

# Summary of Other Measurements

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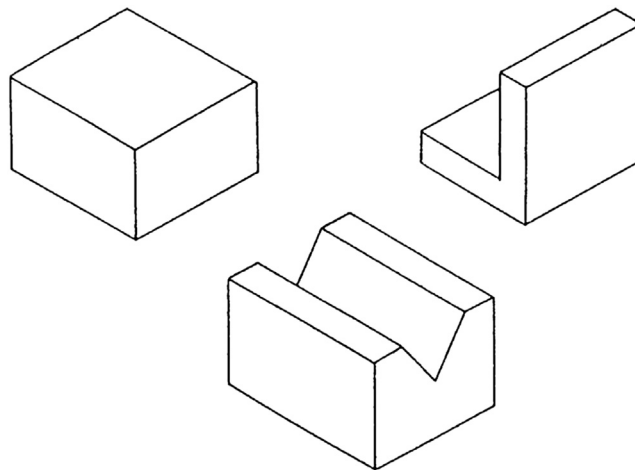
## 21.1 Introduction

The previous chapters in this book have reviewed the measurement techniques that are available for measuring a range of commonly met physical variables. In this discussion, we have explored the measurement of temperature, pressure, the flow rate of both solids and fluids, the level of liquids and powdered/granular solids in a container, mass (including weight), force, torque, and motion in both translational and rotation forms. However, we have certainly not covered an exhaustive list of all the different physical variables that exist in the world. Without doubt, it would be possible to produce an encyclopedia that covered the measurement of every physical variable that exists, but this would inevitably be very expensive and it is certainly not appropriate for inclusion within a textbook such as this. Nevertheless, for the benefit of readers, who may need some information on sensors to measure physical variables that have not been discussed so far, this chapter provides a brief summary of appropriate measurement techniques for a number of lesser-met measurement requirements. The following sections therefore cover the measurement of dimensions, angles, surface flatness, volume, viscosity, moisture (including humidity), sound, and pH (acidity/alkalinity), with a final section on gas sensing and analysis.

## 21.2 Dimension Measurement

Dimension measurement includes measurement of the length, width, and height of components and also the depth of holes and slots within components. Tapes and rules are commonly used to give approximate measurements, and various forms of caliper and micrometer are used, where more accurate measurements are required. Gauge blocks and length bars are also used when very high accuracy is required, although these are primarily intended for calibration duties.

A necessary component in most instances of dimension measurement is a flat and level *reference plane* on which the components being measured are placed. Such reference planes are available in a range of standard sizes, and a means of adjusting the feet is always provided to ensure that the surface is exactly level. Smaller sizes exist as a *surface plate* resting on a supporting table, whereas larger sizes take the form of free standing tables that usually have a projection at the edge to facilitate the clamping of components. They are normally used in conjunction with box cubes and vee blocks (see [Figure 21.1](#)) that locate components in a fixed position. In modern tables, granite has tended to supersede iron as the preferred material for the plate, although iron plates are still available. Granite is ideal for this purpose as it does not corrode, is dimensionally very stable and does not form burrs when damaged. Iron plates, on the other hand, are prone to rusting and susceptible to damage this results in burrs on the surface that interfere with measurement procedures. Surface plates and tables are available in three grades, which are usually called calibration, inspection, and toolroom. These vary according to their flatness, this being defined as the distance between two parallel planes that just contain all points in



**Figure 21.1**  
Box cubes and vee blocks.

the table surface. Standards of flatness vary according to the size of the table. For a large table of dimensions  $2000 \times 1500 \times 300$  mm, the allowable maximum permitted deviation from flatness are 0.005 mm for the calibration grade, 0.010 mm for the inspection grade, and 0.020 mm for the toolroom grade.

As well as using accurate instruments on a flat surface, the quality of dimension measurements is critically dependent on the skill of the human operator using the instruments. Incorrect use can introduce measurement inaccuracy in various ways, and therefore, the scope for human-induced errors is far greater than that which exists when measuring most other physical quantities. Hence, checks on the way that the human operator is using equipment are just as important as calibration checks on the measuring instruments themselves. The golden rule in dimension measurement is that the line of measurement and the line of the dimension being measured should be coincident. In the case of steel rules and tapes, the greatest potential source of user-induced error is failure to position the rule squarely across the dimension being measured. Parallax error is also possible if the user does not position the rule and read it from directly above. Calipers and micrometers are less susceptible to these types of error but it still remains sensible to carry out periodic checks on the way in which these instruments are being used, verifying in particular that measurements are being made squarely.

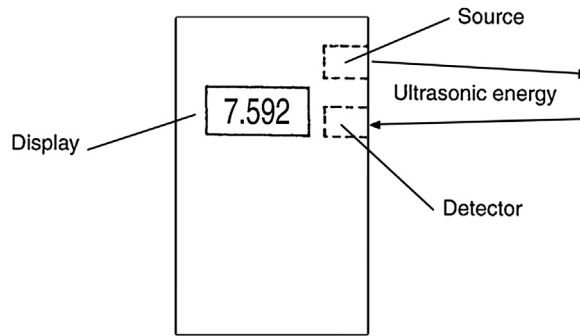
### **21.2.1 Rules and Tapes**

Rules and tapes are the simplest way of measuring larger dimensions. Steel rules are generally only available to measure dimensions up to 1 m. Beyond this, steel tapes (measuring to 30 m) or an ultrasonic rule (measuring to 10 m) is used.

The *steel rule* is undoubtedly the simplest instrument available for measuring length. Measurement accuracy is only modest using standard rules, which typically have rulings at 0.5-mm intervals, but the best rules have rulings at 0.05-mm intervals and a measurement resolution of 0.02 mm. When used by placing the rule against an object, the measurement accuracy is much dependent upon the skill of the human measurer and, at best, the inaccuracy is likely to be at least  $\pm 0.5\%$ .

The retractable *steel tape* is another well-known instrument. The end of the tape is usually provided with a flat hook that is loosely fitted so as to allow for automatic compensation of the hook thickness when the rule is used for internal measurements. Again, measurement accuracy is governed by human skill, but, with care, the measurement inaccuracy can be made to be as low as  $\pm 0.01\%$  of full-scale reading.

The *ultrasonic rule* consists of an ultrasonic energy source, an ultrasonic energy detector, and battery-powered, electronic circuitry housed within a handheld box, as shown in [Figure 21.2](#). Both source and detector often consist of the same type of piezoelectric



**Figure 21.2**  
Ultrasonic rule.

crystal excited at a typical frequency of 40 kHz. Energy travels from the source to a target object and is then reflected back into the detector. The time of flight of this energy is measured and this is converted into a distance reading by the enclosed electronics. Maximum measurement inaccuracy of  $\pm 1\%$  of the full-scale reading is claimed. This is only a modest level of accuracy, but it is sufficient for such purposes as measuring rooms by estate agents prior to producing sales literature, where the ease and speed of making measurements is of great value.

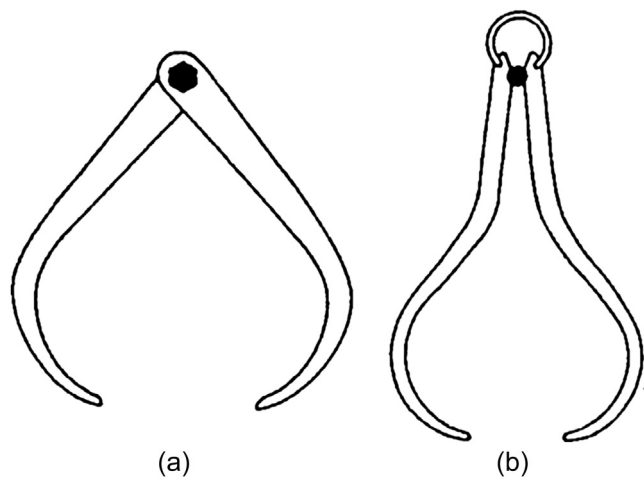
A fundamental problem in the use of ultrasonic energy of this type is the limited measurement resolution (7 mm) imposed by the 7-mm wavelength of sound at this frequency. Further problems are caused by the variation in the speed of sound with humidity (variations of  $\pm 0.5\%$  possible) and the temperature-induced variation of 0.2% per  $^{\circ}\text{C}$ . Therefore, the conditions of use must be carefully controlled if the claimed accuracy value is to be met.

### 21.2.2 Calipers

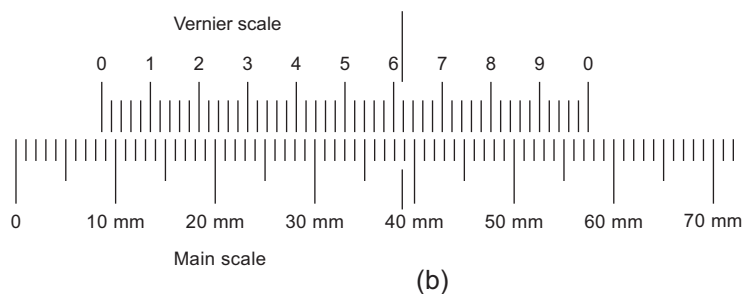
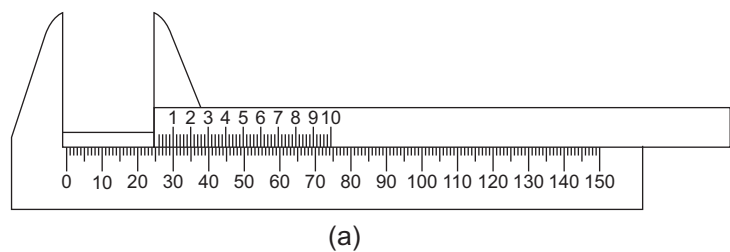
Calipers are generally used in situations, where measurement of dimensions with a rule or tape is not accurate enough. Two versions exist, the standard caliper and the vernier caliper.

Figure 21.3 shows two alternative forms of the *standard caliper*. The range of measurement, according to the version used, is up to 600 mm. Calipers are used to transfer the measured dimension from the workpiece to a steel rule. This avoids the necessity to align the end of the rule exactly with the edge of the workpiece and reduces the measurement inaccuracy by a factor of two. In the basic caliper, careless use can allow the setting of the caliper to be changed during transfer from the workpiece to the rule. Hence, the spring-loaded type, which prevents this happening, is preferable.

The *vernier caliper*, shown in Figure 21.4(a), is a combination of a standard caliper and a steel rule. The main body of the instrument includes a scale and a fixed anvil at one end.



