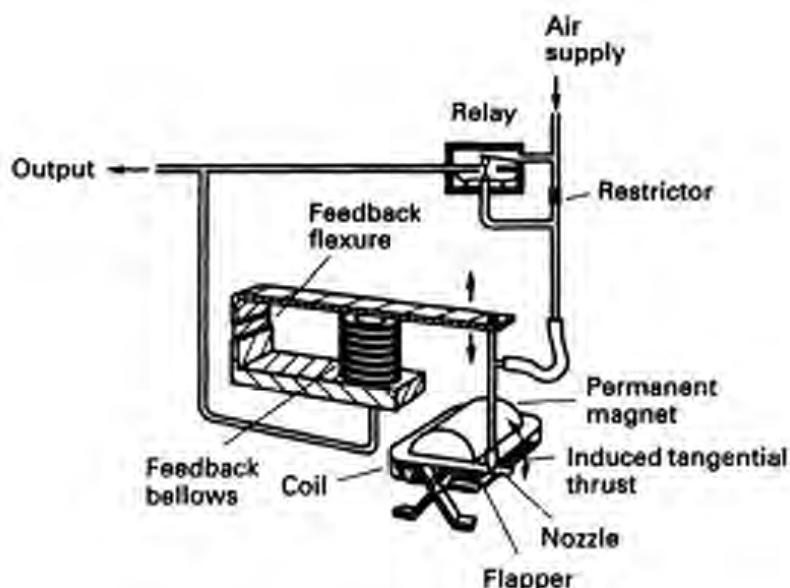


FIG. 6.77. Schematic diagram of electropneumatic (E/P) converter

6.12.5. Smart Transmitters and Associated Protocols—Intelligent Hardware

An instrument which not only measures a variable, but also carries out further processing in order to refine the data obtained before presentation either to an observer or to some other stage of the system, is generally termed *intelligent* or *smart*. In practice, additional functions are usually available as well as the data-processing facility and these are all normally contained within the transmitter of the measuring device. These so-called *smart transmitters* are microprocessor-based and enable the device:

- (a) To produce a higher accuracy of measurement through automatic compensation for systematic errors and changes in ambient conditions.
- (b) To change measurement ranges automatically as required.
- (c) To provide automatic calibration.
- (d) To communicate to the operator or maintenance personnel via a computer interface or hand-held communicator.

The cost of an intelligent instrument can be twice that of the equivalent device without the smart facility (the latter is termed a *dumb* instrument)⁽⁹⁹⁾. However, the use of a smart transmitter does generally improve the inherent accuracy of the sensor itself.

A common feature of smart devices is the ability, either to transmit the normal 4–20 mA analogue output (which is digitally linearised and compensated where necessary), or to provide digital communication with other devices as desired. Digital communication with a smart transmitter can be implemented from a microprocessor within the control room, or by the use of a hand-held terminal. The latter can be inserted at any point within the 4–20 mA current loop and instructions to change the range, calibration, etc. can be sent to a specific smart device⁽¹⁰⁰⁾.

One continuing difficulty with intelligent devices is their compatibility within a given distributed control system or LAN. This problem is particularly acute when individual instruments and other devices within the LAN are purchased from different manufacturers, each of whom employs its own protocol⁽⁹⁴⁾. In such cases, the devices will generally be unable to talk to each other without substantial additional hardware. Attempts are being made to overcome this problem by establishing a common industry communication standard termed *Fieldbus*. Currently, the nearest approach to a cross-company or *open standard* protocol is *HART* (the *Hiway Addressable Remote Transducer* protocol)^(99,101). This is effectively an interim solution in which existing 4–20 mA two wire systems can be used to transmit digital information. It employs the FSK technique (Section 6.12.2) and permits two modes of operation, viz. a 4–20 mA mode with digital signals imposed upon it and an all-digital mode which allows up to 15 intelligent devices to be connected to one cable. Hence, instruments that employ the HART protocol can be accessed by other HART devices, although they may have been purchased from different sources.

