CORIOLIS MASS FLOW METERS FOR GAS AND LIQUID MEASUREMENT

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Introduction

A mass flowmeter is a system that provides a measurement of fluid flow in units of mass; pounds, tons. The Coriolis flowmeter is a type of flowmeter which measures the mass of the fluid flow directly. Coriolis mass flowmeters were first introduced more than 30 years ago. Global acceptance has spread across all industries where precision flow measurement is needed. Today, installations number in the hundreds of thousands of measurement points including those in liquid hydrocarbon and natural gas applications.

This paper will review the Coriolis mass flowmeter technology; describing the differences and similarities between Coriolis flowmeters and electronic and mechanical meters and looking at some latest developments in Coriolis mass meter design and operation.

Coriolis Flowmeter Principle of Operation

The Coriolis mass flowmeter is a multivariable device by design. It directly measures the mass of the flowing fluid, liquids and gases. The meter indirectly measures liquid density and also the temperature of the containment tube. The mass flow and density measurement can be used to calculate gross volume of liquids. The temperature can be used to approximate the temperature of the fluid. The Coriolis flowmeter is bi-directional.

Direct Measurement of Mass Flow Rate

The Coriolis mass flowmeter is named after the French mathematician, Gaspar Gustave de Coriolis, who described the apparent forces on a mass moving through a rotational plane. Coriolis flow meters operate on the principle of the Coriolis Effect.

The first independent measurement in a Coriolis flow meter is the direct determination of mass flow rate. The Coriolis flow sensor can be constructed of one or two intrinsically balanced metal tube(s) fixed at each end. The tube system (or sensor) is oscillated by using a center mounted electro-mechanical system (exciter) that imparts a force to set the tube(s) in motion. This motion is proportional to the applied excitation signal. A variable gain feedback circuit maintains the amplitude of the tube oscillation at the minimum applied excitation current to set the tube(s) in motion. (Figure 1)

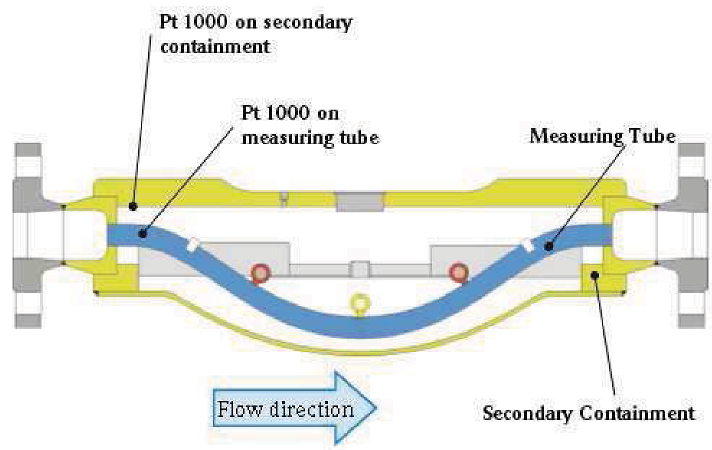

Figure 1

A mass flow dependent Coriolis force occurs in the measurement system when a moving mass is subjected to an oscillation which is perpendicular to the direction of flow. As a fluid passes through the flow sensor, the Coriolis force is created by the oscillatory motion and transferred to the measurement tube(s) which then induces a change of motion. Two motion sensors (electro-dynamic sensors) detect this change, essentially a twisting of the tube(s). Mass flow rate is determined by the phase offset or difference between the inlet and outlet measurement signals derived at the electro-dynamic sensors. (Figure 2) As the mass flow rate increases, the phase offset measured by the electro-dynamic sensors will increase proportionally. As the mass flow rate decreases, the phase offset measured by the electro-dynamic sensors will decrease proportionally. There is no phase offset when flow has stopped. During the calibration process, a calibration factor is determined and retained in the memory of the flowmeter.

The resistance temperature device (RTD) mounted on the flow tube compensates for the increased or decreased flexibility of the flow tube due to process fluid temperature changes. A second RTD may be installed on the sensor housing to compensate for the environmental temperature impact on the sensor.

Unlike volumetric metering systems, no additional correction for temperature or density is required to achieve a direct measurement of mass flow rate in a Coriolis flow meter.

