INSTALLATION AND OPERATION OF DENSITOMETERS

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Introduction

A densitometer is an on-line and continuous device used to measure the density of a flowing stream. In the oil and gas industry, a densitometer is normally used to measure the density of liquid hydrocarbon finished products like propane and gasoline and liquid mixtures like Y-grade natural gas liquids (NGL), but can also be used to measure the density of crude oil. The typical installation is in a single-phase liquid stream, but densitometers can be used to measure single-phase gas or vapor. This paper addresses only continuous, on-line liquid density measurement.

There are a number of applications in the oil and gas industry where measured density is important. First, and probably the most widely used, is to determine the quantity of material passing through a meter. The quantity may be determined either through mass or volumetric measurement techniques, each using the measured density but applying it to the final quantity in a different way. A second use is to detect a pipeline interface, the "plug" of liquid between two dissimilar products shipped in the same pipeline. Continuous, on-line density measurement provides a pipeline operator with the ability to see the density change from one batch to the next and make the appropriate valve changes to properly route liquids to the correct destination. Another common use is in pipeline leak detection where operators look for relatively small leaks by comparing pressures and flow rates at points along a pipeline. Measured density can provide a more accurate prediction of frictional pressure loss in the pipeline since, in addition to flow rate, pressure loss is a function of the Reynolds number which is in turn a function of the fluid density. Lastly, measured density can also provide meaningful data for quality monitoring of finished products and other fluids.

This paper focuses on installing and operating densitometers in dynamic systems used to measure quantities of material passing through a meter from the perspective of custody transfer. Principles detailed in this paper can be applied to installing and operating densitometers for interface, leak detection or quality monitoring services.

Density Meters

Many of the density measurements taken in the oil and gas industry are determined by continuous, on-line densitometers (density meters) installed in a meter station where at least a portion of the flowing stream is passing through or around the densitometer sensing element. Continuous, on-line density measurement is appropriate where stream composition changes frequently or unpredictably. The uncertainty of the density measurement is greatly affected by how well the portion of the flowing stream measured at the densitometer matches the properties at the point of interest – for instance, the volume meter.

Continuous, on-line densitometers commonly used in the oil and gas industry for custody transfer measurement fall into three general classes of devices; vibrating element, buoyant force and continuous weighing. A vibrating element densitometer uses a drive coil to excite a tube or tuning fork to vibrate at its natural or resonant frequency. As the fluid in the tube changes density it causes a change in the resonant frequency because of the change in mass of the tube and its contents. This frequency change is non-linearly proportional to the flowing density of the fluid. A vibrating tube densitometer is often used to measure the density of NGL, liquefied petroleum gas (LPG) and refined products streams like gasoline and may also be used to measure the density of crude oil. Vibrating tube densitometers may be mounted external to the main piping utilizing slipstream arrangements or directly mounted in the line. A direct mount densitometer uses a sensing element, for instance a resonant frequency tuning fork, which is inserted into the meter run piping. Buoyant force densitometers measure fluid density by the change in electrical force required to balance a float in a chamber containing the fluid to be measured. The change in force is proportional to flowing density. Continuous weighting devices utilize fluid passing through a tube or vessel of known volume that is continuously weighed to determine the fluid density.

The densitometer uses electrical power and a mechanical arrangement of tubing, tuning fork, float and chamber or vessel to measure the density of the fluid flowing through the device. The densitometer then transmits an electrical signal representing the measured density to a downstream device like a flow computer, a control system or a recorder for further use.

The resonant frequency of a vibrating tube densitometer is sensitive to the temperature of the tube and its contents. Some densitometer designs sense the temperature and provide corrections for temperature changes. Materials that are relatively insensitive to temperature changes experienced in custody measurement are also available. The densitometer materials must be chemically and structurally compatible with the service intended.

Other density measurement technologies exist including nuclear, hydrostatic, acoustic, capacitance and density calculated from composition, pressure and temperature using an equation of state.

Density can also be measured in discrete batches such as a spot sample like a pycnometer proving, a weigh tank or a hydrometer test but none of these are continuous or on-line devices and cannot be considered densitometers. However, discrete measurements such as a pycnometer test are routinely used to prove a densitometer.