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6.15. NOMENCLATURE

		Units in SI System	Dimension in M,N,L,T, θ ,A
<i>A</i>	Cross-sectional area of flux path	m^2	L^2
<i>A_e</i>	Area of electrodes	m^2	L^2
<i>A_p</i>	Cross-sectional area of pipe	m^2	L^2
<i>A_R</i>	Surface area of resistor	m^2	L^2
<i>A</i>	Absorbance	—	—
<i>a</i>	Activity coefficient	—	—
<i>a_θ</i>	Constants in equations 6.32 and 6.33	—	—
<i>B</i>	Width of notch, channel or venturi throat	m	L
<i>B_f</i>	Width of bluff body	m	L
<i>B</i>	Magnetic flux density	T (tesla)	$MT^{-2}A^{-1}$
<i>b_θ</i>	Constants in equations 6.32 and 6.33	—	—
<i>b₀, b₁</i> etc.	Bits (<i>b₀</i> —least significant bit)	—	—
<i>C</i>	Molar concentration	$kmol/m^3$	NL^{-3}
<i>C_D</i>	Coefficient of discharge	—	—
<i>C</i>	Capacitance	F (farad)	$M^{-1}L^{-2}T^4A^2$
<i>D</i>	Depth of liquid above bottom of notch or in flume	m	L
<i>d</i>	Pipe internal diameter	m	L
<i>d'</i>	Particle diameter, ball diameter—falling sphere viscometer	m	L

		Units in SI System	Dimension in M,N,L,T,Θ,A
d_0	Pipe external diameter	m	L
d_x	Internal dimension of flow conditioner in Fig. 6.9	m	L
E	Electromotive force	V	$ML^2T^{-3}A^{-1}$
E_{orp}	Oxidation-reduction potential	V	$ML^2T^{-3}A^{-1}$
E_{Th}	Thévenin emf	V	$ML^2T^{-3}A^{-1}$
E_{Zr}	Potential difference across Zirconia cell	V	$ML^2T^{-3}A^{-1}$
E	Total energy emitted by black body per unit area per unit time	W/m^2 J	MT^{-3} ML^2T^{-2}
E_{Abs}	Energy absorbed by gas		
E_g	Total energy emitted by grey body per unit area per unit time	W/m^2	MT^{-3}
E_{inc}	Incident energy	J	$ML^{-2}T^{-2}$
ϵ	Young's modulus (modulus of elasticity)	N/m^2	$ML^{-1}T^{-2}$
e	Emissivity	—	—
e_T	Transverse strain	—	—
e_x	Longitudinal strain	—	—
e_λ	Emissivity at wavelength λ	—	—
e	Charge on gaseous ion	C (coulomb)	TA
F	Tensile force	N	MLT^{-2}
F_i	Force exerted on ion	N	MLT^{-2}
F_{mm}	Magnetomotive force	AT (ampere-turn)	A
F	Faraday number	96493 C	TA
\mathcal{E}	Electric field strength	V/m	$ML^{-3}A^{-1}$
f	Sampling frequency	s^{-1}	T^{-1}
f	Function	—	—
G	Mass rate of flow	kg/s	MT^{-1}
g	Gauge factor (equation 6.26)	—	—
g	Acceleration due to gravity	m/s^2	LT^{-2}
h	Heat transfer coefficient	W/m^2K	$MT^{-3}\Theta^{-1}$
h_{mix}	Heat transfer coefficient in equation 6.93	W/m^2K	$MT^{-3}\Theta^{-1}$
h_{ref}	Heat transfer coefficient in equation 6.98	W/m^2K	$MT^{-3}\Theta^{-1}$
h_{RT}	Heat transfer coefficient in equation 6.48	W/m^2K	$MT^{-3}\Theta^{-1}$
I	Moment of inertia	$kg\ m^2$	ML^2
ϕ	Intensity of nuclear radiation	W/m^2	MT^{-3}
i	Current	A	A
i_e	Electron current	A	A
i_i	Ion current	A	A
i_L	Current through load	A	A
i_{Th}	Thévenin current	A	A
J_1	Constant in equations 6.44, 6.47 and 6.49	Wm^2	ML^4T^{-3}
J_2	Constant in equations 6.44, 6.47 and 6.49	mK	$L\Theta$
J_3	Constant in equation 6.45	Wm^2	$L\Theta$
J_{RT}	Sensitivity factor for radiation thermometer	—	—
j	Number of samples or data points	—	—
K_1	Constant in equation 6.5	m^3/s^2	L^3T^{-2}
K_2	Constant in equation 6.6	kg/m^3s^2	$ML^{-3}T^{-2}$
K_3	Constant in equation 6.6	kg/m^3s	$ML^{-3}T^{-1}$
K_{amp}	Amplification factor for instrumentation amplifier	—	—
K_{CM}	Coriolis meter constant	Nm	ML^2T^{-2}
K_D	Constant for Doppler meter	m^3/s^2	L^3T^{-2}
K_{GAM}	Calibration constant for acoustic gas density meter	kg/m^3s^2	$ML^{-3}T^{-1}$
K'_{GAM}	Calibration constant for acoustic gas density meter	s^{-2}	T^{-2}
K_{LAM}	Transducer constant for acoustic liquid density meter	kg/m^3	ML^{-3}
K_{TF}	Constant for time of flight meter	m^3	L^3

