DENSITY MEASUREMENT

Density of a substance is defined as the mass per unit volume ($\rho = m/V$) under fixed conditions. The term is applicable to solids, liquids, and gases. The density depends on temperature and pressure. This dependence is much greater in gases. Although there are many different units, usually the values of density are given in terms of grams per cubic centimeter.

Specific gravity (SG) is an abstract number expressing the ratio of the density of one substance to the density of another reference substance, both obtained at the same temperature and pressure. For solids and liquids, water is taken as the reference substance, whereas air is the reference for gases. The specific gravities of solids, liquids, and gases under reference conditions may be expressed by

$$\text{Liquid (or solid) SG} = \text{density of liquid (or solid)/density of water}$$

$$\text{Gas SG} = \text{density of gas/density of air}$$

Care must be taken to define standard conditions under which the densities or specific gravities are measured, so as not to introduce errors due to variations in measurement conditions. Commonly accepted sets of conditions are Normal Temperature and Pressure (NTP) and Standard Temperature and Pressure (STP). NTP is usually used for solids at the temperature 0°C and a pressure of 760 mm mercury. The STP is used for solids and fluids at a temperature of 15.6°C and a pressure of 1 atm (or 101.325 kPa).

Density measurements are a significant part of instrumentation systems. In many processes, the density is taken as the controlling parameter for the rest of the process; therefore, accurate measurements are necessary. Density measurements are made for at least two important reasons: (1) to determine the mass and volume of products, and (2) to assess the quality of products. In many industrial applications, density measurement ascertains the value of the product. A list of manufacturers offering different types of density meters is provided in Table 1.

In many modern applications, densities are obtained by sampling techniques. However, there are two basic approaches: static density measurements and dynamic (on-line) density measurements. Within each concept, there are many different methods available, depending on physical principles and process characteristics. In many cases, application itself and process conditions determine the best suitable method to be employed. Generally, static methods are well developed, lower in cost, and more accurate. Dynamic samples are expensive, highly automated, and use microprocessor-based signal processing devices. Nevertheless, today, many static methods are also computerized, offering easy to use, flexible, and self calibrating features.

There is no single, universally applicable density measurement technique available. Different methods must be employed for solids, liquids, and gases. Here, some of these measurement techniques and the devices involved are introduced in the relevant sections of solid, liquid, and gas density measurements. Further detailed discussions are given for specific types of instruments.

Table 1. List of Manufacturers

ABB K-Flow Inc
Drawer M Box 849
Millville, NJ 08332
Tel: 800-825 3569

American Density Materials Inc.
Rd 2, Box 38E
Belvidere, NJ 07823
Tel: 908-475 2373

Anton Paar USA
10201 Maple Leaf Court
Ashland, VA 23005
Tel: 800-722-7556

Arco Instrument Company, Inc.
1745 Production Circle,
Riverside, CA 92509
Tel: 909-788 2823
Fax: 909-788 2409

Cambridge Applied Systems, Inc.
196 Boston Avenue,
Medford, MA 02155
Tel: 617-393 6500

Dynatron
Automation Products, Inc.
3032 Max Roy Street
Houston, TX 77008
Tel: 800-231 2062
Fax: 713-869 7332

Kay-Ray/Sensall, Fisher-Rosemount
1400 Business Center Dr.
Mount Prospect, IL 60056
Tel: 708-803 5100
Fax: 708-803 5466

McGee Engineering Co., Inc.
Tujunga Canyon Blvd.
Tujunga, CA 91042
Tel: 800-353 6675

Porous Materials, Inc.
Cornell Business & Technology Park
Ithaca, NY 14850
Tel: 800-825 5764

Princo Instruments Inc
1020 Industrial Hwy., Dept L
Southhampton, PA 18966-4095
Tel: 800-496 5343

Quantachrome Corp.
1900-T Corporate Drive
Boynton Beach, FL 33426
Tel: 800-966 1238

Tricor Systems, Inc.
400-T River Ridge Rd.
Elgin, IL 60123
Tel: 800-575 0161

X-rite, Inc.
3100-T 44th St. S. W
Grandville, MI 49418
Tel: 800-545 0694

DENSITY AND DENSITY MEASUREMENT OF SOLIDS

Theoretically, the density of solids may vary both with operating pressure and temperature. However, in many applications, the effect of pressure may be neglected in solids and incompressible fluids. In some cases, the effect of temperature can also be neglected if the operational temperature is not significantly higher from the temperature at which density measurements are made, or a high degree of accuracy is not required.

The volumetric effect of temperature on the density of liquids or solids may be expressed as

$$V = V_0(1 + \beta \Delta t) \tag{1}$$

where β is the coefficient of expansion of solid or liquid which is consistent with the temperature units used.

As the mass is same before and after temperature rise, the change in density is inversely proportional to the change in volume and can be expressed as

$$\rho/\rho_0 = V/V_0 \tag{2}$$

If the solid sample has a regular shape and uniform, the determination of its density is a simple task. Once the volume and mass of the solid are known, the density may be found by using the basic ratio: density = mass/volume (kg/mg^3). In order to avoid errors, the weights and volumes must be determined by using accurate instruments.

However, in many applications, solids have different constituents and are made up from the mixture of different materials. The volumetric ratios of constituents may also change. A common method of determining the density of irregular and nonuniform samples is the hydrostatic weighting. In some cases, dynamic methods are employed, such as radioactive absorptions and ultrasonic methods.

Powdered solids occlude air between or inside individual particles, giving rise to apparent, bulk, tap, effective, and true densities. The apparent density includes the air lodged in the cavities or pores, and the density is determined without filling up the pores. The numerical value of the density depends on the amount of compacting employed (tap density) which can be achieved by moderate mechanical means and also embedded foreign particles (effective density). For true density, it is necessary to dislodge the air by means of suitable liquids or gases. Special pycnometers are developed for this purpose.

DENSITY AND DENSITY MEASUREMENT OF LIQUIDS

Overall density of fluid is the ratio of total mass to total volume. Point density is the ratio of molecular mass in a volume element centered at a point to the element's volume, the volume being much smaller than the total volume. As in the case of solids, the densities of liquids are affected by temperature and pressure. Most liquids are incompressible; therefore, pressure effects may be neglected. Nevertheless, in determination liquid densities, the effects of temperatures must carefully be monitored as indicated in equations (1) and (2).

The measurements of densities of fluids are much more complex than solids; therefore, there are many different techniques developed. Hydrometers, pycnometers, hydrostatic weighing, flotation methods, drop methods, radioactive methods, optical methods, and so on are typical examples of measuring liquid densities.

Difficulties in the measurement of densities of fluids is due to complexities in processes, variations of fluid densities within the process, and the diverse characteristics of the process and fluids themselves. Some of these methods are custom designed and applicable to special cases only. Others are very similar in principles and technology, and can be used for many different type of fluids. At the present, apart from conventional methods, many novel and unusual techniques are reported to be undergoing extensive development and research stages. For example, densitometers based on electromagnetic principles may be given as a part of intelligent instrumentation systems.

Depending on the application, fluid densities can be measured both in *static* or *dynamic* forms. In general, static density measurements of fluids are well developed, precise, and have greater resolution than most dynamic techniques. Pycnometers and buoyancy are examples of static techniques that can be adapted to cover small density ranges with a high resolution and precision. Nowadays, many manufacturers are offering dynamic instruments previously known to be static. Also, many static density measurement devices are computerized, coming with appropriate supporting hardware and software. In general, static type measurements are employed in laboratory conditions, and dynamic methods are employed for real time measurements where properties of fluids vary from time to time.

