Mass Meters for Gas Measurement

Class # 1200

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Introduction

Since the early 1980s, Coriolis meters have gained worldwide acceptance in gas, liquid, and slurry applications with an installed base of more than one million units. Through significant design enhancements in the early 1990s Coriolis meters have rapidly gained worldwide acceptance in gas phase applications with over 120,000 meters installed worldwide and most notably the 2003 publication of AGA Report Number 11, Measurement of Natural Gas by Coriolis Meter.

Having the ability to bidirectionally measure almost any gas phase fluid from -400 to +400 degrees Fahrenheit without concern of error or damage due to flow profile disturbances, pulsations, regulator noise, surges, compressibility change, and density change, Coriolis meters are becoming the fiscally responsible meter of choice in many applications.

Coriolis is a medium to small line-size technology; currently the largest offering from any vendor for gas applications is a 10” (250mm) flow diameter. The pressure drop and flow range of a Coriolis meter draws a direct relationship to the actual flow area through the meter when comparing it to other metering technologies; i.e. the flow area through a turbine meter is the area not displaced by the turbine internals and rotor, the flow area of an orifice meter is that of the orifice diameter. Because of this relationship, a Coriolis meter will typically be one pipe size smaller than a turbine meter and several sizes smaller than an orifice while having similar pressure drops at flowing pressures in the 300 ANSI class and above.

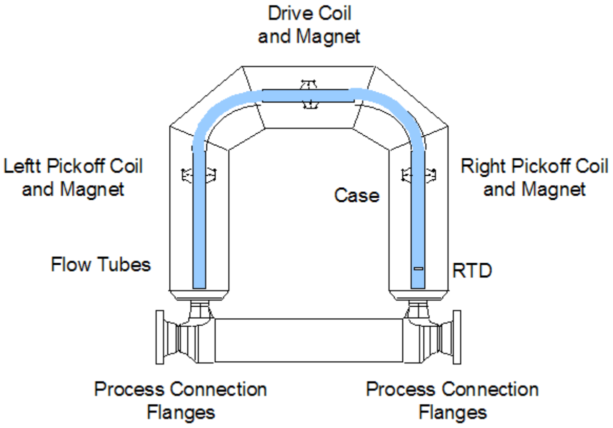
100mm (4”) Coriolis meters installed in 250mm (10”) lines

Being a resonant technology with out wearing parts, Coriolis meters are, for the most part immune, to flow factor shift. Recent advancements in the technology have facilitated the incorporation of resonant modal analysis capability into the design. A Coriolis meter’s flow accuracy can now be verified on-line without disruption in flow, knowledge of process conditions (pressure, temperature, and fluid composition) and without having to visually inspect the internals of the flow element.

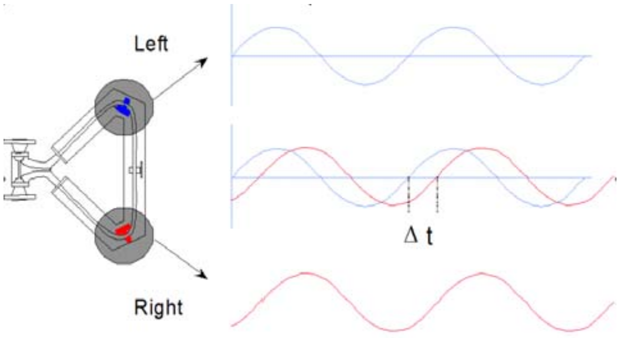
Overall, Coriolis meters offer the least amount of measurement error concern and maintenance in their use as compared to other gas flow technologies. This paper will discuss the theory of operation and guide the user through selection, application, maintenance processes, and provide application examples of the technology for gas measurement.

Theory of Operation

A Coriolis meter is comprised of two main components, a sensor (primary element) and a transmitter (secondary element). Coriolis meters directly infer the gas mass flow rate by sensing the Coriolis force on a vibrating tube(s). The flow conduit consists of one or more tubes that are vibrated at their resonant frequency by a Drive Coil. Sensing pickoff coils located on the inlet and outlet sections of the tube(s), oscillate in proportion to the sinusoidal vibration. During flow, the vibrating tube(s) and gas mass flow couple together, due to the Coriolis force, causing twisting of the flow tube(s), from inlet to outlet, and a phase shift of the signals produced by the pickoff coils. The phase shift or difference in time, which is measured by the Coriolis transmitter, is directly proportional to the mass flow rate through the sensor.



Coriolis Sensor Components



Coriolis Sensing/Pickoff Signals

Note that the vibration frequency of the flow tubes is proportional to the flowing density of the fluid. For gas applications, the flowing or “live” density measured is typically not used, as its potential error is not acceptable for gas flow measurement purposes, but can be used as an indicator of change in a Coriolis meter’s flow factor and/or clean vs. dirty.

Coriolis is a direct inferential mass meter eliminating the requirement to quantify gas at flowing conditions; e.g. the need to measure flowing temperature, flowing pressure, and calculate a flowing compressibility. Equations and methods for the conversion of mass to base volume are documented in AGA Report Number 11, Measurement of Natural Gas by Coriolis Meter and AGA Report Number 8, Compressibility Factors for Natural Gas and Other Hydrocarbon Gases.

Meter Selection - Temperature

The typical operating temperature range of Coriolis meters is -400 to +400 degrees Fahrenheit (-240 to +204 degrees Celsius). Some advanced designs have extended the high temperature operating range up to +660 degrees Fahrenheit (+350 degrees Celsius).

Changes in temperature from calibration temperature can cause a bias in the Coriolis meter's measurement relative to the elasticity change with temperature of the flow tubes. Most meter designs compensate for this effect automatically by measuring the temperature of the Coriolis meter's flow tube(s) and applying a correction relative to the effect of Young's modulus on the flow tube(s).

Other than temperature compensation for the effect of Young's modulus on the flow tube(s), operating/flowing temperature measurement is NOT required for the measurement of mass, base volume, or heating value of gas mixtures with Coriolis meters.

Meter Selection - Pressure

Most Coriolis meters are designed to operate at pressures up to 1480 psi (600 ANSI), with meters constructed of hastalloy capable of operating at pressures up to 2220 psi (900 ANSI).

Changes in operating pressure can produce a bias often referred to as the "flow pressure effect" that can be compensated for. The "flow pressure effect" of a Coriolis meter is caused by stiffening of the Coriolis flow tube(s) as the fluid pressure inside of them increases. This effect is similar to a bicycle inner tube, as its internal air pressure is increased; the tube walls are stretched and become stiffer; i.e. the tube is more flexible at a lower pressure than at a higher pressure.

