CHAPTER 17

Level Measurement

Chapter Outline

17.1 Introduction

Level measurement is required in a wide range of applications and can involve the measurement of solids that are in the form of powders or small particles as well as liquids. While some applications require level to be measured to a high degree of accuracy, other applications only need an approximate indication of level. A wide variety of instruments are available to meet these differing needs.

Simple devices such as dipsticks or float systems are relatively cheap. Although only offering limited measurement accuracy, they are entirely adequate for applications and find widespread use. A number of higher accuracy devices are also available for applications that require a better level of accuracy. The list of devices in common use that offer good measurement accuracy includes pressure-measuring devices, capacitive devices, ultrasonic devices, radar devices, and radiation devices. A number of other devices that are less commonly used are also available. All of these devices are discussed in more detail in the following paragraphs.

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17.2 Dipsticks

Dipsticks offer a simple means of measuring the level of liquids approximately. The *ordinary dipstick* is the cheapest device available. This consists of a metal bar on which a scale is etched, as shown in Figure 17.1(a). The bar is fixed at a known position in the liquid-containing vessel. A level measurement is made by removing the instrument from the vessel and reading off how far up the scale the liquid has wetted. As a human operator is required to remove and read the dipstick, this method can only be used in relatively small and shallow vessels. One common use is in checking the remaining amount of beer in an ale cask.

The *optical dipstick*, illustrated in Figure 17.1(b), is an alternative form that allows a reading to be obtained without removing the dipstick from the vessel, and so is applicable to larger, deeper tanks. Light from a source is reflected from a mirror, passes round the chamfered end of the dipstick, and enters a light detector after reflection by a second mirror. When the chamfered end comes into contact with liquid, its internal reflection properties are altered and light no longer enters the detector. By using a suitable mechanical drive system to move the instrument up and down and measure its position, the liquid level can be monitored.

17.3 Float Systems

Float systems are simple and cheap and provide an alternative way of measuring the level of liquids approximately that is widely used. The system consists of a float on the surface

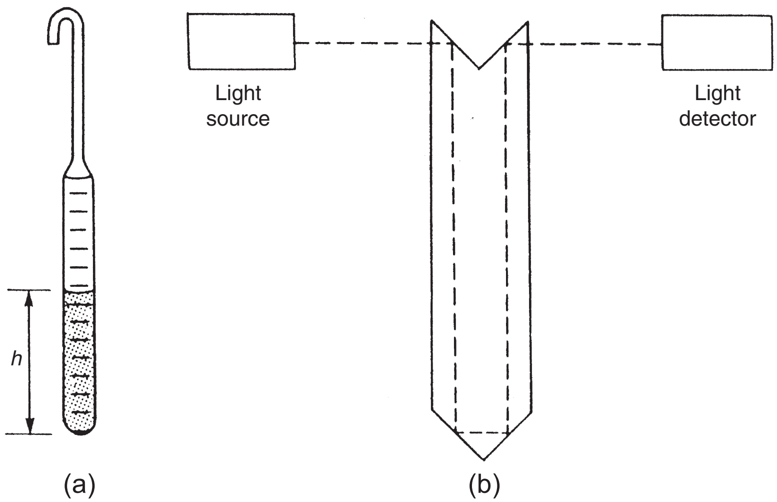

Figure 17.1
Dipsticks: (a) Simple dipstick; (b) optical dipstick.

of the liquid whose position is measured by a suitable transducer. They have a typical measurement inaccuracy of ±1%. The system using a potentiometer, shown earlier in Figure 2.2, is very common, and is well known for its application to monitoring the level in motor vehicle fuel tanks. An alternative system, which is used in greater numbers, is called the *float and tape gauge* (or *tank gauge*). This has a tape attached to the float that passes round a pulley situated vertically above the float. The other end of the tape is attached to either a counterweight or a negative-rate counter-spring. The amount of rotation of the pulley, measured by either a synchro or a potentiometer, is then proportional to the liquid level. These two essentially mechanical systems of measurement are popular in many applications, but their maintenance requirements are always high.