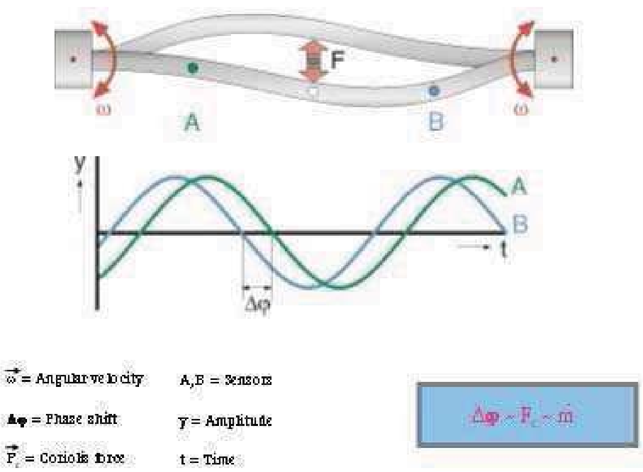

Figure 2

Measurement of the Liquid Density

The Coriolis flowmeter can also be used to measure the density of liquids. Flow tube(s) vibrate at a resonant frequency which corresponds to the sensing tube(s) material and the density of the fluid in the tube(s). Feedback from the sensor electro-dynamic sensors to the excitation current circuit permits the drive frequency to migrate to the resonant frequency. In process, as the fluid density changes the resonant frequency changes. Consequently, the resonant frequency corresponds directly to the liquid density in the sensor. To counter the effect on density due to a change in temperature, an RTD (resistance temperature device) mounted on the flow tube measures the temperature of the flow tube. During the flow meter calibration process, the resonant frequency of each sensor is determined on air and water. This becomes an important "thumbprint", unique to each sensor produced. Just as with vibrating element densitometers, the manufacturer's methodology for factory calibration and ability to define the meter's response against traceable standards will ultimately determine the meter's performance in the field.

In general, liquids are considered incompressible. Vibrating devices are often used to indirectly measure the density of liquids. However, the sensitivity of vibrating devices is generally not sufficient to provide an accurate density measurement of gases. Additionally, gas density is directly influenced by pressure. Coriolis flowmeters are not commonly used to determine the density of gas.

Pressure Effect

In general, Coriolis flowmeters with larger diameter tubes are affected by increasing pressures. The tubes get stiffer and resist the Coriolis force created by the flowing mass. Commonly, the increased pressure causes a reduction in the measured value compared the mass flow at lower pressure. Every Coriolis flowmeter design and size has a different flow pressure effect specification. This correction is normally conducted only when the operating pressure is 100 psi greater than that of the calibration pressure. To adjust the mass flow rate output of a Coriolis meter measuring at pressures other than calibration pressure, a flow pressure effect correction must be applied.

In order to correct for the flow pressure effect in a Coriolis meter's indicated mass flow rate, the following correction factor should be applied to the indicated mass output.

$$F_p = \frac{1}{1 + \left(\left(\frac{P_{Effect}}{100}\right)\left(\left(P_{Static} - P_{calibration}\right)\right)\right.}$$

F_p = Flow pressure effect compensation factor
P_{Effect} = Pressure effect in percent psi
P_{Static} = Measurement fluid static pressure in psi
$P_{Calibration}$ = Calibration static pressure in psi

(From AGA 11, Equation E 8.1)

Gross Liquid Volume

Since the Coriolis flowmeter produces a direct measurement of mass flow rate and also measures the liquid density and temperature, the gross liquid volumetric flow rate can also be computed.

Volume equals the mass divided by density. The Coriolis transmitter can be programmed to output in volume measurement units. The Coriolis meter's volumetric flow rate output is similar to that of other meters such as positive displacement and turbine flow meters. It is necessary to take into account the accuracy of the mass flow measurement and the accuracy of the density measurement when calculating the accuracy of the volume measurement.

The volumetric flow measurement of the Coriolis flowmeter can be influenced by operating conditions.

Standard Gas Volume

The density measurement accuracy of a Coriolis flowmeter does not meet the accuracies required for gas measurement. Instead, the relative density or base density of the gas is entered into a flow computer as determined from either sampling methods or on-line gas analysis.