The stiffening of the flow tubes at higher internal pressures causes the flow tube to be more resistant to the twisting force of the Coriolis Effect than they are at low pressures. As the internal flow tube(s) pressure increases, the Coriolis Effect observed for a given mass flow rate decreases. Likewise, as the internal pressure decreases the Coriolis Effect observed for a given mass flow rate increases.

The amount of over or under registration that occurs is relative to the pressure the meter was calibrated. If Coriolis is applied at a pressure other than calibration pressure, measurement engineers should investigate pressure effect and insure appropriate compensation is implemented.

Every Coriolis meter design and size has a different flow pressure effect specification. Most Coriolis transmitters have provisions for applying an average flow pressure effect correction and for monitoring a static pressure transmitter for live compensation. A Coriolis meter's pressure effect typically ranges from -0.001 to 0.0 percent per a psi (worst case, a 100 psi error in pressure would equate to a 0.1% error in mass flow rate). For applications were static pressure varies significantly, typically more than 200 psi, the use of a fixed/constant pressure effect correction could potentially induce unacceptable errors. Live static pressure should be used for pressure effect compensation in these applications.

Meter Selection - Compressibility, Density, Viscosity, and Reynolds Number

Although change in compressibility, density, viscosity, and Reynolds Number are a concern with almost all metering technologies, the inferred mass flow rate of a curved tube Coriolis meter is insensitive to error caused by these changes.

Meter Selection - Rate of Change

High rates of change or surging flows are the most common cause of damage to rotating element flow meters (i.e. turbine, rotary), causing over speeding, and are prevalent in fuel gas applications to engines, boilers, and burners.

The inlet flow splitter of a Coriolis meter chokes flow to the diameter of the flow tubes and the flowing densities of natural gas mixtures do not provide enough force to be imparted on the flow tubes of a Coriolis meter to damage them. This coupled with the ability of advanced designs to measure up to sonic velocity (choke point) removes any rate of change concern in the use of Coriolis.

Meter Selection - Over Range

Over ranging or over speeding often causes mechanical damage and or loss of measurement in the use of Rotary, Turbine, Orifice, and Ultrasonic meters. A Coriolis meter has the ability measure to sonic velocity (approximately 1400 ft/sec with natural gas mixtures from atmospheric to 2220 psi) without loss of measurement or damage. Manufacturer's should always be consulted on the maximum velocity limit of a particular design, as not all Coriolis meter designs can measure up to choke point.

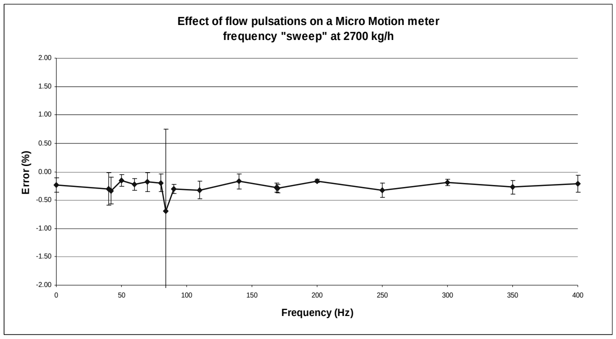
From the standpoint of a high velocity gas eroding the metal of the flow tubes, high gas velocities are not an issue with Coriolis meters. The reason for this is, Coriolis meters are made of nickel alloys. For gas to erode a metal, the metal must oxidize from moisture in the gas and the high velocity gas then erodes the oxide layer. This is why erosion on carbon steel pipe at high gas velocities (above approximately 70 ft/sec) is a concern for many piping engineers. Carbon steel is susceptible to oxidation from the moisture and when subjected to high velocity flow, the oxide layer on the pipe erodes producing the iron oxide dust found in piping systems. A Coriolis meter's immunity to high velocity gas erosion is similar to that of an orifice plate or sonic nozzle, in that they are made of stainless steel and other nickel alloys and are immune to oxidation and thus high velocity erosion. If abrasive particles (i.e. sand, gravel, rocks, welding rods, etc.), filtration should be used upstream of the Coriolis sensor.

Meter Selection - Flow Pulsation

The pulsation of flow is of high concern in the use of every flow metering technology (i.e. Ultrasonic, Orifice, Turbine, Positive Displacement, and Rotary) except Coriolis. Pulsating gas flow can cause measurement error and mechanical damage in metering technologies with load bearings and gears (i.e. Rotary, Positive Displacement and Turbine meters). Gas flow pulsation is a concern on fuel gas lines to reciprocating engines, the inlet and outlet compression lines of reciprocating compressors, and the inlet and outlet lines of regulators.

Advancements in Coriolis flow meter design have yielded designs that maintain accuracy over a wide range of fluid pulsation conditions. Although Coriolis meters, for the most part, are immune to fluid pulsations, they are sensitive to pulsations at the resonant frequency of the meter's flow tubes.

The resonant frequency of the flow tube(s) is meter design and flowing density dependent. Test data of a Coriolis meter subjected to fluid pulsations is shown in the following figure. Note that the area of operation sensitive to pulsation error is at the resonant frequency of the meter's flow tubes.



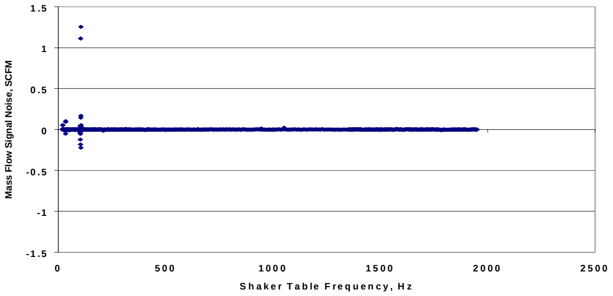
Pulsation Effect on Coriolis Meter

Although measurement error can occur when fluid pulsations are at the same frequency as the frequency of flow tube(s) resonance, convergence of flow tube(s) resonant frequency and fluid pulsation frequency is extremely rare in gas applications. The reason is Coriolis meters typically operate at resonant frequencies above 100 Hz or 6000 cycles per a minute and pulsations in this frequency range are not found in gas systems.

If convergence of a Coriolis meter's resonant frequency and pulsation occurs, it is easily diagnosed by instability in the meter's indicated flow rate, coupled with abnormally high fluctuations in power consumption by the flow tube(s) drive coil.

