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Precision Natural Gas Flow Measurement Using Coriolis Technology

Abstract

Coriolis meters have gained worldwide acceptance in liquid applications since the early 1980's with a worldwide installed base of around 300,000 units. Newer designs have shown greatly improved low-flow sensitivity, lower pressure drop, and immunity to noise; factors which now enable their successful use in gas-phase fluid applications. With more than 15,000 units on gas around the world, groups including the AGA, API, Measurement Canada, German PTB, and Dutch NMi are all involved in writing standards for this "emerging" gas flow technology.

Data will be presented to illustrate both the range of natural gas applications, including production, fuel flow control to gas turbines, master metering, and city/industrial gate custody transfer as well as third-party test data. Laboratories include the Colorado Engineering Experiment Station Inc. (CEESI), Southwest Research Institute (SwRI), and Pigsar (Germany).

Introduction

Market growth for Coriolis technology has been very rapid; Coriolis' growth in gas phase applications is approximately four times faster than for liquid applications. Older designs were known to have some fairly well-justified limitations for use on gas; in general a relatively high pressure drop (around 1000" H_2O) was required to obtain a high accuracy flow reading, and large meters (3"-4" meter) did not work well due to sensitivity to noise and effects of process pressure. Since the market was rapidly growing, Coriolis vendors focused mostly on liquid applications.

Newer designs and technology developments since the early 1990's have changed this, allowing accurate gas flow measurement for even low-pressure gases (50-100 psi). Sensitivity has been dramatically improved, and pressure drop lowered (a typical 500 psi distribution application is now sized for 90" H_2O). All in all, it can be argued that Coriolis technology solves more problems and offers even more value for gas than liquid measurement. This is because gases are compressible, and with traditional technologies (dP/orifice, turbine, rotary, diaphragm), process pressure, temperature, and gas composition must be accurately measured or controlled, the devices regularly maintained (orifice plates checked, turbine bearings rebuilt), and adequate flow conditioning provided for profile-sensitive technologies. Since Coriolis measures the flowing mass of the gas, and accuracy is independent of composition and flow profile/swirl, the meter is more accurate under a wider range of operating conditions, and is often lower cost to install and maintain.

Micro Motion R-Series (1/4" to 2")

Installed R050 (1/2") meter

Coriolis is a smaller line-size technology: the largest offering from any vendor for gas applications of modern design is a 4" meter (handling natural gas flows up to 6-8" lines).

Coriolis meters are very cost competitive with other metering technologies on an installed cost basis, where installed cost includes:

- Instrument purchase price
- Temperature and pressure compensation (volumetric technologies)
- Flow conditioning and straight runs (profile sensitive technologies)
- Flow computer (volumetric technologies) for mass flow & standard volume calculations

Application "sweet spots" include:

- Line sizes 6" and smaller (can install parallel meters for larger lines, but 8" is a realistic upper limit)
- High turndown requirements (20:1 up to 50:1 is common), eliminating parallel metering runs of other technologies
- Dirty or wet gas where maintenance can be an issue
- No room for adequate straight-runs (re: AGA-3 revision)
- Changing gas composition and density
- Critical phase fluids such as Ethylene (C_2H_4) or Carbon Dioxide (CO_2), where volumetric meters are very expensive, especially where custody transfer or process control is mass based

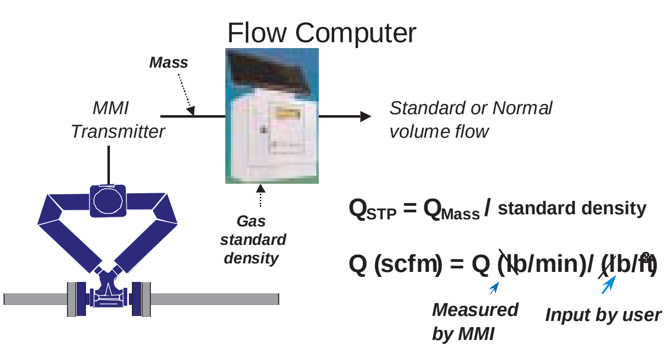
Currently, as measured by flowmeter units sold, around 10% of the worldwide market for Coriolis meters is for gas phase applications. This is in a flow market that is approximately one-fourth (26%) gas, not including steam (Process gas is thought to be approximately 16% with Natural gas being 10%, and steam being 10%). Coriolis is primarily a single-phase flowmeter, although promising early results from wet-gas testing will be mentioned.

