

Halit Eren. "Density Measurement."

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Density Measurement

21.1 Solid Density

21.2 Fluid Density

Pycnometric Densitometers • Buoyancy Type Densitometers • Hydrometers • Hydrostatic Weighing Densitometers • Balance-Type Densitometers • Column-Type Densitometers • Vibrating Element Densitometers • Radioactive Densitometers • Refractometer and Index of Refraction Densitometers • Coriolis Densitometers • Absorption-Type Densitometers

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Density is a significant part of measurement and instrumentation. Density measurements are made for at least two important reasons: (1) for the determination of mass and volume of products, and (2) the quality of the product. In many industrial applications, density measurement ascertains the value of the product.

Density is defined as the mass of a given volume of a substance under fixed conditions. However, ultimate care must be exercised in measurements because density varies with pressure and temperature. The variation is much greater in gases.

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

There is no single universally applicable density measurement technique. Different methods must be employed for different products and materials. In many cases, density is normalized under reference conditions.

The density of a substance is determined by dividing the density of that substance by the density of a standard substance obtained under the same conditions. This dimensionless ratio is called the *specific gravity* (SG), also termed the *relative density*. The specific gravities of liquid and gases under reference conditions are given by:

$$\text{Liquid SG} = \text{density of liquid} / \text{density of water} \quad (21.1)$$

$$\text{Gas SG} = \text{density of gas} / \text{density of air} \quad (21.2)$$

Commonly accepted sets of conditions are *normal temperature and pressure* (NTP) and *standard temperature and pressure* (STP). NTP is usually taken as the temperature of 0.00°C and a pressure of 760 mm Hg. The NTP is accepted as 15.00 or 15.56°C and 101.325 kPa.

21.1 Solid Density

If the uniformity is maintained, the determination of density of solids is a simple task. Once the volume of the solid and its mass are known, the density can be found using the basic ratio: density = mass/volume (kg m^{-3}).

However, in many applications, solids have different constituents and are made up from different materials having different ratios. Their volumes can also change often. In these cases, dynamic methods are employed, such as radioactive absorption types, ultrasonic, and other techniques. Some of these methods are described below.

21.2 Fluid Density

The measurement of densities of fluids is much more complex than for solids. For fluid densities, many different techniques are available. This is mainly due to complexities in processes, variations of fluid densities during the processes, and diverse characteristics of the process and the fluids themselves. Some of these methods are custom designed and applicable to special cases only. Others are very similar in principles and technology, and applicable to many different type of fluids. At present, apart from conventional methods, there are many novel and unusual techniques undergoing extensive development and research. For example, densimeters based on electromagnetic principles [1] can be given as part of an intelligent instrumentation system.

Fluids can be divided to liquids and gases. Extra care and further considerations are necessary in gas density measurements. For example, perfect gases contain an equal number of molecules under the same conditions and volumes. Therefore, molecular weights can be used in density measurements.

Depending on the application, fluid densities can be measured both in *static* and *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 offer dynamic instruments previously known to be static. Also, many static density measurement devices are computerized and come with appropriate hardware and software. In general, static-type measurements are employed in laboratory conditions, and dynamic methods are employed for real-time measurements where the properties of a fluid vary from time to time.

In this chapter, the discussion will concentrate on the commonly applied, modern density measuring devices. These devices include:

1. Pycnometric densimeters
2. Buoyancy-type densimeters
3. Hydrometers
4. Hydrostatic weighing densimeters
5. Balance-type densimeters
6. Column-type densimeters
7. Vibrating element densimeters
8. Radioactive densimeters
9. Refractometer and index of reflection densimeters
10. Coriolis densimeters
11. Absorption-type densimeters

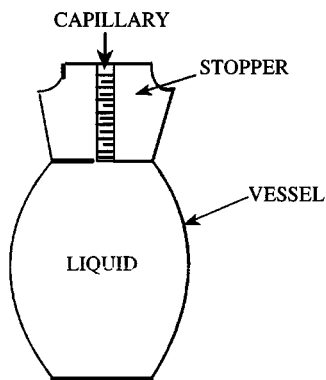


FIGURE 21.1 A pycnometer. A fixed volume container is filled with liquid and weighed accurately; capillary is used to determine the exact volume of the liquid.

