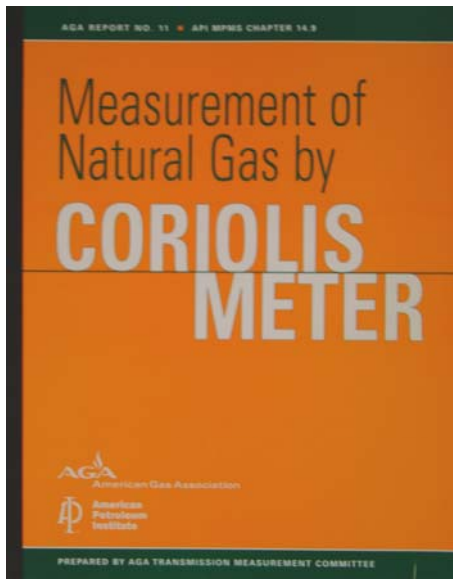


FUNDAMENTALS OF CORIOLIS FLOW METERS FOR GAS MEASUREMENT AGA REPORT NO. 11

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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 100,000 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 from -400 to +660 degrees Fahrenheit with little to no concern of error caused by flow profile disturbances, pulsations, or flow surges, Coriolis meters are becoming the meter of preference in many applications.

Coriolis is a small to medium line-size technology; currently the largest offering from any vendor for gas applications is a 250mm (10") 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

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.



200mm (8") Coriolis meter installed in
250mm (12") line

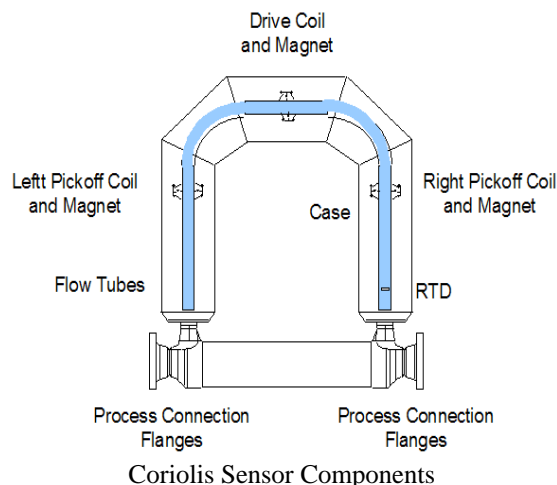
Being a technology without wearing parts, Coriolis meters are for the most part immune to flow factor shift as they age. Most recently, resonant modal analysis techniques have been implemented in some Coriolis meter designs allowing flow accuracy to be verified on-line without disruption in flow and without having to visually inspect the flow element.

Overall, Coriolis meters greatly reduce the amount of measurement and maintenance concern in their use compared to other gas flow technologies. This paper will discuss the theory of operation, application and maintenance, and provide examples of Coriolis meters used in gas measurement applications.

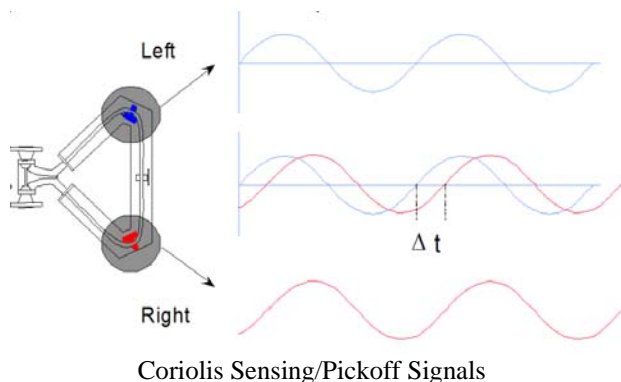
Theory of Operation

A Coriolis meter is comprised of two main components, a sensor (primary element) and a transmitter (secondary). Coriolis meters directly infer the gas mass flow rate by sensing the Coriolis force on a vibrating tube(s). The 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, producing a phase shift between the signals generated by the two pickoff coils. The phase shift or difference in time, which is measured by the Coriolis transmitter, is directly proportional to mass flow rate.



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 by the Coriolis meter is typically not used for gas measurement, as its potential error in relation to gas densities is not acceptable for gas flow measurement purposes. Although this is the case, density measurement in gas applications 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; i.e. 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 +200 degrees Celsius). Some advanced designs have extended the high temperature operating range up to +660 degrees Fahrenheit (+350 degrees Celsius).