Coriolis offers an improved primary element, with familiar outputs. Much like liquid petroleum applications, users desire improved reliability and accuracy, but familiar units.

Coriolis Standard or normal volume output:

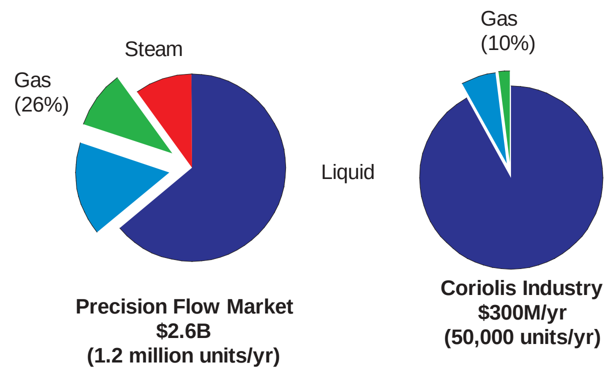
> Coriolis technology measures the mass of fluid (gas or liquid) flowing through the primary element. For liquid applications, the on-line density from the Coriolis meter (similar to other vibrating element densitometers) is used to output actual volume. This is useful for fiscal transfers of liquid petroleum, and if often corrected to base conditions, such as barrels of oil at 60N F.

For gas applications, the meter output can be configured for familiar standard or normal volumetric flow units, such as MMscfd or NM^3/hr. The on-line density from the meter is not used; rather the standard or normal density of the gas is entered into a flow computer from either a sample or on-line analysis, using a gas chromatograph (GC). Coriolis technology uses the following approach to output a highly accurate standard or normal volumetric output, in common usage throughout much of the world:



Somewhat like multipath Ultrasonic technology a few years ago, Coriolis "caught the eye" of the natural gas industry, and is now being actively evaluated for an AGA technical note (AGA TMC#11). Coriolis has been used since the late 1970's for liquid process applications, and has now been used since 1992 for process gas with more than 5000 installed units. Another 10,000 have been used for Compressed Natural Gas (CNG), natural gas at 3000+ psi for vehicle fueling.

This paper will discuss technology improvements and testing that show the technology is now a bona fide option for natural gas applications. Status of major worldwide standards will be presented, with an emphasis on the Americas and Europe, plus a sampling of applications from "wellhead to burner tip".

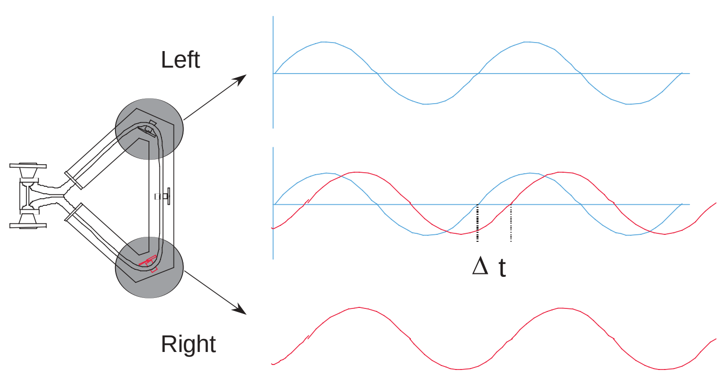


How the technology has improved and third party data

"Elegant design coupled with robust testing"

Elegant design: Earlier versions of Coriolis technology showed limitations on gas, somewhat justifying Coriolis' reputation as a "liquid only" meter. Improvements since 1992, embodied in newer generation designs show highly accurate gas phase flow measurement over wide turndown, with little if any flow conditioning or routine maintenance.

Major investments in R&D have resulted in step-change improvements for gas flows. The main areas of improvement include a) low flow sensitivity and zero point stability, and related b) reduced pressure drop, plus c) greatly increased immunity to flow induced noise and general vibration.

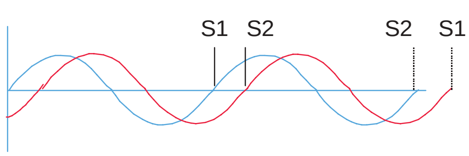


1. Greatly improved (up to 4X) zero point stability, which provided good accuracy at much lower flow rates. Greatly improved coil/magnet (pickoff) design improved the rejection of noise from undesirable mode shapes. Shown below is traditional Coriolis signal processing, with Coriolis effect induced time lag between inlet and outlet sections (D t) being directly proportional to the mass flow (standard volume) of gas.