Pycnometric Densitometers

Pycnometers are static devices. They are manufactured as fixed volume vessels that can be filled with the sample liquid. The density of the fluid is measured by weighing the sample. The simplest version consists of a vessel in the shape of a bottle with a long stopper containing a capillary hole, as shown in [Figure 21.1](#). The capillary is used to determine the exact volume of the liquid, thus giving high resolution when filling the pycnometer. The bottle is first weighed empty, and then with distilled-aerated water to determine the volume of the bottle. The bottle is then filled with the process fluid and weighed again. The density is determined by dividing the mass by the volume. The specific gravity of the liquid is found by the ratio of the fluid mass to water mass. When pycnometers are used, for good precision, ultimate care must be exercised during the measurements; that is, the bottle must be cleaned after each measurement, the temperature must be kept constant, and precision balances must be used. In some cases, to ensure filling of the pycnometer, twin capillary tubes are used. The two capillaries, made of glass, are positioned such that the fluid can be driven into the vessel under vacuum conditions. Accurate filling to graduation marks on the capillary is then made.

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

Pycnometers have advantages and disadvantages. Advantages are that if used correctly, they are accurate; and they can be used for both density and specific gravity measurements. The disadvantages include:

1. Great care must be exercised for accurate results.
2. The sample must 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.
4. Their good performances might depend on the skill of operator.

Buoyancy-Type Densitometers

The buoyancy method basically uses Archimedes principle. A suspended sinker, with a known mass and volume attached to a fine wire, is totally immersed in the sample liquid. A precision force balance is used to measure the force to support the sinker. Once the mass, volume, and supporting weight of the sinker

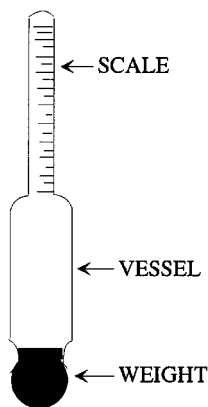


FIGURE 21.2 Hydrometer. A fixed weight and volume bulb is placed into the liquid. The bulb sinks in the liquid, depending on its density. The density is read directly from the scale. Temperature correction is necessary.

are known, the density of the liquid can be calculated. However, some corrections need to be made for surface tension on the suspension wire, the cubicle expansion coefficient of the sinker, and the temperature of process. Buoyancy-type densitometers give accurate results and are used for the calibration of the other liquid density transducers.

One advanced version of the buoyancy technique is the magnetic suspension system. The sinker is fully enclosed in a pressure vessel, thus eliminating surface tension errors. Their uses can also be extended to applications such as the specific gravity measurements under low vapor pressures and density measurements of hazardous fluids.

Hydrometers

Hydrometers are the most commonly used devices for measurement of the 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. 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 [Figure 21.2](#). The bulb is ballasted with a lead shot and pitch, the mass of which depends 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 is graduated in density units such as kg m^{-3} . However, many alternative scales are offered by manufacturers, such as specific gravity, API gravity, Brix, Brine, etc. Hydrometers can be calibrated for different ranges for surface tensions and temperatures. Temperature corrections can be made for set temperature such as 15°C, 20°C, or 25°C. ISO 387 covers a density range of 600 kg m^{-3} to 2000 kg m^{-3} . Hydrometers have a number of advantages and disadvantages. The advantages include:

1. Relatively low cost and easy to use
2. Good resolution for small range
3. Traceable to national and international standards

The disadvantages include:

1. They have small span; therefore, a number of meters are required to cover a significant range.
2. They are made from glass and 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 vapor pressure hydrocarbons, but this adds a need for accurately determining the pressure too.
4. If good precision is required, they are difficult to use, needing surface tension and temperature corrections. Further corrections could be required for opaque fluids.

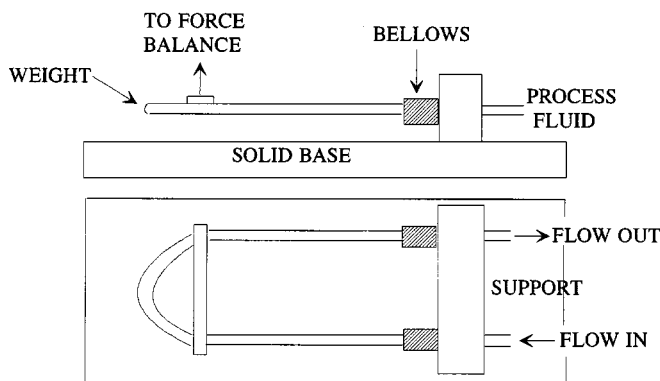


FIGURE 21.3 Hydrostatic weighing. The total weight of a fixed-volume tube containing liquid is determined accurately. The density is calculated using mass: volume ratio.