**Figure 21.3**  
(a) Standard caliper; (b) spring-loaded caliper.



**Figure 21.4**  
Vernier caliper: (a) Basic instrument; (b) details of scale.

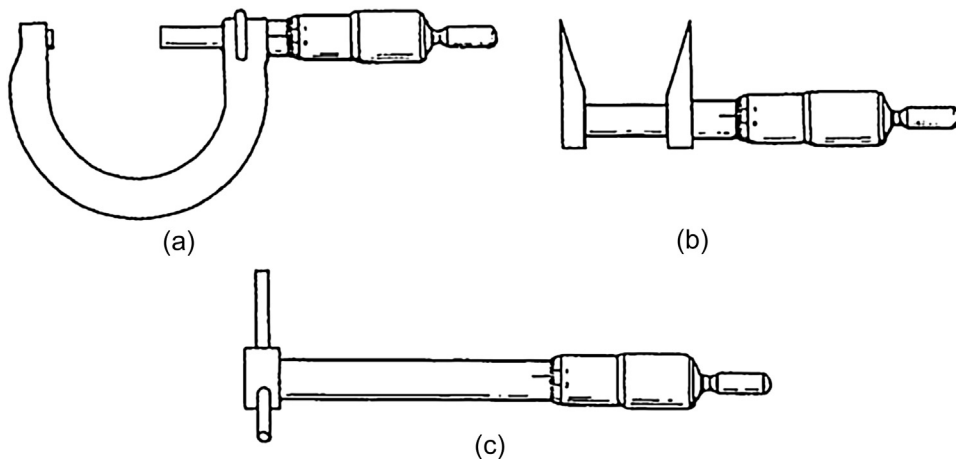
This carries a sliding anvil that is provided with a second, vernier scale. This second scale is shorter than the main scale and is divided into units that are slightly smaller than the main scale units but related to them by a fixed factor. Determination of the point, where the two scales coincide enables very accurate measurements to be made, with typical inaccuracy levels down to  $\pm 0.01\%$ .

Figure 21.4(b) shows details of a typical combination of main and vernier scales. The main scale is ruled in 1 mm units. The vernier scale is 49-mm long and divided into 50 units, thereby making each unit 0.02 mm smaller than the main scale units. Each group of five units on the vernier scale thus differs from the main scale by 0.1 mm and the numbers marked on the scale thus refer to these larger units of 0.1 mm. In the particular position shown in the figure, the zero on the vernier scale is indicating a measurement between 8 and 9 mm. Both scales coincide at a position of 6.2 (large units). This defines the interval between 8 and 9 mm to be  $6.2 \times 0.1 = 0.62$  mm, that is, the measurement is 8.62 mm.

Intelligent digital calipers are now available that give a measurement resolution of 0.01 mm and a low inaccuracy of  $\pm 0.03$  mm. These have automatic compensation for wear, and hence calibration checks have to be very infrequent. In some versions, the digital display can be directly interfaced to an external computer monitoring system.

### 21.2.3 Micrometers

Micrometers provide a means of measuring dimensions to high accuracy. Different forms provide measurement of both internal and external dimensions of components, and of holes, slots, etc., within components. In the *standard micrometer*, shown in Figure 21.5(a), measurement is made between two anvils, one fixed and one that is moved along by the rotation of an accurately machined screw thread. One complete rotation of the screw typically moves the anvil by a distance of 0.5 mm. Such movements of the anvil are measured using a scale marked with divisions every 0.5 mm along the barrel of the instrument. A scale marked with 50 divisions is etched around the circumference of the



**Figure 21.5**

Micrometers: (a) Standard (external) micrometer; (b) internal micrometer; (c) bore micrometer.

spindle holder: each division therefore corresponds to an axial movement of 0.01 mm. Assuming that the user is able to judge the position of the spindle on this circular scale against the datum mark to within one-fifth of a division, a measurement resolution of 0.002 mm is possible.

The most common measurement ranges are either 0–25 mm or 25–50 mm, with inaccuracy levels down to  $\pm 0.003\%$ . However, a whole family of micrometers is available, where each has a measurement span of 25 mm, but with the minimum distance measured varying from 0 up to 575 mm. Thus, the last instrument in this family measures the range from 575 to 600 mm. Some manufacturers also provide micrometers with two or more interchangeable anvils, which extend the span measurable with one instrument to between 50 and 100 mm according to the number of anvils supplied. Therefore, an instrument with four anvils might, for instance, measure the range from 300 to 400 mm, by making appropriate changes to the anvils.

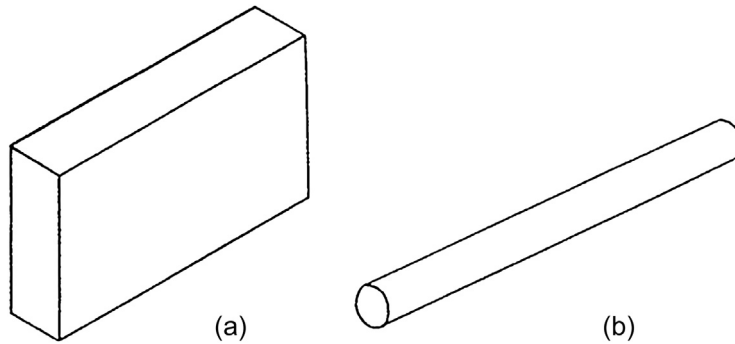
The *internal micrometer* (see [Figure 21.5\(b\)](#)) is able to measure internal dimensions such as the diameter of holes. In the case of measuring holes, micrometers are inaccurate if there is any ovality in the hole, unless the diameter is measured at several points. An alternative solution to this problem is to use a special type of instrument known as a *bore micrometer* ([Figure 21.5\(c\)](#)). In this, three probes move out radially from the body of the instrument as the spindle is turned. These probes make contact with the sides of the hole at three equidistant points, thus averaging out any ovality.

Intelligent micrometers in the form of the electronic *digital micrometer* are now available. These have a self-calibration capability and a digital readout, with a measurement resolution of 0.001 mm (1 micron).

#### **21.2.4 Gauge Blocks (*Slip Gauges*) and Length Bars**

*Gauge blocks*, also known as *slip gauges* (see [Figure 21.6\(a\)](#)), consist of rectangular blocks of hardened steel that have flat and parallel end faces. These faces are machined to very high standards of accuracy in terms of their surface finish and flatness. The purpose of gauge blocks is to provide a means of checking whether a particular dimension in a component is within the allowable tolerance rather than actually measuring what the dimension is. To do this, a number of gauge blocks are joined together to make up the required dimension to be checked. Gauge blocks are available in four grades of accuracy according to the maximum tolerance allowed in the length dimension. Blocks of the grade with the largest tolerance are used for general workplace measurements and those of the grade with the next largest tolerance are used for inspection duties. Blocks of a grade with the next to smallest tolerance are used for workplace calibration. Finally, blocks of the grade with the smallest tolerance are used for higher-level calibration. Unfortunately, these





**Figure 21.6**  
(a) Gauge block; (b) length bar.

different grades are coded differently according to different national/international standards, as summarized in [Table 21.1](#).

Gauge blocks are available in boxed sets containing a range of block sizes, which allows any dimension up to 200 mm to be constructed by joining together an appropriate number of blocks. While 200 mm is the maximum dimension that should be set up with gauge blocks alone, they can be used in conjunction with length bars to set up much greater standard dimensions. Blocks are joined by “wringing,” a procedure in which the two end faces are rotated slowly against each other. This removes the air film and allows adhesion to develop by intermolecular attraction. Adhesion is so good in fact that, if groups of blocks were not separated within a few hours, the molecular diffusion process would continue to the point, where the blocks would be permanently welded together. The typical interblock gap resulting from wringing has been measured as  $0.001\ \mu\text{m}$ , which is effectively zero. Thus, any number of blocks can be joined without creating any significant measurement error.

It is fairly common practice with all block sets except those of the highest reference grade to include an extra pair of 2-mm-thick blocks in the set that are made from wear-resisting

**Table 21.1: Grade standards for gauge blocks**

	Japan: JIS B 7506 Germany: DIN 861 USA: ASME UK: BS 4311	U.S. Federal Standard Specification GGG-G-15C	American National Standard ANSI/ASME B 89.1.9M ISO 3650
Reference grade	Grade AAA	Grade 0.5	Grade 00
Calibration grade	Grade AA	Grade 1	Grade 0
Inspection grade	Grade A	Grade 2	Grade 1
Workplace grade	Grade B	Grade 3	Grade 2

tungsten carbide. These are marked with letter P and are designed to protect the other blocks from wear during use. Where such protector blocks are used, due allowance has to be made for their thickness (4 mm) in calculating the sizes of block needed to make up the required length.

A necessary precaution when using gauge blocks is to avoid handling them more than is necessary. The length of a block that was 100-mm long at 20 °C would increase to 100.02 mm at 37 °C (body temperature). Hence, after wringing blocks together, they should be left to stabilize back to the ambient room temperature before use. This wait might need to be several hours if the blocks have been handled to any significant extent.

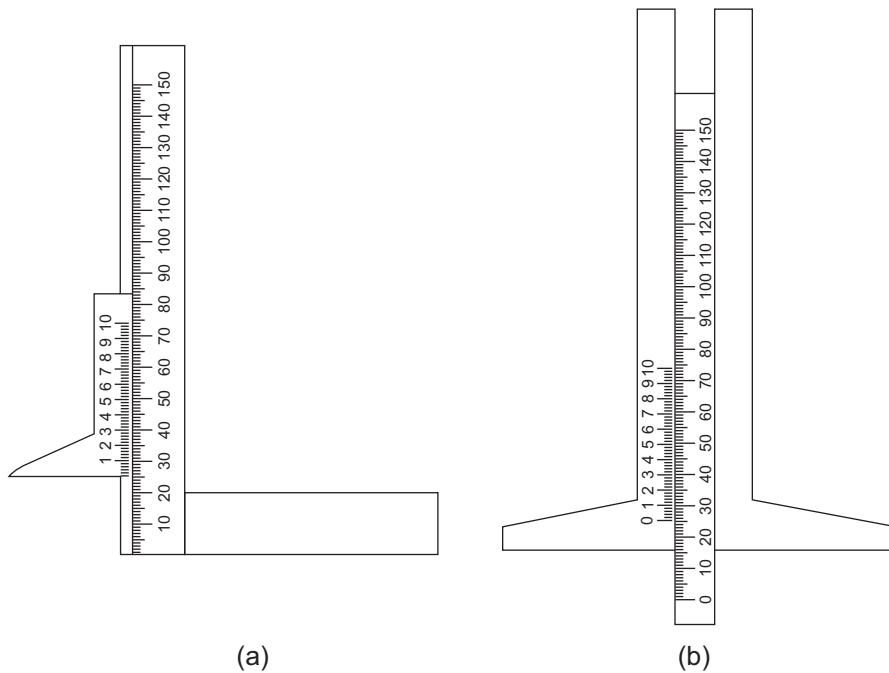
Where a greater dimension than 200 mm is required, gauge blocks are used in conjunction with *length bars* (Figure 21.6(b)). Length bars consist of straight, hardened, high-quality steel bars of a uniform 22-mm diameter and in a range of lengths between 100 and 1200 mm. When using length bars, it is very important that they are exactly horizontal and mounted so that they do not bend under their own weight. This is achieved by mounting the bars at their *airy* points. The airy points are at a distance of  $0.2117L$  from the ends of the bar and are marked by circumferential lines (where  $L$  is the length of the bar).

Length bars are available in four grades of accuracy, reference, calibration, inspection, and workplace. As for gauge blocks, the codes for these grades vary according to different national/international standards. Reference and calibration grades have accurately flat end faces, which allow a number of bars to be wrung together to obtain the required standard length. Inspection grade and workplace grade blocks have threaded ends that allow them to be screwed together. By combining length bars with gauge blocks, any dimension up to about 2 m can be set up with a resolution of 0.0005 mm.