2. Increased sensitivity, through enhanced signal processing and signal pickoff design allowed use of large diameter flow tubes, greatly reducing pressure drop. Primary element pressure drop is a strong function of flow tube diameter: but larger diameter flow tubes are stiffer, resulting in less Coriolis signal, so improved "signal to noise" ratio was required for lower pressure drop, since the secondary (signal processor) had to cleanly resolve a smaller signal.

"New Design" "Older Design"

Older designs generated a maximum of 60 microseconds of Coriolis signal (using 15 psi drop on water as the "upper end"), with a minimum resolvable signal of about 6 microseconds. This yielded a useable turndown of 10:1. With improved signal processing (using zero crossings for S1 and S2, then comparing S2 and S1, effectively canceling out noise), a Coriolis signal of 120 microseconds was generated at 15-psi drop on water. The lower limit of "clean" signal is approximately 1.5 microseconds, producing a "useable" turndown of approximately 80:1 (based on water- like fluids).



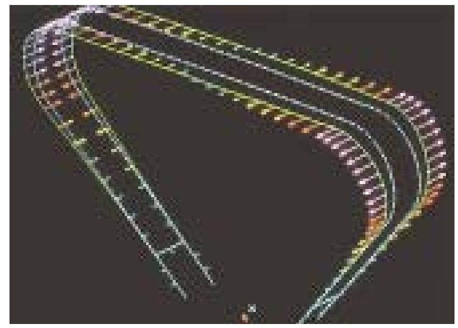
$$\Delta t = (S1-S2)/2$$

Note useable turndown on gas depends on a) gas pressure (higher the pressure the more flow can be passed through the primary at an acceptable pressure drop), and b) limitation of acceptable minimum accuracy at minimum flow.

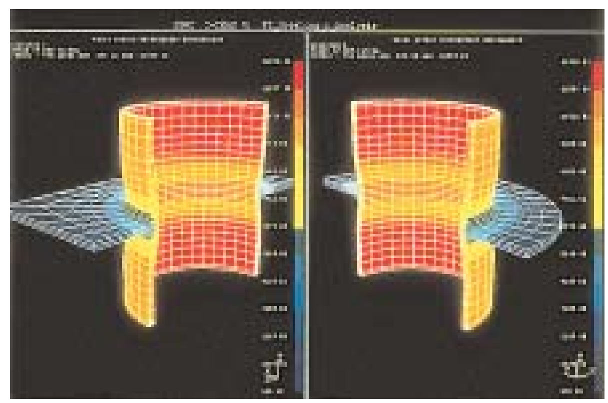
Example: a 1" meter in a natural gas application at 500 psig with a maximum flow rate of 1000 scfm, would have a pressure drop of 100 inches of water drop at the upper end with 0.55% rate accuracy, with better than 2% accuracy at 35 scfm, for a useable turndown of approximately 30:1.

3. Better than two times noise immunity improvement, which allows measurement of high velocity gases. Gases flow at much higher velocity (100-200 fps economic pipeline velocity) than liquids (10-20 fps), and have lower ability to dampen their own flow noise. The same designs that make current meter designs less sensitive to general plant vibration also makes them ideal for "noisy" gas applications

Software modeling and shaker-table testing are used to verify design goals. Pictures below show FEA models used to predict mode shapes, NASTRANS used to predict various primary element stresses (from bending, plus line pressure), and a flowing test setup, with the primary element is mounted on a shaker table.