Hydrostatic Weighing Densitometers

The most common device using a hydrostatic weighing method consists of a U-tube that is pivoted on flexible end couplings. A typical example is shown in [Figure 21.3](#). 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 to do this. The most common commercial meters use a force balance system. The connectors are stainless steel bellows. In some cases, rubber or PTFE are used, depending on the process fluid characteristics and the accuracy required. There are temperature and pressure limitations due to bellows, and the structure of the system may lead to a reading offset. The meter must be securely mounted on a horizontal plane for optimal accuracy.

The advantages of this method include:

1. They give continuous reading and can be calibrated accurately.
2. They are rugged and can be used for two-phase liquids such as slurries, sugar solutions, powders, etc.

The disadvantages of these meters include:

1. They must be installed horizontally on a solid base. These meters are not flexible enough to adapt to any process; thus, the process must be designed around it.
2. They are bulky and cumbersome to use.
3. They are unsuitable for gas density measurements.

Balance-Type Densitometers

Balance-type densitometers are suitable for liquid and gas density measurements. Manufacturers offer many different types; four of the most commonly used ones are discussed below.

Balanced-Flow Vessel

A fixed volume vessel as shown in [Figure 21.4](#) is employed for the measurements. While the liquid is flowing continuously through the vessel, it is weighed automatically by a sensitive scale — a spring balance system or a pneumatic force balance transmitter. Because the volume and the weight of the liquid 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.

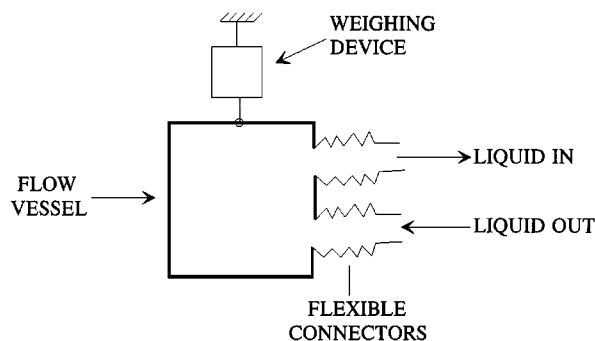


FIGURE 21.4 Balanced flow vessel. An accurate spring balance or force balance system is used to weigh the vessel as the liquid flows through it.

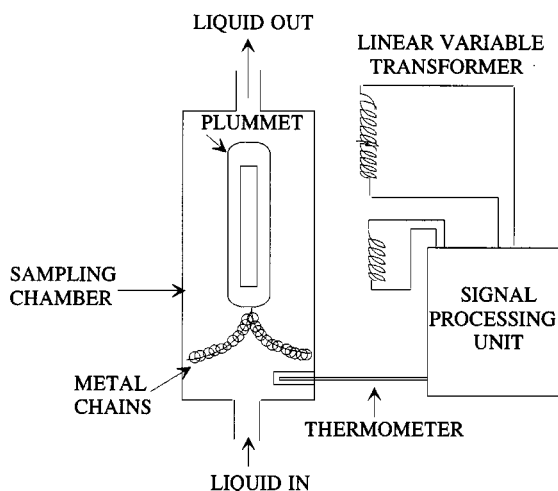


FIGURE 21.5 Chain balance float. The fixed volume and weight plummet totally suspended in the liquid assumes equilibrium position, depending on the density. The force exerted by the chains on the plummet is a function of plummet position; hence, the measured force is proportional to the density of the liquid.

Chain Balanced Float

In this system, a self-centering, fixed-volume, submerged plummet is used for density measurements, as illustrated in [Figure 21.5](#). The plummet is located entirely under the liquid surface. At balance, the plummet operates without friction and is not affected by surface contamination. Under steady-state conditions, the plummet assumes a stable position. 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. The plummet contains a metallic transformer core that transmits changes in the position to be measured by a pickup coil. The voltage differential, a function of plummet displacement, is calibrated as a measure of variations in specific gravity. A resistance thermometer bridge is used for the compensation of temperature effects on density.