Other than temperature compensation for the effect of Young’s modulus, flowing temperature measurement is not required for the measurement of mass, base volume, or energy with Coriolis meters.

Meter Selection - Pressure

Most Coriolis meters are designed to operate at pressures up to 1480 psi (600 ANSI), with meters constructed with hastalloy and duplex tubes capable of operating at pressures up to 3600 psi (1500 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 the stiffening of the Coriolis flow tube(s) as the fluid pressure in them increases. This effect is similar to a bicycle inner tube as its internal air pressure is increased; the inner tube is more flexible at a lower pressure than at a higher pressure.

High fluid pressures cause 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 or twisting of the flow tube(s) 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.

Every Coriolis meter design and size has a different flow pressure effect specification. To correct for flow pressure effect the flow pressure effect compensation factor detailed below is applied to the indicated mass flow rate.

$$F_p = \frac{1}{1 + ((P_{Effect}/100) * (P_{Static} - P_{Cal}))}$$

Where:

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

Most Coriolis transmitters have provisions for applying an average flow pressure effect correction and the monitoring a static pressure transmitter to facilitate live pressure compensation.

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 in flow or flow surges are the most common cause of damage in flow meters with rotating flow elements; e.g. Turbine, Rotary, Positive Displacement, etc. High rates of change in flow cause these meters to over-speed and are typically inherent to engine, boiler, and burner fuel gas applications.

During a flow surge, 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 inertial force to be imparted on the flow tubes to damage them. This coupled with the ability of advanced designs to measure up to sonic velocities (choke point) removes any rate-of-change concern in the use of Coriolis.

Meter Selection - Over Range

Over ranging often causes mechanical damage and/or loss of measurement in the use of almost any flow meter. Some Coriolis meter designs can measure gas flow up to sonic velocity or choke point (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 their particular Coriolis meter design, as not all Coriolis meter designs can measure up to choke point. It should be noted that the stability of flow rate indication decreases when gas velocities exceed approximately 400 ft/sec through a Coriolis sensor, but high speed integration of the flow rates over an extended period of time when this instability is present has proven the average flow rate indication to still be very accurate.

Piping erosion caused by high flow velocities is a common concern in gas applications. Although this concern is valid for carbon steel piping, it is not valid for stainless steel piping or Coriolis meters. For a gas to erode a metal, the metal's surface must first oxidize and then high gas velocities erode the soft oxide layer. In most gas applications, moisture in the gas causes oxidation of carbon steel piping driving the velocity

concerns of many piping engineers. 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 or other nickel alloys which are highly immune to corrosion/oxidation and thus high velocity gas erosion.

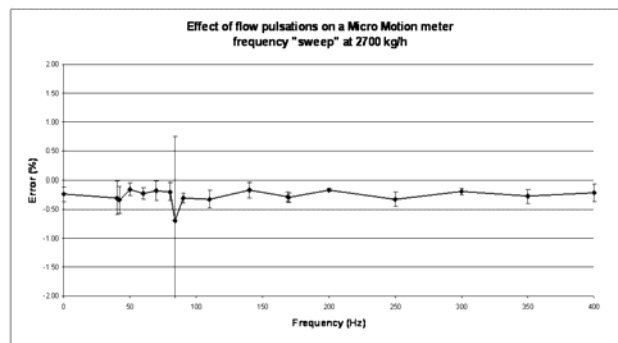
If abrasive contaminants (sand, welding rods, rocks, etc.) are present in the gas flow stream, erosion or damage of the wetted meter components caused by this debris traveling at high flow velocities is of concern. These concerns are application specific, but when present, filtration should be used to protect the meter.

Meter Selection - Flow Pulsation

The pulsation of flow is typically of high concern in the use of every flow metering technology. Pulsating flow can cause measurement error (e.g. fluidic oscillation, orifice/differential head, rotary, turbine, and ultrasonic meters) and mechanical damage in metering technologies with load bearings and gears (e.g. rotary, and turbine meters). Flow pulsations are typically 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 pulsating flow conditions. Although Coriolis meters, for the most part, are immune to error caused by fluid pulsations, they are sensitive to pulsations at the resonant frequency of the meter's flow tubes. In gas applications, Coriolis meters typically operate at resonant frequencies above 100 Hz or 6000 cycles per a minute, where gas pulsations are typically not found.

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.