DENSITY AND DENSITY MEASUREMENT OF GASES

The density of a gas will vary significantly with absolute pressure. Increasing the pressure of a gas at a constant temperature causes the gas to be compressed to a smaller volume of the same mass, thus increasing the density. Boyle's Law states that for ideal gases or a mixture of ideal gases at a constant temperature, the volume, V, is inversely proportional to the absolute pressure; that is

$$V = Constant/P \tag{3}$$

The following formula may be written for comparing the volumes of an ideal gas at a constant temperature but at different pressures, P:

$$V/V_0 = P_0/P \tag{4}$$

Charles' Law states that the density of gas will vary significantly with absolute temperature, T. Increasing the temperature of a gas at constant pressure causes the gas molecules to increase their activities and motions in relation to each other, whereby increasing the volume and decreasing the density of gas for the same mass. Charles' Law may be stated in the following form:

$$V/V_0 = T/T_0 \tag{5}$$

Charles' and Boyle's Laws can be combined to yield the Ideal Gas Law as

$$PV = nRT \tag{6}$$

where R is the universal gas constant in consistent units, and n is the number of moles.

The Ideal Gas Law can also be expressed in the following form:

$$V/V_0 = TP_0/T_0P \tag{7}$$

During gas density measurements, when variations in pressure and temperature are small, the temperature and pressure act almost independently of each other; thus, estimates of reasonable accuracy can be obtained by adding percentage temperature and pressure deviations from a given set of conditions.

Often, density measurements of Non-Ideal Gases are required which do not act as ideal gases at certain conditions, such as at high pressures, low temperatures, or under saturation. Their non-ideal behavior may be accounted for by modifying the Ideal Gas Law with a Z factor, as

$$V/V_0 = TP_0Z/T_0PZ_0 \tag{8}$$

The Z factor is numerically dependent on operating conditions and can be read from generalized compressibility charts, as shown in Fig. 1, with a reasonable degree of accuracy.

Due to the above reasons, extra care and further considerations are necessary in gas density measurements. For exam-

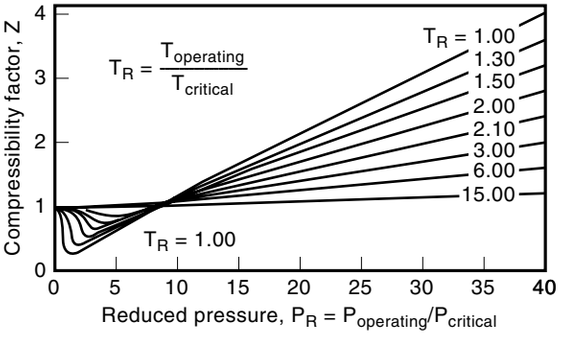

Figure 1. Generalized gas compressibility chart. In many applications, densities of Non-Ideal Gases are required. Non-Ideal gases do not act as ideal gases at certain conditions, such as at high pressures, low temperatures, or under saturation. Their behavior may be accounted for by modifying the Idea-Gas Law with a Z factor. The Z factor is numerically dependent to different operating conditions and can be read from generalized compressibility charts such as this one.

ple, perfect gases contain equal numbers of molecules under same conditions and equal volumes. Therefore, molecular weights may be a better option in density measurements. Flask methods, gas balance methods, optical methods, x-ray methods are typical techniques employed for gas density measurements.

MAGNETIC AND VIBRATIONAL METHODS

Magnetic Method

This method is used for both liquids and gases. It allows the determination of effects of pressures and temperatures down to cryoscopic range. Basically, the device contains a small ferromagnetic cylinder, encased in a glass jacket. The jacket and ferromagnetic material combination constitutes a buoy or float. The cylinder is held at a precise height within the medium by means of solenoid which is controlled by a servo system integrated with a height sensor. The total magnetic force on the buoy is the product of the induced magnetic moment by the solenoid and the field gradient in vertical direction. The total magnetic force at a particular distance in vertical direction in the solution compensates the difference in the opposing forces of gravity (downwards) and buoyancy (upwards) exerted by the medium, through the Archimedes' principle. The magnetic force is directly proportional to the square of the current in the solenoid. If the buoyant force is sufficient to make the ferromagnetic assembly float on the liquids of interest, the force generated by the solenoid must be downward to add to the force of gravity for equilibrium.

By the use of precision resistors and accurate differential voltmeters, the measurements simply consist of reading and recording voltages. Calibrated curves obtained from standard solutions of known densities must be used for a given buoy, to be referred to solutions under test. Buoys cover a limited range of density; hence, many buoys must be provided to cover large density ranges. The complete measurement of a sample requires about 5 minutes for insertion, temperature, and buoy stabilization. The sensitivity of the devices is in the region of ± 0.01 mV with a tight temperature control. Their uses can also be extended into applications such as the specific gravity measurements under low pressures and density measurements of hazardous fluids.

In some instruments, a smaller buoy is used containing tiny permanent magnets. By this way, the sample volume and errors from adhering bubbles are reduced, and the current in the solenoid is linearized as a function of density. This provides a greater precision in calibrations. In other instruments, a rotating magnetic field is superimposed on a standard device via remotely situated field coils in such a way that controlled rotation of the immersed buoy can be accomplished. Since the rate of rotation is proportional to the viscosity of the medium, the density and viscosity are determined simultaneously.

Vibrational Methods

Devices based on vibrations are used for liquid and gas density measurements. They make use of the changes in natural frequency of vibration of a body containing fluid in it or surrounded by it. The natural frequency of the vibrating body is directly proportional to the stiffness and inversely proportional to the combined masses of the body and the fluid. It also depends on the shape size and elasticity of materials, induced stresses, and the total mass and mass distribution of the body. Basically, the vibrations may be equated to the motion of a mass attached to a mechanical spring. Hence, expression for the frequency may be written as

$$\text{Resonant frequency} = \sqrt{(K/(M + k\rho))} \tag{9}$$

where K is the system stiffness, M is the transducer mass, k is the system constant, and ρ is the fluid density.

A factor common to all types of vibrating element densitometers is the problem of setting the element in vibration and maintaining its natural resonance. There are two drives available for this purpose, these being the magnetic drives and the piezoelectric drives.

Magnetic Drives. Magnetic drives of the vibrating element and the pick up sensors of vibrations are usually achieved using small coil assemblies. Signals picked up by the sensors are amplified and fed back for maintaining the disturbing forces on the vibrating body.

In order to achieve steady drives and minimize external effects, vibrating elements may be made from nonmagnetic materials. In this case, small magnetic armatures are attached to maintain vibrations.

The main advantage of the magnetic drive and pick up system is that they are noncontact methods. They use conventional copper windings, are simple to construct, and are reliable within the temperatures of -200 to $+200$°C.

Piezoelectric Drives. The piezoelectric drives are mechanically fixed on the vibrating element by adhesives. Therefore, attention must be paid for the careful placement of the mount in order to reduce the strain experienced by the piezo elements, due to thermal and pressure stresses while the instrument is in service. A wide range of piezoelectric materials are available to meet the requirements. These materials demonstrate good temperature characteristics as in magnetic drive types. They have high impedances, thus making the signal conditioning circuitry relatively easy and cost effective.