Meter Selection – Mechanical Vibration

Coriolis meters, for the most part, are immune to mechanical vibrations. Although this is the case, they are sensitive to vibrations at the resonant frequency of the flow tube(s). The resonant frequency of the flow tube(s) is meter design and fluid density dependent. Testing of a Coriolis meter subjected to mechanical vibrations is shown in the following figure. Note that the area of sensitivity is only at the resonant frequency of the meter's flow tubes.



Vibration Effects on Coriolis Meter

Although measurement error can occur when vibration disturbances are at the same frequency as the flow tube(s) frequency of resonance, convergence of flow tube(s) resonant frequency and vibration disturbances is rare and typically not a concern in most gas applications. Similar to pulsations, mechanical vibrations at resonant frequency are easily diagnosed. If this problem occurs in a particular measurement application, Coriolis manufacturers can selectively pick or tune a replacement meter that operates in a higher or lower resonant frequency range to correct the problem.

Meter Selection - Gas Quality

Coriolis meters have high error immunity to dirty processes, should debris (i.e. sand, gravel, welding rods, welding slag, etc.) exist that could erode, scar, or plug the flow tubes, filtration should be utilized in the metering system design to protect the meter. Although fine soft particles like iron oxide, oils, and dust will not damage the flow tubes of a Coriolis meter, build-up of this debris can cause an imbalance in the flow tubes and out of specification shift in the meter's zero. An out of specification zero will induce an abnormally high error on the low end of a Coriolis meter's flow range, but is typically insignificant and undetectable at flows in the high end of the flow range. The maintenance “Zero Check” discussed later in this document will identify if this condition is present and correction of same. In should be noted that in most applications gas velocities through the flow tubes at the high end of the meters flow range is usually sufficient to maintain a meter's cleanliness in most gas applications.

Meter Selection – Bidirectional Measurement

Coriolis meters are bidirectional flow meters, during flow the signal from the inlet pick-off coil lags the outlet pick-off coil signal, by determining which pickoff signal is lagging, flow direction is determined.

Meter Selection - Measurement Accuracy

The measurement accuracy of a Coriolis meter is design and fluid specific. Coriolis meters can typically measure gas mixtures at an accuracy of +/- 1% or better. Advanced designs can achieve accuracies of +/- 0.35%.

Meter Selection – Flow Range

The volume flow range of a Coriolis meter is determined on the low end by minimum acceptable accuracy and worst-case drift (Zero Stability) in a meter's zero over its specified operating range. Zero Stability is the potential error in all indicated flow rates. Due to this fact, a Coriolis meter's accuracy naturally improves as mass flow rate increases until a maximum accuracy, dictated by meter design and measurement fluid, is reached.

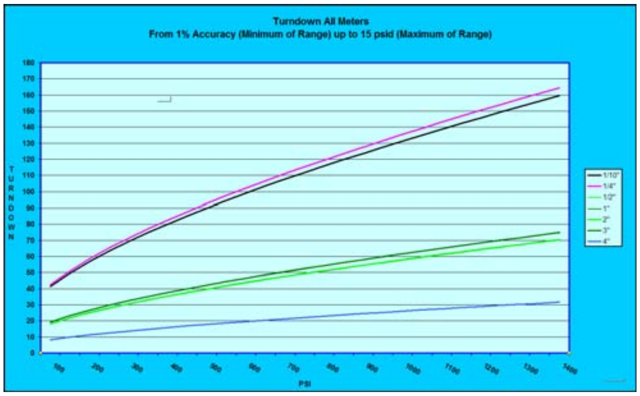
The high end of a Coriolis meter's flow range is determined by gas flow velocity. Most Coriolis meter designs can measure gas velocities up to 200 ft/sec and advanced designs can measure at velocities up to sonic velocity or choke point without loss of measurement or damage. Although some Coriolis meter designs can measure gas flows up to sonic velocity, a maximum allowable pressure drop dictated by the application in which they will be applied typically determines maximum flow. Operationally, in gas applications, Coriolis meters can not be over-ranged or damaged due to flow surges. This is quite different from other flow technologies, where measurement accuracy is lost and/or damage occurs to the flow element when it is subjected to flows above a maximum design limit.

Therefore, the appropriate size of Coriolis meter for an application and its flow range are determined by the following.

- Allowable Pressure Drop @ Maximum Flow
- Minimum Acceptable Accuracy @ Minimum Flow

If the non-linearity of compressibility is ignored and temperature is assumed to be constant, it can be stated that the flow through a Coriolis meter for a given pressure drop changes directly with the square root of static pressure change. With a constant pressure drop, if static pressure doubles, flow would increase by a multiplier of 1.4; i.e. $\sqrt{2}$ x (flow prior to pressure change). Like wise if static pressure drops in half, with pressure drop constant, flow would decrease by a multiplier of 0.707; i.e. $\sqrt{0.5}$ x (flow prior to pressure change).

An example of this relationship is shown in the following figure, where the turndown of multiple meters is graphed across pressure range while pressure drop across the meters is held to a constant 15 psi and the minimum acceptable flow accuracy is 1%. Since flow through the meter increases with square root of static pressure change, applying a meter at higher pressures, in effect, increases operating range and turndown.



Coriolis Turndown versus Operating Pressure

In summary, the available turndown for a given pressure drop can be increased by installing a Coriolis meter at high-pressure locations or upstream of regulation versus downstream.

Meter Selection – Low Flow

The following equation is the most utilized method for determining the minimum flow rate of a Coriolis meter.

$$MinFlow = \frac{ZeroStability}{Accuracy\%/100}$$

Since Zero Stability can be expressed in standard volume (scf) units for a given relative density, the minimum standard volume flow rate at a user specified acceptable accuracy never changes regardless of flowing pressure and temperature for a given meter design and size. This is different from other gas measurement technologies were the minimum flow rate varies with pressure and temperature.

Meter Selection - Maximum flow

Advanced Coriolis meter designs can measure gas flows up to choke point or a flow velocity equivalent to sonic velocity (Mach 1) of the gas mixture (Approximately 1400 ft/sec on natural gas mixtures from atmospheric to 2220 psi). Although this is the case, in most applications Coriolis meters are sized to operate at 1/3 Mach or less.

