6.10 Gas Densitometers

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Types:
A. Displacement (buoyancy gas balance)
   A1. Specific gravity detector at ambient conditions
   A2. Density sensor of gases under pressure
   A3. Electromagnetically suspended dumbbell
B. Centrifugal
C. Fluid dynamic (jet backpressure)
D. Gas column balance (hydrostatic head manometer)
E. Thermal conductivity
D. Viscous drag
G. Vibrating design discussed in Sections 6.5 and 6.8
H. Ultrasonic density

Design Pressure:
A. Up to 1500 PSIG (103 bars)
D, E, F, H. Generally atmospheric
G. Up to 3000 to 5000 PSIG (207 to 345 bars [see Sections 6.5 and 6.8])

Design Temperature:
D, E, F. Generally ambient
G. −13 to 500°F (−25 to 260°C) for Section 6.8; −400 to 400°F (−240 to 204°C) for Section 6.5
H. −40 to 450°F (−40 to 230°C)

Materials of Construction:
A, B. Aluminum, cast iron, steel, and stainless steel
C. Stainless steel
D, E, F. Pyrex, brass, nickel, Monel, and stainless steel
G. Ni-Span C, stainless steel, Hastelloy, tantalum, titanium, zirconium, Incoloy, borosilicate glass, Tefzel lining (see Sections 6.5 and 6.8)
H. Corrosion resistant

Minimum Span (SG values based on air):
C. Detects gases at molecular weights from 2 to 100
E. 0.5 SG
F. 0.1 SG
G. About 20 times the error (see Sections 6.5 and 6.8)
H. 2 to 120 Mw

Inaccuracy (SG values based on air):
A1, A3. 1 to 2% of span
A2. 0.25% of span
B. 0.1 to 0.5% of span
C. 2% of span
D. 0.001 SG
E. 0.01 SG
F. 1 to 2% of span
G. Typically 0.002 SG (see Sections 6.5 and 6.8)
H. 1.8%

Costs:
F $7000 to 12,000
G. From $4000 to $25,000 (see Sections 6.5 and 6.8)
H. About $20,000
INTRODUCTION

This section gives a historical perspective on gas density measurement techniques, including the mechanical designs, which have been widely used in the past, but have lost their popularity or have been completely discontinued. This is due to their moving parts and their associated high maintenance. This trend toward solid-state instrumentation is a general trend throughout the industry, and in the case of gas densitometers, it resulted in the proliferation of oscillating and vibrating sensors. These are discussed separately in Sections 6.5 and 6.8, but some of their features and suppliers have been also mentioned in the feature summary above under type G, for the reader’s convenience.

THEORY OF OPERATION

Gas density measurement relies on some of the same laws of physics that are used in liquid density measurement. Liquids have typical densities on the order of 40 to 80 lbm/ft³ (600 to 1300 kg/m³); gases have densities on the order of 0.05 to 0.5 lbm/ft³ (0.8 to 8.0 kg/m³). The methods used include the weighing of a known volume either passively or actively. Passive weighing is measuring the static forces created by gravity. An example is a laboratory balance.

Active weighing is the process of moving or shaking the volume and determining the density from the required acceleration or the Coriolis forces (Section 6.5) or container displacement, or the oscillation frequency (Section 6.8). Another scheme varies the gas pressure until the buoyancy force is equal to that air at atmospheric pressure; at this condition, the ratio of the absolute pressures equals the specific gravity (SG). The speed of sound through a gas is inversely proportional to the square root of the density and this relationship has been used. Thermodynamic properties, such as heat capacity, have been used as the basis of instruments. Gas jet deflection has been used; gas jet impact pressure recovery is also sensitive to gas density. The centrifugal fan laws can be the basis for measuring density—see any mechanical engineering handbook. The head pressure generated is a function of the gas density.

Density is mass per unit volume. Relative density (also called specific gravity) is the ratio of the density of a gas to that of air at the same temperature, pressure, and moisture content. Confusing absolute density with specific density can have disastrous effects on engineering calculations and designs. The relative density is equal to the ratio of molecular weights of the gas and of air, which is usually taken as 28.9644.

The density of an ideal gas can be calculated from its specific gravity (or molecular weight), the absolute temperature, and the absolute pressure, because equal numbers of moles of gas occupy equal volumes. See Section 6.1 for details.