A number of different types of densitometers are developed which utilize properties of vibrating bodies in liquids and gases. The three main commercial types are introduced here. In all cases, vibrations are maintained either through magnetic dives or piezoelectric drives. In recent years, the coriolis effect is used for density measurements yielding a new type of density meters.

In general, vibrating element meters have advantages and disadvantages. The advantages are

1. Suitability for both liquid and gas density measurements under static and dynamic conditions, with reasonable accuracy
2. Real time measurements may easily be interfaced to computers since they operate on frequencies and are inherently digital
3. They are relatively robust and easy to install, and
4. Programmable and computerized versions are available. Programmable versions make all the corrections automatically. They provide the output of process den-

sity, density at reference conditions, relative density, specific gravity, concentration, solid contents, etc.

The main disadvantage is that they do not relate directly to primary measurements; therefore, they have to be calibrated. They also have problems of measuring densities of multi-phase fluids.

Vibrating Tube Densitometers

These devices are suitable in highly viscous liquids or slurry applications. The mode of operation of vibration tube meters is based on the transverse vibration of single or twin tubes as shown in Fig. 2. The tube and the driving mechanisms are constrained to vibrate on a single plane. As the liquid moves inside the tube, the density of the entire mass of liquid is measured. The tube length is approximately 20 times greater than the tube diameter.

One major design problem with the vibrating tube method is the conflict to limit the vibrating element to a finite length, and also the accuracy of fixing the nodes. Special attention must be paid to avoid any exchange of vibrational energy outside the sensory tube. The single tube has the disadvantage of presenting obstructing to the flow, thus having some pressure losses. The twin tubes, on the other hand, offer very small blockage, and they can easy be inspected and cleaned. Their compact sizes are another distinct advantage. In some densitometers, the twin tubes are designed to achieve a good dynamic balance with the two tubes vibrating in anti-phase. Their nodes are fixed at the ends, demonstrating maximum sensitivity to installation defects, clamping, and mass loadings.

The main design problems of the vibrating tube sensors are in minimizing the influence of end padding and overcoming the effects of pressure and temperature. Bellows are used at either ends of the sensor tubes to isolate the sensors from external vibrations. Bellows also minimize the end loadings due to differential expansions and installation stresses.

The fluid runs through the tubes; therefore, it does not need pressure balances. Nevertheless, in some applications, the pressure stresses the tubes, resulting in stiffness changes. Some manufacturers modify the tubes to minimize the pressure effects. In these cases, corrections are necessary only when high accuracy is needed. The changes in the Young's modulus with temperature may be reduced to almost zero by using Ni-span-C materials whenever corrosive properties of fluids permit. Usually, manufacturers provide pressure and temperature correction coefficients for their products.

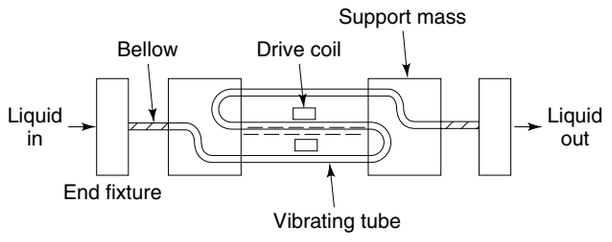

Figure 2. Vibrating tube densitometer. A tube containing fluids is vibrated at resonant frequency by electromagnetic or piezoelectric vibrators. The tube and the driving mechanisms are constrained to vibrate on a single plane. The resonant frequency is a function of the density of the fluid moving inside the tube. The tube is isolated from the fixtures by carefully designed bellows. These devices are not suitable in highly viscous liquids or slurry applications. The tube length is approximately 20 times greater than tube diameter.

It is customary to calibrate each vibration element densitometer against other methods as a transfer of standards. Often, the buoyancy method is used for calibration purposes. The temperature and pressure coefficients are normally found by exercising the transducer over a range of temperatures and pressures on some liquid of well known properties. Prior to calibration, the vibration tube densitometers are subjected through a programmed burn-in cycle for stabilization against temperatures and pressures.

Vibrating Cylinder Densitometers

A thin walled cylinder, with a 3 to 1 ratio of length versus diameter, is fixed with stiff ends. The thickness of the wall of the cylinder varies from 25 to 300 μm, depending on the density range and type of fluid used. The cylinder can be excited to vibrate in a hoop mode by magnetic drives mounted either in or outside the cylinder.

For good magnetic properties, the cylinder is made from corrosion-resistant magnetic materials. Steel such as FV520 is used for the purpose. Such materials have good corrosion resistance characteristics. Unfortunately, due to their poor thermoelastic properties, they need extensive temperature corrections. Often, nickel iron alloys such as Ni-span-C are used to avoid temperature effects. Especially since once correctly treated, the Ni-span-C alloy has near zero Young's modulus properties. Since the cylinder is completely immersed in the fluid, there are no pressure coefficients.

The change in the resonant frequency is determined by the local mass loading of the fluid in contact with the cylinder. The curve of frequency against density is nonlinear and has a parabolic shape, thus requiring linearization to obtain practical outputs. The resonant frequency range varies from 2 to 5 kHz depending on the density range of the instrument. The cylinders need precision manufacturing and, thus, are very expensive to construct. Each meter needs to be calibrated individually for different temperatures and densities to suit specific applications. In the case of gas density applications, gasses with well known properties such as pure argon or nitrogen are used for calibrations. In this case, the meters are subjected to gas environment with controlled temperature, and pressure and calibration curves are achieved by repetitions to suit requirements of individual customers for their particular applications. In the case of liquids, the meters are calibrated with liquids of known density, or they are calibrated against another standard such as pycnometer or buoyancy type densitometers.

Vibration cylinder type densitometers have zero pressure coefficients and they are ideal for liquidised gas products or refined liquids. Due to relatively small clearances between cylinder and housing, they require regular cleaning. They are not suitable with liquids or slurries with high viscous properties.

Tuning Fork Densitometers

These densitometers make use of the natural frequency of a low mass tuning forks, shown in Fig. 3. In some cases, the liquid or gas is taken into a small chamber in which the elec-

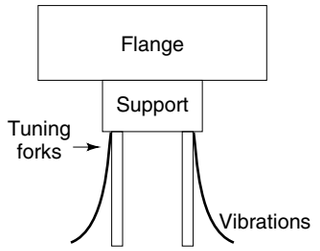

Figure 3. Tuning fork densitometer. Twin forks are inserted into the liquid or gas media whose density needs to be measured. Since the natural frequency of the forks is a function of the density of the media, small changes in the natural frequencies must be monitored accurately. Calibration is necessary in each application.

tromechanically driven forks are situated. In the other cases, the fork is inserted directly into the liquid. Calibration is necessary in each application.

Coriolis Densitometers

Another type of vibrational density meter is based on the coriolis principle. The device is similar in vibrating tube methods with slight variations in physical design. They are comprised of sensors and a signal processing transmitters. Each sensor consists of one or two flow tubes enclosed in a sensor housing. The sensor tubes are fixed at one end and free at the other end, shown in Fig. 4. The sensor operates by applying Newton's Second Law of motion ($F = ma$).

Inside the housing, the tubes are vibrated at their natural frequencies using drive coils and a feedback circuit. This resonant frequency of the assembly is a function of the geometry of the element, materials of construction, and mass of the tube assembly. The tube mass is comprised of two parts: the mass of the tube itself and the mass of the fluid inside the tube. The mass of the tube is fixed for a given sensor. The mass of fluid in the tube is equal to the fluid density multiplied by the volume. Since the tube volume is constant, the frequency of oscillation can be directly related to the fluid density. Therefore, for a given geometry of a tube and the material of the construction, the density of the fluid can be determined by measuring the resonant frequency of vibration. Temperature sensors are used for overcoming the effects of changes in the modulus of elasticity of the tube. The fluid density is calculated using a linear relationship between the density and the vibrations of the tube and calibration constants.