### 21.2.5 Height and Depth Measurement

The height of objects and the depth of holes, slots etc., are measured by the height gauge and depth gauge respectively. A dial gauge is often used in conjunction with these instruments to improve measurement accuracy. The *height gauge*, shown in Figure 21.7(a), effectively consists of a vernier caliper mounted on a flat base. Measurement inaccuracy levels down to  $\pm 0.015\%$  are possible. The *depth gauge* (Figure 21.7(b)), is a further variation on the standard vernier caliper principle that has the same measurement accuracy capabilities as the height gauge.

In practice, certain difficulties can arise in the use of these instruments, where either the base of the instrument is not properly located on the measuring table or where the point of contact between the moving anvil and the workpiece is unclear. In such cases, a dial gauge, which has a clearly defined point of contact with the measured object, is used in conjunction with the height or depth gauge to avoid these possible sources of error. These



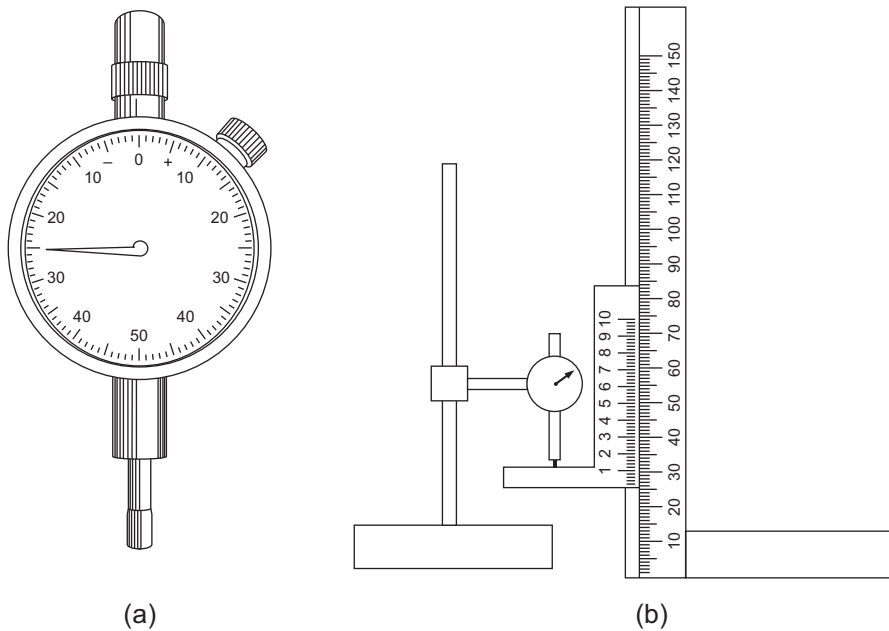
**Figure 21.7**  
(a) Height gauge; (b) depth gauge.

instruments can also be obtained in intelligent versions that give a digital display and have self-calibration capabilities.

The *dial gauge*, shown in [Figure 21.8\(a\)](#), consists of a spring-loaded probe that drives a pointer around a circular scale via rack and pinion gearing. Typical measurement resolution is 0.01 mm. When used to measure the height of objects, it is clamped in a retort stand and a measurement taken of the height of the unknown component. Then, it is put in contact with a height gauge ([Figure 21.8\(b\)](#)) that is adjusted until the reading on the dial gauge is the same. At this stage, the height gauge is set to the height of the object. The dial gauge is also used in conjunction with the depth gauge in an identical manner. (Gauge blocks can be used instead of height/depth gauges in such measurement procedures if greater accuracy is required.)

### 21.2.6 Calibration of Dimension Measurements

Instruments measuring dimensions up to 200 mm are calibrated in the workplace by comparing their reading with standard dimensions set up with calibration-grade gauge blocks used on an inspection grade surface table that is itself calibrated for surface flatness and horizontal alignment. For higher-level calibration, reference-grade gauge blocks on a

**Figure 21.8**

Dial gauge (a) Basic instrument; (b) use in conjunction with height gauge.

calibration-grade surface table are used. In both cases, a high-magnification comparator is required to test the alignment between the scale markings of the instruments being calibrated and the edge of the gauge blocks. Special end fittings are also used with gauge blocks when they are used for calibrating micrometers and calipers. Gauge blocks used as a calibration reference must themselves be calibrated against gauge blocks of the next higher grade. This calibration must include a check on their flatness and the degree of parallelism of the opposing end faces, as these latter two parameters are just as important as length in determining the possible error in total length when a number of blocks are wrung together. At the top of the calibration chain, reference gauge blocks are calibrated by National Standards Organisations using interferometric methods.

Mention should also be made of the **setting gauge**, which is used for calibrating internal micrometers. For testing instruments measuring up to 50 mm, the setting gauge consists of a 25-mm-diameter steel disc (with  $\pm 0.001$  mm tolerance on its diameter). For testing larger range instruments, the setting gauge consists of either a flat-ended or a spherical-ended steel rod, with a length tolerance which varies from  $\pm 0.002$  mm on a 125-mm-long gauge to  $\pm 0.006$  mm on a 575-mm-long gauge.

Extra comments are also necessary about the calibration of external micrometers, where it is important to check measurement accuracy at intermediate positions of the thimble as well as for full revolutions of the thimble. Recommended procedure for a 0–25  $\mu\text{m}$  is to

set up gauge blocks to give the following dimensions in turn: 2.5, 5.1, 7.7, 12.9, 15.0, 17.6, 20.2, 22.8, 25.0 mm. This tests the thimble at equidistant positions during its rotation. Calibration checks should also include testing the flatness and parallelism of the anvil faces. Flatness is checked by bringing the anvil into contact with an optically flat glass plate, where the degree of nonflatness is indicated by the color and number of interference bands on the surface. Parallelism of the measuring faces is tested by moving an optical flat about between them and observing the changes in the number of interference bands. If calibration checks show up errors in length measurement, micrometers are provided with a means of adjustment to take up small amounts of wear in the screw thread. They also usually have some means of rotating the body scale so that the zero mark can be reset.

Some further comment is also needed about the calibration of height gauges, depth gauges, and dial gauges. These are calibrated against reference piles of gauge blocks using a special form of dial gauge that has a measurement resolution of 1  $\mu\text{m}$ .

For instruments measuring between 200 mm and 2 m, standard dimensions for calibration are set up by using gauge blocks in conjunction with length bars. Again, calibration-grade length bars are used for workplace calibration and reference grade for higher-level calibration. As in the case of gauge blocks, checking the parallelism of their end faces is very important when calibrating the length bars themselves.

Very specialized equipment is needed to calibrate steel tapes, which are routinely used to measure dimensions greater than 2 m. This equipment comprises a flat, horizontal, stainless steel bench up to 60 m long, which has a measuring carriage consisting of a cube corner reflector and an attached microscope. The tape is stretched along the table and the scale graduations are located through the microscope. The position of each graduation is determined by a laser interferometer attached to the carriage. This equipment is very expensive and therefore tape calibration is normally devolved to specialist calibration companies or tape manufacturers. Ultrasonic rules are also used for measuring distances greater than 2 m, but, since these only give approximate measurements anyway, calibration using a steel tape is adequate.

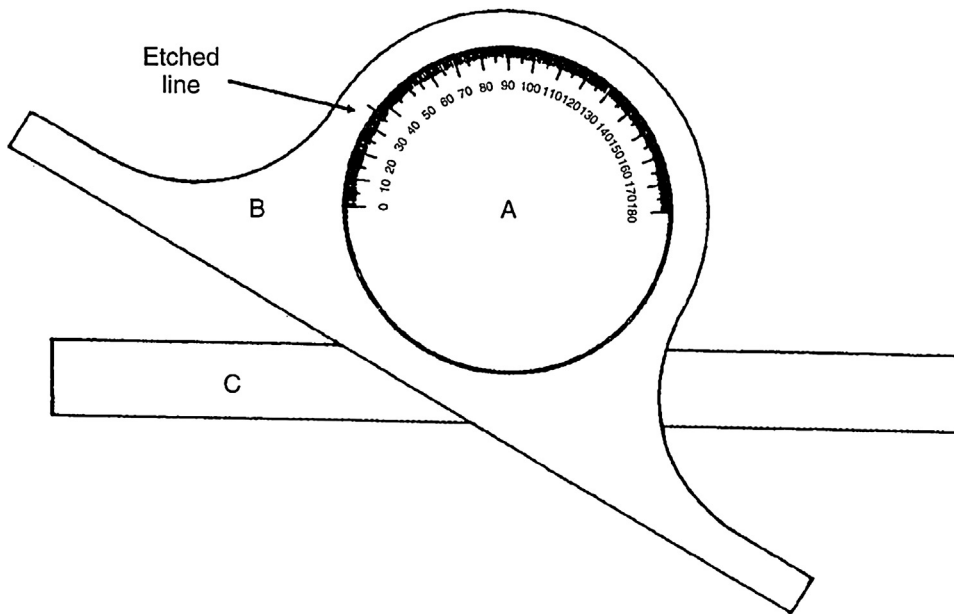
The necessary frequency of calibration, as with so many other types of measuring instrument, depends largely upon the rate and conditions of usage of dimension-measuring instruments. Usage records and the results of calibration checks are the only means of setting a sensible calibration frequency. However, whatever recalibration period is defined, a vigilant watch must be kept for signs of physical damage to the instrument at intermediate times. Instruments are often abused and mistreated, for instance, by using the end of rulers to open tins and using vernier calipers as a spanner! Whenever such misuse is suspected, the instrument must be withdrawn immediately for calibration checks to be carried out.

### 21.3 Angle Measurement

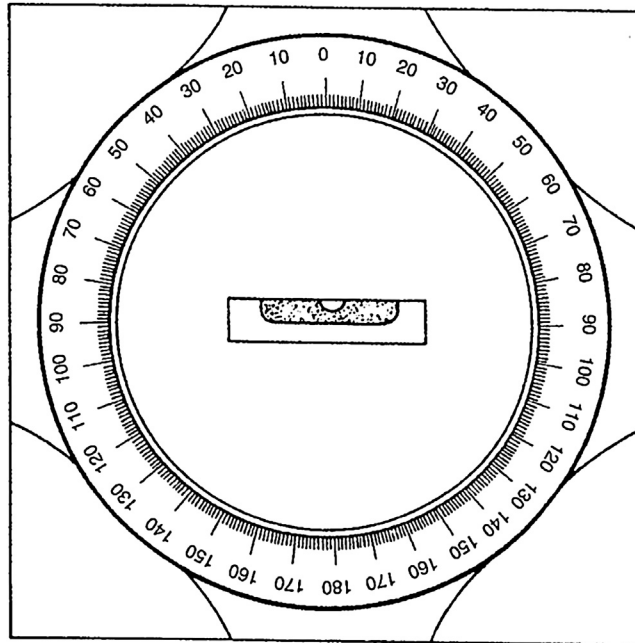
Measurement of angles is one of the less-common measurement requirements that instrumentation technologists are likely to meet. However, angle measurement is required in some circumstances, such as when the angle between adjoining faces on a component must be checked. The main instruments used are protractors and a form of angle-measuring spirit level.