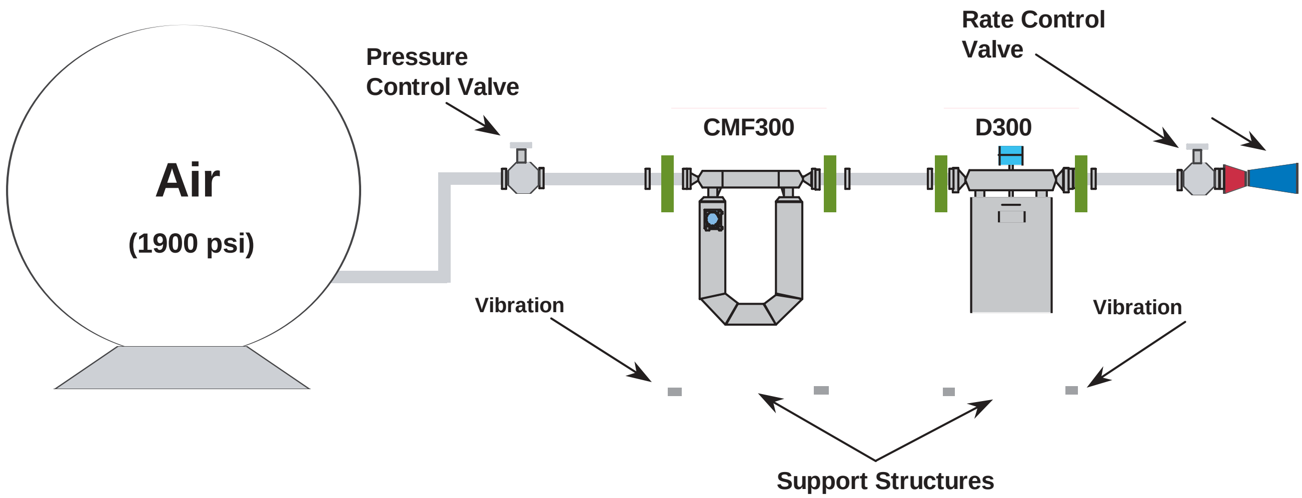
FEA Model to predict vibrational mode shapes



NASTRANS model for primary element stresses

Flowing shaker table: note NIST traceable gravimetric weigh tank

Technology improvements provided great optimism that the promise of Coriolis-level performance on gas applications was possible. However, the "proof is in the pudding", so robust testing was desired to verify the design models, in "real life" test situations on flowing gas.