Special peripherals, based on microprocessors, are offered by manufacturer for a variety of measurements. However, all density peripherals use the natural frequency of the sensor coupled with the sensor temperature to calculate the on-line density of the process fluid. Optional communication, interfacing facilities, and appropriate software are also offered. These devices come in different shapes and sizes.

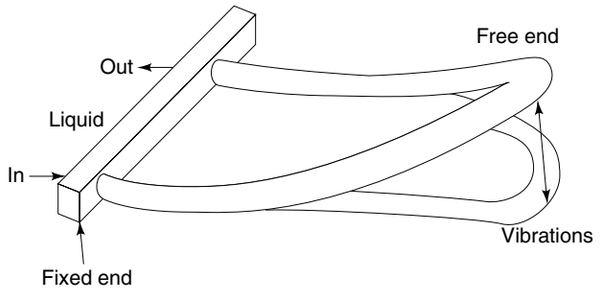

Figure 4. Coriolis densitometer. Each sensor consists of one or two flow tubes enclosed in a sensor housing. Inside the housing, the tubes are vibrated at their natural frequencies using drive coils and a feedback circuitry. This resonant frequency of the assembly is a function of the geometry of the element, material of construction, and mass of the tube assembly. Vibration of the tube is detected and related to the mass and flow rate of the fluid. They are manufactured in various shapes and sizes.

WEIGHT/WEIGHING SYSTEM/ MASS MEASUREMENT METHODS

Pycnometric Densitometers

Pycnometers are static devices used for measuring densities of liquids and gases. They are manufactured as fixed volume vessels which can be filled with sample fluids. The density of the fluid is measured by weighing the sample with the vessel. The simplest version consists of a glass vessel in the shape of a bottle with a long stopper containing a capillary hole as shown in Fig. 5. The volume and variation of volume with temperature has been accurately determined. The capillary is used to determine the exact volume of the liquid, thus giving high resolution when filling the pycnometer. If the weight of the empty pycnometer is W_1 and the weight of the pycnometer, when containing a volume V of liquid at temperature t, is W_2, the density of liquid ρ_1 may be calculated directly from

$$\rho_1 V = W_2 - W_1 \tag{10}$$

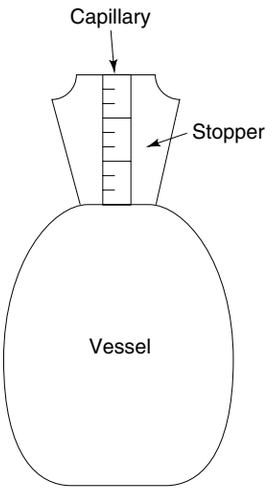

Figure 5. Pycnometer. A fixed volume container is filled with liquid and weighed accurately. The capillary is used to determine the exact volume of the liquid, thus giving high resolution when filling the pycnometer. For accuracy and good precision in results, the bottle must be cleaned after each measurement, the temperature must be kept constant, and precision balances must be used. It is necessary to apply accurate buoyancy and thermal expansion corrections. In some cases, to ensure filling of the pycnometer, twin capillary tubes are used.

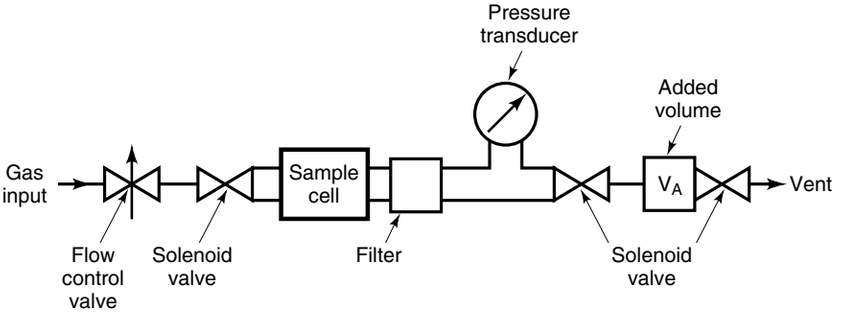

Figure 6. Use of a pycnometer for porous or powdered solids. Pycnometers are used for measuring density of solid substances, such as carbon black, cement, fibers, ceramics, charcoals, fertilizers, pharmaceutical, and powdered materials, and so on. In powder technology, pycnometers are used to measure the true volume of the solid materials by employing Archimedes' principle of fluid displacement. The displacing fluid is usually helium gas which can penetrate the finest pores to assure maximum accuracy. In some cases, water, mercury, or other fluids are used as displacers.

For accuracy and good precision in results, ultimate care must be exercised during measurements. That is, the bottle must be cleaned after each measurement, the temperature must be kept constant, and precision balances must be used. For precise measurements, it is necessary to apply buoyancy and thermal expansion corrections. In some cases, to ensure filling of the pycnometer, twin capillary tubes are used. The two capillaries, made in glass, are positioned such that fluid can be driven into the vessel under vacuum conditions. Accurate filling to graduation marks on capillary is then made.

The pycnometers have to be light weight, strong enough to contain samples, and nonmagnetic for accurate weighing to eliminate possible ambient magnetic effects. Very high resolution balances have to be used to detect small differences in weights of gases and liquids. Although many pycnometers are made of glass, they are also made in metals to give enough strength for the density measurements of gases and liquids at extreme high pressures. In many cases, metal pycnometers are necessary for taking samples from the line of some rugged processes.

Pycnometers are used, Fig. 6, for measuring density of solid substances, such as carbon black, cement, fibers, ceramics, charcoals, fertilizers, pharmaceutical and powdered materials, *etc.* The density is computed from the mass difference between the pycnometer filled with sample together with a displacer fluid which penetrates into pores of the solid, and with fluid only. In some cases, mercury is used as the displacing liquid. The accuracy increases with the increasing quantity of solid which can be used. In powder technology, pycnometers are used to measure the true volume of the solid materials by employing Archimedes' principle of fluid displacement. The displaced fluid is a gas which can penetrate the finest pores to assure maximum accuracy. Usually, helium is used because of its small atomic dimension, thus penetrating into crevices and pores effectively.

The pycnometers have advantages and disadvantages. The advantages are that if used correctly, they are accurate and can be used for both density and specific gravity measurements. The disadvantages are

1. Great care must be exercised for accurate results
2. The sample has to be taken off-line with consequent time lag in results. This creates problems of relating samples to the materials that exist in the actual process
3. High precision pycnometers are expensive. They require precision weighing scales and controlled laboratory conditions. Specialized techniques must be employed to take samples in high pressure processes and hostile conditions such as offshore installations.

Hydrostatic Weighing Densitometers

These devices are suitable for solid and liquid density measurements only. The density of a solid is often measured by weighing it first in air, and afterwards in a suitable liquid of known density. The latter weighing is done by suspending the solid under the pan of a precision balance by means of a very thin wire. A typical commonly used example of such devices is the Westphal balance, as shown in Fig. 7. If the weight of the plummet in air is W_a, its volume, V, and its weight when suspended in liquid, W_1, the equilibrium of vertical forces on the plummet gives

$$W_1 + \rho_1 V - W_a = 0 \tag{11}$$

from which the density ρ_1 at the temperature t may be calculated.