In some circumstances, a simple protractor of the sort used in school for geometry exercises can be used. However, the more sophisticated form of angle protractor shown in [Figure 21.9](#) provides better measurement accuracy. This consists of two straight edges, one of which is able to rotate with respect to the other. Referring to [Figure 21.9](#), the graduated circular scale *A* attached to the straight edge *C* rotates inside a fixed circular housing attached to the other straight edge *B*. The relative angle between the two straight edges in contact with the component being measured is determined by the position of the moving scale with respect to a reference mark on the fixed housing *B*. With this type of instrument, measurement inaccuracy is at least  $\pm 1\%$ . An alternative form, the *bevel protractor*, is similar to this form of angle protractor, but it has a vernier scale on the fixed housing. This allows the inaccuracy level to be reduced to  $\pm 10$  min of arc.

The form of *spirit level* shown in [Figure 21.10](#) is an alternative angle-measuring instrument. It consists of a standard spirit level attached to a rotatable circular scale that is



**Figure 21.9**  
Angle protractor.



**Figure 21.10**

Angle-measuring spirit level.

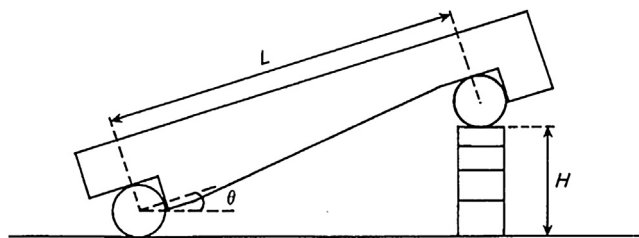
mounted inside an accurately machined square frame. When placed on the sloping surfaces of components, rotation of the scale to centralize the bubble in the spirit level allows the angle of slope to be measured. Again, measuring inaccuracies down to  $\pm 10$  min of arc are possible if a vernier scale is incorporated in the instrument.

The *electronic spirit level* contains a pendulum, whose position is sensed electrically. Measurement resolution as good as 0.2 seconds of arc is possible.

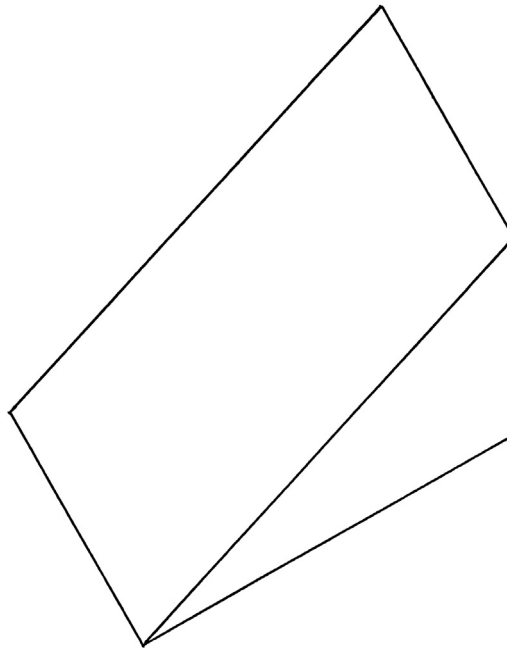
### 21.3.1 Calibration

The simplest piece of equipment available for calibrating angle-measuring instruments is the **sine bar**, which is illustrated in [Figure 21.11](#). This is used in conjunction with gauge blocks on a surface table of inspection grade or better. The sine bar consists of a rectangular-section piece of steel in which a pair of rollers is located. The distance between the centers of the rollers is known very accurately and is commonly set to be 250 mm or some multiple thereof. By setting the bar up with one roller on a reference table and the other resting on a pile of gauge blocks, any angle can be set up, given by (see [Figure 21.11](#))

$$\theta = \sin^{-1}(H/L)$$



**Figure 21.11**  
Sine bar.

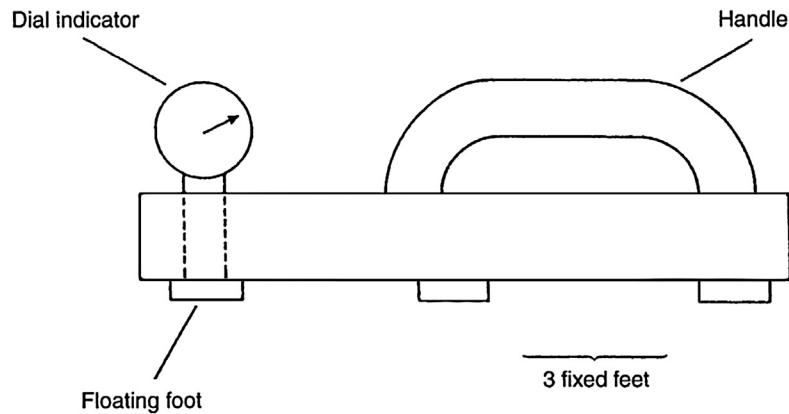


**Figure 21.12**  
Angle block.

Maximum measurement inaccuracy is 30 seconds of arc (1/120th of a degree or  $145 \mu\text{rad}$ ).

An alternative way of calibrating angle-measuring instruments is to use *angle blocks*. These consist of a set of steel blocks, with each block having some specific (but different) angle between its faces. A typical angle block is shown in [Figure 21.12](#). The blocks can be stacked together in various combinations on a surface table to provide a range of different reference angles. Each block is calibrated to a very high standard of accuracy, with a typical measurement uncertainty of 0.1 s of arc ( $0.5 \mu\text{rad}$ ). In use, the total measurement uncertainty is normally some multiple of 0.1 s of arc according to how many blocks are stacked together to provide the reference angle required. However, this is clearly a substantially higher standard of accuracy than that provided by a sine bar.





**Figure 21.13**  
Variation gauge.

## 21.4 Surface Flatness Measurement

The only dimensional parameter not so far discussed, where a measurement requirement sometimes exists is the flatness of the surface of a component. This is measured by a *variation gauge*. As shown in [Figure 21.13](#), this has 4 feet, three of which are fixed and one of which floats in a vertical direction. Motion of the floating foot is measured by a dial gauge that is calibrated such that its reading is zero when the floating foot is exactly level with the fixed feet. Thus, any nonzero reading on the dial gauge indicates nonflatness at the point of contact of the floating foot. By moving the variation gauge over the surface of a component and taking readings at various points, a contour map of the flatness of the surface can be obtained.

### 21.4.1 Calibration of Variation Gauge

The accuracy of flatness measurements made by a variation gauge depends firstly on the calibration of the dial gauge within the variation gauge and secondly on the repeatability of the measurement obtained when the dial gauge is brought down onto a horizontal surface. Calibration of the dial gauge itself is obtained by moving it down to gauge blocks set to known heights. The measurement repeatability is tested by moving the dial gauge down to a reference surface table a number of times and recording the variation in the readings obtained.

## 21.5 Volume Measurement

Volume measurement is required in its own right as well as being required as a necessary component in some techniques for the measurement and calibration of other quantities

such as volume flow rate and viscosity. The volume of vessels of a regular shape, where the cross-section is circular or oblong in shape, can be readily calculated from the dimensions of the vessel. Otherwise, for vessels of irregular shape, it is necessary to use either gravimetric techniques or a set of calibrated volumetric measures.

In the gravimetric technique, the dry vessel is weighed and then is completely filled with water and weighed again. The volume is then simply calculated from this weight difference and the density of water. Measurement uncertainty is low, since it is possible to measure the two weights to a high degree of accuracy. However, since the arithmetic operation of subtracting the two weights amplifies errors, it is sensible to arrange for the difference between the two weights to be as large as possible.

The alternative technique involves transferring the liquid from the vessel into an appropriate number of volumetric measures taken from a standard-capacity, calibrated set. Each vessel in the set has a mark that shows the volume of liquid contained when the vessel is filled up to the mark. Special care is needed to ensure that the meniscus of the water is in the correct position with respect to the reference mark on the vessel when it is deemed to be full. Normal practice is to set the water level such that the reference mark forms a smooth tangent with the convex side of the meniscus. This is made easier to achieve if the meniscus is viewed against a white background and the vessel is shaded from stray illumination.

The measurement uncertainty using calibrated volumetric measures depends on the number of measures used for any particular measurement. The total error is a multiple of the individual error of each measure, typical values of which are shown in [Table 21.2](#).

### 21.5.1 Calibration of Volume Measurements

Calibration of volume measurements is normally achieved with the gravimetric technique, as described above, but with certain special precautions applied. First, the water used to fill the vessel is either distilled or deionized. (Where very large vessels are

**Table 21.2: Typical measurement uncertainty of calibrated volumetric measures**

Capacity	Volumetric Uncertainty
1 ml	$\pm 4\%$
10 ml	$\pm 0.8\%$
100 ml	$\pm 0.2\%$
1 l	$\pm 0.1\%$
10 l	$\pm 0.05\%$
100 l	$\pm 0.02\%$
1000 l	$\pm 0.02\%$

being calibrated and it is impractical to use anything other than tap water, the difference in water density compared with pure water gives a typical error of 0.02%.) Second, the calibration is carried out under specified temperature and pressure conditions, and sufficient time must be allowed for the vessel and water to become in close thermal equilibrium. This latter condition is most easily achieved by maintaining a store of distilled or deionized water in the calibration laboratory, which ensures that the water is automatically at the correct temperature. Lastly, correction may have to be made for changes in air buoyancy, which become significant if calibration is carried out at altitudes greater than 150 m.

## 21.6 Viscosity Measurement

Viscosity measurement is important in many process industries. In the food industry, the viscosity of raw materials such as dough, batter, and ice cream has a direct effect on the quality of the product. Similarly, in other industries such as the ceramic one, the quality of raw materials affects the final product quality. Viscosity control is also very important in assembly operations that involve the application of mastics and glue flowing through tubes. Clearly, successful assembly requires such materials to flow through tubes at the correct rate and therefore it is essential that their viscosity is correct.

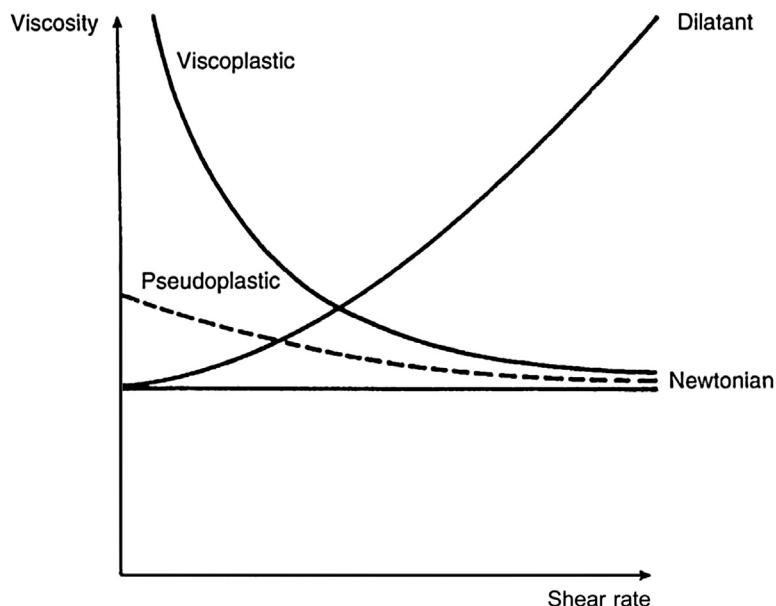
Viscosity describes the way in which a fluid flows when it is subject to an applied force. Consider an elemental cubic volume of fluid and a shear force  $F$  applied to one of its faces of area  $A$ . If this face moves a distance  $L$  and at a velocity  $V$  relative to the opposite face of the cube under the action of  $F$ , the shear stress ( $s$ ) and shear rate ( $r$ ) are given by

$$s = F/A; \quad r = V/L$$

The *coefficient of viscosity* ( $C_V$ ) is the ratio of shear stress to shear rate, that is,  $C_V = s/r$ .