		Units in SI System	Dimension in M,N,L,T,θ,A
K_v	Capillary and falling ball viscometer constant	m^2/s^2	L^2T^{-2}
K'_v	Capillary viscometer correction factor for fast flow	m^2	L^2
K''_v	Pulsed current viscometer constant	$\text{kg}^2/\text{m}^4\text{s}$	$\text{M}^2\text{L}^{-4}\text{T}^{-1}$
K_{vp}	Correction for velocity profile	—	—
K_x	Constant in equation 6.97	—	—
k	Thermal conductivity <i>or</i> intercept of straight line	W/mK	$\text{MLT}^{-3}\theta^{-1}$
k_{Abs}	Absorption constant	m^2/kmol	N^{-1}L^2
k_c	Conductivity cell constant	m^{-1}	L^{-1}
k_i	Constant for inductive pressure transducer	m^{-1}	L^{-1}
k_m	Number of multiplexed signals in equation 6.115	—	—
k_{Zr}	Zirconia cell constant	V	$\text{ML}^2\text{T}^{-3}\text{A}^{-1}$
ℓ'	Number of information digits	—	—
L	Length of tube defined in Figs 6.6 and 6.9	m	L
L_p	Path length	m	L
L_{\max}	Maximum permissible length of probe (equation 6.97)	m	L
\mathcal{L}	Inductance	H (henry)	$\text{ML}^2\text{T}^{-2}\text{A}^{-2}$
ℓ	Total length of flux path, length of liquid column	m	L
ℓ_c	Height of cylindrical capacitive sensing element	m	L
ℓ_p	Path length of column of gas	m	L
M	Mutual inductance	H (henry)	$\text{ML}^2\text{T}^{-2}\text{A}^{-2}$
m	Mass (of fluid) <i>or</i> gradient of straight line	kg	M
m_i	Mass of ion	kg	M
N	Total number of data points, number of terms of series	—	—
N_p	Number of drive pulses per unit time	s^{-1}	T^{-1}
N_T	Number of turns	—	—
N	Number of quantisation levels	—	—
n	Integer mode of frequency	—	—
n_a	Number of anions	—	—
n_c	Number of cations	—	—
\sim	Number of binary digits (bits)	—	—
n_{bcd}	Number of binary coded decimal bits	—	—
P	Pressure	N/m^2	$\text{ML}^{-1}\text{T}^{-2}$
P'	Partial pressure	N/m^2	$\text{ML}^{-1}\text{T}^{-2}$
Q	Average volumetric flowrate <i>or</i> electric charge	m^3/s C (coulomb)	L^3T^{-1} TA
Q_H	Quantity of heat	J	ML^2T^{-2}
R	Resistance	Ω	$\text{ML}^2\text{T}^{-3}\text{A}^{-2}$
R_c	Resistance of conductivity cell	Ω	$\text{ML}^2\text{T}^{-3}\text{A}^{-2}$
R_{CL}	Resistance of compensating leads	Ω	$\text{ML}^2\text{T}^{-3}\text{A}^{-2}$
R_F	Resistance Pirani gauge active filament	Ω	$\text{ML}^2\text{T}^{-3}\text{A}^{-2}$
R_f	Resistance of amplifier	Ω	$\text{ML}^2\text{T}^{-3}\text{A}^{-2}$
R_L	Resistance of load	Ω	$\text{ML}^2\text{T}^{-3}\text{A}^{-2}$
R_s	Resistance of Pirani gauge reference filament	Ω	$\text{ML}^2\text{T}^{-3}\text{A}^{-2}$
R_θ	Resistance at temperature θ	Ω	$\text{ML}^2\text{T}^{-3}\text{A}^{-2}$
R	Universal gas constant	$\text{J}/\text{kmol K}$	$\text{MN}^{-1}\text{L}^2\text{T}^{-2}\theta^{-1}$
\mathcal{R}	Resolution of A/D converter	—	—
\mathcal{R}_b	Transmission bit rate	s^{-1}	T^{-1}
r	Radius	m	L
r_e	Radius of path of ion in electric field	m	L
r_g	Radius of gyration	m	L
r_m	Radius of path of ion in magnetic field	m	L
\mathcal{G}	Magnetic reluctance	A/Wb (ampere/weber)	$\text{M}^{-1}\text{L}^{-2}\text{T}^2\text{A}^2$