The inaccuracies of this type of device are mainly limited by the irregularity of meniscus around the wire, particularly

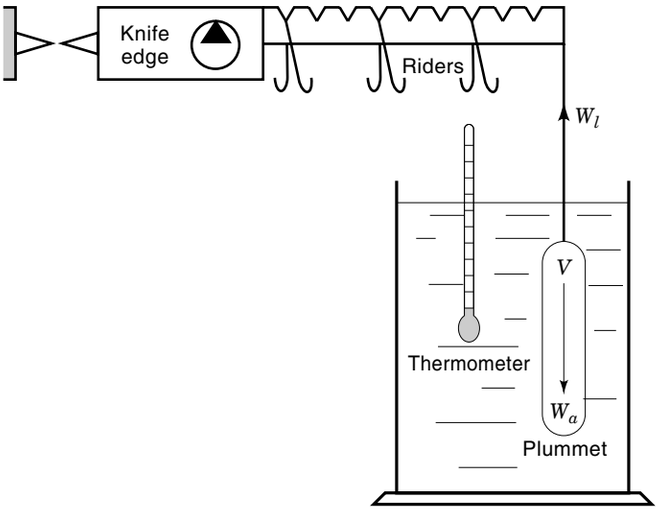

Figure 7. Hydrostatic weighing densitometers. The density of a solid is often measured by weighing it first in air, afterwards in a suitable liquid of known density. The latter weighing is done by suspending the solid under the pan of a precision balance by means of a very thin wire. A typical commonly used example of such devices is the Westphal balance. Riders are used for precision measurements. Accurate temperature measurement is necessary.

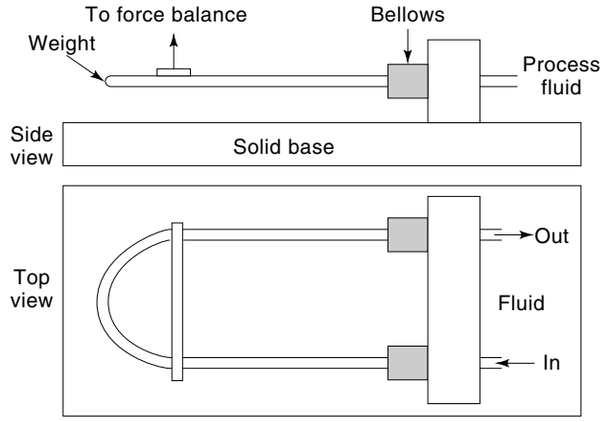

Figure 8. Hydrostatic weighing. This device consists of a U-tube which is pivoted on flexible end couplings. The total weight of the tube changes depending on the density of fluid flowing through it. The change in the weight needs to be measured accurately. There are temperature, flow rate, and pressure limitations due to bellows and the structure of the system may lead to a reading offset. The meter must securely be mounted on a horizontal plane for best accuracy.

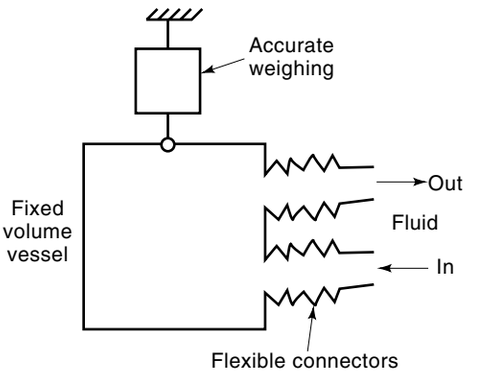

Figure 9. Balanced-flow vessel. Liquid or gas flows through a fixed volume vessel. The vessel is weighed continuously by a sensitive scale while the fluid is flowing through it. Since the volume and the weight of the fluid are known, the density or specific gravity can be calculated and scaled in respective units. In the design process, extra care must be exercised for the flexible end connections.

in the case of water and aqueous solutions. The wetting of the wire may be improved by covering it electrolytically with platinum black.

A common device using hydrostatic weighing of liquids consists of a U-tube which is pivoted on flexible end couplings. A typical example is shown in Fig. 8. The total weight of the tube changes, depending on the density of fluid flowing through it. The change in the weight needs to be measured accurately, and there are a number of methods employed for it. The most common commercial meters use a force balance system. The connectors are stainless steel bellows. In some cases, rubber or other materials are used, depending on the process fluid characteristics and the accuracy required. There are temperature, flow rate, and pressure limitations due to bellows, and the structure of the system may lead to a reading offset. The meter must securely be mounted on a horizontal plane for best accuracy.

The hydrostatic weighing methods of liquids give continuous readings for two phase liquids such as slurries, sugar solutions, powders, etc. They are rugged, give accurate results, and are used for the calibration of the other liquid density transducers. However, they must be installed horizontally on a solid base; hence, they are not flexible enough to adapt for any process. Thus, the process must be designed around it.

Balance Type Densitometers

Balance type densitometers are based on gravity and/or weighing principles, and they are suitable for liquid and gas density measurements. Manufacturers offer many different types; four most commonly used ones are discussed below.

Balanced-Flow Vessel. A fixed volume vessel, as shown in Fig. 9, is employed for the measurements. While the liquid or gas is flowing continuously through the vessel, the total assembly is weighed automatically by a sensitive scale, a spring balance system, or a pneumatic force balance transmitter. Since the volume and the weight of the fluid are known, the density or specific gravity can easily be calculated and scaled in respective units. In the design process, extra care must be exercised for the flexible end connections.

Buoyancy Hydrostatic-Weighing Methods. The buoyancy method basically uses Archimedes' principle. A displacer with a known mass and volume is immersed in the liquid whose density is to be measured. Position of the displacer is kept constant by bellows, as exemplified in Fig. 10. Once the mass, the volume, the displacer, the bellow position, and pressure are known, the density of the liquid can be calculated. However, some corrections need to be made for cubicle expansion coefficients of the displacer and the temperature of the process. Buoyancy type densitometers give accurate results, and they are used for the calibration of the other liquid density transducers.

Chain Balanced Float. In this system, a self centering fixed volume submerged plummet is used for density measure-

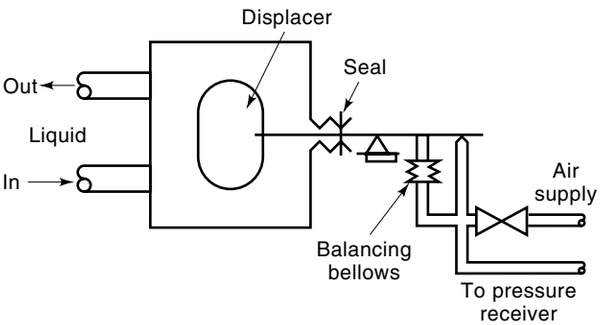

Figure 10. Buoyancy hydrostatic-weighing method. A displacer with a known mass and volume is immersed in the liquid whose density is to be measured. The displacer is kept in position by sensitive balancing bellows. Buoyancy type densitometers give accurate results, and they are used for the calibration of the other liquid density transducers.

ments, as illustrated in Fig. 11. The plummet is located entirely under the liquid surface. At balance, the plummet operates without friction, assuming a stable position based on mass balance technique. The effective weight of the chain on the plummet varies, depending on the position of the plummet which, in turn, is a function of the density of the liquid. Any change in the density of the process causes the plummet to move to a new equilibrium point by transferring the chain weight between the reference point and the plummet. In some cases, the plummet contains a metallic transformer core which transmits changes in the position to be measured by a pick up coil or a linear variable transformer (LVDT). When LVDTs are used, the voltage differential, a function of plummet displacement, is calibrated as a measure of variations in density or specific-gravity. A resistance thermometer bridge is used for the compensation of temperature effects on density. The range of the instrument can be from 0.5 g/mL to 3.5 g/mL. Their accuracy is in the region of ±3% of the range. Viscosity limits (50 centipoise) and flow rates of the liquid (2 to 3 L/min) are the main limitations.

