APPLICATION OF DENSITOMETERS TO LIQUID MEASUREMENT

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INTRODUCTION

One of the many parameters that must be accurately measured for product quality control, custody transfer, process control, or liquid interface detection purposes is liquid density. Often, density measurement is combined with flow measurement to determine the mass flow rate of a liquid in a pipeline. In this article, we will discuss the principle of operation of vibrating tube densitometers, design suggestions for densitometer installation, and calibrating, or "proving", the system.

DENSITOMETER TYPES

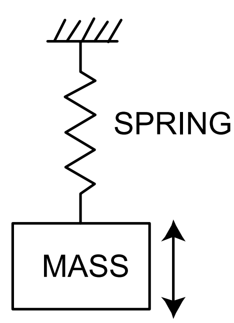
There are different types of densitometers in use today. Some of the various operational principles in use for these devices are listed as follows:

- Vibration
- Buoyancy
- Nuclear
- Acoustic

Each operational principle has advantages and disadvantages. The selection of the densitometer type usually depends on the application, performance requirements, and budget. In this article, we will restrict our discussions to vibrating tube densitometers.

THEORY OF OPERATION

The simplest vibrating system consists of a spring and mass mechanically connected together as shown in Figure 1. If the mass is displaced and released, the system will vibrate at a known frequency defined by the following equation,



$$Frequency = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

where,

k = spring constant

m = total mass

If the spring constant, k, or the mass, m, changes, the frequency of vibration, or the "natural frequency", will change. This concept can be related to a vibrating tube densitometer. The spring constant is related to the stiffness of the tubing. The mass is related to the mass of the tubing plus the mass of the liquid inside the tubing. As the mass (or density) of the fluid in the tubing varies the natural frequency varies

VIBRATING TUBE DENSITOMETERS

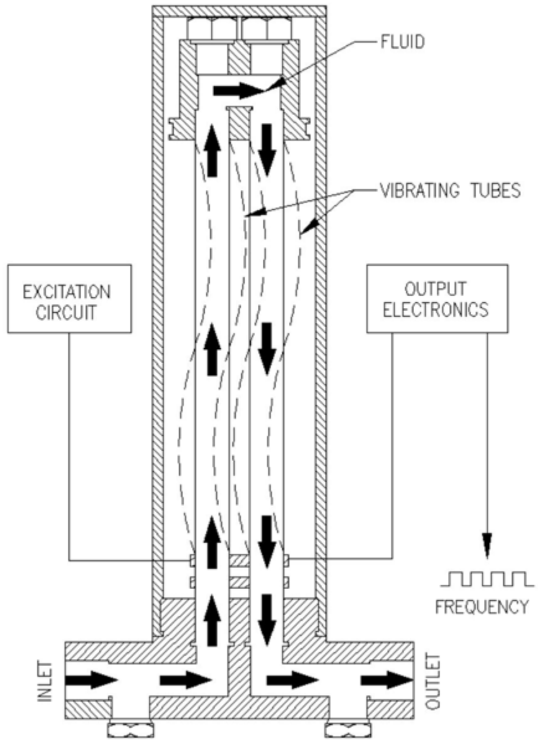


Figure 2

A vibrating tube densitometer is basically a ***spring-mass*** system where the frequency of vibration of the tubing is measured and related to the fluid density. The tube assembly is supported at each end and is mechanically "excited" or "displaced" using electro-mechanical devices so that the assembly will vibrate at the natural frequency. As previously discussed, the frequency of vibration of the tube assembly will vary as the density of the fluid in the tubing changes. The tube assembly must have appropriate mechanical properties to resist corrosive attack from the fluid, contain the pipeline pressure, and have desired vibration characteristics. The actual arrangement of the tubes will vary with manufacturer, with parallel tubes, U-tube, and in-line tubing being the most common. The tube material is usually Ni-Span C, Stainless Steel, or Hastelloy although other materials have been used. An efficient densitometer installation design will ensure that a representative liquid pipeline sample is located inside the tube(s) at all times.