Effect of Flow Pulsation on a Coriolis Meter

Although measurement error can occur when fluid pulsations are at the same frequency as the flow tube(s) frequency of resonance, convergence of flow tube(s) resonant frequency and fluid pulsation frequency is extremely rare in gas applications.

Meter Selection - Gas Quality

Should debris (i.e. sand, gravel, welding rods, welding slag, rodents) 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. Coriolis meters have high error immunity to dirty processes because an out of specification zero caused by debris buildup will induce detectable errors only at the low end of a meter's flow range and are typically insignificant/undetected at flows in the high end of the flow range.

In most applications, gas velocities through the flow tubes at the high end of the flow range are typically sufficient to maintain a meter's cleanliness. A "Zero Check" performed during maintenance will identify if debris buildup or coating is affecting the meter's measurement accuracy. If an out of tolerance condition exists the meter's zero can be recalibrated to regain accuracy.

Meter Selection - Bidirectional

Coriolis meters are bidirectional 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. Most bending mode Coriolis meters can measure gas mixtures at accuracies better than 1%. Some advanced Coriolis designs can achieve accuracies of +/- 0.35%.

Meter Selection – Flow Range

The flow range of a Coriolis meter is determined on the low end by minimum acceptable accuracy and worst-case drift in a meter's zero, referred to as "Zero Stability". 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

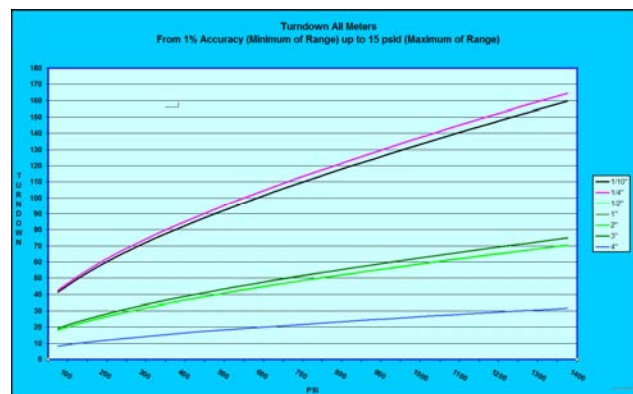
until a maximum accuracy, dictated by meter design and measurement fluid, is reached.

The high end of a Coriolis meter's flow range is determined by flow velocity. Most Coriolis meters can measure gas velocities up to 200 ft/sec and advanced designs can measure gas flow 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. This is quite different from traditional flow technologies where maximum flow is where measurement is lost and/or flow damage occurs to the flow element.

Therefore, the appropriate size of Coriolis meter for an application is determined by the following.

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

Since flow through the meter increases with square root of static pressure change and the minimum flow through the meter is constant and relative to the minimum acceptable accuracy, applying a meter at higher pressures, in effect, increases operating range and turndown.



Coriolis Turndown versus Operating Pressure

In summary the operating range 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.

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

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 pressure or temperature for a given meter design and size. This is different from other gas measurement technologies where the minimum flow rate varies with pressure and temperature.

Meter Selection - Maximum flow

Some 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 for natural gas mixtures from atmospheric to 2220 psi). Although this is the case, Coriolis are typically sized within an acceptable pressure drop limit dictated by the application. Utilizing a set of gas reference conditions, often found in the manufacturers specifications, the following equation can be utilized for calculating the flow rate through a meter at a given pressure drop.

$$\frac{\left[\sqrt{\frac{\Delta P_{AppGas} \rho_{fRe fGas}}{\Delta P_{Re fGas} \rho_{fAppGas}}} Q_{vfRe fGas} \rho_{fAppGas} \right]}{\rho_{bAppGas}} = Q_{vbAppGas}$$

Where:

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

$\rho_{fRe fGas}$ = Density of reference gas at flowing conditions in lb/cf

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

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

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

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

$Q_{vbAppGas}$ = 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 – Up and Downstream Piping

Installation effects testing performed by Southwest Research Institute (SwRI) and sponsored by the Gas Research Institute (GRI) in 2002 confirmed bent tube Coriolis meters to be mostly 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.

Perturbation testing including pulsation and regulator valves placed in close proximity of a bent tube Coriolis meters has also been conducted by other organizations and independent parties and has shown flow conditioning or straight pipe up and downstream of a Coriolis meter is not required.