Gas Specific Gravity Balance

A tall column of gas is weighed by the floating 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 for any gas density measurement.

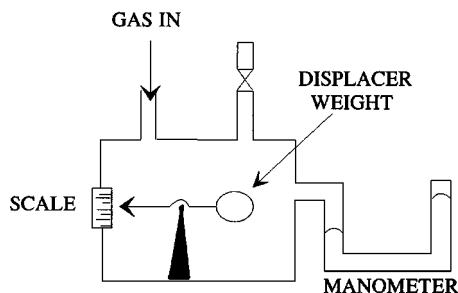


FIGURE 21.6 Buoyancy gas balance. The position of the balance beam is adjusted by a set pressure air, air is then displaced by gas of the same pressure. The difference in the reading of the balance beam gives the SG of the gas. The pressures are read on the manometer.

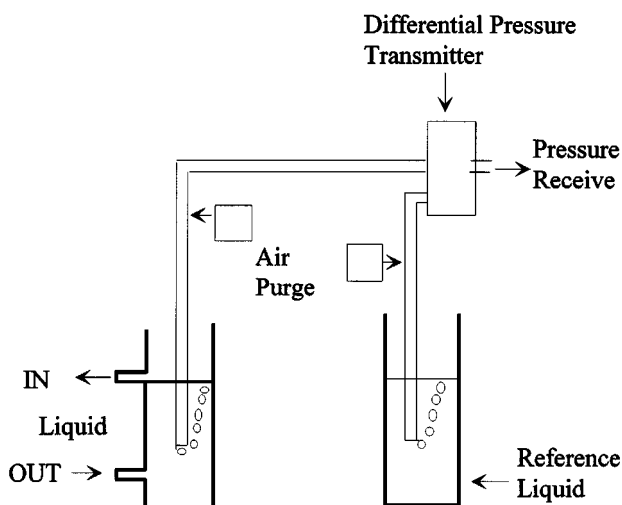


FIGURE 21.7 Reference column densitometer. Two identical tubes, having the same distance from the surface, are placed in water and liquid. Water with known density characteristics is used as the reference. The pressures necessary to displace the fluids inside the tubes are proportional to the densities of the fluids. The pressure difference at the differential pressure transmitter is translated into relative densities.

Buoyancy Gas Balance

In this instrument, a displacer is mounted on a balance beam in a vessel, as shown in [Figure 21.6](#). 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 the pressure of gas is then the density of the gas relative to air. This method is commonly applied under laboratory conditions and is not suitable for continuous measurements.

Column-Type Densitometers

There are number of different versions of column methods. As a typical example, a reference column method is illustrated in [Figure 21.7](#). A known head of sample liquid and water from the 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

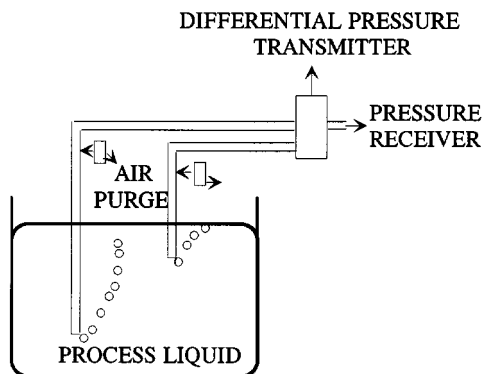


FIGURE 21.8 Two-tube column densitometer. The pressure difference at the differential pressure transmitter depends on the relative positions of the openings of the pipes and the density of liquid. Once the relative positions are fixed, the pressure difference can be related to the equivalent weight of the liquid column at the openings of the pipes, hence the density of the liquid.