The following equation is used to relate the frequency of vibration of the tubing to the actual fluid density:

$$\text{Uncorrected Density} = K_0 + K_1 t + K_2 t^2$$

Where,

K_0 = Calibration coefficient

K_1 = Calibration coefficient

K_2 = Calibration coefficient

t = 1/frequency = Period of vibration

For increased accuracy, compensation for the effects of changing temperature, T, and pressure, P, on the tubing must be performed. To relate to the spring-mass example, the changes in pipeline T and P cause small changes to the stiffness of the spring, causing variation in the frequency of vibration. In most cases, the frequency shift caused by changing temperature and pressure can be described with second-order equations with coefficients that are unique for each densitometer.

The coefficients used in these equations are supplied by the manufacturer when the densitometer is purchased or re-certified. During field calibration, or proving, of the densitometer, a density correction factor, DCF, is used to adjust the indicated, or observed, density of the densitometer to the actual density of the liquid. If the DCF varies beyond manufacturer recommendations, or the accuracy varies with the fluid density, the densitometer must be examined for possible defects and re-certified.

DENSITOMETER SIGNAL PROCESSING

The signal output from a vibrating tube densitometer is a "square wave" signal with a frequency equaling the vibration frequency of the tube assembly. From this signal, the frequency must be measured, and the corrections for the effects of fluid temperature and pressure must be applied. The final determination is the density of the fluid. A computer is used to perform these calculations. In many cases, the computer is also measuring the pipeline fluid flow rate using a turbine flow meter, an orifice meter, or other flow measurement device. Using the accumulated data, the fluid mass flow rate can be determined. Depending on the application, the flow computer output values may be transferred to another computer or process via 4-20 mA signals, or through the use of a communication network (Fieldbus, Profibus, Modbus, HART, etc....)

DENSITOMETER INSTALLATION

The performance of a densitometer is highly dependent on the design of the installation. The following items must be considered during the design phase (Ref. Figures 3 and 4):

- Flow rate.

  Densitometers may be connected in parallel (bypass) or series (inline) to a pipeline. When connected in series, the maximum flow rate through the densitometer must be considered. Densitometers are usually connected in parallel to the pipeline using a "bypass loop" if the pipeline flow rate is high. In this case, the flow rate in the loop must be sufficient to provide a representative liquid sample from the pipeline, through the densitometer, and back to the pipeline. If this flow rate is too low, the time required to sense a change in pipeline density may be excessive and erratic density readings may occur. The flow rate through the densitometer bypass loop is created using "scoops" in the main pipeline to induce flow. The differential pressure between the inlet and discharge scoops of the loop must be sufficient to induce adequate flow. In some cases, an orifice plate must be used to increase the differential pressure and the loop flow rate.

- Liquid phase

  Unless stated otherwise, most densitometers are intended for use with single-phase fluids. Unpredictable density measurements result if the liquid consists of varying mixtures of liquid and gas.

- Distance from pipeline and related flow measurement devices

  The distance between the densitometer, the pipeline, pycnometer connections, temperature and pressure measurements, and flow measurement devices must be minimized. By reducing these distances, the pressure drop through the bypass loop is minimized and the temperature of the entire system is uniform.

- Densitometer insulation

  The insulation of the densitometer and bypass loop is critical to provide a uniform temperature at the densitometer, at the pycnometer, and at the flow measurement site (turbine flow meter or orifice plate).

- Orientation

  The orientation of the densitometer is usually vertical or horizontal. The densitometer manufacturer has specific guidelines for performance in all orientations.

- Pycnometer connection

  An insulated secondary flow loop must be provided for the pycnometer upstream of the densitometer in the primary flow loop. This loop is used when the densitometer must be proved (i.e. calibrated).

- Thermowells and pressure transducers

  The final accuracy of the density and mass flow measurement is also dependent on the accuracy of the temperature and pressure measurements. The location of these measurements and the stability of the readings must be carefully considered.

DENSITOMETER PROVING

To verify the accuracy of the entire system, a densitometer must be calibrated or "proved" periodically. The device used to perform this calibration is known as a "pycnometer".