17.4 Pressure-Measuring Devices (Hydrostatic Systems)

Pressure-measuring devices measure liquid level to a better accuracy and use the principle that the hydrostatic pressure due to a liquid is directly proportional to its depth and hence to the level of its surface. Several instruments that use this principle are available, and they are widely used in many industries, particularly in harsh chemical environments. In the case of open-topped vessels (or covered ones that are vented to the atmosphere), the level can be measured by inserting a pressure sensor at the bottom of the vessel, as shown in Figure 17.2(a). The liquid level h is then related to the measured pressure P according to $h = P/\rho g$, where ρ is the liquid density and g is the acceleration due to gravity. One source of error in this method can be imprecise knowledge of the liquid density. This can be a particular problem in the case of liquid solutions and mixtures (especially hydrocarbons), and in some cases only an estimate of density is available. Even with single liquids, the density is subject to variation with temperature, and therefore temperature measurement may be required if very accurate level measurements are needed.

Where liquid-containing vessels are totally sealed, the liquid level can be calculated by measuring the differential pressure between the top and bottom of the tank, as shown in Figure 17.2(b). The differential pressure transducer used is normally a standard diaphragm type, although silicon-based microsensors are being used in increasing numbers. The liquid level is related to the differential pressure measured, δP, according to $h = \delta P/\rho g$. The same comments as for the case of the open vessel apply regarding uncertainty in the value of ρ. An additional problem that can occur is an accumulation of liquid on the side of the differential pressure transducer that is measuring the pressure at the top of the vessel. This can arise because of temperature fluctuations, which allow liquid to alternately vaporize from the liquid surface and then condense in the pressure tapping at the top of the vessel. The effect of this on the accuracy of the differential pressure measurement is severe, but the problem is easily avoided by placing a drain pot in the system.

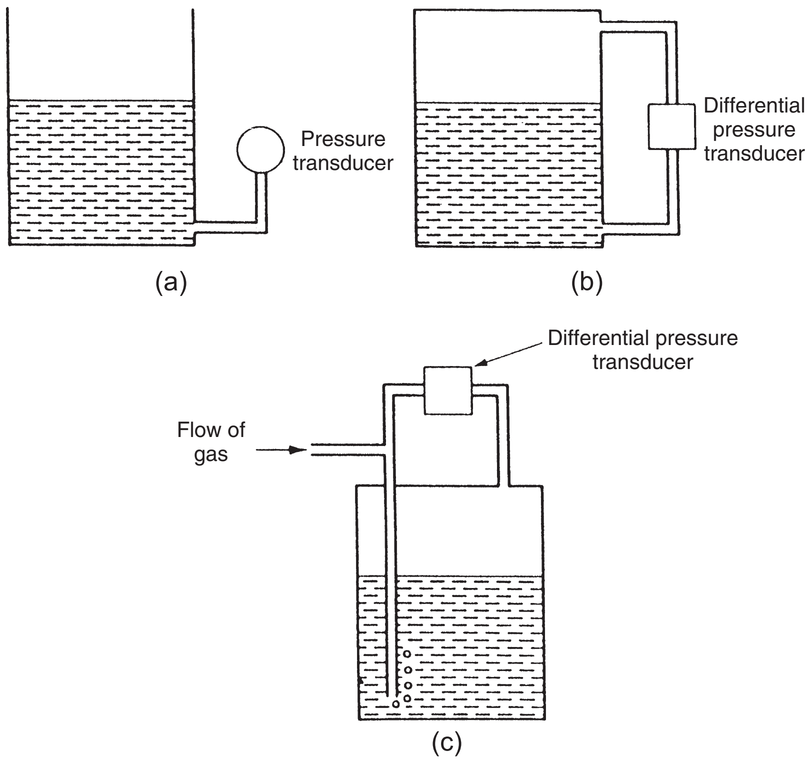

Figure 17.2
Hydrostatic systems: (a) Open-topped vessel; (b) sealed vessel; (c) bubbler unit.

A final pressure-related system of level measurement is the *bubbler unit* shown in Figure 17.2(c). This uses a dip pipe that reaches to the bottom of the tank and is purged free of liquid by a steady flow of gas through it. The rate of flow is adjusted until gas bubbles are just seen to emerge from the end of the tube. The pressure in the tube, measured by a pressure transducer, is then equal to the liquid pressure at the bottom of the tank. It is important that the gas used is inert with respect to the liquid in the vessel. Nitrogen, or sometimes just air, is suitable in most cases. Gas consumption is low, and a cylinder of nitrogen may typically last for 6 months. The method is suitable for measuring the liquid pressure at the bottom of both open and sealed tanks. It is particularly advantageous in avoiding the large maintenance problem associated with leaks at the bottom of tanks at the site of the pressure tappings required by alternative methods.