		Units in SI System	Dimension in M,N,L,T,θ,A
<i>s</i>	Magnitude of position vector	—	—
<i>T</i>	Absolute temperature	K	θ
<i>T</i>	Torque	Nm	ML²T⁻²
<i>T'</i>	Torque per unit length of cylinder	N	MLT⁻²
<i>T</i>	Transmittance	—	—
<i>t</i>	Time	s	T
<i>t_{down}</i>	Downstream elapsed time	s	T
<i>t_e</i>	Elapsed time (Fig. 6.75)	s	T
<i>t_{up}</i>	Upstream elapsed time	s	T
<i>u</i>	Velocity	m/s	LT⁻¹
<i>u₀</i>	Terminal falling velocity	m/s	LT⁻¹
<i>u_l</i>	Velocity of liquid	m/s	LT⁻¹
<i>u_{free}</i>	Free stream velocity	m/s	LT⁻¹
<i>u_i</i>	Velocity of ion	m/s	LT⁻¹
<i>u_{max}</i>	Maximum velocity of process fluid	m/s	LT⁻¹
<i>u_s</i>	Speed of sound in liquid	m/s	LT⁻¹
<i>u</i>	Fluid velocity vector	m/s	LT⁻¹
<i>V</i>	Voltage	V	ML²T⁻³A⁻¹
<i>V_o</i>	Output voltage	V	ML²T⁻³A⁻¹
<i>V_i</i>	Input voltage	V	ML²T⁻³A⁻¹
<i>V_{int}</i>	Interference voltage due to inductive coupling	V	ML²T⁻³A⁻¹
<i>V_L</i>	Potential difference across output load or width of air gap in equation 6.19	V	ML²T⁻³A⁻¹
<i>V_s</i>	Voltage source	V	ML²T⁻³A⁻¹
<i>W_λ</i>	Power spectral density for black body radiator	W/m ³	ML⁻³
<i>w</i>	Deflection of diaphragm in Fig. 6.11	m	L
<i>X</i>	Thermometric property	—	—
<i>x</i>	Length or distance in <i>x</i> direction or width of air gap in equation 6.19	m	L
<i>x_d</i>	Thickness of diaphragm in Fig. 6.11	m	L
<i>x_e</i>	Distance between conductivity cell electrodes	m	L
<i>x_s</i>	Distance travelled by inductor core (stroke)	m	L
<i>x_T</i>	Tip travel of Bourdon tube	m	L
<i>y</i>	Length in <i>y</i> direction	m	L
<i>Z_a</i>	Number of charges carried by anion	—	—
<i>Z_c</i>	Number of charges carried by cation	—	—
<i>Ζ_L</i>	Input impedance of load	Ω	ML²T⁻³A⁻²
<i>Ζ_{Th}</i>	Thévenin impedance	Ω	ML²T⁻³A⁻²
<i>Ζ_N</i>	Norton impedance	Ω	ML²T⁻³A⁻²
<i>Ζ_T</i>	Transmitter output impedance	Ω	ML²T⁻³A⁻²
<i>z</i>	Length in <i>z</i> direction or liquid level in tank	m	L
<i>α</i>	Half angle of triangular notch or angle between pipe wall and ultrasonic signal	—	—
<i>α_c</i>	Critical angle	—	—
<i>α_{CM}</i>	Coriolis angle of twist	—	—
<i>α_G</i>	Gap angle—cone and plate viscometer	—	—
<i>β₁</i>	Thermoelectric coefficient in equation 6.38	V/K	ML²T⁻³θ⁻¹A⁻¹
<i>β₂</i>	Thermoelectric coefficient in equation 6.38	V/K ²	ML²T⁻³θ⁻²A⁻¹
<i>β_c</i>	Temperature coefficient for ionic conductivity	1/K	θ⁻¹
<i>β_{θ,1}</i>	Temperature coefficient of resistance	Ω/K	ML²T⁻³θ⁻¹A²
<i>β_{θ,2}</i>	Temperature coefficient of resistance	Ω/K ²	ML²T⁻³θ⁻²A⁻¹
<i>γ</i>	Rate of shear	s ⁻¹	T⁻¹
<i>δ_c</i>	Vertical separation of capacitor plates (equation 6.14)	m	L
<i>ε</i>	Permittivity	(coulomb) ² /Nm ²	M⁻²L⁻⁵T⁶A²