A pycnometer is a precision sphere of known mass and volume that is capable of withstanding pipeline pressures. The pycnometer is recommended for use by API for densitometer proving.

During the proving of a densitometer, the pycnometer is connected in series or parallel with the densitometer. Once temperature stability (±0.2°F) has been achieved at all locations in the flow loop, the pycnometer is removed and weighed. Once the "tare mass" or empty mass of the pycnometer has been subtracted, the liquid mass per unit volume, or density is calculated. This test is normally repeated until the readings are repeatable. Once this occurs, the density value is used to calculate the "density correction factor", DCF, and is used to calculate the actual density in the flow computer or signal converter. The following equations are used:

$$DCF = \frac{Density_{pyc}}{Density_{obs}}$$

$$Density_{pyc} = \frac{M_{pyc} - M_{empty}}{V_{pyc}}$$

where,

$Density_{pyc}$ = Pycnometer density

M_{pyc} = Pycnometer mass (filled with fluid

M_{empty} = Pycnometer empty mass (under vacuum)

V_{pyc} = Pycnometer volume (corrected)

$Density_{obs}$ = Observed density

A certified, traceable weighing device must be used to determine the mass of the pycnometer. For optimum accuracy, verify the calibration of the weighing device using certified masses before proving a densitometer. Since the pycnometer empty mass is determined at standard temperature and pressure, and standard gravity (980 cm/sec^2), compensation for a difference in buoyancy at local ambient conditions and local gravity must be applied to the weight values. See Reference 1 for a standard on density proving using a pycnometer.

GLOSSARY

- Density: The mass per unit volume of a gas or liquid.
- Relative density (Specific gravity): For a gas, the ratio of the density of the gas to the density of air at standard temperature and pressure. For a liquid, the ratio of the density of the liquid to the density of water at standard temperature and pressure.
- Standard Temperature and Pressure: The standard (reference) temperature and pressure at which gas volumes are calculated. In the U.S., the base temperature is 60°F and the base pressure will vary (14.65, 14.696, 14.73 Psia) depending on local standards. When comparing gas volumes, verify that the base conditions are the same.
- Mass: A quantity of matter. Matter is any material that occupies space and has mass.
- Weight: The force with which mass is attracted to earth due to local gravity.

  Weight = Mass x Local gravity (Gc)

REFERENCES

1. API "Manual of Petroleum Measurement Standards", Chapter 14, Section 6.

Figure 3.

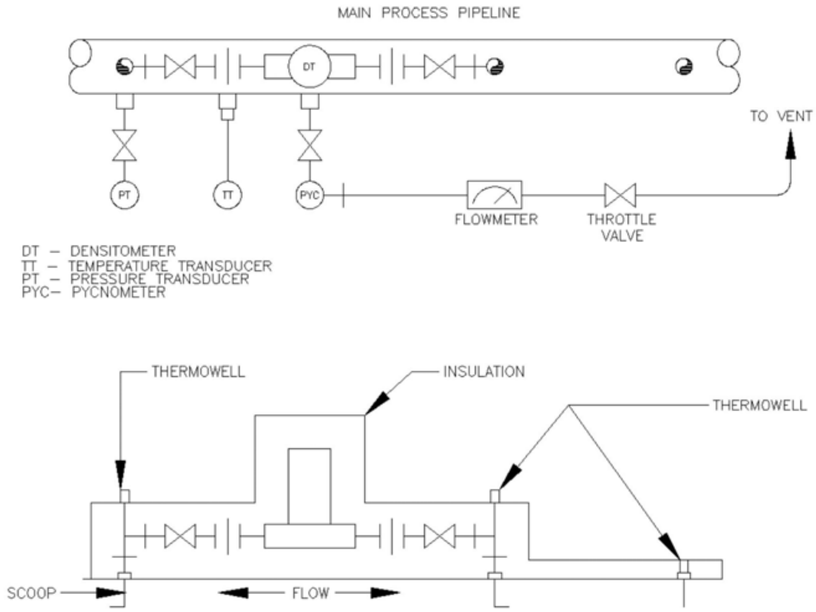


Figure 4