Coriolis are typically sized within an acceptable pressure drop limit dictated by the application. Utilizing a set of gas reference test conditions, often found in the manufacturers specifications, the following equation can be utilized for calculating the maximum flow rate relative to allowable pressure drop.

$$\frac{\left[\sqrt{\frac{\Delta P_{AppGas}\,\rho_{f_{\mathrm{Re}\,fGas}}}{\Delta P_{\mathrm{Re}\,fGas}\,\rho_{f_{AppGas}}}}\right] Q_{vf_{\mathrm{Re}\,fGas}}\,\rho_{f_{AppGas}}}{\rho_{b_{AppGas}}} = Q_{vb_{AppGas}}$$

Where:

ΔP_{AppGas} = Maximum allowable pressure drop across the Coriolis meter with an application gas density ($\rho_{f_{AppGas}}$) in psi

$\rho_{f_{\mathrm{Re}\,fGas}}$ = Density of reference gas at flowing conditions in lb/cf

$\Delta P_{\mathrm{Re}\,fGas}$ = Reference differential pressure across Coriolis meter with reference gas density ($\rho_{f_{\mathrm{Re}\,fGas}}$) in psi

$\rho_{f_{AppGas}}$ = Density of application gas at flowing conditions in lb/cf

$Q_{vf_{\mathrm{Re}\,fGas}}$ = Volume flow rate of reference gas at flowing conditions of $\rho_{f_{\mathrm{Re}\,fGas}}$ and $\Delta P_{\mathrm{Re}\,fGas}$ in cf/hr

$\rho_{b_{AppGas}}$ = Density of application gas at base conditions in lb/cf

$Q_{vb_{AppGas}}$ = Volume flow rate of application gas at base conditions in cf/hr or scf/hr

Installation - Electrical Classification

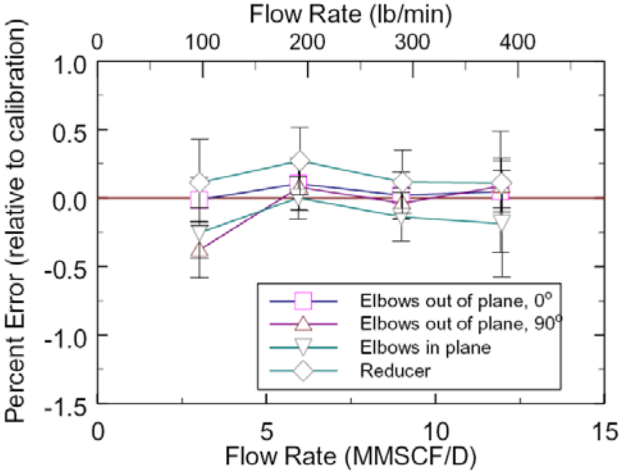
Most Coriolis meters are designed to meet Class 1, Division 1 and Class 1, Division 2 hazardous area classifications.

Installation - Above and Below Ground

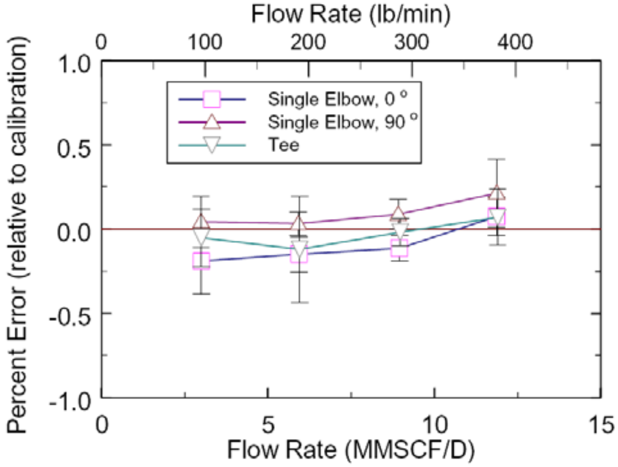
Most Coriolis meters are designed for above ground installations (i.e. low flooding probability installation), but some manufacturers have hardware configurations that can be installed below ground if the electrical enclosures and conduits are properly sealed or weather proofed.

Installation – Up and Downstream Piping

Installation effects testing performed by Southwest Research Institute (SwRI) and sponsored by the Gas Research Institute (GRI) in 2002 confirmed curved tube Coriolis meters to be immune, within the uncertainty of the flow lab, to upstream installation effects. The test results can be found in GRI Topical Report GRI-01/0222. Some of the installation effects test data contained in this report are shown in following figures.



Installation Effects (Complex)



Installation Effects (Common)

The test data shows that flow perturbations placed in close proximity upstream of a bent tube Coriolis meter is not of concern and flow condition or straight pipe up and downstream of a Coriolis meter is not required.

Installation - Meter Mounting

Consideration should be given to the support of the sensor and the alignment of the inlet and outlet piping flanges with the sensor's flanges. For field fabrication of piping, a spool piece should be used in place of the meter to align pipe-work prior to welding the Coriolis sensor mating flanges; i.e. slip fit of the Coriolis sensor is ideal.

Piping should follow typical industry piping codes. Meter performance, specifically zero stability, can be affected by axial, bending, and torsion stresses. When these stresses exist, pressure, weight, and thermal expansion effects can amplify them. Although most Coriolis meters are designed to be relatively immune to these effects, utilizing properly aligned pipe-work and piping supports insures the utmost performance of any meter design and in many cases yields performance better than the manufacturer's specifications.

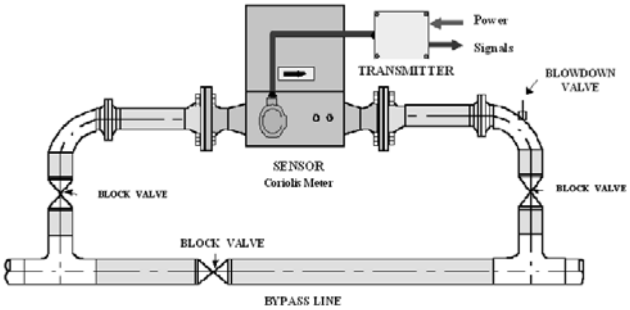
Installation - Meter Orientation

Coriolis meters are immune to orientation effects when measuring single-phase fluids, many fluids are rarely always in a single phase or free from sporadic entrainment of fluids in the opposite phase. As a rule in gas measurement, the Coriolis sensor should be oriented in such a way as to minimize the possibility of heavier components like condensate settling in the sensor flow tube(s). Solids, sediment, plugging, coating, or trapped liquids can affect the meter performance, especially when present during zeroing of the meter. Allowable sensor orientations will depend on the application and the geometry of the vibrating flow tube(s). In gas service, the ideal orientation of the sensor is with the flow tubes in the upright position.