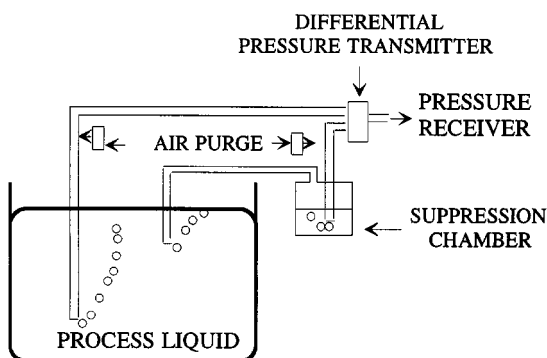


FIGURE 21.9 Suppression-type, two-tube column densitometer. Operation principle is the same as in Figures 21.7 and 21.8. In this case, the suppression chamber affords greater accuracy in readings.

range of measurements can be obtained. Both columns must be maintained at the same temperature to avoid the necessity for corrections of temperature effects.

A simpler and more widely used method of density measurement is achieved by the installation of two bubbler tubes as illustrated in [Figure 21.8](#). 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 the bubbler tubes. The outlet of one tube higher than the other and the distances of 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, and calibrations can be made that have a 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 during measurements.

Another version is the range suppression type, which has an additional constant pressure drop chamber as shown in [Figure 21.9](#). This chamber is in series with the low-pressure side to give advantages in scaling and accurate readings of densities.

Vibrating Element Densitometers

If a body containing or surrounded by a fluid is set to resonance at its natural frequency, then the frequency of oscillation of the body will vary as the fluid properties and conditions change. The natural frequency is directly proportional to the stiffness of the body and inversely proportional to the combined mass of the body and the fluid. It is also dependent on the shape, size, and elasticity of the material, induced stress, mass, and mass distribution of the body. Basically, the vibration of the body can be equated to motion of a mass attached to a mechanical spring. Hence, an expression for the frequency can be written as:

$$\text{Resonant frequency} = \text{SQRT} \left(K / (M + k\rho) \right) \quad (21.3)$$

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 for the purpose.

Magnetic Drives

Magnetic drives of the vibrating element and the pickup sensors of vibrations are usually achieved using small coil assemblies. Signals picked up by the sensors are amplified and fed back as a drive to maintain the disturbing forces on the vibrating body of the meter.

In order to achieve steady drives, the vibrating element sensor can be made from nonmagnetic materials. In this case, small magnetic armatures are attached.

The main advantage of magnetic drive and pickup systems is they are noncontact methods. They use conventional copper windings and they are reliable within the temperature range of -200 to $+200^\circ\text{C}$.

Piezoelectric Drives

A wide range of piezoelectric materials are available to meet the requirements of driving vibrating elements. These materials demonstrate good temperature characteristics as do magnetic drive types. They also have the advantage of being low in cost. They have high impedance, making the signal conditioning circuitry relatively easy. They do not require magnetic sensors.

The piezoelectric drives are mechanically fixed on the vibrating element by adhesives. Therefore, attention must be paid to the careful placement of the mount in order to reduce the strain experienced by the piezo element due to thermal and pressure stresses while the instrument is in service.

A number of different types of densitometers have been developed that utilize this phenomenon. The three main commercial types are introduced here.

Vibrating Tube Densitometers

These devices are suitable for highly viscous liquids or slurry applications. The mode of operation of vibration tube meters is based on the transverse vibration of tubes as shown in [Figure 21.10](#). 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 the liquid is measured. The tube length is approximately 20 times greater than the tube diameter.

A major design problem with the vibrating tube method is the conflict to limit the vibrating element to a finite length and accurately fix 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 obstruction to the flow, thus experiencing some pressure losses. The twin tube, on the other hand, offers very small blockage ([Figure 21.11](#)) and can easily be inspected and cleaned. Its compact size is another distinct advantage. In some densitometers, the twin tube is designed to achieve a good dynamic balance, with the two tubes vibrating in antiphase. Their nodes are fixed at the ends, demonstrating maximum sensitivity to installation defects, clamping, and mass loading.

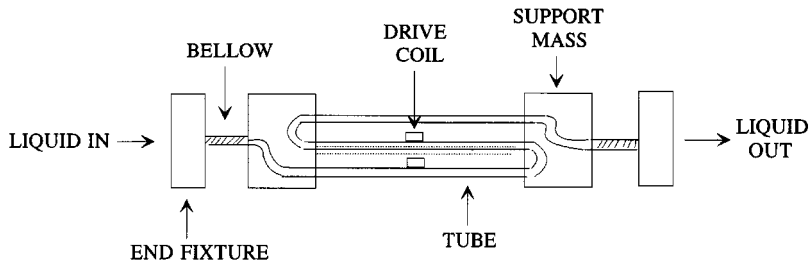


FIGURE 21.10 Vibrating tube densitometer. Tube containing fluid is vibrated at resonant frequency by electromagnetic vibrators. The resonant frequency, which is a function of the density of the fluid, is measured accurately. The tube is isolated from the fixtures by carefully designed bellows.