Measurement uncertainty varies according to the application and the condition of the measured material. A typical value would be ±0.5% of the full-scale reading, although ±0.1% can be achieved in some circumstances.

17.5 Capacitive Devices

Capacitive devices are widely used for measuring the level of both liquids and solids in powdered or granular form. They perform well in many applications, but become inaccurate if the measured substance is prone to contamination by agents that change the dielectric constant. Ingress of moisture into powders is one such example of this. They are also suitable for use in extreme conditions measuring liquid metals (high temperatures), liquid gases (low temperatures), corrosive liquids (acids, etc.), and high-pressure processes. Two versions are used according to whether the measured substance is conducting or not. For nonconducting substances (less than 0.1 μmho/cm^3), two bare metal capacitor plates in the form of concentric cylinders are immersed in the substance, as shown in Figure 17.3. The substance behaves as a dielectric between the plates according to the depth of the substance. For concentric cylinder plates of radius a and b ($b > a$), and total height L, the depth of the substance h is related to the measured capacitance C by:

$$h = \frac{C \log_e(b/a) - 2\pi\varepsilon_o}{2\pi\varepsilon_o(\varepsilon - 1)} \tag{17.1}$$

where ε is the relative permittivity of the measured substance and ε_o is the permittivity of free space. In the case of conducting substances, exactly the same measurement techniques

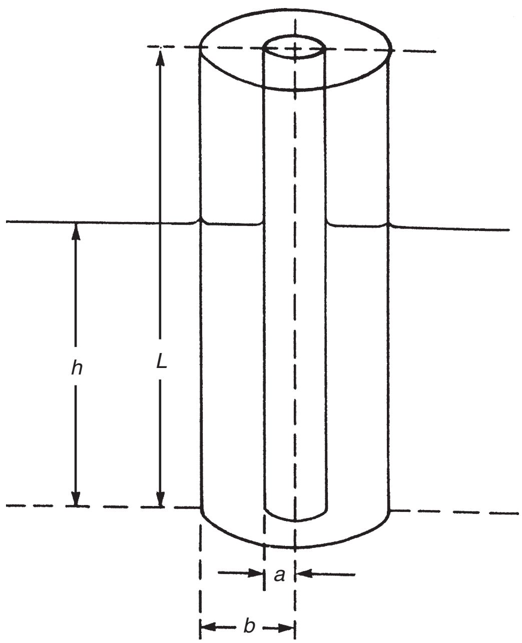

Figure 17.3
Capacitive level sensor.

are applied, but the capacitor plates are encapsulated in an insulating material. The relationship between C and h in Eqn (17.1) then has to be modified to allow for the dielectric effect of the insulator. Measurement uncertainty is typically 1−2%.

17.6 Ultrasonic Level Gauge

Ultrasonic level measurement is one of a number of noncontact techniques available. It is primarily used to measure the level of materials that are either in a highly viscous liquid form or in a solid (powder or granular) form. The principle of the ultrasonic level gauge is that energy from an ultrasonic source above the material is reflected back from the material surface into an ultrasonic energy detector, as illustrated in Figure 17.4. Measurement of the time of flight allows the level of the material surface to be inferred. In alternative versions (only valid for liquids), the ultrasonic source is placed at the bottom of the vessel containing the liquid, and the time of flight between emission, reflection off the liquid surface, and detection back at the bottom of the vessel is measured.