The method for applying the gas physical property information required by AGA8 Gross Method 1, Gross Method 2, or Detail Method into the flow computer is the same as that which is required by volumetric meters; i.e. Turbine, Orifice, Rotary, and Ultrasonic. Coriolis technology uses the following calculations to output a highly accurate standard or normal volumetric output.

$$SCF_{(gas)} = (Mass/\rho_b)\ F_p$$

where:

$SCF_{(gas)}$ = Gas volume at T_b and P_b
Mass = Weight of gas (Coriolis output)
ρ_b = Density at T_b and P_b

$$SCF_{(gas)} = (Mass/(G_{r(Gas)} * \rho_{b(air)}))\ F_p$$

and

$$\rho_b = (P_b * M_r) / (Z_b * R * T_b)$$

where:

T_b = Temperature at base conditions
P_b = Pressure at base conditions
Z_b = Compressibility at base conditions (T_b and P_b)
$G_{r(Gas)}$ = Real Gravity at T_b and P_b
R = Universal gas constant
M_r = Molar Weight
F_p = Flow pressure effect compensation factor

Coriolis Flow Sensor

Coriolis flowmeters differ dramatically from one manufacturer to another as far as design of the vibrating tubes including tube shape and the way flow enters the meter. Dual or single, bent or straight, the designs all will have unique characteristic benefits described by the manufacturer. Even though there are numerous design variations, Coriolis flowmeters offer many advantages over other flow measurement technologies. Process influences that may damage other flowmeters will have minimal effect on Coriolis flowmeters. Coriolis meters are not intended to meter multiphase fluids, specifically fluids that are a mixture of gas and liquids, though air or gas slugs do not damage the meter.

Coriolis flowmeters have the advantage of a large turndown. However, the pressure drop across the meter should be known in order to select the proper size sensor. Pressure drop should always be considered with any flow meter that is operating near a fluid's equilibrium vapor pressure so that the liquid does not cavitate or flash at the operating flow rate.

Coriolis Transmitter

Coriolis flow sensors are powered and require an associated electronic device that interprets the measurement signals and provides an output. The flowmeter transmitter provides pulse, analog, or digital outputs; singularly or in combination. The electronic transmitters may be directly attached to the body of the Coriolis sensor or remote with an interconnecting cable. Advances in the electronic technology have reduced the size of the processing electronics. Some Coriolis flowmeters have a lower power specification and a single digital communication output directly from the sensor wiring compartment. Some newer Coriolis flowmeters can be powered directly from the analog 4-20 milliamp loop. These meters are typically used in process and not intended for custody transfer where the pulses are commonly proved.

Whether in a separate housing or located on the meter, there is a processor within the electronics that is programmed to provide the required output. The processor may be programmed with the meter's calibration coefficients and also programmed to output in the required units of measurement. Since there is no discrete mechanical action in the meter that would produce a discrete pulse, the processor may be programmed to create the scaled pulses that are required for totalizing and for proving. Electronic flowmeters are described as creating "manufactured pulses".

Coriolis transmitter can also generate alarms triggered by faults or diagnostic levels. It can provide analog outputs used for pump control. The transmitter can calculate net quantities and concentrations. The Coriolis meter is configurable and it is common for the meter to have either basic password security or a form of physical security to limit access to authorized personnel.

Applications

The Coriolis flowmeters are recognized in the American Petroleum Institute (API), Manual on Petroleum Measurement Standards and the American Gas Association (AGA) Report Number 11. Several manufacturers' Coriolis flowmeters have been approved under type evaluation programs and found to comply with the national and international standards which describe requirements for devices used in trade.

Applications where Coriolis flowmeters are used continue to expand in the petroleum industry. These applications include:

1. liquid separators, net oil
2. crude oil and condensate gathering
3. lease automated custody transfer (LACT)
4. liquid pipeline
5. refinery applications
6. railcar and truck loading
7. truck mounted
8. liquefied petroleum gas
9. ethanol receiving

10. viscosity measurement
11. natural gas; storage, transmission and distribution

Applications which are unique to Coriolis flowmeters are those which combine the power of mass flow measurement with the online density measurement.

Custody transfer of liquid hydrocarbons is based on the volume. Although it is rare for custody transfer to take place based on direct mass measurement in the liquid petroleum industry, other commodities used or produced in association with this industry such as natural gas liquids and CO_2 are commonly measured on a mass or standard volume basis.