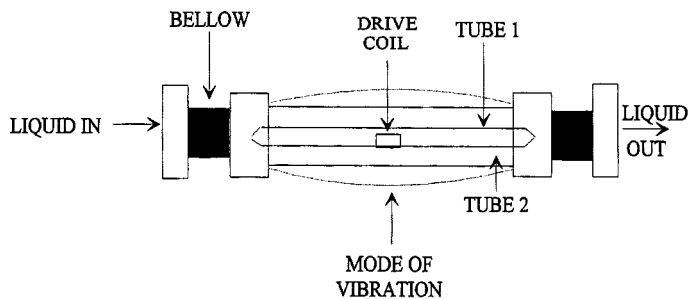


FIGURE 21.11 Two-tube vibrating densitometer. Two tubes are vibrated in antiphase for greater accuracy. Twin-tube densitometers are compact in size and easy to use.

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 both 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, no pressure balance is required. 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 mandatory. The changes in the Young's modulus with temperature can be reduced to near-zero using Ni-span-C materials whenever corrosive properties of fluids permit. Usually, manufacturers provide pressure and temperature correction coefficients for their products.

It is customary to calibrate each vibration element densitometer against others 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 a liquid with well-known properties. Prior to calibration, the vibration tube densitometers are subjected to a programmed burn-in cycle to stabilize them against temperatures and pressures.

Vibrating Cylinder Densitometers

A thin-walled cylinder, with a 3:1 length:diameter ratio, is fixed with stiff ends. The thickness of the cylinder wall varies from 25 μm 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 of corrosion-resistant magnetic materials. Steel such as FV520 is often used for this purpose. Such materials have good corrosion-resistance characteristics; unfortunately, due to their poor thermoelastic properties, they need extensive temperature corrections.

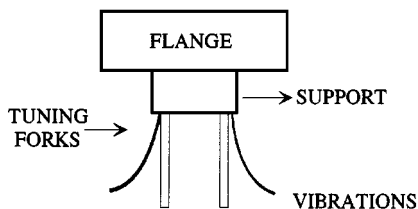


FIGURE 21.12 Tuning fork densitometer. Twin forks are inserted into the fluid and the natural frequencies are measured accurately. The natural frequency of the forks is a function of the density of the fluid.

Nickel-iron alloys such as Ni-span-C are often used to avoid temperature effects. Once correctly treated, the Ni-span-C alloy has near-zero Young's modulus properties. Because 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 kHz 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, gases with well-known properties (e.g., pure argon or nitrogen) are used for calibrations. In this case, the meters are subjected to a gas environment with controlled temperature and pressure. The calibration curves are achieved by repetitions to suit the requirements of individual customers for particular applications. In the case of liquids, the meters are calibrated with liquids of known density, or they are calibrated against another standard (e.g., pycnometer or buoyancy type densitometers).

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

Tuning Fork Densitometers

These densitometers make use of the natural frequency of low-mass tuning forks, shown in [Figure 21.12](#). In some cases, the fluid is taken into a small chamber in which the electromechanically driven forks are situated. In other cases, the fork is inserted directly into the liquid. Calibration is necessary in each application.

The advantages of vibrating element meters include:

1. They are suitable for both liquids and gases with reasonable accuracy.
2. They can be designed for real-time measurements.
3. They can easily be interfaced because they operate on frequencies and are inherently digital.
4. They are relatively robust and easy to install.
5. Programmable and computerized versions are available. Programmed versions make all the corrections automatically. They provide the output of live density, density at reference conditions, relative density, specific gravity, concentration, solid contents, etc.

The disadvantages include:

1. They do not relate directly to primary measurements; therefore, they must be calibrated.
2. They all have problems in measuring multiphase liquids.