CEESI Test setup; 1992 "old and "new" technologies

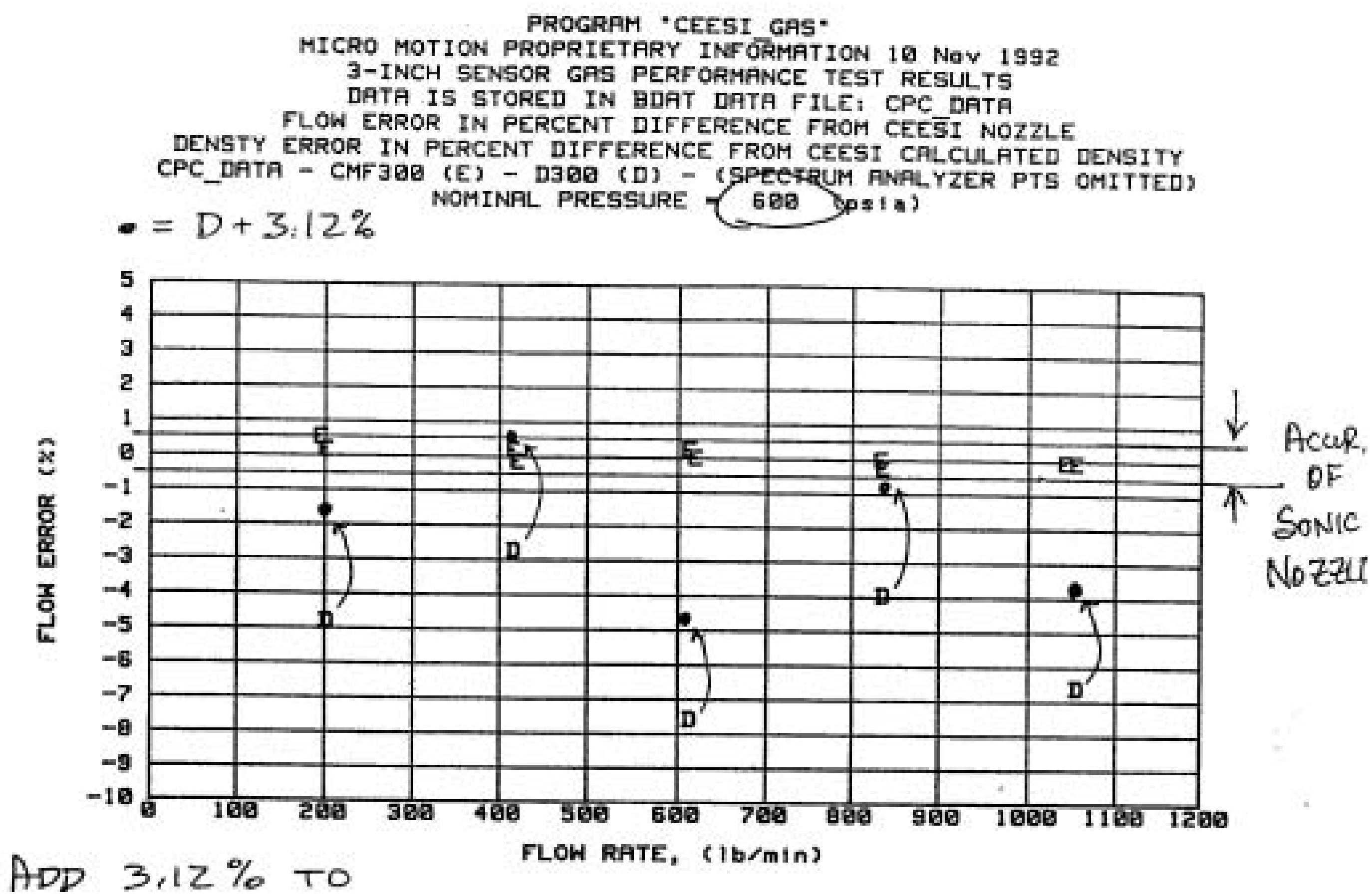
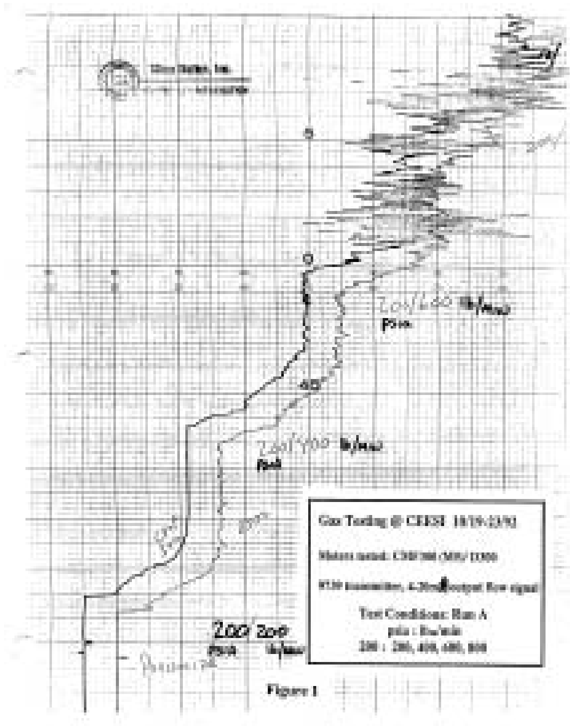
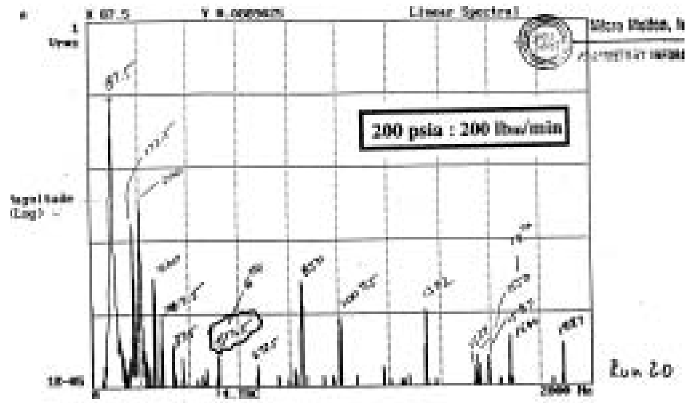


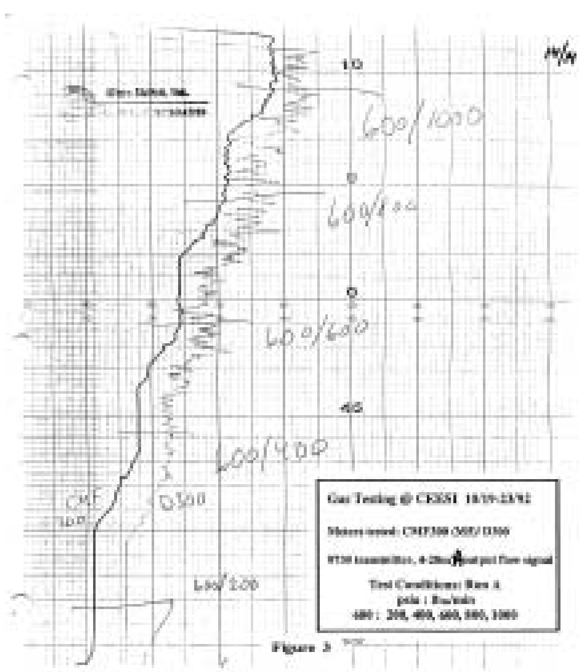
Figure 2 --CEESI Test results, 1992. Note that "New" technology meter accuracy was within accuracy of lab. E= CMF300 (New technology); D= D300 (Older technology).