Installation - Meter Mounting Eq. (6.3)

Consideration should be given to the support of the sensor and the alignment of the inlet and outlet piping flanges with the sensor. 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 is ideal.

Piping should follow typical industry piping codes. Meter performance, specifically meter zero, 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

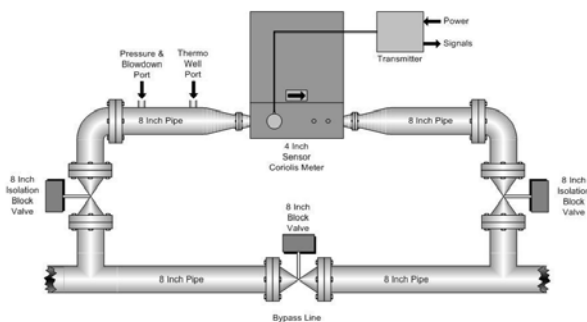
contaminates in the opposite phase. As a rule in gas measurement, the Coriolis sensor should be oriented in such a way as to minimize the possibility of heavier components, like condensate, settling in the sensor flow tube(s). Solids, sediment, plugging, coatings, or trapped liquids can affect the meter 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 or bent tube Coriolis flow sensors are immune to velocity profile distortion and swirl effects, thus allowing the designer flexibility restricted only by good piping 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 to the customer is an issue.

Although the pressure port for flow pressure effect compensation has a preferred location upstream of the Coriolis sensor, it can be located up or downstream of the Coriolis sensor. A temperature port for verification of the Coriolis sensor's measured temperature should be located upstream of the sensor due to the Joule Thomson effect at high differential pressures across the sensor.



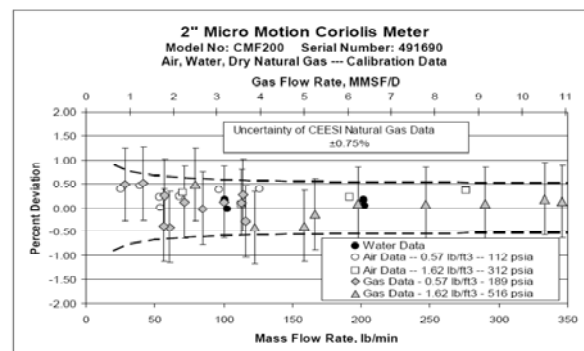
Typical Coriolis Meter Installation

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 correction factor should be applied to the indicated mass output.

$$F_p = \frac{1}{1 + ((P_{Effect}/100) * (P_{Static} - P_{Cal}))}$$

Where:

F_p = Flow pressure effect compensation factor

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 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. 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.

$$SCF_{(gas)} = \frac{Mass_{(gas)}}{\rho_{b(Gas)}} F_p$$

$$SCF_{(gas)} = \frac{Mass_{(gas)}}{Gr_{(Gas)} \times \rho_{b(Air)}} F_p$$

$$\rho_b = \frac{P_b \times M_r}{Z_b \times R \times T_b}$$

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

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 = Molar Weight

F_p = Flow pressure effect compensation factor

Field Maintenance and Meter Verification

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

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

Field Maintenance – Zero Verification

The meter zero should be verified periodically and recalibrated if it is not within the manufacturer's specification. 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. After the first year of operation zero verification intervals can be extended based on the historic performance of the meter's zero for the application.

Drift in Zero Reading

Product buildup, erosion, or corrosion will affect the meter zero 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. If the buildup is causing a shift in the meter zero, cleaning and re-zeroing will bring the meter's performance back to its original specification. At any given level of coating, if the coating is stable, the meter can be re-zeroed without cleaning and meter performance can be restored. But if coating of the sensor continues, the zero may continue to drift.

Although rare in gas applications, flow tube erosion or corrosion will affect a meter's zero performance and likewise its calibration. A repeated out of specification zero found during the zero verification process is a potential indicator of erosion and corrosion. Confirmation of the condition can be made by performing a density verification; i.e. a negative out of specification bias in density is caused by reduction in flow tube wall thickness.

Inspection and Re-zeroing

Improper zeroing will result in measurement error. Prior to inspection of the meter zero and re-zero the meter, if required, thermal equilibrium of the meter's flow tubes must be achieved. To insure meter thermal equilibrium, a flow rate above the transitional flow must be established and the meter's indicated temperature must be verified as stable. Once thermal equilibrium is achieved the meter is

to be blocked in and the meter's zero verified. Even though the stream is not flowing, the flow meter may indicate a small amount of flow bias, either positive or negative. Causes for a bias in the zero are usually related to the differences between previous and current zero flow conditions, which include.