Ultrasonic techniques are especially useful in measuring the position of the interface between two immiscible liquids contained in the same vessel, or measuring the sludge or precipitate level at the bottom of a liquid-filled tank. In either case, the method used is to

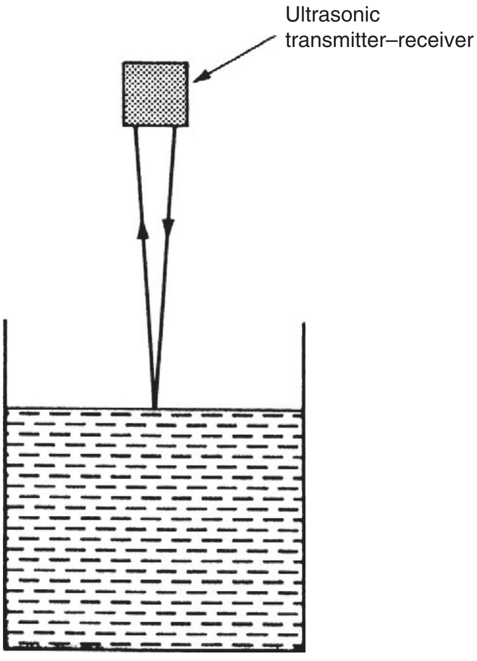

Figure 17.4
Ultrasonic level gauge.

fix the ultrasonic transmitter–receiver transducer at a known height in the upper liquid, as shown in Figure 17.5. This establishes the level of the liquid–liquid or liquid–sludge level in absolute terms. When using ultrasonic instruments, it is essential that proper compensation is made for the working temperature if this differs from the calibration temperature, since the speed of ultrasound through air varies with temperature (see Chapter 13). Ultrasound speed also has a small sensitivity to humidity, air pressure, and carbon dioxide concentration, but these factors are usually insignificant. Temperature compensation can be achieved in two ways. First, the operating temperature can be measured and an appropriate correction can be made. Second, and preferably, a comparison method can be used in which the system is calibrated each time it is used by measuring the transit time of ultrasonic energy between two known reference points. This second method takes account of humidity, pressure, and carbon dioxide concentration variations as well as providing temperature compensation. With appropriate care, measurement uncertainty can be reduced to about $\pm 1\%$.

17.7 Radar (Microwave) Sensors

Level-measuring instruments using microwave radar are an alternative technique for noncontact measurement. Currently, they are still very expensive (~$4000), but prices are falling and usage is expanding rapidly. They are able to provide successful level measurement in applications that are otherwise very difficult, such as measurement in

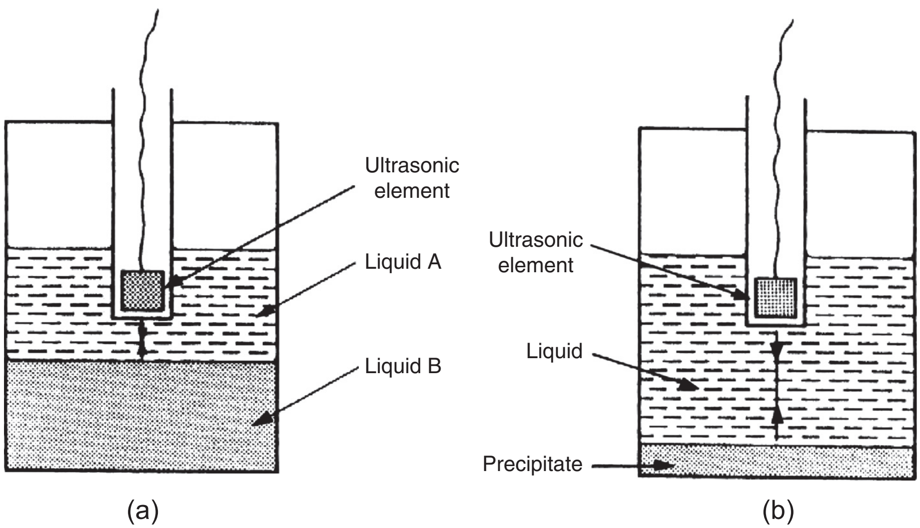

Figure 17.5
Measuring interface positions: (a) Liquid–liquid interface; (b) liquid–precipitate interface.

closed tanks, measurement where the liquid is turbulent, and measurement in the presence of obstructions and steam condensate. They can also be used for detecting the surface of solids in powder or particulate form. The technique involves directing a constant amplitude-, frequency-modulated microwave signal at the liquid surface. A receiver measures the phase difference between the reflected signal and the original signal transmitted directly through air to it, as shown in Figure 17.6. This measured phase difference is linearly proportional to the liquid level. The system is similar in principle to ultrasonic level measurement, but has the important advantage that the transmission time of radar through air is almost totally unaffected by ambient temperature and pressure fluctuations. However, as the microwave frequency is within the band used for radio communications, strict conditions on amplitude levels have to be satisfied and the appropriate licenses have to be obtained.