Density

Density is a measure of mass per unit volume, and may be expressed in grams per cubic centimeter, pounds per gallon, kilograms per meter cubed or another set of engineering units. A density reading in one set of units may be directly converted to another set by converting the mass and/or the volume units. Relative density is the ratio of the mass of a given volume of a substance to that of another equal volume of a reference standard substance. For oil and gas applications, liquids are referenced to water at a base temperature of 60ºF, 15ºC or 20ºC and to a base pressure of atmospheric pressure if the liquid has a vapor pressure less than atmospheric or its equilibrium vapor pressure if greater than atmospheric. Relative density is synonymous with the historical term specific gravity. It is important to note that although the relative density of a liquid is numerically close to the density in grams per cubic centimeter, it is not the same because the density of water is not exactly 1 gram per cubic centimeter.

Composition and temperature have a significant effect on density. To illustrate the effect of the composition of a stream, water is about twice as dense as propane, and a mixture of normal butane and gasoline is more dense than a nearly-pure stream of isobutane. Temperature effects result from the volume increasing as the temperature increases and volume decreasing as the temperature drops. While the volume changes with changes in temperature, the mass does not change. Since density is the ratio of mass to volume, the density decreases as temperature increases. Additionally, the rate of expansion of a hydrocarbon as a function of temperature can be about 10 times greater than that of water and varies among the hydrocarbons. Pressure also influences density, but to a lesser degree than composition or temperature. However, the effect of pressure on density is more pronounced in light hydrocarbons like ethane and high-ethane content raw mixes, in supercritical fluids like ethylene and carbon dioxide and of course in gases. For crude oil, water-based solutions and slurries, the affect of pressure on density is often insignificant.

Measuring Quantities

In the oil and gas industry, the main reason to measure density is to determine the quantity of material passing through a meter. Density is an important variable in the calculation procedure, whether one uses a volumetric method or a mass measurement technique. In both methods the density is used to determine the volume at base conditions. Base conditions are usually specified in the contracts associated with each metering facility and typically are 60ºF or 15ºC for base temperature and atmospheric pressure or the equilibrium vapor pressure of the liquid for base pressure.

Inferred mass measurement involves multiplying the measured volume at flowing conditions by the flowing density at the same conditions as the measured volume over time to determine the pounds or kilograms or other mass unit of measure for the liquid that has passed through the meter. Using the weight percent analysis of a sample representative of the liquid that passed through the meter, one may calculate the mass and volume of each component that passed through the meter. Density measurement uncertainty has the same impact on mass measurement as uncertainty in volume measurement since flowing density is a direct multiplier in determining the total mass. Mass measurement is commonly used where the liquid contains both small and relatively large molecules, such as in mixed NGL production from a gas plant. When the liquid contains a mix of these different sized molecules there are solution mixing and intermolecular adhesion effects. Solution mixing and intermolecular adhesion is illustrated by imagining a mixture of 1,000 cubic feet of gravel and 1,000 cubic feet of sand. Because the sand fills the voids around and between the gravel, the total volume of the mixture is less than 2,000 cubic feet even though the mass (or weight) of the gravel and the sand individually is the same as the weight of the mixture. Density increases due to solution mixing effects. Mass measurement techniques can effectively separate the components in the stream, represented by the gravel and sand, and provides the correct volume measurement for each pure component at base conditions.

Specification products, like propane, isobutane and gasoline, may rely on published tables and equations to correct for the effects of temperature (Ctl) and pressure (Cpl) as a function of measured density. Measuring the flowing density can result in a more accurate determination of Ctl and Cpl than assuming the density based on product specifications or an assumed composition. Since Ctl and Cpl are functions of density, the sensitivity of the volume calculation to density uncertainty is lower than in mass measurement. This generally means the densitometer in a mass measurement station requires a lower uncertainty than in a volumetric meter station.

Design

A successful densitometer installation measures flowing density at the uncertainty level appropriate for the measurement technique, is easy to operate and maintain, and is installed at the lowest cost. Accuracy, operation, maintenance and cost can be conflicting objectives. Careful attention to developing a complete design can achieve a satisfactory balance of uncertainty, risk, operational satisfaction, maintainability, installed costs and ongoing costs.

In all cases, the installation must meet codes, standards and company policies to protect people, property and the environment. Terms and conditions specified in the contract must also be followed. Many times, the contract references API Manual of Petroleum Measurement Standards (MPMS) Chapter 14, Section 6, Continuous Density Measurement for design, installation, operation and maintenance.