- Differences between the calibration media density and the 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.

If the zero is within specification re-zeroing the meter is unwarranted. If outside of specification the current zero value and meter temperature should be recorded for future reference and the zeroing procedure specified by the meter manufacturer should be followed.

Field Maintenance – Diagnostics

Diagnostic LED(s) and display are typically provided to indicate the operating status of the sensor and transmitter. The diagnostics of the Coriolis transmitter verify the integrity of the CPU and insure operational parameters are within tolerance. 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 problems with them.

Some Coriolis sensor designs also provide on-line verification of the flow tube(s) structure. The flow tube structure of a Coriolis sensor dictates its flow calibration factor. This method of verification measures flow tube(s) stiffness to infer density and mass calibration factor as unchanged. Utilizing resonant modal analysis techniques the transmitter actively tests the flow tube(s) stiffness during flowing conditions and determines if an out of tolerance stiffness change has occurred.

Coriolis meter verification by resonant modal analysis method is a significant advancement in Coriolis technology. This capability allows for verification a Coriolis meter's accuracy without interruption in flow or inspection of the meter's components for damage.

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 typically 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, a high accuracy transmitter is unwarranted
- Temperature measurement - Integral to Coriolis sensor design
- Specialty upstream and downstream piping and/or flow conditioning – Not required
- 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 verification procedures required by meter design, adopted by the user's organization, or dictated by regulatory requirements. Typical operating expenditures required in the use a Coriolis metering system include the following.

- Routine verification/inspection of sensor zero and meter diagnostics
- The replacement of battery backup power cells, if used, when their efficiency has declined.

Coriolis technology reduces or eliminates several of the operating expenditures associated with gas flow technologies. Typical operating expenditures that are reduced or eliminated are as follows.

- 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 typically 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 structural integrity diagnostics that verify the sensor's flow factor or identify the requirement for recalibration. 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 to medium line size meter, ideally suited to the following gas metering “sweet spots”:

- Line sizes 250mm (12”) 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 and production gas applications)
- Pulsating gas flows (fuel gas and compression gas in the use of reciprocating compressors)
- Applications where abnormally high flow rates can occur.

Coriolis meters can be sized for very low-pressure drop (100” H₂O), but can also be installed upstream of the pressure regulator with high pressure drops 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” H₂O) 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 an average 0.35% base volume accuracy over 95% of the upper flow range).

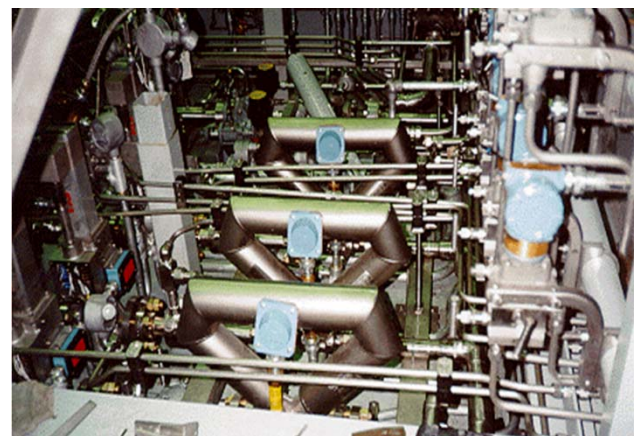
Separator gas: Saudi Aramco uses a number of Coriolis meters on both the liquid and gas side of separators. This application is of particular note because the gas stream is wet, with entrained hydrocarbon condensates. Measurement of this stream is within a few percent over a wide range of conditions,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

operation and accurately quantifying the value of the liquid hydrocarbon entrained stream.



Coriolis Liquid and Gas Separator Measurement

Fuel Control: A major US vendor of gas 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. The combination of no damage due to flow rate-of-change at start-up, high turndown, high accuracy, immunity to vibration in a very high vibration environment, along with ease of installation due to no straight pipe run requirement, makes Coriolis the technology of choice.



Coriolis Fuel Gas Measurement on a Gas Turbine

Natural Gas Fiscal Transfer: One specific example of 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.

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.



Western Australia: Previous installation using turbine meters for 50:1 turndown



“After” installation since 1996, with two operating and one “hot spare” meter for 80:1 turndown.