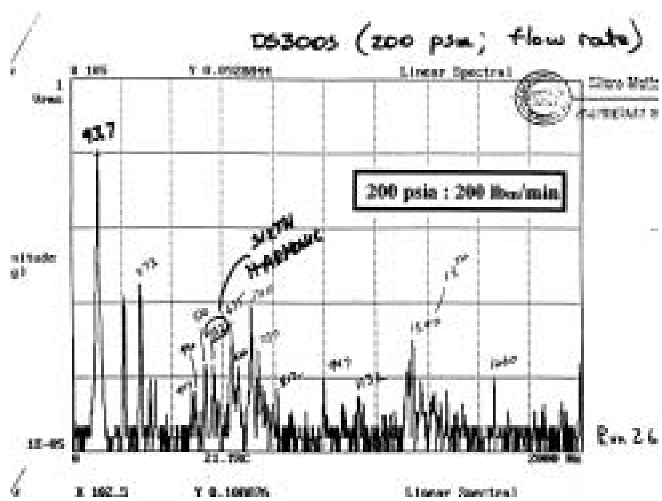
CEESI Test results: 200 psia, various flow rates. Both meters accurate.



CEESI Test Results: Spectrum analyzer. Note low noise "floor" of newer technology.



CEESI Test results: 600 psia, various flow rates. Older technology accuracy degrades Flow stability relates to accuracy graph (Figure 2 above).



CEESI Results, 1992. Spectrum analyzer results for older technology. Noise interfered with Coriolis signal.

"Robust Testing": Third party testing at NIST-traceable laboratories confirmed these technology improvements, and over 5000 units installed in gas applications verified performance in "real life" conditions. Testing has been performed at four different labs around the world, including the Colorado Engineering Experiment Station, Inc. (CEESI), and Pigsar/Ruhrgas in Germany. A sample test from Pigsar, using natural gas as a test fluid, is presented below for a 3" meter. Accuracy is better than +/-0.2% for an 18:1 flow range.

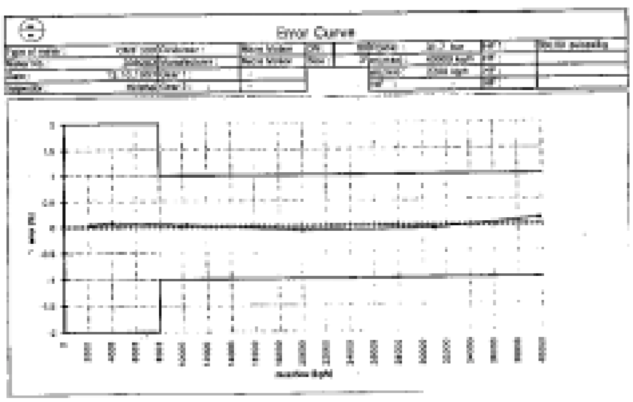


Figure 1. 3" meter tested at Pigsar/Ruhrgas in Dorsten, Germany. Natural gas at 464 psia, 2.6 - 47 MMSCFD.

Based in part on the testing at Pigsar, PTB (German Weights and Measures) approval for custody transfer was made to the first Coriolis meter two years ago. Netherlands Measurement Institute (NMi) approval was received in June 1999.

Pages 4 and 5 show results from a 1992 test of both older and newer technologies, on flowing air, at CEESI in Nunn, Colorado. This test was conducted to a) verify performance limitations of older designs (model DS300) and b) test for improved performance of newer designs (model CMF300). This was somewhat of a "worst case" test using large meters, previously known to show limitations. Note that smaller, older design Coriolis meters had been used successfully on medium to high pressure (500 psi and higher) gases for years. Conclusions/results from these tests are:

1. Older designs, especially larger sizes had limitations caused by flowing gas noise caused by difficulty in resolving the Coriolis signal from the flow-induced noise. "Rules of thumb" existed, specifying minimum operating densities around 0.6 lb/ft^3 (200 psi on natural gas)
2. Newer designs showed dramatically improved performance, generally within the accuracy of the test facility (+/- 0.4% to 0.5%)
3. Overall immunity to noise was greatly improved, as evidenced by the much lower "noise floor"

Future direction and products for gas: Significant investments continue for Coriolis, with the latest developments being in high-performance, single straight tube technology. Micro Motion® T-Series meters are available with Micro Motion® MVD™ technology. One of the many advantages is the use of digital signal processing (DSP) to further refine signal processing, extracting a cleaner flow signal from a single, compact, straight tube design.