		Units in SI System	Dimension in M,N,L,T,θ,A
ϵ_0	Permittivity of free space	(coulomb) ² /Nm ²	M ⁻² L ⁻⁵ T ⁶ A ²
ϵ_r	Relative permittivity	—	—
η	Refractive index	—	—
θ	Temperature	K	θ
κ	Conductivity (conductance per metre)	S/m	M ⁻¹ L ⁻³ T ³ A ²
κ'	Conductance	S (Siemen)	M ⁻¹ L ⁻² T ³ A ²
Λ	Molar conductivity defined by equation 6.72	Sm ² /kmol	M ⁻¹ N ⁻¹ T ³ A ²
Λ^0	Molar conductivity at infinite dilution	Sm ² /kmol	M ⁻¹ N ⁻¹ T ³ A ²
λ_a^0	Ionic conductivity per unit charge of anion at infinite dilution	Sm ² /kmol (anions)	M ⁻¹ N ⁻¹ T ³ A ²
λ_c^0	Ionic conductivity per unit charge of cation at infinite dilution	Sm ² /kmol (cations)	M ⁻¹ N ⁻¹ T ³ A ²
λ_T^0	Ionic conductivity per unit charge of ion at infinite dilution	Sm ² /kmol	M ⁻¹ N ⁻¹ T ³ A ²
μ	Dynamic viscosity	Ns/m ²	ML ⁻¹ T ⁻¹
μ_0	Permeability of free space	N/A ²	MLT ⁻² A ⁻²
μ_r	Relative permeability	—	—
ν	Poisson's ratio or kinematic viscosity	—	—
ξ	Mass absorption coefficient	m ² /s	L ² T ⁻¹
ρ	Density	m ² /kg	M ⁻¹ L ²
ρ'	Resistivity	kg/m ³	ML ⁻³
σ	Stephan—Boltzmann constant or standard deviation	Ωm	M ² L ² T ⁻³ A ⁻²
ϕ	Magnetic flux	W/m ² K ⁴	MT ⁻³ θ ⁻⁴
Ξ_{\max}	Maximum quantification error	—	—
χ	$r^2 \beta_\theta R_\theta / A_R$ (equation 6.97)	W/m ² K	MT ⁻³ θ ⁻¹
ψ	Bandwidth	s ⁻¹	T ⁻¹
ω	Angular frequency	radians/s	T ⁻¹
ω_v	Angular velocity	radians/s	T ⁻¹
$\Delta\omega_D$	Doppler frequency shift	s ⁻¹	T ⁻¹
Re'	Particle Reynolds number at terminal falling velocity	—	—
$u_0 d' \rho / \mu$	—	—	—
S	Strouhal number $\omega B_f / u_{\text{free}}$	—	—

Prefix δ represents small finite changes in relevant variable.*Suffix* j refers to j th sampling instant, or to j th data point.