Gas Specific Gravity Balance. A tall column of gas is weighed by a float located at the bottom of the vessel. This weight is translated into the motion of an indicating pointer which moves over a scale graduated in units of density or specific gravity. This method can be employed in the density measurements of many gases.

Buoyancy Gas Balance. In this instrument, a displacer is mounted on a balance beam in a vessel, shown in Fig. 12. The displacer is balanced for air, and the manometer reading is noted at the exact balance pressure. The air is then displaced by gas, and the pressure is adjusted until the same balance is restored. The ratio of the pressure of air to pressure of gas is then the density of gas relative to air. This method is commonly applied under laboratory conditions and is not suitable for continuous measurements.

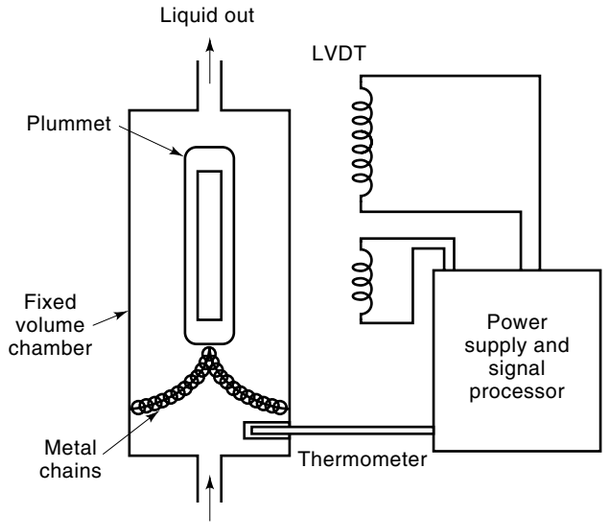

Figure 11. Chain balanced float. The fixed volume and weight plummet totally suspended in the liquid assumes equilibrium position depending on the density. The force exerted by the chains on the plummet is a function of plummet position; hence, the measured force is proportional to the density of the liquid. Any change in the density process causes the plummet to move to a new equilibrium point. In some cases, the plummet contains a metallic transformer core which transmits changes in the position to be measured by a pick up coil or a linear variable transformer (LVDT).

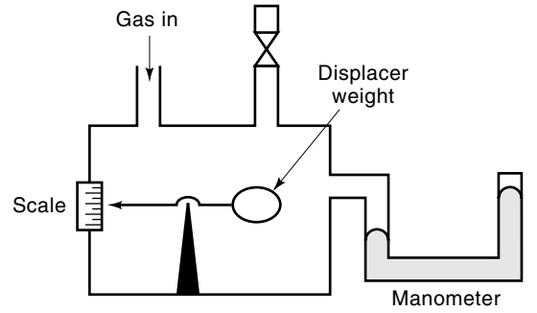

Figure 12. Buoyancy gas balance. Position of the balance beam is adjusted by a set pressure air; air is then displaced by gas of the same pressure. The difference in the reading of the balance beam gives the specific gravity (SG) of the gas. The pressures are read on the manometer. This method is commonly applied in laboratories and not suitable for continuous measurements.

REFERENCE METHODS

Hydrometers

Hydrometers are direct reading instruments, the most commonly used devices for measurement of density of liquids. They are so commonly used that their specifications and procedure of use are described by national and international standards such as ISO 387. The buoyancy principle is used as the main technique of operation. Almost all hydrometers are made from high grade glass tubing. The volume of fixed mass is converted to a linear distance by a sealed bulb shaped glass tube containing a long stem measurement scale, shown in Fig. 13. The bulb is ballasted with a lead shot and pitch, the mass of which is dependent on the density range of the liquid to be measured. The bulb is simply placed into the liquid, and the density is read from the scale. The scale may be graduated in density units such as kg/m^3. Hydrometers can be calibrated for different ranges for surface tensions and temperatures. Temperature corrections can be made for set temperature such as 15, 20, 25°C. ISO 387 covers a density range of 600 to 2000 kg/m^3.

Hydrometers may be classified according to the indication provided by graduations of the scale: density hydrometers, specific gravity hydrometers, percentage hydrometers showing the percentage of solution, for example, sugar, and arbitrary scale hydrometers. Customized scales are also available, for example, lactometers for testing milk, alcoholometers for alcohol levels, *etc.* Many other alternative scales are offered by manufacturers such as specific gravity, API gravity, Brix, Brine, *etc.*

The best way to read a hydrometer in clear liquids is to start with the eyes slightly below the plane of the liquid surface, and slowly raise the eyes until the surface of liquid appears as a straight line. The place where the line crosses the scale is the reading. With opaque liquids, such as oils, it is necessary to read the hydrometer at the top of the meniscus.

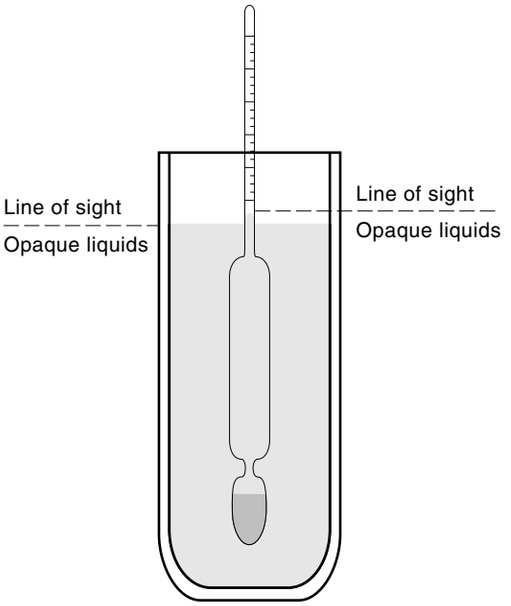

Figure 13. Hydrometer. A fixed weight and volume bulb is placed into the liquid. The bulb sinks in the liquid depending on its density. The density is read directly from the scale. They are classified according to the indication provided by graduations of the scale. The best way to read a hydrometer in clear liquids is to start with the eyes slightly below the plane of the liquid surface, and slowly raise the eyes until the surface of liquid appears as a straight line. The place where the line crosses the scale is the reading. With opaque liquids, such as oils, it is necessary to read the hydrometer at the top of the menicus.

For accurate readings, the stem must be absolutely clean. Also, the surface of the liquid must be clean and free of dust. With precision grade hydrometers, with long small diameter stems, density values may be read to 0.0001. In general use of hydrometers, the uncertainty of readings may be in the region of ± 0.01.

Hydrometers are low cost devices and are easy to use with a good resolution. However, they have a number of disadvantages, such as

1. They have small span; therefore, a number of meters are required to cover a significant range.
2. They are made from glass and are fragile. Metal and plastic versions are not as accurate.
3. The fluid needs to be an off line sample, not representing the exact conditions of the process. There are pressure hydrometers for low vapour pressure hydrocarbons, but this adds a need for accurately determining of pressure.
4. If good precision is required, they are difficult to use, needing surface tension and temperature corrections. Further corrections may be required for opaque fluids.