To avoid redundancy, some of these devices, such as the vibration-based devices (Section 6.8) and Coriolis-type (Section 6.5) designs, are not covered here.

Gas density measurement is of interest for several different reasons. Density compensation is used to correct some flowmeters that are sensitive to density. For this purpose, it is preferred to measure the actual gas density at the flowing pressure and temperature. A flow computer is often used for this purpose when the measurement has sufficient value.

The other major use is to infer or to determine composition. Specific gravity relative to air is most conveniently measured at or near atmospheric conditions. Some of the designs, such as the displacement, centrifugal, and fluid dynamic designs, may also operate at higher pressures and can measure either specific gravity or actual density. Orientation Table 6.1a provides an overview of the capabilities of the different designs.

DISPLACEMENT-TYPE DENSITOMETERS

The buoyant force exerted upon a body immersed in a gas is proportional to the density of that gas. If the gas is at ambient conditions, the buoyant force is a measure of the molecular weight or specific gravity of the sample.

The principle is demonstrated in Figure 6.10a. It consists of a chamber containing a balance beam with a glass cylinder...
6.10 Gas Densitometers

on one end and a counterweight on the other. The manual version requires first filling the chamber with dry air until the beam just balances and noting the corresponding air pressure $P_a$ as shown on the manometer. Then the chamber is evacuated and filled with sample gas, increasing the pressure until the beam is once more balanced. This gas pressure $P_g$ is noted and the specific gravity of the sample gas is calculated as the ratio of the two pressures is converted to absolute and measured in the same units. Pressures are normally moderate and any deviation from the ideal gas laws should not create errors.

$$SP_g = \frac{P_g}{P_a} \quad 6.10(1)$$

It is not necessary to balance the unit in air each time the gauge is used; once it has been balanced, the manometer scale can be calibrated in either molecular weight or specific gravity units. The sample molecular weight is determined by:

$$M_{wg} = M_{wa} \frac{P_g}{P_a} \quad 6.10(2)$$

This sort of instrument is no longer made and is included in this discussion for completeness of the discussion and to illustrate the applied physics.

The lower drawing in Figure 6.10a shows a variation on this design. Here the arc through which the beam swings is the measure of sample density and is indicated on the calibrated scale. If the bulb and beam are balanced in air and the gas sample introduced is at the same pressure, temperature, and humidity as the balancing air, then the gauge can read out either in specific gravity or in molecular weight units. This instrument is no longer available.

The sensors shown in Figure 6.10a operate on the buoyancy gas balance principle, where the buoyant forces of air and gas are compared. In the upper instrument, the operating pressure is adjusted until the gas density is the same as the reference air. In the lower instrument, the calibration accuracy is a function of the calibration of the measuring balance.

The accuracy of measurement is largely a function of eliminating those factors (pressure, temperature, humidity) that can influence density. If the air and gas are compared under identical conditions then the accuracy can be as great as ±0.0002 SG. These sensors are used for high-precision laboratory measurements. Their main drawback is that they cannot be adapted for continuous measurement. Issues such as the humidity of the reference air and the sample gas must be addressed. Some instruments use desiccant dryers to take water from the air and the sample.

Continuous Units for Pressurized Operation

The densitometer shown in Figure 6.10b measures the gas density at actual flowing conditions. The effects of process pressure, temperature, super-compressibility, or specific gravity changes are eliminated and the density is measured directly. Archimedes’ principle is that the buoyant force on a float (displacer) is a function only of the fluid density surrounding the float.

The manually operated version of this gauge is illustrated in Figure 6.10b. It consists of a buoyant float attached to one end of a pivoted beam and a temperature-insensitive spring attached to the other end. The spring tension in this case is adjusted manually using a micrometer until the beam is brought into a null position. The readout linkage is attached to the spring and provides linear density data. These are no longer available.

Besides the manual method described above, the spring tension can be adjusted by pneumatic relays or electric motors. Figure 6.10c shows an electronic densitometer transmitter. This is no longer available, but instruments may still exist.

For accurate measurement of flowing density, the sample must be at the same operating conditions as in the process line. This is improved with the use of short (close-coupled) sample lines and by relatively high sample flow rates (10 SCFH, or 280 l/hr) and good thermal insulation.
Density Measurement

Spans from 1.0 to 25.0 lbm/ft³ (16 to 400 kg/m³) can be obtained for measurements at 0.25% of full-scale accuracy.