Installation – Piping Configuration

Curved tube Coriolis flow sensors are immune to velocity profile distortion and swirl effects, thus allowing the designer flexibility restricted only by good piping fabrication and support practices to minimize structural stresses on the sensor body.

The piping configuration of a Coriolis installation should consist of block valves up and downstream of the Coriolis meter with bleed valves to facilitate purging of the piping, zeroing of the meter, and maintenance procedures. A bypass should be installed around the meter if interruption of service is an issue.

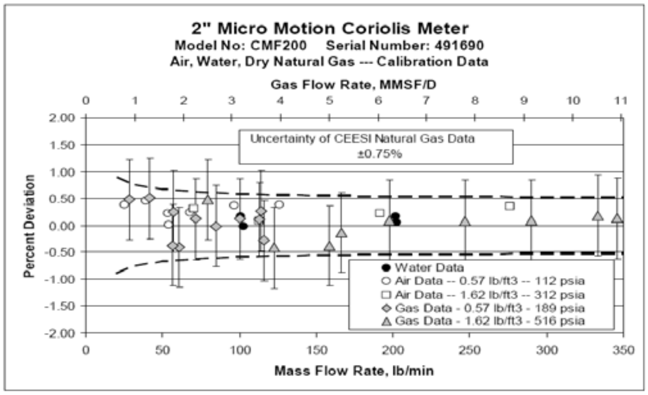


Typical Piping Configuration for Coriolis Meters

Metrology - Calibration

Due to the variability of manufacturing processes, all Coriolis meters require a flow calibration to adjust their performance to the accuracy limits inherent to their particular design. As a common practice, most Coriolis manufacturers capitalize on the economics and high stability of a water calibration to perform these calibrations. Some advanced Coriolis meter designs are immune to fluid phase, density, and viscosity; enabling water calibrations to transfer to all other fluids; i.e. gas, liquid, and slurries.

Testing by numerous European and North American flow labs has confirmed the transferability of water calibration data on a Coriolis meter to gas applications. Most notably testing sponsored by the Gas Research Institute in 2004 and documented in report GRI-04/172, which covers water to gas transferability and wet gas performance of Coriolis meters. Conclusions in the report state, "The single fluid calibration tests show that a water calibration of a Coriolis mass flow meter can be used for natural gas applications without loss of accuracy".



GRI 04/0172 Water, Air, and Gas Transferability Data

Industry testing has shown there is minimal benefit, from a calibration uncertainty perspective, in performing a gas calibration over a water calibration on Coriolis meters intended for gas measurement. Although this is the case the user should review industry recommended practices, standards, and regulatory requirements when establishing calibration policy for Coriolis.

Coriolis meters are an attractive technology when the availability, capability, or economic viability of gas calibrations is limited. Highly accurate water calibrations and construction of water calibration facilities are achieved at a fraction the cost of their gas counterparts.

Metrology – Volume Measurement

To accurately quantify the mass output of a Coriolis meter applied at pressures other than calibration pressure, a flow pressure effect correction must be applied. Every Coriolis meter design and size has a different flow pressure effect specification. In order to correct for the flow pressure effect in a Coriolis meter's indicated mass flow rate, the following equation should be utilized.

$$Mass_{\mathrm{Re}\,al} = \frac{Mass_{Raw}}{1 + ((P_{Effect} / 100) * (P_{Static} - P_{Cal}))}$$

Where: $Mass_{\mathrm{Re}\,al}$ = Mass real or mass compensated for pressure

$Mass_{Raw}$ = Mass raw or mass uncompensated for pressure

P_{Effect} = Pressure effect in percent psi

P_{Static} = Measurement fluid static pressure in psi

P_{Cal} = Calibration static pressure in psi

For gas applications, the measurement accuracy of flowing density by a Coriolis meter is relative to a liquid densitometer's accuracy, this does not meet the accuracies required for gas measurement. Therefore the on-line density from the meter is not used for flow measurement with gas; rather 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 data. It should be noted that the gas physical property information required by AGA8 Gross Method 1, Gross Method 2, or Detail Method and procedural methods for applying this information in the use of a Coriolis meter are identical to those 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.

$$SCF_{(gas)} = \frac{\text{Mass}_{(\text{gas})}}{\rho_{b(Gas)}}$$

$$SCF_{(gas)} = \frac{\text{Mass}_{(\text{gas})}}{Gr_{(Gas)} \text{ x } \rho_{b(Air)}}$$

$$\rho_b = \frac{P_b \text{ x } M_{r\,(\text{Gas})}}{Z_b \text{ x } R \text{ x } T_b}$$

Where: SCF = Volume at T_b and P_b

$Mass$ = Weight of gas (Coriolis output)

ρ_b = Density at T_b and P_b

T_b = Temperature at base conditions

P_b = Pressure at base conditions

Z_b = Compressibility at base conditions (T_b and P_b)

$Gr_{(Gas)}$ = Real Gravity at T_b and P_b

R = Universal gas constant

M_r = Gas Molar Weight

Field Maintenance

The field maintenance of a Coriolis meter is an inspection process consisting of the following

1) Zero Verification
2) Temperature Verification
3) Transmitter Diagnostics Verification
4) Sensor Diagnostics Verification

Field Maintenance – Zero Check

The meter zero should be checked periodically and reset if it does not meet the manufacturer's specifications. At a minimum, inspection of the meters zero should be performed seasonally in the first year of operation to identify any installation or process issues.

Product buildup, erosion, or corrosion will affect the meter performance. Product buildup (coating) may bias the meter zero. It should be noted that a zero shift will affect a Coriolis meter's accuracy more at low flows than at high flows. This is dictated by the "MinFlow" equation called out in the previous "Sizing and Selection" section of this document. If the buildup is causing a zero drift, cleaning and re-zeroing the meter should bring performance back to its original performance specification. If coating of the sensor continues, the zero will continue to drift. Although rare, erosion or corrosion will permanently affect meter calibration and will compromise sensor integrity.

When used within the specified fluid and ambient condition limits, fatigue of the sensing tubes of a Coriolis meter due to vibration during the meter lifetime is not of concern, and does not need to be considered when inspecting a meter. However, operating the meter in more extreme corrosive or erosive applications will shorten the meter's expected life.