17.8 Nucleonic (or Radiometric) Sensors

Nucleonic, sometimes called radiometric, sensors are relatively expensive. They use a radiation source and detector system located outside a tank in the manner shown in Figure 17.7. The noninvasive nature of this technique in using a source and detector system outside the tank is particularly attractive. The absorption of both beta rays and gamma rays varies with the amount of material between the source and detector, and hence is a function of the level of the material in the tank. The gamma ray source

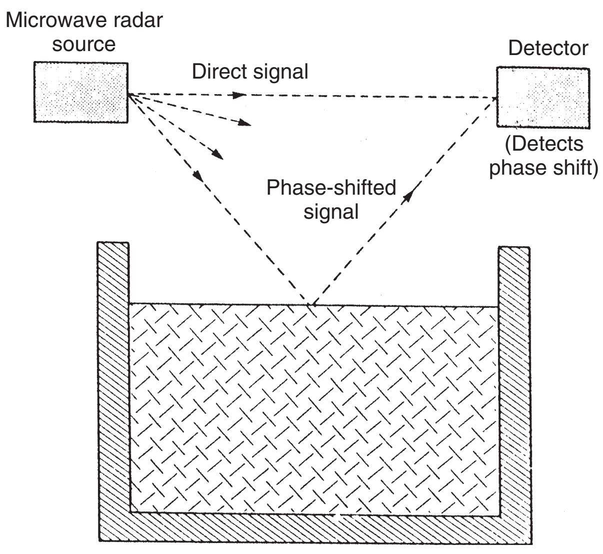

Figure 17.6
Radar-level detector.

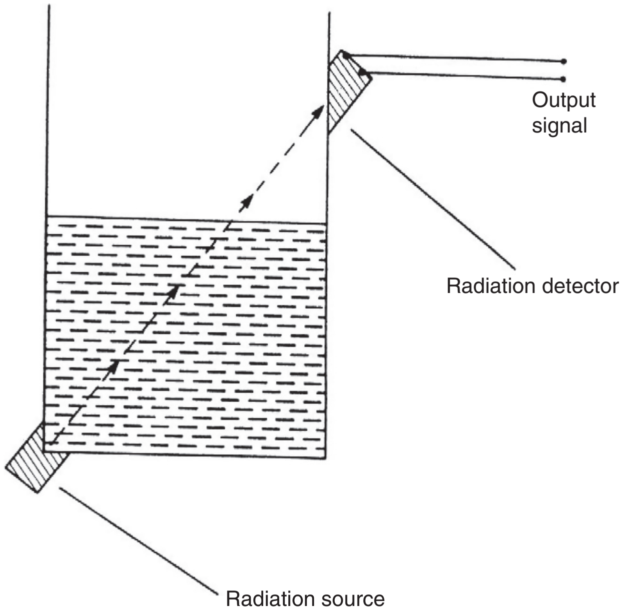

Figure 17.7
Using a radiation source to measure level.

commonly used is either cesium-137 or cobalt-60. The radiation level measured by the detector I is related to the length of material in the path x according to:

$$I = I_o \exp(-\mu \rho x) \tag{17.2}$$

where I_o is the intensity of radiation that would be received by the detector in the absence of any material, μ is the mass absorption coefficient for the measured material, and ρ is the mass density of the measured material.

In the arrangement shown in Figure 17.7, the radiation follows a diagonal path across the material, and therefore some trigonometrical manipulation has to be carried out to determine the material level h from x. In some applications, the radiation source can be located in the center of the bottom of the tank, with the detector vertically above it. Where this is possible, the relationship between the radiation detected and material level is obtained by directly substituting h in place of x in Eqn (17.2). Apart from use with liquid materials at normal temperatures, this method is commonly used for measuring the level of hot, liquid metals and also for measuring solid materials in a powdered granular form.

Unfortunately, because of the obvious dangers associated with using radiation sources, very strict safety regulations have to be satisfied when applying this technique. Very low activity radiation sources are used in some systems to overcome safety problems but the system is then sensitive to background radiation and special precautions have to be taken regarding the provision of adequate shielding. Because of the many difficulties in using this technique, it is only used in special applications.