$C_V$  is often described simply as the “viscosity.” A further term, *kinematic viscosity*, is also sometimes used, given by  $K_V = C_V/\rho$ , where  $K_V$  is the kinematic viscosity and  $\rho$  is the fluid density. To avoid confusion,  $C_V$  is often known as the *dynamic viscosity*, to distinguish it from  $K_V$  ·  $C_V$  is measured in units of poise or  $\text{Ns/m}^2$  and  $K_V$  is measured in units of Stokes or  $\text{m}^2/\text{s}$ .

Viscosity was originally defined by Newton, who assumed that it was constant with respect to shear rate. However, it has since been shown that the viscosity of many fluids varies significantly at high shear rates and the viscosity of some even varies at low shear rates. The worst non-Newtonian characteristics tend to occur with emulsions, pastes, and slurries. For non-Newtonian fluids, subdivision into further classes can also be made according to the manner in which the viscosity varies with shear rate, as shown in [Figure 21.14](#).



**Figure 21.14**  
Different viscosity/shear rate relationships.

The relationship between the input variables and output measurement for instruments that measure viscosity normally assumes that the measured fluid has Newtonian characteristics. For non-Newtonian fluids, a correction must be made for shear rate variations. If such a correction is not made, the measurement obtained is known as the **apparent viscosity**, and this can differ from the true viscosity by a large factor. The true viscosity is often called the **absolute viscosity** to avoid ambiguity. Viscosity also varies with fluid temperature and density.

Instruments for measuring viscosity work on one of the following three physical principles:

- Rate of flow of the liquid through a tube
- Rate of fall of a body through the liquid
- Viscous friction force exerted on a rotating body

#### *Capillary and tube viscometers*

These are the most accurate types of viscometer, with typical measurement inaccuracy levels down to  $\pm 0.3\%$ . Liquid is allowed to flow from a reservoir, under gravity, through a tube of known cross-section. In different instruments, the tube can vary from capillary-sized to a large diameter. The pressure difference across the ends of the tube and the time

for a given quantity of liquid to flow are measured, and then the liquid viscosity for Newtonian fluids can be calculated as (in units of poise) follows:

$$C_V = \frac{1.25\pi R^4 PT}{LV}$$

where  $R$  is the radius (m) of the tube,  $L$  is its length (m),  $P$  is the pressure difference ( $\text{N/m}^2$ ) across the ends, and  $V$  is the volume of liquid flowing in time  $T$  ( $\text{m}^3/\text{s}$ ).

For non-Newtonian fluids, corrections must be made for shear rate variations. For any given viscometer,  $R$ ,  $L$ , and  $V$  are constants and the above equation can be written as

$$C_V = KPT$$

where  $K$  is known as the viscometer constant.

### *Falling body viscometer*

The falling body viscometer is particularly recommended for the measurement of high-viscosity fluids. It can give measurement uncertainty levels down to  $\pm 1\%$ . It involves measuring the time taken for a spherical body to fall a given distance through the liquid. The viscosity for Newtonian fluids is then given by Stoke's formula as (in units of poise) follows:

$$C_V = \frac{R^2 g (\rho_s - \rho_l)}{450V}$$

where  $R$  is the radius (m) of the sphere,  $g$  is the acceleration due to gravity ( $\text{m/s}^2$ ),  $\rho_s$  and  $\rho_l$  are the specific gravities ( $\text{g/m}^3$ ) of the sphere and liquid respectively, and  $V$  is the velocity (m/s) of the sphere.

Unfortunately, the falling body viscometer is only accurate for Newtonian fluids, since correction for the variation in shear rate that occurs in non-Newtonian fluids is very difficult.

### *Rotational viscometers*

Rotational viscometers are relatively easy to use but their measurement inaccuracy is at least  $\pm 10\%$ . All types have some form of element rotating inside the liquid at a constant rate. One common version has two coaxial cylinders with the fluid to be measured contained between them. One cylinder is driven at a constant angular velocity by a motor and the other is suspended by torsion wire. After the driven cylinder starts from rest, the suspended cylinder rotates until an equilibrium position is reached, where the force due to the torsion wire is just balanced by the viscous force transmitted through the liquid. The viscosity (in poise) for Newtonian fluids is then given by

$$C_V = 2.5G \left( \frac{1/R_1^2 - 1/R_2^2}{\pi h \omega} \right)$$

where  $G$  is the couple (Nm) formed by the force exerted by the torsion wire and its deflection,  $R_1$  and  $R_2$  are the radii (m) of the inner and outer cylinders,  $h$  is the length of the cylinder (m), and  $\omega$  is the angular velocity (rad/s) of the rotating cylinder. Again, corrections have to be made for non-Newtonian fluids.

### **21.6.1 Viscosity Calibration**

Viscosity standards are only defined for Newtonian fluids. No such standards exist for non-Newtonian fluids.

Viscosity calibration for Newtonian liquids is carried out using a set of glass-capillary tubes with accurately known viscometer constants. These provide reference standards over a range of viscosities. The set is calibrated by a “step-up” procedure from a calibration on distilled water, using a series of standard liquids. The steps in this procedure are as follows:

1. A “master” viscometer is calibrated first using distilled water as the flowing fluid.
2. The “master” is then used to measure the viscosity of the first standard-viscosity liquid.
3. This liquid is then used to calibrate the first standard viscometer.
4. After this, the viscosity of the second standard liquid is measured by the first standard viscometer and then the second standard viscometer is calibrated using the second standard liquid.
5. This procedure is repeated to calibrate the other standard viscometers in the set using the other standard liquids.

It is common practice to maintain two sets of such standard viscometers, one as a working set for routine calibrations and one as a reference set for calibration checks on the working set. Higher-level calibration is provided by comparison with a set of standard glass-capillary viscometers maintained by National Standards Organisations. Such organizations also commonly supply a range of standard-viscosity liquids as an alternative calibration source. Where standard liquids are kept for calibration, they must be checked periodically to ensure their continuing stability as they age.

As there are no absolute physical quantities that the calibration of viscosity values can be checked against, the various National Standards Organisations carry out cross-checks between each other’s laboratories. These checks take two forms. One is to transport a reference set of viscometers between laboratories and to compare the viscometer constants measured, with appropriate correction for differences in the value of  $g$  (acceleration due to gravity). The other form of check is to compare measurements made on standard liquids at a specified temperature.

In the case of non-Newtonian fluids, as has already been stated, there are no formal viscosity standards. Therefore, the only course of action available for checking

viscometers intended to measure non-Newtonian fluids, is to calibrate them against standard-viscosity Newtonian fluids.

## **21.7 Moisture Measurement**

There are many industrial requirements for the measurement of the moisture content in materials. The material containing moisture may be either in solid, liquid, or gaseous form. There are several common reasons for needing to know the moisture of materials in each form.

The physical properties and storage stability of most solid materials are affected by their water content. There is also a statutory requirement to limit the moisture content in the case of many materials sold by weight. In consequence, the requirement for moisture measurement pervades a large number of industries involved in the manufacture of foodstuffs, pharmaceuticals, cement, plastics, textiles, and paper.

Measurement of the water content in liquids is commonly needed for fiscal purposes, but is also often necessary to satisfy statutory requirements. The petrochemical industry has wide-ranging needs for moisture measurement in oil and so on. The food industry also needs to measure the water content of products such as beer and milk.

In the case of moisture in gases, the most common measurement is the amount of moisture in air. This is usually known as the *humidity* level. Humidity measurement and control is an essential requirement in many buildings, greenhouses, and vehicles.

### **21.7.1 Industrial Moisture Measurement Techniques**

Industrial methods for measuring moisture are based on the variation of some physical property of the material with moisture content in it. Many different properties can be used, and therefore the range of available techniques, as listed below, is large.

#### ***Electrical methods***

The most common technique for determining moisture content is to measure the amount of absorption of *microwave energy* beamed through the material. This uses the principle that microwaves at wavelengths between 1 mm and 1 m are absorbed to a much greater extent by water than by most other materials. Wavelengths of 30 or 100 mm are commonly used because “off-the-shelf” equipment to produce these is readily available from instrument suppliers. The technique is suitable for measuring the moisture content of solids, liquids, and gases at moisture-content levels up to 45% and measurement uncertainties down to  $\pm 0.3\%$  are possible.

The *capacitance moisture meter* uses the principle that the dielectric constant of materials varies according to their water content. The moisture content of materials is therefore related to the capacitance. The instrument is useful for measuring moisture-content levels up to 30% in both solids and liquids, and measurement uncertainty down to  $\pm 0.3\%$  is possible. Drawbacks of the technique include (1) limited measurement resolution owing to the difficulty in measuring small changes in a relatively large standing capacitance value and (2) difficulty when the sample has a high electrical conductivity. An alternative capacitance charge transfer technique overcomes these problems by measuring the charge-carrying capacity of the material. In this technique, wet and dry samples of the material are charged to a fixed voltage and then simultaneously discharged into charge-measuring circuits.

The *electrical conductivity* of most materials varies with moisture content and this therefore provides another means of measurement. Techniques using electrical conductivity variation are cheap and can measure moisture levels up to 25%. However, the presence of other conductive substances in the material such as salts or acids affects the measurement accuracy.

A further electrical method is to measure the frequency change in a *quartz crystal* that occurs as it takes in moisture.

### *Neutron moderation*

Neutron moderation measures moisture content using a radioactive source and a neutron counter. Fast neutrons emitted from the source are slowed down by hydrogen nuclei in the water, forming a cloud, whose density is related to the moisture content. Measurements take a long time because the output-density reading may take up to a few minutes to reach steady state, according to the nature of the materials involved. Also, the method cannot be used with any materials that contain hydrogen molecules, such as oils and fats, as these slow down neutrons as well. Specific humidities up to 15% can be measured, with a measurement uncertainty of  $\pm 1\%$ .

### *Low-resolution nuclear magnetic resonance*

Low-resolution nuclear magnetic resonance (NMR) involves subjecting the sample to both a unidirectional and an alternating radio frequency (RF) magnetic field. The amplitude of the unidirectional field is varied cyclically, which causes resonance once per cycle in the coil producing the RF field. Under resonance conditions, protons are released from the hydrogen content of the water in the sample. These protons cause a measurable moderation of the amplitude of the RF oscillator waveform that is related to the moisture content of the sample.

Materials that naturally have hydrogen content cannot normally be measured. However, pulsed NMR techniques have been developed that overcome this problem by taking



advantage of the different relaxation times of hydrogen nuclei in water and oil. In such pulsed techniques, the dependence on the relaxation time limits the maximum fluid flow rate for which moisture can be measured.