Electromagnetic Suspension-Type Units

The main working component of this detector is a small dumbbell supported on a quartz fiber. One of the spheres on the dumbbell is sensitive to buoyancy effects (changes in gas density); the other is not. Insensitivity to buoyancy is achieved by puncturing that sphere (see Figure 6.10d).

A mirror fixed to the dumbbell axis reflects a light beam to a dividing mirror that splits the beam equally between two photocells. A change in gas density tends to rotate the dumbbell, causing the light to be unevenly divided between the photocells. Therefore, the signals produced by the photocells will differ; when this difference is amplified it can be applied to recenter the dumbbell. This is achieved by applying a new electrical potential to the electrodes that generate the electrostatic field around one of the spheres. Measuring the electrical potential required to stabilize the dumbbell gives a linear indication of the torque created by the differential buoyancies, which in turn is an indication of sample density. If the sample is at ambient conditions, the instrument scale can be calibrated in specific gravity or molecular weight units.

In contrast with the manual displacement units, these detectors are adaptable for continuous measurements and generate output signals for remote readout. They are available with spans of 0.01 to 2.0 SG based on air with ±1% full scale accuracy. Single-range units have a total span of 1.0 SG, and multirange designs are available with a 5:1 range ratio. The measurements are performed at near-atmospheric pressures and ambient temperatures, utilizing sample flow rates in the 50 to 500 cc/min range. Depending on this flow rate, the 95% response time of the detector varies from a few seconds to 1 min. Due to the small openings and the optical parts involved, the sample gas must be clean upon entering the sensing cell. This detector is compensated for barometric changes and is manually calibrated on air or other reference gases.

This device was selected for those installations where high precision overrides the cost considerations. This instrument is no longer made.

CENTRIFUGAL GAS DENSITY SENSORS

The centrifugal detector also measures the gas density at flowing pressure and temperature conditions. As shown in Figure 6.10e, a small centrifugal blower operating at constant high speed (3000 to 13,000 r/min) extracts a small sample of gas from a tank or pipeline. The impeller is driven by magnetic coupling to allow removal of the driver and to prevent gas leakage. Gas enters the impeller at the center and is thrown outward by centrifugal force. This action creates a pressure differential across the impeller which is directly proportional to the gas density. The differential pressure (d/p) can be indicated locally or used as the input signal into a d/p transmitter for remote readout.

FIG. 6.10c
Continuous gas density sensor electronic transmitter.

FIG. 6.10d
Electromagnetic suspension-type sensor.

This device was selected for those installations where high precision overrides the cost considerations. This instrument is no longer made.

FIG. 6.10e
Density detector with centrifugal element.
Some designs can be close-coupled around an orifice plate in the pipeline; others can be installed directly in tanks or pipes.

When the gas sample is dirty, deposits may accumulate in the unit, affecting the sample flow rate. This will not influence the measurement accuracy until the material buildup becomes substantial.

Errors can be introduced by temperature differences between the process and the density chamber. This temperature difference may be caused by the difference between ambient and process temperatures and also by the motor and friction heat developed in the sensor. The error can be as high as 0.1 or 0.2% $\Delta F$. In most installations, close-coupling and insulating the detector is sufficient. In the case of critical measurements, the process and chamber temperatures are detected and automatic correction is applied for the difference.

Available density spans vary from 1.0 to 20 lbm/ft$^3$ (16 to 300 kg/m$^3$) with full-scale inaccuracies at ±1% or less. Repeatability can be as good as ±0.05%.

Wetted components are available in cast iron, aluminum, steel, or stainless steel. The detectors can be exposed to pressures up to 2000 PSIG (14 MPa) and temperatures up to 300°F (149°C).

The maximum pressure differentials developed by the blower are a function of the impeller size selected, speed of rotation, and density span. The differential varies between 30 and 100 in. H$_2$O (7.5 to 25 kPa). The relationship between density and pressure differential developed is linear within the range of 5:1. This technology has been replaced by the vibrating sensor type.