Improper zeroing will result in measurement error. In order to adjust the zero of the meter there must be no flow through the flow sensor and the sensor must be filled with gas at process conditions. Even though the stream is not flowing, the flow meter may indicate a small amount of flow, either positive or negative. Causes for the zero error are usually related to the differences between the calibration conditions and the actual installation, which include the following:

- Differences between the calibration media density and the application gas density
- Differences in temperature
- Differing mounting conditions

The meter should read a mass flow rate that is less than the manufacturer's zero stability specification under the no-flow condition.

The zeroing of the meter must be performed at nominal operating condition with no flow through the meter. Once it has been confirmed that there is no flow through the meter, the zeroing procedure specified by the meter manufacturer should be followed.

Field Maintenance – Temperature

Coriolis meters measure the temperature of their flow tubes to compensate for change in the flow tube(s) elasticity. The temperature measured by the Coriolis meter should be verified to be within the manufacturer's specifications at regular maintenance intervals.

Field Maintenance – Diagnostics

A diagnostic LED(s) and display may be provided to indicate operating status of the sensor and secondary (transmitter) elements. The diagnostics of the Coriolis transmitter verify the integrity of the CPU and insure operational parameters are not outside their limits. Coriolis sensor diagnostics verify the sensing components of the sensor are not damaged and operating within normal limits. Sensor diagnostics also provide insight into the process flow conditions and potential measurement issues.

Advanced Coriolis sensor designs also provide an on-line "Structural Integrity Verification" of the flow tubes. The flow tube structure of a Coriolis sensor dictates its flow calibration factor. By using resonant modal analysis techniques, the structure of the flow tubes are verified to be unchanged from when the sensor was calibrated. Structural Integrity Verification is a significant advancement in Coriolis technology and flow metering technologies in general. This capability makes Coriolis the only flow measurement technology available today that can verify its accuracy without interruption in flow, use of a flow reference, inspection of primary element, and calibration verification of secondary elements.

CAPEX

Capital Expenditures ("CAPEX") to implement Coriolis measurement will vary dependent upon meter design, size, pressure ratings, materials of construction, and accuracy. Typical capital expenditures required in the implementation of a Coriolis metering system include the following.

- Coriolis Sensor
- Flow Computer or Transmitter
- Power System

- Installation and Startup

Coriolis technology reduces or eliminates several of the capital expenditures required in the application of other gas flow technologies and associated with natural gas metering. Typical capital expenditures that are reduced or eliminated are as follows.

- Pressure measurement - Typically not required for flow measurement and if required, high accuracy pressure measurement is unwarranted
- Temperature measurement - Integral to Coriolis sensor design
- Specialty upstream and downstream piping and/or flow conditioning
- Gas flow calibration of sensor - Factory water flow calibration transfers to natural gas measurement
- Installation and startup

OPEX

Operating Expenditures ("OPEX") to maintain Coriolis measurement will vary dependent upon meter design, power system, cleanliness of process, and accuracy verification procedures required by meter design, adopted by the user's organization, or dictated by regulatory requirements. Typical operating expenditures required in the use of a Coriolis metering system include the following.

- Routine inspection of sensor zero and diagnostics
- The replacement of battery backup power cells, if used, when their efficiency has declined.
- Pressure calibration – Although pressure measurement, if used, will require periodic verification its recalibration with a precision reference is typically not required.
- Temperature measurement - Although temperature measurement will require periodic verification its recalibration with a precision reference is not required
- Inspection and cleaning of specialty upstream and downstream piping and/or flow conditioning
- Validation of flow factor - Coriolis meters can be validated with water flow references, which are typically more economical than that of their natural gas counterparts. Some Coriolis designs incorporate advanced structural diagnostics that verify the sensor's flow factor or identify the requirement for re-verification. Structural diagnostics eliminate unnecessary flow validations or recalibrations.

Application Examples

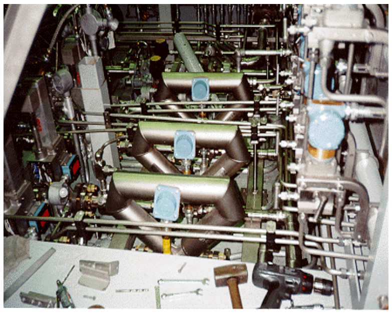
Coriolis meters are applied in a wide variety of applications, from the "wellhead to the burner tip". Coriolis meters are primarily a smaller line size meter, ideally suited to the following gas metering "sweet spots":

- Line sizes 400mm (16") and smaller
- 300 ANSI through 900 ANSI
- High turndown requirements
- Dirty, wet, or sour gas where maintenance can be an issue with other technologies
- There is no room for long straight-runs
- Changing gas composition and density
- Sudden changes in gas flow velocity (fuel gas applications)
- Pulsating gas flows (fuel gas and compression gas in the use of reciprocating compressors)
- Applications were abnormally high flow rates can occur.
- Gas delivery locations were pressure reduction is required (industrial, commercial, and city gates)
- All energy metering locations

Coriolis meters can be sized for very low-pressure drop (100” H_2O), but can also be installed upstream of the pressure regulator with high pressure drops of up to 40% of available pressure for increased turndown without concern of damage or malfunction due to flow noise. For instance, in one application for custody transfer of nitrogen, a 50-psid drop (1390” H_2O) was allowed across the Coriolis meter and the pressure regulator adjusted accordingly. This allowed the use of a 1” Coriolis meter instead of a 3” meter downstream of the regulator and a 40:1 useable turndown (Better than 1% accuracy at minimum flow and better than 0.35% base volume accuracy over 95% of the upper flow range).

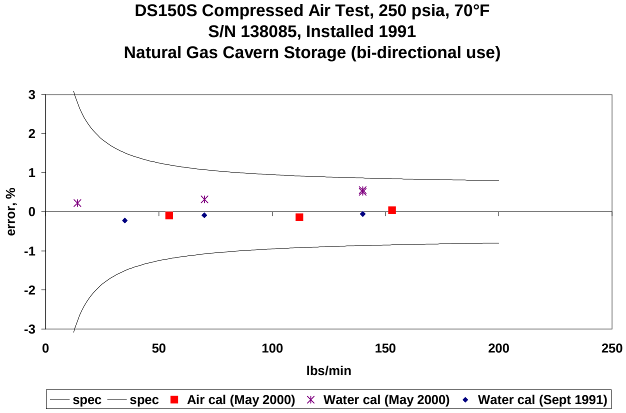
Separator gas: Saudi Aramco uses a number of Coriolis meters on both the liquid and gas side of separators. This application is of particular note because the gas stream is wet, with entrained hydrocarbon condensates. Measurement of this stream is within a few percent over a wide range of conditions, greatly enhancing separator operation and accurately quantifying the value of the gas/entrained liquid hydrocarbons in the flow stream.