### *Optical methods*

The *refractometer* is a well-established instrument that is used for measuring the water content of liquids. It measures the refractive index of the liquid, which changes according to the moisture content.

Moisture-related *energy absorption* of near-infrared light can be used for measuring the moisture content of solids, liquids, and gases. At a wavelength of 1.94  $\mu\text{m}$ , energy absorption due to moisture is high, whereas at 1.7  $\mu\text{m}$ , absorption due to moisture is zero. Therefore, measuring absorption at both 1.94 and 1.7  $\mu\text{m}$  allows absorption due to components in the material other than water to be compensated for, and the resulting measurement is directly related to energy content. The latest instruments use multiple-frequency infrared energy and have an even greater capability for eliminating the effect of components in the material other than water that absorb energy. Such multifrequency instruments also cope much better with variations in particle size in the measured material.

In alternative versions of this technique, energy is either transmitted through the material or reflected from its surface. In either case, materials that are either very dark or highly reflective give poor results. The technique is particularly attractive, where applicable, because it is a noncontact method that can be used to monitor moisture content continuously at moisture levels up to 50%, with inaccuracy as low as  $\pm 0.1\%$  in the measured moisture level.

### *Ultrasonic methods*

The presence of water changes the speed of propagation of ultrasonic waves through liquids. The moisture content of liquids can therefore be determined by measuring the transmission speed of ultrasound. This has the inherent advantage of being a noninvasive technique, but temperature compensation is essential because the velocity of ultrasound is particularly affected by temperature changes. The method is best suited to measurement of high moisture levels in liquids that are neither aerated nor of high viscosity. Typical measurement uncertainty is  $\pm 1\%$  but measurement resolution is very high, with changes in moisture level as small as 0.05% being detectable.

### *Mechanical properties*

Density changes in many liquids and slurries can be measured and related to moisture content, with good measurement resolution up to 0.2% moisture. Moisture content can also be estimated by measuring the moisture-level-dependent viscosity of liquids, pastes, and slurries.

### 21.7.2 Laboratory Techniques for Moisture Measurement

Various laboratory techniques for measuring moisture content are available as described below. While these generally take much longer to produce a measurement than the industrial techniques described above, the measurement accuracy obtained is usually much better.

#### *Water separation*

A number of laboratory techniques are available that enable the moisture content of liquids to be measured accurately by separating the water from a sample of the host liquid. Separation is effected either by titration (Karl Fischer technique), distillation (Dean and Stark technique), or a centrifuge. Any of these methods can measure water content in a liquid with measurement uncertainty levels down to  $\pm 0.03\%$ .

#### *Gravimetric methods*

Moisture content in solids can be measured accurately by weighing the moist sample, drying it, and then weighing again. Great care must be taken in applying this procedure, as many samples rapidly take up moisture again if they are removed from the drier and exposed to the atmosphere before being weighed. The normal procedure is to put the sample in an open container, dry it in an oven, and then screw an airtight top onto the container before it is removed from the oven.

#### *Phase-change methods*

The boiling and freezing point of materials are altered by the presence of moisture, and therefore the moisture level can be determined by measuring the phase-change temperature. This technique is used for measuring the moisture content in many food products and also in some oil and alcohol products.

#### *Equilibrium relative humidity measurement*

This technique involves placing a humidity sensor in close proximity to the sample in an airtight container. The water vapor pressure close to the sample is related to the moisture content of the sample. The moisture level can therefore be determined from the humidity measurement.

### 21.7.3 Humidity Measurement

The term *humidity* describes the moisture content of air. This moisture content can be expressed in three alternative ways, which are known as the absolute humidity, the specific humidity, and the relative humidity.

**Absolute humidity** is the mass of water in a unit volume of moist air.

**Specific humidity** is the mass of water in a unit mass of moist air.

**Relative humidity** is the ratio of the actual water vapor density in air to the saturation vapor density, usually expressed as a percentage. The saturation vapor density varies with temperature, and so the relative humidity also varies with temperature for any given measured value of actual vapor density.

The three major instruments used for measuring humidity in industry are the electrical hygrometer, the psychrometer, and the dew point meter. The dew point meter is the most accurate of these and is commonly used as a calibration standard.

#### *The electrical hygrometer*

The electrical hygrometer measures the change in capacitance or conductivity of a hygroscopic material as its moisture level changes. Instruments measuring conductivity change use two noble metal electrodes either side of an insulator coated in a hygroscopic salt such as calcium chloride. Capacitance types have two plates either side of a hygroscopic dielectric such as aluminum oxide.

These instruments are suitable for measuring moisture levels between 15% and 95%, with typical measurement uncertainty of  $\pm 3\%$ . Atmospheric contaminants and operation in saturation conditions both cause drift in the characteristics of the instrument, and therefore the recalibration frequency has to be determined according to the conditions of use.

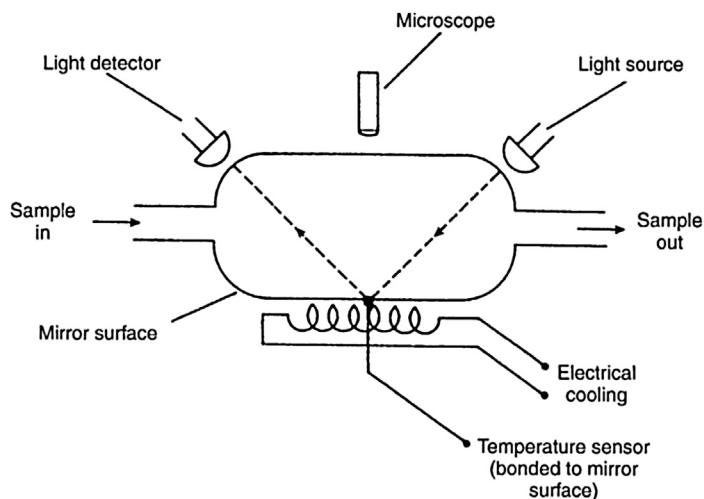
#### *The psychrometer (wet- and dry-bulb hygrometer)*

The psychrometer, also known as the wet- and dry-bulb hygrometer, has two temperature sensors, one exposed to the atmosphere and one enclosed in a wet wick. Air is blown across the sensors, which causes evaporation and a reduction in temperature in the wet sensor. The temperature difference between the sensors is related to the humidity level. The lowest measurement uncertainty attainable is  $\pm 4\%$ .

#### *Dew point meter*

The elements of the dew point meter, also known as the dew point hygrometer, are shown in [Figure 21.15](#). The sample is introduced into a vessel with an electrically cooled mirror surface. The mirror surface is cooled until a light source-light detector system detects the formation of dew on the mirror, and the condensation temperature is measured by a sensor bonded to the mirror surface. The dew point is the temperature at which the sample becomes saturated with water. Therefore, this temperature is related to the moisture level in the sample. A microscope is also provided in the instrument so that the thickness and nature of the condensate can be observed.

Even small levels of contaminants on the mirror surface can cause large changes in the dew point, and therefore the instrument must be kept very clean. When necessary, the mirror should be cleaned with deionized or distilled water applied with a lint-free swab.



**Figure 21.15**  
Dew point meter.

Any contamination can be detected by a skilled operator, as this makes the condensate look “blotchy” when viewed through the microscope. The microscope also shows up other potential problems such as large ice crystals in the condensate that cause temperature gradients between the condensate and the temperature sensor. When used carefully, the instrument is very accurate and is often used as a reference standard.

#### *MEMS relative humidity sensor*

MEMS relative humidity sensors usually incorporate two sensing elements, one to measure humidity and one to measure temperature (since the relative humidity for any given value of measured water vapor density varies with temperature). The humidity sensor is a differential capacitance type that consists of a layer sensitive to water vapor that is sandwiched between two electrodes that act as capacitor plates. The upper electrode consists of a grid that allows water vapor to pass into the sensitive layer, thus altering the capacitance between the two electrodes. On-chip circuits carry out automatic calibration and signal processing to produce a relative humidity measurement.

#### **21.7.4 Calibration of Moisture and Humidity Measurements**

Microwave techniques as described in [Section 21.7.1](#) are usually accurate enough for working standard calibration. The electrical hygrometer can also be used for calibration at this level providing that it is not subjected to near-saturation conditions and provided that it is stored carefully away from possible contaminants. The dew point meter is also suitable for workplace calibration. For calibration to a higher standard of accuracy,

gravimetric or water-separation laboratory techniques (see [Section 21.7.2](#)) are used. In the case of calibration even further up the calibration chain to secondary and primary reference standards, the method used depends on whether the instrument being calibrated is designed to measure a fluid (liquid or gas) or a solid.

In the case of calibration of instruments measuring the moisture content of gases and liquids to secondary and primary reference standards, test samples are used. These are created by making up mixtures of a gas or liquid with water in known proportions, such that the water content is accurately known. The instrument being calibrated is applied to these samples to see whether its output reading agrees with the known water content. Test samples created in a company's own calibration laboratory can be used as a secondary reference standard. However, for calibration to primary reference standards, test samples provided by National Standards Organisations must be used.

The calibration of instruments measuring the moisture content of solids to secondary and primary reference standards is less easy. It is often difficult to make up a test sample with an even distribution of water through it. Therefore, gravimetric techniques of calibration (see [Section 21.7.2](#)) are normally used instead.

## 21.8 Sound Measurement

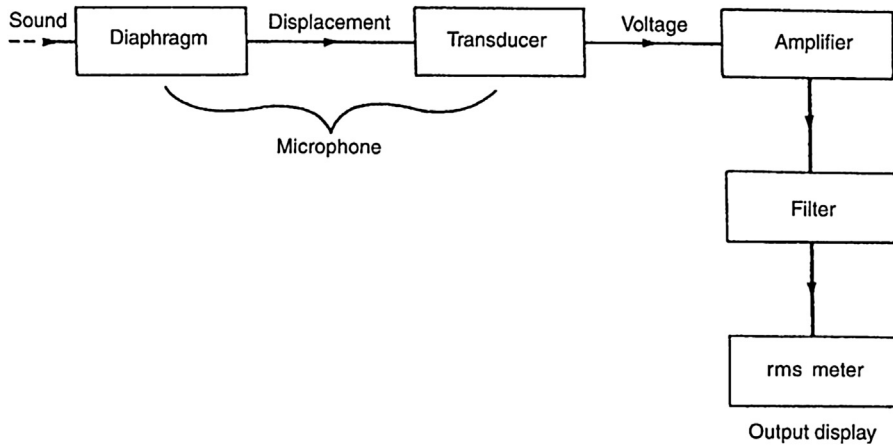
Noise can arise from many sources in both industrial and nonindustrial environments. Even low levels of noise can cause great annoyance to the people subjected to it and high levels of noise can actually cause hearing damage. Apart from annoyance and possible hearing loss, noise in the workplace also causes loss of output, where the persons subjected to it are involved in tasks requiring high concentration. Extreme noise can even cause material failures through fatigue stresses set up by noise-induced vibration.

Most countries have legislation to control the creation of noise. Court orders can be made against houses or factories in a neighborhood that create noise exceeding a certain acceptable level. In extreme cases, where hearing damage may be possible, health and safety legislation comes into effect. Such legislation clearly requires the existence of accurate methods of quantifying sound levels. Sound is measured in terms of the *sound pressure level*,  $S_p$ , which is defined as

$$S_p = 20 \log_{10} \left( \frac{P}{0.0002} \right) \text{ decibels (dB)}$$

where  $P$  is the rms sound pressure in  $\mu\text{bar}$ .