**FLUID DYNAMIC DENSITOMETER**

The fluid dynamic densitometer (Figure 6.10f) is used to measure the densities of gases and liquids. It is composed of two chambers (A and B) each having a supply nozzle (C$_s$ and C$_m$) and an opposing receiver port (D$_r$ and D$_m$). One chamber is used as a reference chamber having only a small outlet port; it is filled with a suitable supply of nitrogen or other fluids (E) such that the dynamic pressure ($P_d$) of this jet on the receiver port (D$_r$) serves as a reference value. Directly adjacent to this reference chamber is a similar measuring chamber (B) that has large inlet and outlet ports through which the measured fluid is pumped by the action of the same supply fluid (E). The product whose density is to be measured, being entrained by this supply jet, affects the dynamic pressure ($P_m$) of this jet on the receiver port, which is inversely proportional to the density. A comparison of the pressure differential produced between the reference chamber and the measurement pressure is a measure of the density of the unknown product.

The fluid dynamic densitometer can be used for measurement of density of process stream and effluents in both liquids and gases. It has no moving parts, a very high sensitivity, and a high rate of response, but it is not particularly suitable for non-Newtonian fluids. It can be made of a wide variety of materials and can be mounted directly in a body or stream of fluid to give precise point measurements. Thus, petroleum and petrochemical refineries, natural gas processing plants, ethylene production, chemical process plants, and the pulp and paper industry are typical applications. There are other embodiments of the general principle of a gas jet and recovered pressure. These seem to be no longer available—another victim of the vibrating sensor. The design described above is only one of a number of schemes that have been used.

**GAS COLUMN BALANCE SENSORS**

As their name implies, these instruments operate on the principle of measuring the difference in weight between a column of gas and a column of air of equal heights and pressures.

As shown in Figure 6.10g, the gas sample flows continuously to the interior of the oil-sealed working bell on the right and then leaves the bell through a column of set height into the atmosphere. At the same time, dry air enters the interior of the reference bell and exits to the atmosphere through a column of equal height. The weight of gas and air in the columns exerts an upward force on the bells, and the difference in weight between the two columns is the force, which causes the beam movement. Beam movement is resisted by the weight of a pendulum, which allows the pen mechanism to move in direct ratio to the specific gravity of the gas flowing through the unit.

The sample flow rate is 2 SCFH (0.9 l/m) or less at near-atmospheric pressure, limited by the oil seal in the unit.
This corresponds to an approximate measurement time lag of 3 min. Available spans vary between 0.25 and 1.0 SG, and ranges can be selected between 0 and 2.5 SG, based on air. Detection accuracy is ±0.002 SG.

The wetted parts can be made of brass or stainless steel, and a large number of accessories and features are available, including direct recorders, controllers, and transmitters of both electronic and pneumatic types.

Whenever the basis of operation for a density sensor is to compare the gas sample to air in arriving at a specific gravity reading, it is important to compensate for the following:

1. Ambient temperature variations
2. Barometric pressure variations
3. The moisture content of the air

The sensor illustrated on Figure 6.10g is provided with an automatic temperature compensator. This is a bimetallic coil calibrated to shift the pendulum weight center of gravity in direct ratio to the temperature effect on the density. Therefore, regardless of the ambient temperature variations, the specific gravity readout is always based on 60°F (16°C).

The forces acting on the working bell are very small. At 0.5 SG, the total resulting pressure head is 0.036 in. H₂O (9 Pa), and the instrument sensitivity of 0.002 SG corresponds to only 0.00014 in. H₂O (0.04 Pa). With such sensitivity, even barometric pressure variations are sufficient to introduce an error. As an example, a change of 0.5 in. Hg (0.065 kPa) in the barometric pressure can result in an error of 1%. Compensation can either be by manual adjustment of column height or by use of an aneroid barometer that automatically corrects for barometric pressure changes.

When air contains moisture, its density at the same barometric pressure is less than what it would be under dry conditions. Changes in humidity have a very definite effect on measurement precision. Therefore, a silica gel drier is installed to keep the reference air purge dry.

From the above discussion, it is clear that this detector can automatically correct its readings for humidity, temperature, and barometric pressure variations. These are no longer manufactured.

**THERMAL CONDUCTIVITY DENSITY GAUGES**

Thermal conductivity-type sensors are also discussed separately in Section 8.12 and also under Section 8.57. Because the thermal-type elements are most frequently used as analyzers or as components in analyzer systems, their coverage here will be brief and limited to that design that is suitable for direct specific gravity detection.