Radioactive Densitometers

As radioactive isotopes decay, they emit radiation in the form of particles or waves. This physical phenomenon can be used for the purposes of density measurement. For example, γ rays are passed

through the samples and their rate of arrivals are measured using ion- or scintillation-based detection [2]. Generally, γ -ray mass absorption rate is independent of material composition; hence they can be programmed for a wide range materials. Densitometers based on radiation methods can provide accuracy up to $+0.0001 \text{ g mL}^{-1}$. Many of these devices have self-diagnostic capabilities and are able to compensate for drift caused by source decay, thus pinpointing any signaling problems.

If γ rays of intensity J_0 penetrate a material of a density ρ and thickness d then the intensity of the radiation after passing through the material can be expressed by:

$$J = J_0 \exp(-n \rho d) \quad (21.4)$$

where n is the mass absorption coefficient.

The accuracy of the density measurement depends 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.

For accurate operations, there are many arrangements for relative locations of transmitters and detectors, some of which are illustrated in Figures 21.13 and 21.14. Generally, the source is mounted in a lead container clamped onto the pipe or the container wall. In many applications, the detector is also clamped onto the wall.

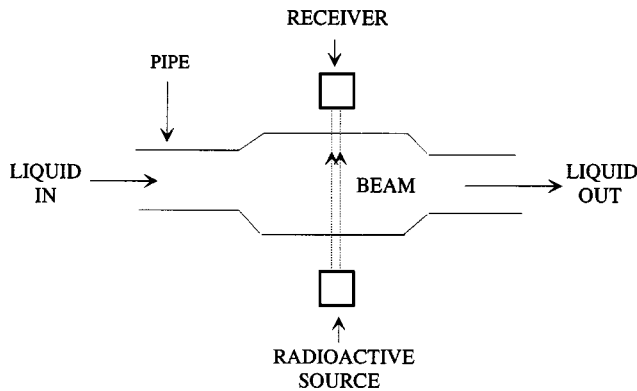


FIGURE 21.13 Fixing radioactive densitometer on an enlarged pipe. The pipe is enlarged to give longer beam length through the liquid, and hence better attenuation of the radioactive energy.

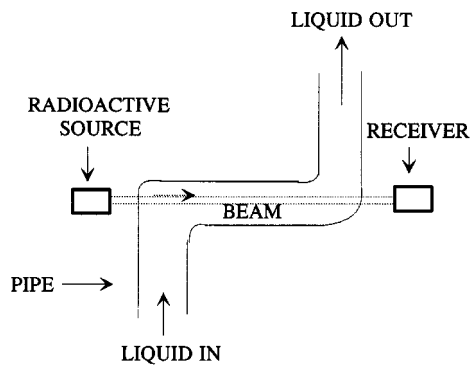


FIGURE 21.14 Fixing radioactive densitometer on an elongated pipe. Elongated path yields a longer path length of the radioactive energy through the liquid; hence, a stronger attenuation.

The advantages of using radioactive methods include:

1. The sensor does not touch the sample; hence, there is no blockage to the path of the liquid.
2. Multiphase liquids can be measured.
3. They come in programmable forms and are easy to interface.
4. They are most suitable in difficult applications, such as mining and heavy process industries.

The disadvantages include:

1. A radioactive source is needed; hence, there is difficulty in handling.
2. For reasonable accuracy, a minimum path length is required.
3. There could be long time constants, making them unsuitable in some applications.
4. They are suitable only for solid and liquid density measurements.

Refractometer and Index of Refraction Densitometers

Refractometers are essentially optical instruments operating on the principles of refraction of light traveling in liquid media. Depending on the characteristics of the samples, measurement of refractive index can be made in a variety of ways (e.g., critical angle, collimation, and displacement techniques). 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 take place. For example, 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 can include signal outputs adjustable in both frequency and duration.

Another version of a refractometer is the index of refraction type densitometer. For example, in the case of position-sensitive detectors, the index of refraction of 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 [Figure 21.15](#), 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 adulteration of liquids of common use (e.g., edible oils, wines, and gasoline). They also find application in pulp and paper, food and beverage, sugar, dairy, and other chemical industries.