The quietest sound that the average human ear can detect is a tone at a frequency of 1 kHz and sound pressure level of 0 dB ( $2 \times 10^{-4} \mu\text{bar}$ ). At the upper end, sound pressure levels of 144 dB (3.45 mbar) cause physical pain.



**Figure 21.16**  
Components in a sound meter.

Sound is usually measured with a sound meter. This essentially processes the signal collected by a microphone, as shown in Figure 21.16. The microphone is a diaphragm-type pressure-measuring device that converts sound pressure into a displacement. The displacement is applied to a displacement transducer (normally capacitive, inductive, or piezoelectric type) which produces a low-magnitude voltage output. This is amplified, filtered, and finally gives an output display on an rms meter. The filtering process has a frequency response that usually approximates to that of the human ear so that the sound meter “hears” sounds in the same way as a human ear. In other words, the meter selectively attenuates frequencies according to the sensitivity of the human ear at each frequency, so that the sound-level measurement output accurately reflects the sound level heard by humans. However, if sound-level meters are being used to measure sound to predict vibration levels in machinery, then they are used without filters so that the actual rather than the human-perceived sound level is measured.

*MEMS sound sensors* are also now available in which the varying-capacitance sensing element consists of a fixed back-plate and a movable membrane-plate. Acoustic holes in the membrane-plate allow sound to pass through, which modulates the air gap and hence capacitance between the plates. Different forms of sensor offer both analog and digital forms of output. The analog type converts the capacitance change into a varying voltage output whereas, the digital type converts the capacitance change into a form of pulse density modulation. Such MEMS devices are very useful in applications like cell phones, where their small size and weight are of extreme importance.

### 21.8.1 Calibration of Sound Meters

Calibration of sound meters requires the use of a sound-calibrating instrument that generates standard sound pressure levels at several defined frequencies. The reading of

the sound meter is then compared with the magnitude of the sound pressure level emitted by the calibration instrument at each defined sound frequency. In practice, great skill is needed in performing the calibration to ensure that the results are accurate, since there are several potential difficulties. Appropriate instructions are provided with proprietary calibration instruments but it is generally safer to give the task of sound meter calibration to specialist calibration companies or the sound meter manufacturer.

## 21.9 pH Measurement

pH is a parameter that quantifies the level of acidity or alkalinity in a chemical solution. It defines the concentration of hydrogen atoms in the solution in grams/liter and is expressed as:  $\text{pH} = \log_{10}[1/\text{H}^+]$  where  $\text{H}^+$  is the hydrogen ion concentration in the solution.

The value of pH can range from 0, which describes extreme acidity, to 14, which describes extreme alkalinity. Pure water has a pH of 7. pH measurement is required in many process industries, and especially those involving food and drink production. The most universally known method of measuring pH is to use litmus paper or some similar chemical indicator that changes color according to the pH value. Unfortunately, this method gives only a very approximate indication of pH unless used under highly controlled laboratory conditions. However, at the present time, the device known as the glass electrode is by far the most common used.

### *The glass electrode*

The glass electrode consists of a glass probe containing two electrodes, a measuring one and a reference one, separated by a solid glass partition. Neither of the electrodes is in fact glass. The reference electrode is a screened electrode, immersed in a buffer solution, which provides a stable reference emf that is usually 0 V. The tip of the measuring electrode is surrounded by a pH-sensitive glass membrane at the end of the probe, which permits the diffusion of ions according to the hydrogen ion concentration in the fluid outside the probe. The measuring electrode therefore generates an emf proportional to pH that is amplified and fed to a display meter. The combination of a glass electrode and its display meter is commonly known as a *pH meter*. These are available in both benchtop and handheld versions.

While being theoretically capable of measuring the full range of pH values between 0 and 14, the upper measurement limit is generally a pH value of about 12 in practice because electrode contamination at very high alkaline concentrations becomes a serious problem and also glass starts to dissolve at such high pH values. However, measurement of any pH value requires careful use of a glass electrode type of pH probe. First, the measuring probe has a very high resistance (typically  $10^8 \Omega$ ) and a very low output. Hence, the output signal from the probes must be electrically screened to prevent any stray pickup and

electrical insulation of the assembly must be very high. The assembly must also be very efficiently sealed to prevent the ingress of moisture.

A second problem with the glass electrode is the deterioration in accuracy that occurs as the glass membrane becomes coated with various substances it is exposed to in the measured solution. Cleaning at prescribed intervals is therefore necessary and this must be carried out carefully, using the correct procedures, to avoid damaging the delicate glass membrane at the end of the probe. The best cleaning procedure varies according to the nature of the contamination. In some cases, careful brushing or wiping is adequate, whereas in other cases spraying with chemical solvents is necessary. Ultrasonic cleaning is often a useful technique, though it tends to be expensive. Steam cleaning should not be attempted, as this damages the pH-sensitive membrane. Mention must also be made about storage. The glass electrode must not be allowed to dry out during storage, as this would cause serious damage to the pH-sensitive layer, and normal procedure is to keep it in a potassium chloride solution if it is normally used for measuring alkaline pH levels (pH above 7) or in weak sulfuric acid if it is used for measuring acidic pH levels (pH 0–7).

The response time of a glass electrode also requires careful attention. The instrument has a relatively large time constant of 1–2 min, and so it must be left to settle for a long time before the reading is taken.

Various forms of glass electrode are available to maximize performance under various measurement conditions. High-temperature versions made from special glass are available for measurement in high temperatures. These are designed to minimize the premature aging that occurs when ordinary electrodes are used at high temperature, which reduces both their accuracy and their service life. Special low-temperature versions are available made from low-resistivity glass that maximizes their speed of response when used in low temperatures. Flat-profile electrodes are available for use in situations, where there are high levels of particles present in the measured liquid, such as occurs in paper-making applications. The flat profile makes them largely self-cleaning and avoids the rapid degradation in performance that would occur with standard glass electrodes. Special glass is also needed for pH measurement in acid solutions containing fluoride, since standard glass dissolves in such an environment.

#### *Other methods of pH measurement*

The *antimony electrode* has a similar construction to the glass electrode but uses antimony instead of glass. The device is more robust than the glass electrode and can be cleaned by rubbing it with emery cloth. However, its time constant is very large and its output response is grossly nonlinear, limiting its application to environments, where the glass electrode is unsuitable. Such applications include acidic environments containing fluoride and environments containing very abrasive particles. The normal measurement range is pH 1–11.



*Solid-state pH electrodes* are another relatively recent development. These are based on an ion-selective field-effect transistor in which the current flowing between two semiconductor elements in the device varies with pH in an analogous way to the variation in potential difference within a glass electrode. Such solid-state sensors are physically much smaller than glass electrodes and they are also much more robust, both of which are significant advantages in some applications. However, their current mode of output means they cannot be used within a standard pH meter and their accuracy is inferior to that of glass electrodes.

A *fiber-optic pH* sensor is another available device, as described earlier in Chapter 13, in which the pH level is indicated by the intensity of light reflected from the tip of a probe coated in a chemical indicator, whose color changes with pH. Unfortunately, this device only has the capability to measure over a very small range of pH (typically 2 pH) and it has a short life.

### **21.9.1 pH Calibration**

The characteristics of the glass electrode are very dependent on ambient temperature, with both zero drift and sensitivity drift occurring. Thus, temperature compensation is essential and it is normally necessary to recalibrate the measurement system every time there is a change in temperature.

Calibration is performed by immersing the probe in buffer solutions at reference pH values. These solutions are available commercially and can either be bought as a ready-made-up solution or in a solid form. In the case of the solid form, the buffer solution is made by dissolving the solid in deionized water. Whatever the source of the calibration buffer solution, great care must be taken to control the temperature at which the calibration is performed and ensure that it is the same as that specified with the buffer solution for its pH value to be valid.

### **21.10 Gas Sensing and Analysis**

Gas sensing and analysis is required in many applications. A primary role of gas sensing is in hazard monitoring to predict the onset of conditions, where flammable gases are reaching dangerous concentrations. Danger is quantified in terms of the *lower explosive level*, which is usually reached when the concentration of a flammable gas in air is in the range of between 1% and 5%.

Gas sensing also provides a fire detection and prevention function. When materials burn, a variety of gaseous products result. Most sensors that are used for fire detection measure carbon monoxide concentration, as this is the most common combustion product. Early fire detection enables fire-extinguishing systems to be triggered, preventing serious damage

from occurring in most cases. However, fire-prevention is even better than early fire detection, and solid-state sensors, based on a sintered mass of polycrystalline tin oxide, can now detect the gaseous products (generally various types of hydrocarbon) that are generated when materials become hot but before they actually burn.

Health and safety legislation creates a further requirement for gas sensors. Certain gases, such as carbon monoxide, hydrogen sulfide, chlorine, and nitrous oxide, cause fatalities above a certain concentration and sensors must provide warning of impending danger. For other gases, health problems are caused by prolonged exposure, and so the sensors in this case must integrate gas concentration over time to determine whether the allowable exposure limit over a given period of time has been exceeded. Again, solid-state sensors are now available to fulfill this function.

Concern about general environmental pollution is also making the development of gas sensors necessary in many new areas. Legislation is growing rapidly around the world to control the emission of everything that is proven or suspected to cause health problems or environmental damage. The present list of controlled emissions includes nitrous oxide, oxides of sulfur, carbon monoxide, carbon dioxide, CFCs, ammonia, and hydrocarbons. Sensors are required both at the source of these pollutants, where concentrations are high, and also to monitor the much lower concentrations in the general environment. Oxygen concentration measurement is also often of great importance in pollution control, as the products of combustion processes are greatly affected by the air/fuel ratio.

Sensors associated with pollution monitoring and control usually have to satisfy quite stringent specifications, particularly where the sensors are located at the pollutant source. Robustness is usually essential, as such sensors are subjected to bombardment from a variety of particulate matters, and they must also endure conditions of high humidity and temperature. They are also frequently located in inaccessible locations, such as in chimneys and flues, which means that they must have stable characteristics over long periods of time without calibration checks being necessary. The need for such high-specification sensors makes such pollutant-monitoring potentially very expensive if there are several problem gases involved. However, because the concentration of all output gases tends to vary to a similar extent according to the condition of filters etc., it is frequently only necessary to measure the concentration of one gas, from which the concentration of other gases can be predicted reliably. This greatly reduces the cost involved in such monitoring.

Various devices are currently available that detect, quantify the concentration, and analyze gases. These are discussed in the following paragraphs. However, the comment must be added that research into gas sensors is a very active field and new developments are being made all the time.

### *Catalytic bead (calorimetric) sensors*

Catalytic sensors, also known as calorimetric sensors, have widespread use for measuring the concentration of combustible hydrocarbon gases. They consist of a coil of wire that is coated first with glass or a ceramic material and then with a catalyst on the outside. The coil is electrically heated to a temperature where the monitored gas starts to burn. The burning process liberates heat proportional to the gas concentration. The consequent increase in the temperature of the wire coil increases its resistance, and the gas concentration can then be calculated by measuring the resistance change.