Figure 6.10h illustrates a design that is suitable for both gas chromatography and on-stream molecular weight determination. A pneumatic Wheatstone bridge with two hot-wire detectors is mounted in the vertical plane. The reference gas tends to cool the thermistors and, as long as the flow is balanced, the two detectors are equally cooled. When a sample gas is introduced, it will upset the system balance if its molecular weight is different from that of the reference gas. Zero balance is checked by introducing the reference gas as sample. If the sample gas is lighter than the reference gas, the sample molecules will tend to rise, partially obstructing the reference gas flow at detector #1, and, therefore, causing a temperature rise at that point. Simultaneously, a corresponding increase of reference gas flow will be experienced at detector #2, causing a drop in temperature at that point. The temperature difference between the two thermistors is a measure of the sample gas molecular weight.

The reference gas selected should have sufficient difference in density from the sample for accurate measurement, and preferably have high molecular weight, high heat capacity, and low viscosity. Nitrogen, argon, or carbon dioxide tend to satisfy these requirements. The sample flow is normally...
maintained at about 10 cc/min, while the reference flow is set at about 10 times that to avoid back-diffusion.

The main advantage of this design is that the sample gas never comes in contact with the detectors, and, therefore, they cannot become coated, coked, or contaminated by the sample. Another desirable feature is that the cell contains no moving parts.

Due to the tubular design, brass, stainless steel, Monel, or nickel construction materials can be provided without substantial difference in cost.

Variations in ambient temperature can introduce errors. Therefore, the cell temperature is normally controlled within ±1°F (±0.6°C).

**VISCOS DRAG-TYPE DENSITY SENSORS**

Another method of detecting the density of a gas relative to air (specific gravity or molecular weight) is illustrated in Figure 6.10i.

The unit consists of a sample chamber and an air chamber with a motor-driven impeller and an impulse wheel in each. Impeller #1 draws in air and spins it against the vanes of impulse wheel #3, creating a clockwise torque proportional to the air density. Impeller #2 draws in the gas sample and sets it in a counterclockwise rotation. The whirling gas strikes the impulse wheel #4 and imparts a counterclockwise torque to its shaft proportional to the gas density. The difference between the opposing torques is a measure of the sample specific gravity. It is transmitted through a lever and linkage arrangement to the pointer, which moves in front of the scale, which is calibrated in specific gravity, molecular weight, or percent concentration units.

As in the case of the previously discussed detectors, the sample temperature, pressure, humidity, and solid particle content will affect the precision of measurement.

The sample gas temperature should be the same as that of ambient air. This is normally guaranteed by the large surface area of the sample tubing that brings the gas temperature to ambient without need for auxiliary devices.

Because both the gas and air are vented to atmosphere, the barometric pressure variations are automatically balanced.

If the sample gas is under pressure, it has to be reduced to less than an inch of water pressure before entering the instrument. If it is under vacuum, the two exhausts must be connected into the same vacuum system.

The relative humidity of air and gas should be the same. This can be achieved either by saturating both streams with a humidifier or by drying both streams through a desiccant dryer.

Sample filters are normally used to remove suspended particles or corrosive constituents because the wetted parts are not highly corrosion-resistant. Brass, aluminum, and stainless steel are in contact with the sample.

The sample flow rate of about 20 SCFH (9 l/m) provides a response time of less than 20 s.

Spans from 0.1 to 2.0 SG are available within the limits of 0.1 and 3.0 SG. The measurement inaccuracy varies between 1 and 2% of full scale, and the unit is normally calibrated on the actual sample gas.

This instrument can still be obtained as an indicator, recorder, switch, or transmitter.

**ULTRASONIC DENSITY DETECTION**

Some models of transit time ultrasonic flowmeters (see Section 2.26) include the ability to report density. Typical applications are for vent and flare stacks. Costs are high and the user should review the claimed specifications for suitability.

**CONCLUSIONS**

Of the mechanical measurement technologies reviewed in this section, only one—the viscous drag-type sensor is still available. The vibrating surface type devices now dominate the market (see Sections 6.5 and Section 6.8). The high value of natural gas has led to the use of gas chromatographs and Btu analyzers to determine the value of the gas from composition and/or the heating value of fuel gases for a more accurate measurement of value and flow than the composition inferred from density instruments. The American Society for Testing and Materials’ “Standard Test Methods for Relative Density of Gaseous Fuels (ASTM D-1070)” includes operating procedures for some of these older instruments.
Bibliography