17.9 Vibrating Level Sensor

The principle of the vibrating level sensor is illustrated in Figure 17.8. The instrument consists of two piezoelectric oscillators fixed to the inside of a hollow probe that generate flexural vibrations in the probe at its resonant frequency. The resonant frequency of the probe varies according to the depth of its immersion in the liquid. A phase-locked loop circuit is used to track these changes in resonant frequency and adjust the excitation frequency applied to the probe by the piezoelectric oscillators. Liquid level measurement is therefore obtained in terms of the output frequency of the oscillator when the probe is resonating. The sensor operates reliably and is easy to clean. Its operation is also little affected by any buildup of material deposits on the probe.

A variation of this technique is also used in the *vibrating level switch*. This can be used with both liquids and powder/granular solids. When the probe comes in contact with the material being monitored, there is a step change in the vibration frequency and the sensor outputs a switching command.

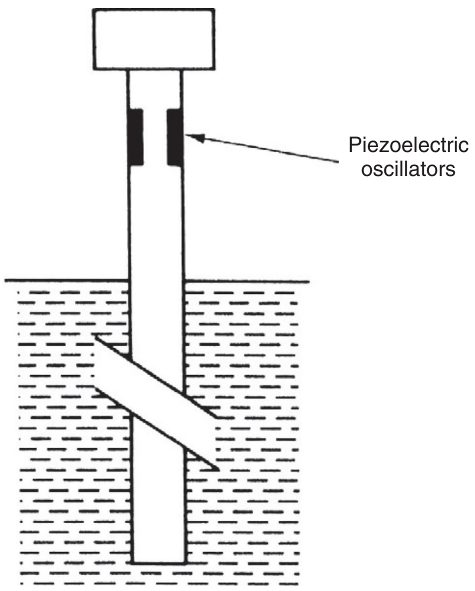

Figure 17.8
Vibrating level sensor.

17.10 Intelligent Level-Measuring Instruments

Most types of level gauge are now available in intelligent form. The pressure-measuring devices (Section 17.3) are obvious candidates for inclusion within intelligent level-measuring instruments, and versions claiming ±0.05% accuracy are now on the market. Such instruments can also carry out additional functions, such as providing automatic compensation for liquid density variations. Microprocessors are also used to simplify installation and setup procedures.

17.11 Choice between Different Level Sensors

The first consideration in choosing a level sensor is whether it is a liquid or a solid that is being measured. The second consideration is the degree of measurement accuracy required.

If liquids are to be measured and a relatively low level of accuracy is acceptable, dipsticks and float systems would often be used. Of these, dipsticks require a human operator whereas float systems provide an electrical output that can be recorded or output to an electronic display as required.

Where greater measurement accuracy is required in the measurement of liquid level, a number of different devices can be used. These can be divided into two distinct classes according to whether the instrument does, or does not, make contact with the material whose level is being measured. The advantage of noncontact devices is that they have a higher reliability than contact devices for a number of reasons. All pressure-measuring devices (hydrostatic systems) fall into the class of devices that does make contact with the measured liquid and are used quite frequently. Capacitive sensors are also commonly used, but are unsuitable for applications in which the liquid may become contaminated, since this changes its dielectric constant and hence the capacitance value. However, if there is a particular need for high reliability, noncontact devices such as ultrasonic or radiation devices are preferred. Ultrasonic sensors are less affected by contamination of the measured fluid but only work well with highly viscous fluids. Radar (microwave) and radiation sensors have the best immunity to changes in the temperature, composition, moisture content and density of the measured material, and so are preferred in many applications. However, both of these are relatively expensive. Further guidance on this can be found elsewhere.

In the case of measuring the level of solids (which must be in powdered or particle form), the choice of instrument is limited to the options of capacitive, ultrasonic, radar (microwave), and radiation sensors. As for measuring the level of liquids, radar and radiation sensors have the best immunity to changes in the temperature, composition, moisture content and density of the measured material, and so they are preferred in many applications. However, they both have a high cost. Both capacitive and ultrasonic devices provide a cheaper solution. Capacitive devices generally perform better but become inaccurate if the measured material is contaminated, in which case ultrasonic sensors are preferred out of these two cheaper solutions.