Column Type Densitometers

These devices are used for liquid density measurements. There are a number of different versions of column methods. As a typical example, a reference column method is illustrated in Fig. 14. A known head of sample liquid and water from their respective bubbler pipes are used. A differential pressure measuring device compares the pressure differences, proportional to relative densities of the liquid and the water. By varying the depth of immersion of the pipes, a wide range of measurement may be obtained. Both columns must be maintained at the same temperature in order to avoid the necessity for corrections of temperature effects.

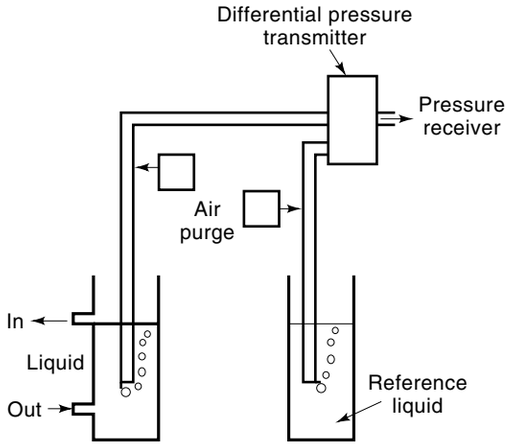

Figure 14. Reference column densitometer. Two identical tubes, having the same distance from the surface, are placed in water and liquid. Water with known density characteristics is used as a reference. The pressures necessary to displace the fluids inside the tubes are proportional to the densities of the fluids. By varying the depth of immersion of the pipes, a wide range of measurement may be obtained. Both columns must be maintained at the same temperature.

A simpler and most widely used method of density measurement is achieved by the installation of two bubbler tubes as illustrated in Fig. 15. The tubes are located in the sample fluid such that the end of one tube is higher than that of the other. The pressure required to bubble air into the fluid from both tubes is equal to the pressure of the fluid at the end of

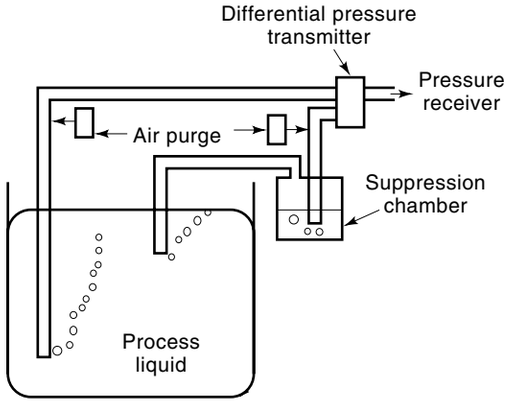

Figure 15. Two tube column densitometer. The pressure difference at the differential pressure transmitter depends on the relative positions of the openings of the pipes and the density of liquid. Once the relative positions are fixed, the pressure difference can be related to the equivalent weight of the liquid column at the openings of the pipes, hence the density of the liquid.

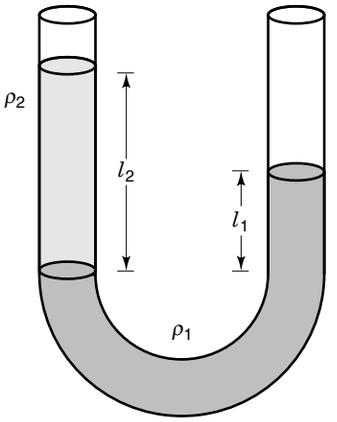

Figure 16. U-tube method. Unknown density of a liquid may be obtained from the known density of another liquid by placing them in a U-tube and measuring the lengths of liquid columns. In this method, the liquids must not be miscible. The method is not accurate but gives a quick idea about the density of the liquid.

the bubbler tubes. The openings of the tubes are fixed; hence, the difference in the pressure is the same as the weight of a column of liquid between the ends. Therefore, the differential pressure measurement is equivalent to the weight of the constant volume of the liquid. Therefore, calibrations can be made with direct relationship to the density of the liquid. This method is accurate to within 0.1 to 1% specific gravity. It must be used with liquids that do not crystallize or settle in the measuring chamber.

U-Tube Method

The unknown density of a liquid may be obtained from the known density of another liquid by placing them in a U-tube as in Fig. 16. By measuring the lengths of liquid columns, l_1 and l_2, and using the manometer principles, the following equation may be written

$$\rho_1 l_1 = \rho_2 l_2 \tag{12}$$

thus allowing ρ_1 to be calculated. In this method, the liquids must not be miscible. This method gives a quick idea about the density of the liquid and is not usually accurate because the various menisci prevent accurate measurements of the lengths of the liquid columns.

RADIOACTIVE METHODS

Radioactive density measurements are suitable for both liquids and solids undergoing dynamic processes. The principle relies on the radioactive isotopes decay emitting radiation in the form of particles or waves which may be used for density measurements. For example, gamma-rays passing through the samples under test are absorbed depending on the volume, mass, and density of samples, as illustrated in Fig. 17. The rate of arrival of the rays after the absorption can be measured by using ion or scintillation based detection. By comparing the amount of rays entered into the known volume sample and with the rays detected at the end, the value of absorption may be determined accurately.

Generally, γ-ray mass absorption rate is independent of material composition; hence, they can be programmed for a wide range of materials. Densitometers based on radiation methods can provide accuracy up to +0.0001 g/mL. Many of these devices have self-diagnostic capabilities and are able to compensate for drift caused by source decay, thus pinpointing any signalling problems.

If a γ-ray of an intensity J_0 penetrates a material of a density ρ and thickness d, then the intensity of the radiation after passing through the material may be expressed by

$$J = J_0 \exp(n\rho d) \tag{13}$$

where n is the mass absorption coefficient.

The accuracy of the density measurement is dependent on the accuracy of the measurement of the intensity of the radiation and the path length d. A longer path length through the material gives a stronger detection signal. Hence, for accurate operations, many different arrangements can be made for relative locations of transmitters and detectors, as illustrated in Fig. 18. Generally, the source is mounted in a lead container which is clamped onto the pipe or the container wall. In many applications, the detector is also clamped onto the wall.

The advantages of using radioactive methods are

1. The sensor does not touch sample; hence, there is no blockage on the path of the liquid.
2. Multiphase liquids can be measured.
3. They come in programmable forms and are easy to interface.

The disadvantages are

1. A radioactive source is needed; hence, it is difficult to handle.

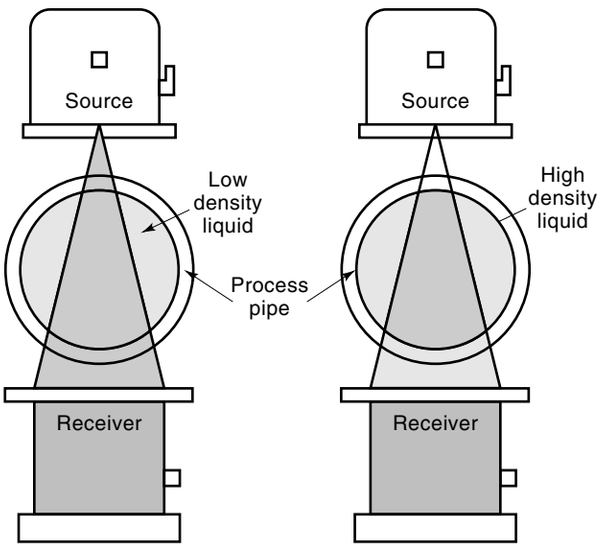

Figure 17. Radioactive density gage. The gamma-ray passing through samples is absorbed depending on the volume, mass, and density of the sample. The rate of arrival of the rays after absorption is determined by ion or scintillation based detection. The amount of absorption is proportional to the density of samples. Generally, γ-ray mass absorption rate is independent of material composition.