The designer must know the purpose of the density measurement. Will it be used to calculate the quantity of liquid changing custody through a fiscal meter or will it measure density for pipeline interface detection? What is the risk involved, in other words, what might be the cost of density measurement uncertainty? Is the density used for inferred mass measurement or for determining temperature and pressure corrections for volumetric measurement? What experience does the operating company have in measuring density? Answers to these questions lead to selecting a type of densitometer from the classes of continuous and discrete measurement. If a continuous densitometer is selected, a further choice must be made between vibrating element, buoyant force and continuous weighing designs or other technologies.

A densitometer manufacturer needs to know the composition of the fluid to be measured, what normal, minimum and maximum temperatures and pressures to expect, whether the fluid is corrosive or has erosive tendencies and the expected flowing density range. Without complete answers to these questions, the densitometer may not perform properly and could fail. Be aware that density uncertainty is different between models of densitometers, and that the effect on density uncertainty due to temperature changes is different between models and manufacturers. Consult with the densitometer manufacturer to select the appropriate model.

Piping design and layout is critical to a successful installation. MPMS Chapter 14.6 shows a number of piping arrangements for installing density meters. The most important piping design consideration, after addressing all mechanical integrity and safety issues, is to ensure the densitometer measures a representative sample of the flowing stream. A representative sample exists when it has the same composition, pressure and temperature in time as exists at the volume meter. Since the effect of composition, pressure, temperature and time on density varies between fluids, an evaluation of properties over the ranges expected and the resulting changes in density should be performed. Careful attention to providing sufficient flow through the densitometer without undue pressure loss will prevent many composition, temperature and time problems in the field.

If an externally mounted densitometer is selected, slipstream piping must be designed. MPMS Chapter 14.6 shows piping arrangements for these slipstream systems. The piping arrangements are based on supplying a representative sample of the fluid to be measured to the densitometer. Many times the slipstream piping, densitometer, pycnometer piping and the volume meter and its piping must be insulated to maintain temperature stability through the system. It is common to install the densitometer downstream of the volume meter to avoid pressure losses that occur from flow conditioners, valves and strainers that upstream of the meter. For best overall measurement, make sure the densitometer is operating at pressures and temperatures as close as possible to the conditions existing at the volume meter.

One common way to provide a sufficient flow to the densitometer is to create a differential pressure to drive the slipstream. This can be done with a control valve, slipstream flow meter and flow controller, with an orifice restriction or with a pump. If a pump is used in the densitometer loop for light liquid hydrocarbons and specification products, it must be installed downstream of the densitometer such that it does not add heat or pressure to the stream measured in the densitometer. Crude oil systems have successfully installed pumps upstream of the densitometer. Velocity head devices, like sample scoops, can in some cases provide sufficient flow through the densitometer. Some meter designs include both a differential pressure-producing device, like an orifice plate, together with a sample scoop to pull the densitometer sample from the center one-third of the pipe. If an orifice restriction is selected, consider using a dual chamber or a single chamber orifice fitting to eliminate or at least reduce downtime for occasions when the orifice plate must be changed in response to flow rate changes.

If an insertion type density meter is selected and installed directly in the flowing stream, the designer must be sure there will be no stratification in the piping and that the fluid being measured is reasonably clean. Consider whether the fluid velocity in the piping is fast enough to avoid stratification but less than the maximum velocity for the density meter.

Specify, buy and install a density meter designed for the appropriate electrical area classification. Consider power sources in the design and the type of electrical output signal required. The typical density output signal is a frequency fed to a flow computer.

Installation

Consider the needs of the individuals operating and maintaining the density meter when arranging and installing the densitometer, piping, conduit and wiring. A technician will periodically test and calibrate the densitometer, and may have to clean, inspect and maintain it.

Piping must be arranged such that low points can be drained and high points can be vented. Test temperature, pressure and pycnometer locations must be included in the design. Temperature and pressure test points must be installed at the densitometer, pycnometer and volume meter. Refer to MPMS Chapter 14.6 for guidance. Keep in mind that the technician must be able to safely reach all of these locations to read temperatures and pressures and catch the pycnometer samples. Piping arranged with the technician and operator in mind helps to maintain density measurement quality and accuracy. In driving flow through the densitometer, ensure the densitometer and pycnometer piping does not bypass the volume meter or the volume meter proving connections.