Fuel Gas: A major US vendor of gas power turbines designs a high-efficiency, low emissions offering. This design utilizes a trio of Coriolis meters to measure the natural gas burned in each of three combustion zones (fuel “rails”). The combination of no damage due to high rates of change at start-up, high turndown, high accuracy, immunity to vibration in a high vibration environment, ease of installation (no pressure, temperature, and straight run requirement) and improved accuracy in the measurement of energy over volumetric makes Coriolis the technology of choice.

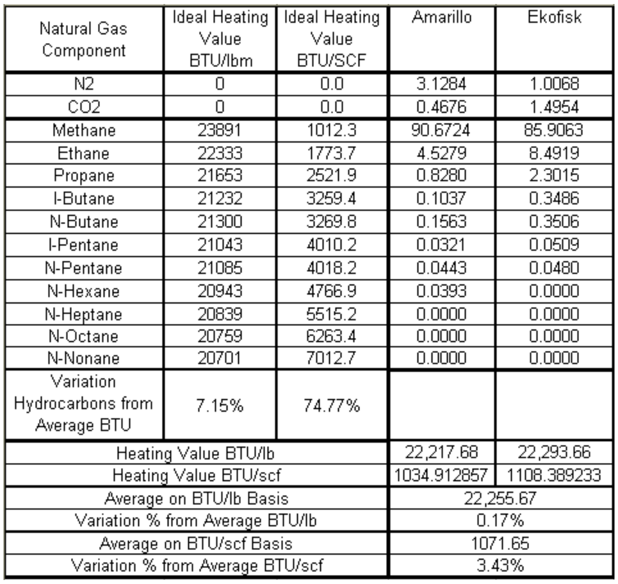


Natural Gas Storage: A storage field in Hungary utilizes 27 two-inch Coriolis meters for the injection and withdrawal measurement of natural gas. The storage reservoir consists of a multilayer sandstone formation with an aquifer flowing through it. Due to the complexity of managing the water level in a sandstone formation on the injection and withdrawal of natural gas, multiple small wells are required. The withdrawal gas is also fully saturated, contains H2S, and during high flows the wells produce sand. In this difficult application, only Coriolis meters can provide bidirectional measurement, long-term accuracy, and achieve the wide turndowns required for reservoir management.

The graph below shows performance testing on a Coriolis meter from an identical metering application in Redfield, Iowa where the meter tested was subjected to saturated gas, laden with H2S, sand, and iron sulfide over a 9 year period. The post 9 year data shows the meter is maintaining an accuracy of 0.5% or better and still performing within the manufacturer's specifications.



<u>Energy Metering:</u> Energy per unit volume on natural gas mixtures varies on average 10 times or more than that of energy per a unit weight for hydrocarbons. If composition varies and an average relative density and/or heating value is utilized for energy measurement, Coriolis can achieve total energy accuracies on energy determination unparalleled by volumetric meters utilizing the same average values. A Coriolis meter by itself offers a very affordable method of inferring energy flow rates. Figure 1 is an example of the difference in variation between volume and weight based heating value between two typical natural gas mixtures. Figure 2 shows the mathematical relationship between gravity the heating value of the hydrocarbon constituents in a natural gas mixture and why inferring BTU variations directly from specific gravity variation is in many cases is very accurate. This same relationship allows for the direct inference of Energy with a Coriolis meter. Procedures for implementing these methods are documented in AGA Report Number 5, copyright 1981.



Natural Gas Component	Ideal Heating Value BTU/lbm	Ideal Heating Value BTU/SCF	Amarillo	Ekofisk
N2	0	0.0	3.1284	1.0068
CO2	0	0.0	0.4676	1.4954
Methane	23891	1012.3	90.6724	85.9063
Ethane	22333	1773.7	4.5279	8.4919
Propane	21653	2521.9	0.8280	2.3015
I-Butane	21232	3259.4	0.1037	0.3486
N-Butane	21300	3269.8	0.1563	0.3506
I-Pentane	21043	4010.2	0.0321	0.0509
N-Pentane	21085	4018.2	0.0443	0.0480
N-Hexane	20943	4766.9	0.0393	0.0000
N-Heptane	20839	5515.2	0.0000	0.0000
N-Octane	20759	6263.4	0.0000	0.0000
N-Nonane	20701	7012.7	0.0000	0.0000
Variation Hydrocarbons from Average BTU	7.15%	74.77%		
Heating Value BTU/lb			22,217.68	22,293.66
Heating Value BTU/scf			1034.912857	1108.389233
Average on BTU/lb Basis			22,255.67	
Variation % from Average BTU/lb			0.17%	
Average on BTU/scf Basis			1071.65	
Variation % from Average BTU/scf			3.43%	

Figure 1

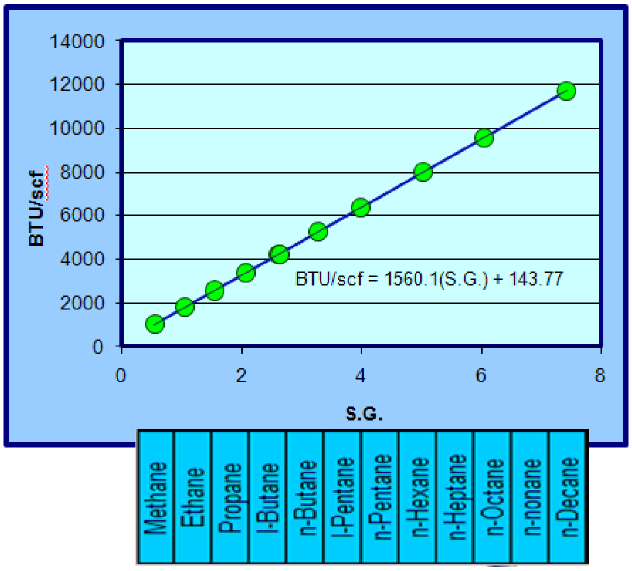
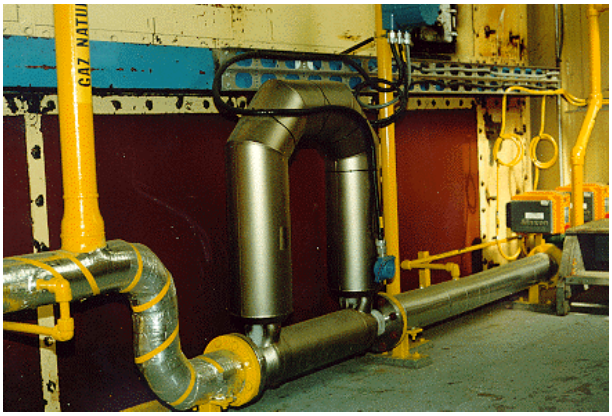


Figure 2

<u>Combustion Control to Boilers</u>: In this application, a Pulp mill in Quebec sought a more reliable way to meet EPA emissions requirements. Combustion control was easier, based on the mass ratio between the natural gas and combustion air. High turndown and concern of damage to the measurement element, due to flow surge when the boilers fire, drove the selection of Coriolis for this application.