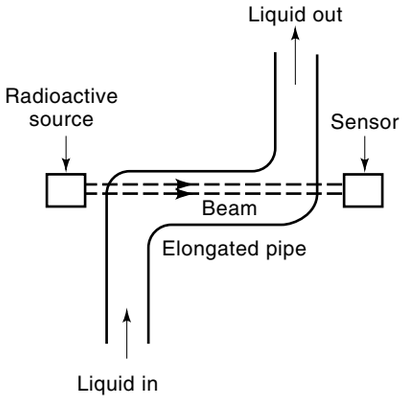

Figure 18. Fixed radioactive densitometer. An elongated path gives longer path length of the radioactive energy through the liquid, hence stronger attenuation. In some cases, the pipe may be enlarged to give longer beam length through the liquid.

2. For a reasonable accuracy, a minimum path length is required.
3. There may be long time constants, making them unsuitable in some applications.
4. They are suitable only for solid and liquid density measurements.

OPTICAL METHODS

Refractometric Methods

This method is suitable for density measurements of gases and clear liquids. They are essentially optical instruments operating on the principles of refraction of light travelling in liquid or gas media. Depending on the characteristics of the samples, measurement of refractive index can be made in a variety of ways: critical angle, collimation, and displacement techniques are a few methods to mention. Usually, an in-line sensing head is employed, whereby a sensing window, commonly known as a prism, is wetted by the product to be measured. In some versions, the sensing probes must be installed inside the pipelines or in tanks and vessels. They are most effective in reaction type process applications where blending and mixing of liquids takes place. For example, the refractometers can measure dissolved soluble solids accurately.

Infrared diodes, lasers, and other lights may be used as sources. However, this measurement technique is not recommended in applications in processes containing suspended solids, high turbidity, entrained air, heavy colors, poor transparency and opacity, or extremely high flow rates. The readings are automatically corrected for variations in process temperature. The processing circuitry may include signal outputs adjustable in both frequency and duration.

Another version of refractometers is the index of refraction type densitometer. There are many versions available. For example, in the case of position sensitive detectors, the index of refraction of a liquid under test is determined by measuring the lateral displacement of a laser beam. When the laser beam impinges on the cell at an angle of incidence, as in Fig. 19, the axis of the emerging beam is displaced by the cell wall and by the inner liquid. The lateral displacement can accurately be determined by position sensitive detectors. For maximum sensitivity, the devices need to be calibrated with the help of interferometers.

Refractometers are often used for the control of the adulteration of liquids of common use, such as edible oils, wines, and gasoline. They also find applications in industries such as pulp and paper, food and beverage, sugar, dairy, and other chemical processes.

Absorption Type Densitometers

Absorption techniques are also used for density measurements in specific applications. X-rays, visible light, UV, and sonic absorptions are typical examples of this method. Essentially, attenuation and phase shift of a generated beam going through the sample is sensed and related to the density of the sample. Most absorption type densitometers are custom designed for applications having particular characteristics. Two typical examples are (1) UV absorption or x-ray absorptions are used for determining the local densities of mercury deposits in arc discharge lamps, and (2) ultrasonic density sensors are used in connection with difficult density measurements such as density measurement of slurries. The lime slurry, for example, is a very difficult material to handle. It has a strong tendency to settle out and to coat all equipment it contacts. An ultrasonic density control sensor can fully be emerged into an agitated slurry, thus avoiding the problems of coating and clogging. Since the attenuation of the ultrasonic beam is proportional to the suspended solids, the resultant electronic signal is proportional to the specific gravity of the slurry. Such devices can give accuracy up to 0.01%. The ultrasonic device measures the percentage of the suspended solids in the slurry by providing a close approximation of the specific gravity.

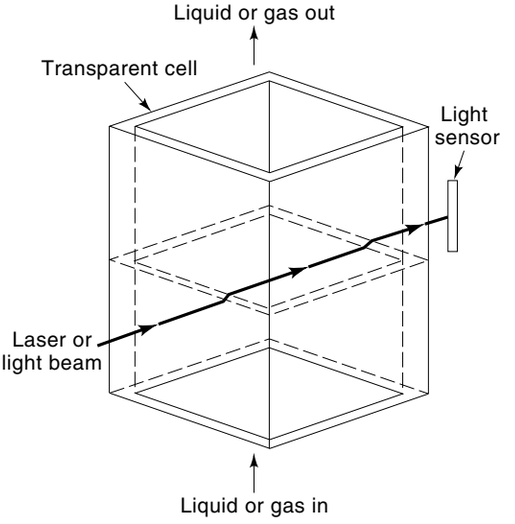

Figure 19. Index of refraction type densitometer. Angle of refraction of the beam depends on the shape, size, and thickness of the container, and the density of fluid in the container. Since the container has the fixed characteristics, the position of the beam can be related to density of the fluid. Accurate measurements of the position of the beam is necessary.

FALLING-SLUG METHOD

Drop Method

These methods are useful when only extremely small quantities of liquid or solid samples are available. Small drops of constant volume are put in a liquid which does not mix with the sample. The time necessary for sinking through a given height is a measure of the density of the drops. In this method, the volume sample may be as low as 0.1 mL.

In another method, a density gradient is established by diffusion of two different liquids into one another. The drops reach an equilibrium position in the mixture, depending upon their density. In both cases, the calibration by drops of known density is necessary.

BIBLIOGRAPHY

H. Bettin, F. Spieweck, and H. Toth, A computer-operated fluid-density measuring device using a balance and two permanent magnets, *Meas. Sci. Technol.,* **12** (11): 1036–1038, 1991.

H. Eren, Particle concentration characteristics and density measurements of slurries using electromagnetic flowmeters, *IEEE Trans. Instrum. Meas.,* **44**: 783–786, 1995.

Kay-Ray, Solution for Process Measurement, Fisher-Rosemount, USA, 1995.

P. Mason, Liquid and gas density measurements-Fluid density, *Meas. Control,* **25**: 297–302, 1993.

J. A. McDowel, *Measuring density, and pressure-searching for structure,* Toronto: Holt, Rinehart and Winston, 1975.

R. W. Miller, *Flow measurement engineering handbook,* 3rd ed., New York: McGraw-Hill, 1996.

J. Moon, Monitor fluid density accurately, *Hydrocarbon Processing,* **73** (2): 87–89, 1994.

Micro Motion Product Catalogue, USA: Fisher-Rosemount, 1995.

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DEPENDABLE COMPUTING. See FAULT TOLERANT COMPUTING.

DEPOLARIZATION. See REFRACTION AND ATTENUATION IN THE TROPOSPHERE.

DEPOSITION, PLASMA. See CHEMICAL VAPOR DEPOSITION.

DEPOSITION, SPUTTER. See SPUTTER DEPOSITION.

DESIGN. See LOGIC DESIGN.

DESIGN FOR MANUFACTURE. See CONCURRENT ENGINEERING.