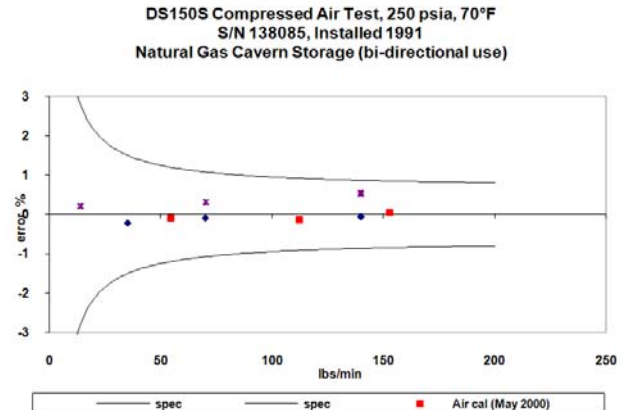
Natural Gas Storage: A storage field in Hungary utilizes 27 two-inch Coriolis meters for the injection and withdrawal measurement of natural gas. The storage reservoir consists of a multilayer sandstone formation with an aquifer flowing through it. Due to the complexity of managing the water level in 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 flow 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.



Coriolis Natural Gas Storage Measurement in Hungary

The following graph 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 manufacturers specifications.



Energy Metering: Energy per SCF can vary as much as 10 times that of energy per a unit weight for Hydrocarbons. If the total concentration of CO₂ and N₂ in the natural gas mixture remains fairly constant and most of the variation in composition is related to hydrocarbon concentrations, an average heating value can be utilized for energy measurement allowing Coriolis to achieve total energy accuracies unparalleled by volumetric meters utilizing the same average value. A Coriolis meter by itself offers a very affordable method of inferring energy flow rates on some natural gas streams.

Natural Gas Component	Ideal Heating Value Btu/lbm	Ideal Heating Value Btu/scf	Mix A	Mix B
N ₂	0	0.0	0.9000	1.0000
CO ₂	0	0.0	0.8000	1.2000
Methane	23.891	1,012.3	98.3000	85.0000
Ethane	22.333	1,773.7	0.0000	4.5000
Propane	21.653	2,521.9	0.0000	3.5000
I-Butane	21.232	3,259.4	0.0000	2.5000
N-Butane	21.300	3,269.8	0.0000	1.5000
I-Pentane	21.043	4,010.2	0.0000	0.8000
N-Pentane	21.085	4,018.2	0.0000	0.0000
N-Hexane	20.943	4,786.9	0.0000	0.0000
N-Heptane	20.839	5,515.2	0.0000	0.0000
N-Octane	20.759	6,263.4	0.0000	0.0000
N-Nonane	20.701	7,012.7	0.0000	0.0000
Variation Hydrocarbons from Average Btu	7.15%	74.77%		
Heating value Btu/lbm			23,009.45	22,278.70
Heating value Btu/scf			996.90	1,195.04
Average on Btu/lb basis			22,644.07	
Variation % from average Btu/lb			1.61%	
Average on Btu/scf basis			1095.98	
Variation % from average Btu/scf			9.04%	

Combustion control to boilers: 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 over damage to the measurement element due to flow surge when the boilers fired drove the selection of Coriolis for this application.



Combustion control application to boilers

Ethylene gas 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, 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 the natural gas industry, Coriolis meters have gained worldwide acceptance as the ideal meter for measurement of many fluids 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. Most countries and measurement organizations have approved or published standards for the use of 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 largely been overcome, with high accuracy measurement now possible at low-pressure drop. Coriolis “sweet spots” are line sizes of 300mm (12”) and smaller, 300 to 900 ANSI, where high turndown is needed, flow conditioning with other technologies to meet 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 a bona fide contender to complement Ultrasonic in low cost of ownership metering for natural gas applications. These two technologies overlap in the 100mm (4”) to 300mm (12”) line size range.



Parallel 3" Coriolis and 16" ultrasonic in a fuel gas metering installation.

Third-party data from CEESI, Pigsar, SwRI, and others show little if any effect of flow profile and the transferability of a factory water calibration to natural gas measurement applications.

Common Coriolis gas applications range from wellhead separator, medium to high-pressure fiscal metering, and fuel gas to power turbines, reciprocating engines, and boilers. As users of gas meters investigate Coriolis they are finding it to be the fiscally responsible choice for gas measurement in today's competitive business environment.

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