17.12 Calibration of Level Sensors

The sophistication of calibration procedures for level sensors depends on the degree of accuracy required. If the accuracy demands are not too high and a tank is relatively shallow, a simple dipstick inserted into a tank will suffice to verify the output reading of any other form of level sensor that is being used for monitoring the liquid level in the tank. However, this only provides one calibration point. Other calibration points can only be obtained by putting more liquid into the tank or by emptying some liquid from the tank. Such variation of the liquid level may or may not be convenient. However, even if it can be done without too much disturbance to the normal use of the tank, the reading from the dipstick is of very limited accuracy because of the ambiguity in determining the exact point of contact between the dipstick and the meniscus of the liquid.

If the dipstick method is not accurate enough or is otherwise unsuitable, the alternative method of calibrating level is to use a calibration tank that has vertical sides and a flat bottom of known cross-sectional area. Tanks with both circular and rectangular bottoms are commonly used. With the level sensor in situ, measured quantities of liquid are emptied into the tank. This increases the level of liquid in the tank in steps, and each step creates a separate calibration point. The quantity of liquid added at each stage of the calibration process can be measured either in terms of its volume or in terms of its mass. If the volume of each quantity of liquid added is measured, knowledge of the cross-sectional area of the tank bottom allows the liquid level to be calculated directly. If the mass of each quantity of liquid added is measured, the specific gravity of the liquid has to be known in order to calculate its volume and hence the liquid level. In this case, use of water as the calibration liquid is beneficial as its specific gravity is unity and therefore the calculation of level is simplified.

To measure added water in terms of its volume, calibrated volumetric measures are used. If a 1 L measure is used, this has a typical inaccuracy of $\pm 0.1\%$. Unfortunately, the errors in the measurement of each quantity of water added are cumulative, and therefore the possible error after 10 quantities of water have been added increases 10-fold to $\pm 1.0\%$. If 20 quantities are added to create 20 calibration points, the possible error is $\pm 2.0\%$, and so on.

Better accuracy can be obtained in the calibration process if the added water is measured in terms of its mass. This can be done conveniently by mounting the calibration tank on an electronic load cell. The typical inaccuracy of such a load cell is ±0.05% of its full-scale reading. This means that the inaccuracy of the level measurement when the tank is full is ±0.05% if the load cell is chosen such that it is giving its maximum output mass reading when the tank is full. Since the total mass of water in the tank is measured at each point in the calibration process, the measurement errors are not cumulative. However, the errors do increase for smaller volumes of water in the tank because the measurement uncertainty is expressed as a percentage of the full-scale reading of the load cell. Therefore, when the tank is only 10% full, the possible measurement error is ±0.5%. This means that calibration inaccuracy increases for smaller quantities of water in the tank but the measurement uncertainty is always less than the case where measured volumes of water are added to the tank even for low levels.

Wherever possible, the liquid used in the calibration tank is water, since this avoids the cost involved in using any other liquid, and it also makes the calculation of level simpler when the quantities of water added to the tank are measured in terms of their volume. Unfortunately, the liquid used in the tank often has to be the same as that which the sensor being calibrated normally measures. For example, the specific gravity of the measured liquid is crucial to the operation of both hydrostatic systems and capacitive level sensors. Another example is level measurement using a radiation source, since the passage of radiation through the liquid between the source and detector is affected by the nature of the liquid.

17.13 Summary

We have seen that level sensors can be used to measure the position of the surface within some form of container of both solid materials in the form of powders and liquids. We have looked at various types of level sensor, following which we considered how the various forms of level sensor available could be calibrated.

One very important observation that we made at the start of our discussion was that the accuracy requirements during level measurement vary widely, and this has an important effect on the type of sensor that is used in any given situation and the corresponding calibration requirements. For example, if the surface level of a liquid within a tank that is used for cooling purposes in an industrial process is being monitored, only a very approximate measurement of level is needed to allow a prediction about how long it will be before the tank needs refilling. However, if the level of liquid of a consumer product within a container is being monitored during the filling process, high accuracy is required in the measurement process.

Where only approximate measurements of liquid level are needed, we saw that dipsticks provide a suitable, low-cost method of measurement, although these require a human operator and so cannot be used as part of an automatic level-control system. Float systems are also relatively low-cost instruments and have an electrical form of output that can be used as part of an automatic level control systems, although the accuracy is little better than that of dipsticks.