This type of sensor is cheap, small, and robust. Unfortunately, the catalysts normally used in these devices are adversely affected by many common industrial substances such as lead, phosphorous, silicon, and sulfur. Also, devices with a standard catalyst cannot be used to measure high gas concentrations because the corresponding high temperature that they have to operate at adversely affects them. Fortunately, new types of poison-resistant and heat-resistant catalyst are now available and used in sensors available from several manufacturers.

### *Paper tape sensors*

By moving a paper tape impregnated with a reagent sensitive to a specific gas (e.g., lead acetate tape to detect hydrogen sulfide) through an air stream at a constant speed, the time-history of the concentration of gas is indicated by the degree of color change in the tape. This technique is now quite old technology but it is still widely used as a low accuracy but reliable and cheap means of detecting the presence of hydrogen sulfide and ammonia.

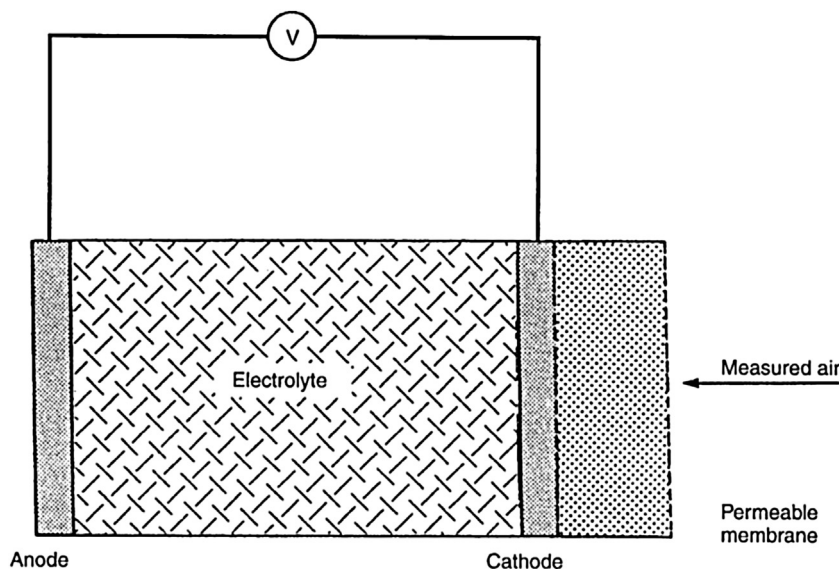
### *Color change badges*

The principle of paper tape sensors is used in special badges worn by personnel to indicate the presence of toxic gases. Badges are available for detecting hydrogen sulfide, chlorine, hydrazine, carbon monoxide, ozone, nitrogen dioxide, ammonia, and other gases.

### *Liquid electrolyte electrochemical cells*

These consist of two electrodes separated by electrolyte, to which the measured air supply is directed through a permeable membrane, as shown in [Figure 21.17](#). The gas in the air to which the cell is sensitive reacts at the electrodes to form ions in the solution. This produces a voltage output from the cell.

Electrochemical cells have stable characteristics and give good measurement sensitivity and accuracy even when monitoring low concentrations of gas. However, they are expensive and their durability is relatively poor, with life being generally limited to about 1 or 2 years at most. A further restriction is that they cannot be used above temperatures



**Figure 21.17**  
Liquid electrolyte electrochemical cell.

of about 50 °C, as their performance deteriorates rapidly at high temperatures because of interference from other atmospheric substances.

The main use of such cells is in measuring toxic gases in satisfaction of health and safety legislation. Versions of the cell for this purpose are currently available to measure carbon monoxide, chlorine, nitrous oxide, hydrogen sulfide, and ammonia. Cells to measure other gases are currently under development.

In addition, electrochemical cells are also used to a limited extent to monitor carbon monoxide emissions in flue gases for environmental control purposes. Precooling of the emitted gases is a necessary condition for this application.

#### *Solid-state electrochemical cell (zirconia sensor)*

This type of cell, commonly called the zirconia sensor, is primarily used for measuring oxygen concentration. The oxygen-measurement cell consists of two chambers separated by a zirconia wall. One chamber contains gas with a known oxygen concentration and the other contains the air being measured. Ions are conducted across the zirconia wall according to the difference in oxygen concentration across it and this produces an output emf. The device is rugged but requires high temperatures to operate efficiently. It is however well proven and a standard choice for oxygen measurement. In industrial uses, it is often located in chimney stacks, where quite expensive mounting and protection systems are needed. However, very low-cost versions are now used in some vehicle exhaust systems as part of the engine management system.

### *Catalytic gate FETs*

These consist of field effect transistors with a catalytic, palladium gate that is sensitive to hydrogen ions in the environment. The gate voltage, and hence characteristics of the device, change according to the hydrogen concentration. They can be made sensitive to gases such as hydrogen sulfide, ammonia, and hydrocarbons as well as hydrogen. They are cheap and find application in workplace monitoring, in satisfaction of health and safety legislation, and in fire detection (mainly detecting hydrocarbon products).

### *Semiconductor (metal oxide) sensors*

In these devices, use is made of the fact that the surface conductivity of semiconductor metal oxides changes according to the concentration of certain gases with which they are in contact. Gas concentration is therefore indicated by measuring the change in resistance. This type of sensor is used to detect hydrogen sulfide and some hydrocarbons. It is in fact regarded as the best device available for measuring low concentrations of hydrogen sulfide. Particular advantages of this type of sensor are that they are cheap and robust.

### *Infrared sensors*

This technique uses infrared light at a particular wavelength that is directed across a chamber between a source and detector. The amount of light absorption is a function of the unknown gas concentration in the chamber. The instrument normally has a second chamber containing gas at a known concentration across which infrared light at the same wavelength is directed to provide a reference. Sensitivity to carbon monoxide, carbon dioxide, chlorine, ammonia, hydrocarbons, and some other gases can be provided according to the wavelength used. Microcomputers are now routinely incorporated in the instrument to reduce its sensitivity to gases other than the one being sensed and so improve measurement accuracy. These sensors tend to be relatively expensive and they can be adversely affected by moisture in the monitored gas. Nevertheless, the instrument requires little maintenance and finds widespread use in chimney/flue emission monitoring and in general process measurements.

### *Mass spectrometers*

The mass spectrometer is a laboratory device for analyzing gases. It first reduces a gas sample to a very low pressure. The sample is then ionized, accelerated, and separated into its constituent components according to the respective charge-to-mass ratios. Almost any mixture of gases can be analyzed and the individual components quantified, but the instrument is very expensive and requires a skilled user. Mass spectrometers have existed for over half a century but recent advances in electronic data processing techniques have greatly improved their performance.

### *Gas chromatography*

This is also a laboratory instrument in which a gaseous sample is passed down a packed column. This separates the gas into its components, which are washed out of the column in turn and measured by a detector. Like the mass spectrometer, the instrument is versatile but expensive and it requires skilled use.

#### **21.10.1 Calibration of Gas Sensors**

Gas detectors are particularly susceptible to drift in their characteristics, which may result in either overestimation or underestimation of the true gas concentration. The rate and extent to which characteristics change depend entirely on the nature of the sensor, the identity of the gas involved and the temperature of the environment being sensed. Hence, the necessary recalibration frequency can only be determined by practical experience of the use of the sensor involved measuring a particular gas in the normal environment conditions of measurement. However, the advice of the sensor manufacturer should be sought in the first instance.

The only way of calibrating sensors is to test them on standard gas mixtures which contain a certified concentration of the relevant gas. Such mixtures are available from many suppliers and consist of the sensed gas mixed with either air or nitrogen. Such calibration gas mixtures can be obtained in concentrations as low as a few parts per billion. As well as mixtures of a single gas with air or nitrogen, mixtures of several gases in given concentrations can also be obtained, for example, a mixture of carbon monoxide, methane, pentane, and oxygen.

#### **21.11 Summary**

This final chapter has been concerned with looking at techniques for measuring a number of physical variables that have not been covered earlier in the book. In this coverage, we have looked in turn at the measurement of dimensions, angles, surface flatness, volume, viscosity, moisture (including humidity), sound, and pH (acidity/alkalinity), with a final section on gas sensing and analysis. This is certainly not a full list of physical variables that have been covered earlier since, as noted in the introduction to this chapter, a proper coverage of the techniques available to measure every physical variable that exists would be prohibitive in both size and cost. The material in this final chapter does however provide some reference material for the reader in respect of some of the variables that he/she may have a requirement to measure at some future point in their career.

## 21.12 Problems

- 21.1 What is a reference plane? How is it used in dimension measurement?
- 21.2 Explain, with the aid of a sketch, what the following are, how they work, and what they measure: Standard caliper, Vernier caliper.
- 21.3 Name and sketch three different types of micrometer. Explain briefly the characteristics of each and give typical uses?
- 21.4 What are gauge blocks and how are they used?
- 21.5 Draw a sketch of (a) a height gauge and (b) a depth gauge. What practical difficulties may be met in using these instruments and how are they solved?
- 21.6 Discuss the main procedures involved in workplace calibration of dimension-measuring instruments (discussion of instruments used in calibration further up the calibration chain is NOT expected).
- 21.7 What instruments are available for measuring angles? How are these instruments calibrated?
- 21.8 What are the main ways of measuring the volume of vessels? How are measurements of volume calibrated?
- 21.9 How is viscosity defined? In what circumstances is viscosity difficult to measure? Name some industrial situations, where viscosity measurement is needed and briefly explain why measurement is necessary.
- 21.10 What are the three main principles on which viscosity measurement is based? Describe one instrument that works on each of these principles.
- 21.11 How is viscosity measurement in Newtonian liquids calibrated?
- 21.12 Name some industrial situations, where measurement of the moisture content in materials is needed and briefly explain why measurement is necessary.
- 21.13 Discuss the main electrical methods of measuring the moisture content in materials in an industrial environment.
- 21.14 Discuss the methods other than electrical ones that exist to measure the moisture content in materials in an industrial environment.
- 21.15 What are the main laboratory techniques for measuring the moisture content in materials? Briefly explain each technique.
- 21.16 What are the three alternative ways in which humidity can be defined? What are the four main instruments used for measuring humidity? Briefly discuss how each of these works, using simple sketches where possible to illustrate your discussion as appropriate.
- 21.17 How is sound defined and measured? In what circumstances is sound measurement required?
- 21.18 What are the main components in a sound meter and how are these combined to produce a sound magnitude measurement? How are sound meters calibrated?

- 21.19 What is pH and how is it defined? Briefly discuss the main methods of pH measurement?
- 21.20 Discuss the characteristics of a glass electrode.
- 21.21 What alternatives to the glass electrode exist for measuring pH? Briefly describe each of these alternatives.
- 21.22 What is the need for gas sensing? What functions do gas sensors perform?
- 21.23 Discuss the mode of operation and characteristics of each of the following types of gas sensor: (a) calorimetric sensor, (b) paper tape sensor, (c) color change personnel badge.
- 21.24 What are the two main types of electrochemical cell used as gas sensors? Discuss the main features of each type.
- 21.25 Briefly explain how each of the following work and what they are typically used for: (a) catalytic gate FET gas sensor, (b) metal oxide gas sensor, (c) infrared gas sensor, (d) mass spectrometer.