Installation Requirements

In general, the metering system design is similar to other traditional liquid flow metering installations. The user is advised to follow the manufacturer's installation recommendations in providing piping support for the meter.

The meter should be oriented such that the meter remains completely filled with liquid at all times during the operation of the flowmeter and in a manner that air cannot be trapped inside the tube(s). Solids settlement, plugging or trapped condensate can affect the meter's performance. The alignment of the inlet and outlet flanges is critical to avoid piping stresses that may affect the resonance of the tube(s) inside the meter.

Unlike meters with moving parts, the Coriolis meter can tolerate pipeline solids without damage to the meter however, a strainer upstream of the meter is recommended to protect the meter prover and other system components. A backpressure valve should be located downstream of the meter to avoid flashing and possible cavitation.

Coriolis meters do not require flow conditioning. The flow velocity through a Coriolis meter is generally higher because it is sized to operate in the upper end of its performance range. Velocity should be considered for erosive liquids with high solids content and also when considering piping limitations including pressure drop.

Proving access taps downstream of the meter facilitate proving of the meter and should be located as close to the Coriolis sensor as possible in order to maintain the same pressure and temperature operating conditions. Consideration should be given to the location of the meter electronics that generate the pulse output for portable provers so that the proving connections and the transmitter are located in close proximity.

Proving

Proving the Coriolis flowmeter as a volumetric flowmeter follows the same procedures as when proving any other type of flow meter. When the flowmeter is measuring in volume units the high-resolution pulse output is scaled such that it provides the required level of pulses to the prover counter. The resultant meter factor determined for the Coriolis flowmeter is typically entered into the flow computer.

Proving a Coriolis flowmeter that is metering in mass units, using a volumetric prover, requires the additional measurement of density at the prover in order to determine a meter factor for the mass output. A densitometer is mounted on the prover for this purpose. The densitometer should be proved prior to proving the Coriolis flowmeter. The reproducibility of the density correction factor from proving to proving is directly reflected in the reproducibility of the Coriolis flowmeter factor. As mentioned previously, when utilizing a Coriolis flowmeter on liquid hydrocarbons in custody transfer applications the flowmeter is most often configured for volumetric measure and not mass.

As with proving any flowmeter, it is most important that the flow rate and density of the liquid remains stable throughout the proving. This issue is often reflected in pulse or meter factor repeatability between proving runs. Due to the inability to totally control pipeline operations during proving, it may be necessary to change to one of the acceptable averaging techniques for repeatability calculations or to extend the number of runs.

Evolution and Advances

Early Coriolis flowmeters were of single tube design installed in bolted housing assemblies. They were required to be mounted to massive support structures such as walls, I-beams or floors because they referenced the measurement signal from the tube to the case. They used integrated circuit chips and analog circuitry. When the sensors evolved to balanced dual tubes, the measuring chamber could then be installed directly in the line because the signal could then be referenced from one tube to the other. Today's flow sensors are welded assemblies, some with rated containment. Some sensor assemblies have single tubes some flow sensors have straight tubes. One manufacturer has recently released a four tube Coriolis for high flow rates in a compact design. Newer designs incorporate unique methods of construction to resolve tube signal stability. Coriolis flow sensor design shapes continue to evolve for unique applications and to reduce manufacturer's cost.

For many years, the pipe diameter size was limited. Today, manufacturers are providing both larger sizes Coriolis flow sensors for petroleum pipeline transfer and ship bunkering applications as well as smaller flow sensors for very low flow chemical addition such as for liquefied petroleum gas odorant applications

Today's transmitters are digitally based with both conventional analog and pulse outputs but also with digital communication output. Digital communication is now extending to Ethernet capability with remote connectivity. Even wireless communication is offered in some applications. Loop powered Coriolis flowmeters have been recently introduced for some applications.

Conclusion

Coriolis flowmeters are easily applied into liquid hydrocarbon and natural gas service. Coriolis technology affords users multivariable measurement in a single device with high accuracy and long term reliability. The Coriolis flowmeter technology continues to evolve both in design and functionality. Advances in the Coriolis flowmeter functionality broaden the acceptance and into more liquid hydrocarbon applications. Recognition in industry standards such as those of the AGA, API and type evaluation approvals bears proof of the acceptance of Coriolis flowmeters.

References:

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