Our discussion then moved on to sensors that provide greater measurement accuracy. First, among these were hydrostatic systems. These are widely used in many industries for measuring liquid level, particularly in harsh chemical environments. Measurement uncertainty is usually about ±0.5% of the full-scale reading, although this can be reduced to ±0.1% in the best hydrostatic systems. Since accurate knowledge of the liquid density is important in the operation of hydrostatic systems, serious measurement errors can occur if these systems are used to measure the level of mixtures of liquids since the density of such mixtures is rarely known to a sufficient degree of accuracy.

Moving on to look at capacitive level sensors, we observed that these were widely used for measuring the level of both liquids and solids in powdered or granular form, with a typical measurement uncertainty of 1−2%. They are particularly useful for measuring the level of difficult materials such as liquid metals (high temperatures), liquid gases (low temperatures), and corrosive liquids (acids, etc.). However, they become inaccurate if the measured substance is prone to contamination by agents that change the dielectric constant.

Next on the list of devices studied was the ultrasonic level sensor. We noted that this is one of a number of noncontact techniques available. It is primarily used to measure the level of materials that are either in a highly viscous liquid form or in a solid (powder or granular) form. We also observed that it is particularly useful for measuring the position of the interface between two immiscible liquids contained in the same vessel, and also for measuring the sludge or precipitate level at the bottom of a liquid-filled tank. The lowest measurement uncertainty achievable is ±1%, but errors increase if the system is not properly calibrated, particularly in respect of the ambient temperature because of the changes in ultrasound speed that occur when the temperature changes.

The discussion then moved on to radar sensors, another noncontact measurement technique. We saw that this, albeit very expensive technique, provided a method for measuring level in conditions that are too difficult for most other forms of level sensors. Such conditions include measurement in closed tanks, measurement where the liquid is turbulent, and measurement in the presence of obstructions and steam condensate. Like ultrasonic sensors, they can also measure the level of solids in powder or granular form.

We then looked at nucleonic sensors. These provide yet another means of noncontact level measurement that finds niche applications in measuring the level of hot, molten metals, and also in measuring the level of powdered or granular solids. However, apart from the high cost of nucleonic sensors, it is necessary to adhere to very strict safety regulations when using such sensors.

Having then briefly looked at two other less common level sensors, namely, the vibrating level sensor and laser-based sensors, we went on to make brief comments about intelligent level sensors. We noted that most of the types of level sensor discussed were now available in an intelligent form that quoted measurement uncertainty values down to $\pm 0.05\%$.

The final subject covered in this chapter was that of level sensor calibration. We noted that devices like a simple dipstick could be used to calibrate sensors that were only required to provide approximate measurements of level. However, for more accurate calibration, we observed that it was common to use a calibrated tank in which quantities of liquid were added, measured either by weight or by volume, to create a series of calibration points. We concluded that greater accuracy could be achieved in the calibration points if each quantity of liquid was weighed rather than measured with volumetric measures. We also noted that water was the cheapest liquid to use in the calibration tank but observed that it was necessary to use the same liquid as normally measured for certain sensors.

17.14 Problems

17.1 How do dipsticks and float systems work and what are their advantages and disadvantages in liquid level measurement?

17.2 Sketch three different kinds of hydrostatic level measurement systems. Briefly discuss the mode of operation and applications of each.

17.3 Discuss the mode of operation of the following, using a sketch to aid your discussion as appropriate: capacitive level sensor, ultrasonic level sensor.

17.4 What are the merits of microwave and radiometric level sensors? Discuss how each of these devices works.

17.5 What are the main things to consider when choosing a liquid level sensor for a particular application? What type of devices could you use for an application that required (1) low measurement accuracy, (2) high measurement accuracy where contact between the sensor and measured liquid is acceptable, (3) high measurement accuracy where there must not be any contact between the sensor and measured liquid?

17.6 Discuss the range of devices that are able to measure the level of the surface of solid material in powdered form contained within a hopper.

17.7 What procedures could you use to calibrate a sensor that is only required to provide approximate measurements of liquid level?

17.8 What is the best calibration procedure to use for sensors that are required to give high accuracy in level measurement?