Coriolis Densitometers

The Coriolis density metering systems are similar to vibrating tube methods, but with slight variations in the design. They are comprised of a sensor and a signal-processing transmitter. Each sensor consists of one or two flow tubes enclosed in a sensor housing. They are manufactured in various sizes and shapes [3]. The sensor tubes are securely anchored at the fluid inlet and outlet points and force is vibrated at the free end, as shown in [Figure 21.16](#). The sensor operates by applying Newton's second law of motion ($F = ma$).

Inside the housing, the tubes are vibrated in 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, material of construction, and mass of the tube assembly. The tube mass comprises 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 volume. Because the tube volume is constant, the frequency of oscillation can be related directly to the fluid density. Therefore, for a given geometry

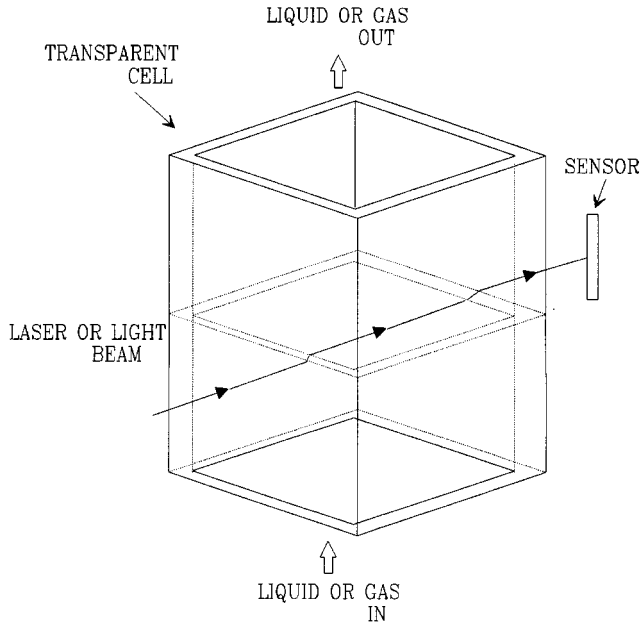


FIGURE 21.15 Index of refraction-type densitometer. The angle of refraction of the beam depends on the shape, size, and thickness of the container, and the density of fluid in the container. Because the container has the fixed characteristics, the position of the beam can be related to density of the fluid. Accurate measurement of the position of the beam is necessary.

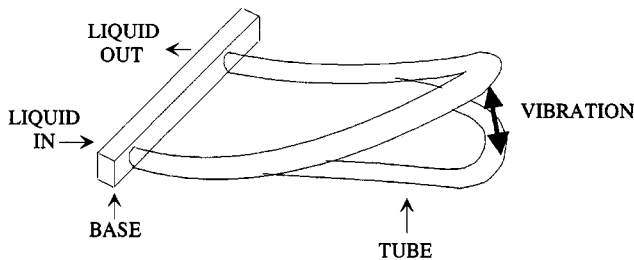


FIGURE 21.16 Coriolis densitometer. Vibration of the tube is detected and related to the mass and flow rate of the fluid. Further calibrations and calculations must be made to determine the densities.

of 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 modulus of elasticity of the tube. The fluid density is calculated using a linear relationship between the density and the tube period and calibration constants.

Special peripherals, based on microprocessors, are offered by various manufacturers for a variety of measurements. However, all density peripherals employ the natural frequency of the sensor coupled with the sensor temperature to calculate on-line density of process fluid. Optional communication, interfacing facilities, and appropriate software are also offered.

Absorption-Type Densitometers

Absorption techniques are also used for density measurements in specific applications. X-rays, visible light, UV light, 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 (e.g., 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 coat all equipment with which it comes in contact. An ultrasonic density control sensor can fully be emerged into an agitated slurry, thus avoiding the problems of coating and clogging. Inasmuch as 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.

References

1. H. Eren, Particle concentration characteristics and density measurements of slurries using electromagnetic flowmeters, *IEEE Trans. Instr. Meas.*, 44, 783-786, 1995.
2. Micro Motion Product Catalogue, Mount Prospect, IL: Fisher-Rosemount, 1995.
3. Kay-Ray, Solution for Process Measurement, Mount Prospect, IL: Fisher-Rosemount, 1995.

Appendix

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, J 07823
Tel: (908) 475-2373

Anton Paar U.S.A.
13, Maple Leaf Ct.
Ashland, VA 23005
Tel: (800) 221-0174

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
Southampton, 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