Densitometer manufacturers will specify how their device must be installed for the intended service. For instance, a vibrating element densitometer may have to be installed such that flow is vertically up through the densitometer which often results in it being the highest point on the meter skid. Be aware of the possibility of lightening strikes and properly ground and isolate the equipment. A buoyant force meter likely will have to be level horizontally. Consult with the densitometer manufacturer for applicable constraints.

Excessive vibration causes inaccurate density measurement. Piping must be adequately supported and anchored, allowing sufficient room for expansion and contraction without subjecting the densitometer to excessive forces, to minimize or eliminate vibrations caused by pumps, control valves and other devices.

Operation

The densitometer will provide a signal proportional to the density of the fluid flowing through it as long as the fluid remains single-phase and at a sufficient flow rate to provide a stable signal. Refer to MPMS Chapter 14.6 for further operational details.

Periodic testing and calibration are part of routine operation. Densitometers are typically tested and calibrated at least once a month. The most common test method is a pycnometer proving as described in MPMS Chapter 14.6. Pycnometer proving involves filling and weighing a pycnometer to determine the test density, comparing the test density to the densitometer flowing density, repeating the test and calculating a density correction factor from two consecutive tests. The density correction factor causes the measured density to match the pycnometer test density. A pycnometer is a spherical sample container with its weight and volume known to low uncertainty. It is normally made of stainless steel and its expansion characteristics due to temperature and pressure are accurately known. Use a double-walled pycnometer in LPG, NGL and other high pressure services where fluid thermal expansion is expected. Hydrometer, pressure thermohydrometer and density calculated by equations of state may also provide an independent density measurement, however their uncertainty is usually higher than allowed for fiscal measurement in light hydrocarbon service.

Troubleshooting

Densitometers can provide long, trouble-free service, however problems may arise from several areas. Normally these problems are seen in erratic readings or in density proving factors for which the difference between consecutive provings exceeds some tolerance, such as 0.25% above or below the previous factor.

A restriction in the densitometer piping will cause errors if the stream flowing through the densitometer is no longer a representative sample because of its pressure, temperature, composition or relevance in time. A flow meter on the densitometer slipstream piping or a differential pressure gauge across the orifice plate or control valve can help to diagnose this problem.

Problems may also be caused by two-phase flow in the densitometer or by excessive vibration. Further problems in vibrating element densitometers may result from entering incorrect calibration coefficients in the flow computer. These coefficients are used to convert the non-linearly proportional densitometer tube vibration frequency to a density reading in engineering units like grams per cubic centimeter. Consult the densitometer calibration certificate or the manufacturer for calibration coefficients for each densitometer. No signal at all may result from a blown fuse on the densitometer power supply, a broken signal wire or a failed safety barrier.

Summary

Density measurement is important to many fiscal transactions, both for mass measurement techniques as well as volumetric techniques. When density measurement is required on a flowing stream, users have a number of options. An understanding of the technologies available, the advantages and limitations of a specific technology and its measurement uncertainty are key elements to a successful installation. A density meter can then be selected and its installation designed after satisfactorily balancing density measurement uncertainty, risk tolerance at this meter station, the desire for operability and maintainability, while minimizing installed costs and ongoing costs. Proper operation and maintenance provide for performance within the uncertainty expectations for the station. The techniques learned in the oil and gas industry over the last 30 years and the knowledge documented in industry standards are valuable to the industry. For installations focused on interface detection, quality monitoring or pipeline leak detection, the techniques and knowledge used in fiscal measurement provide useful guidance.

Glossary

Density – the ratio of mass per unit volume with the volume at a specified temperature and pressure, usually base conditions.

Mass – a measure of the quantity of matter which is constant from one location to another.

Pycnometer – a vessel whose volume and evacuated weight are known within 0.02 percent.

Hydrometer – a graduated glass tube weighted to float upright in a liquid calibrated to indicate density or relative density

Pressure thermohydrometer – a hydrometer with a self-contained thermometer

Cpl – liquid pressure correction factor to compensate for the change in volume resulting from applying pressure, a function of liquid density and temperature.

Ctl – liquid temperature correction factor, proportional to the thermal coefficient which is a function of liquid density and temperature.

References

1. American Petroleum Institute, Manual of Petroleum Measurement Standards, Chapter 14, Section 6, Continuous Density Measurement.
2. Gas Processors Suppliers Association / Gas Processors Association, Engineering Data Book.