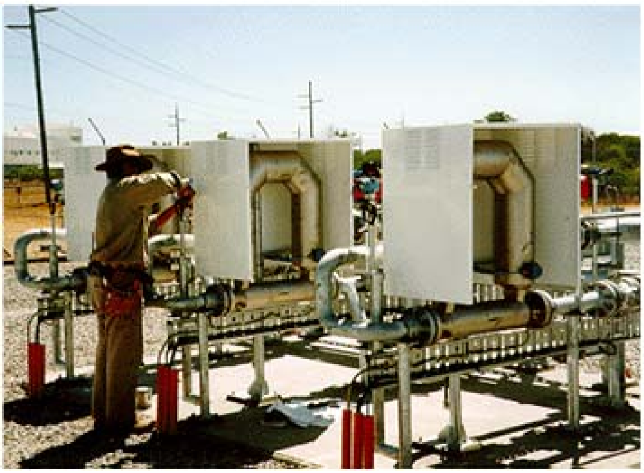
Combustion control application to boilers

<u>Low Flow Fuel Gas Metering</u>: At many city and industrial gate applications, the medium to large the medium to large meters installed do not have the ability to measure low flow rates to the user. This is especially the case at peaking power plants and user locations with boilers and engines, where the facilities consume low idle flow rates until power generation or manufacturing processes are commenced. In some cases, small rotary and turbine meters have been installed in parallel with medium to large meters to measure these low flows. Although restrictor plates are installed to limit maximum flow rates through these low flow meters; the <u>rate of change</u> in flow when engines or boiler fire still causes these meters to over spin and damage bearings and gears over time. Users at these locations are now installing and replacing these rotating element low flow meters with Coriolis based on Coriolis's ability to measure extremely low flows and be subjected to high rates of change in flow without damage or loss of accuracy.

The following figure shows an example, where Coriolis low flow meters are installed in parallel with a large diameter ultrasonic meter, eliminating the maintenance and accuracy issues associated with low flow rotating element meters in peaking flow rate applications.

A ½" Coriolis and 12" ultrasonic in a fuel gas metering installation.

Natural Gas Custody Transfer: An example of this gas measurement capability is at a natural gas utility in Western Australia. Two 3" meters are used in parallel with a third used as a "hot spare" for monthly verifications of the transfer meters.



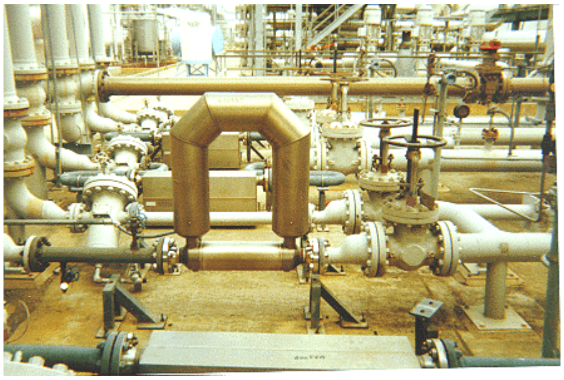
Western Australia: Previous installation

"After" installation since 1996, with operating and one "hot spare" meter

The justification for using the Coriolis meters was based on installation and calibration/maintenance cost improvements over the more traditional gas metering systems. Since Coriolis meters require no straight runs or flow conditioning the installed costs were reduced by five times, even with the parallel meters required to handle the highest flows.

Additionally, periodic maintenance costs were reduced due to the intrinsic reliability of Coriolis meters (i.e. no moving parts). Similarly, reliability improvements reduced calibration and proving costs. Internal checks by the customer have shown agreement to better than 0.1% on all gas transfers over a 6 year period.

Ethylene Transfer: Ethylene is commonly viewed as a difficult to measure gas, due to its highly non-ideal nature. In this application, Coriolis meters are used for intra-plant transfers attaining accuracies unattainable by volumetric meters (i.e. orifice, ultrasonic, turbine, etc.); helping to meet both unit mass-balance goals, as well as reactor feed rate requirements.



Ethylene application, where ethylene is fed continuously to a polymerization reactor

Summary

Although a relatively new technology for natural gas applications, Coriolis meters have gained worldwide acceptance for many fluids and in other industries.. With a worldwide installed base of over one million units, Coriolis technology is seeing expanded use for both liquid petroleum and natural gas. A number of countries and groups have published standards or are in the process of studying the technology. Most notably is AGA and API who have jointly published AGA Report No. 11 / API MPMS Chapter 14.9, Measurement of Natural Gas by Coriolis Meter.

Technology limitations of earlier designs have been largely overcome, with high accuracy measurement now possible at low-pressure drop. Coriolis "sweet spots" are in lines of 250mm (16) and smaller, 300 to 900 ANSI, where high turndown is needed, flow conditioning with other technologies to meet new AGA requirements is costly, flow surges occur, pulsations are present, energy metering is required, and/or the gas is of dirty, sour, or changing composition.

Coriolis technology merits serious consideration as an improvement in real-life measurement accuracy over traditional volumetric measurement technologies and attractive alternate to ultrasonic in many applications. From a flow range perspective, ultrasonic and Coriolis overlap in the 100mm (2") to 200mm (16") line size range in 300 ANSI and above pressure classes.

Third-party data from CEESI, Pigsar, SwRI, and others show little to no effect caused by flow profile change and in transferring water calibration to natural gas measurement.

Common Coriolis gas applications range from wellhead separator, transmission and distribution metering, fuel gas to power turbines, reciprocating engines, and boilers. Users in today's competitive business environment are finding Coriolis to be the consistently accurate, trouble free, and fiscally economical meter they can own.