Gas testing on this promising new design is currently underway (April 2000), and results will be presented as they are available. Originally designed for highly viscous, sticky liquids in the Food, Beverage, and Pharmaceutical markets, interest in this design for gas applications has driven design changes as well as a complete test plan for gas flows.

Standards work and approvals

Coriolis meters have long been used for process control, and a number of worldwide approvals or documents exist for fiscal transfer of liquids. These include:

- USA NIST C.O.C.
- USA API (draft; pending)
- German PTB
- Dutch NMi
- Numerous other countries, including Canada, Switzerland, Belgium, Austria, and Russia

Beginning in the mid-1990's, some of these groups and industry also began studying the technology for gaseous applications. The German weights and measures group (PTB) has recently extended custody transfer approval to include both gas and liquid phase fluids. As well, Dutch weights and measures (NMi) has performed testing and published a statement that the flow calibration factor established on water transfers without field calibration to gas phase applications, within a certain tolerance.

Copies of both these documents are available from the author/speaker.

Most exciting to the natural gas industry in the "Americas" and world areas influenced by North American expertise, is the working group AGA TMC#11, Coriolis for Natural Gas measurement. The chairman of this committee is Mr. Steve Baldwin of Unocal. Currently, the working group has established a test matrix, with two main focus areas:

1. *Flow profile:* Establish if Coriolis is truly insensitive to flow profile and swirl. Test matrix includes "AGA-3 like" testing for single and double elbows in and out of plane. Early

Micro Motion T-Series with MVD technology.

results from Micro Motion, Inc. show there is no effect at least within 5d; one researcher (Dr. Umesh Karnik of TCPL) found some profile dependence, as reported at the 4th International Fluid Flow Symposium (July, 1999 Denver, CO USA). Other vendors have indicated some small profile sensitivity, so this testing is critical to the establishment of a technical note and/or standard.

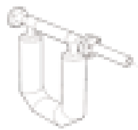


Figure 1a -- Straight Inlet

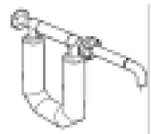


Figure 1b -- Single 90° Elbow Parallel to Sensor Tube Plane

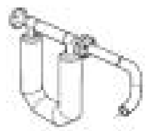
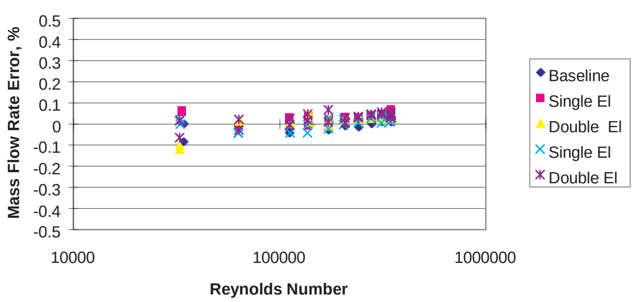


Figure 1c -- Double Elbow. Elbow Closest to Sensor Parallel to Sensor Tube Plane .

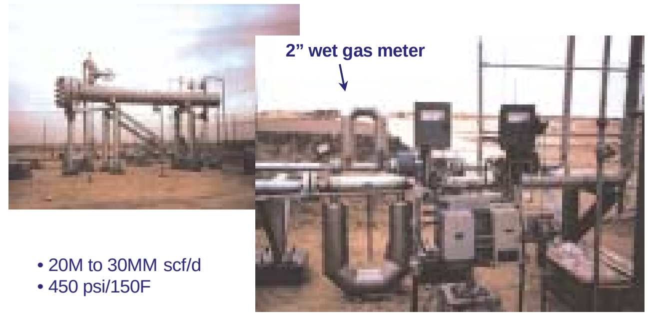
Figure 1d -- Single 90° Elbow Perpendicular to Sensor Tube Plane



Results from a 1995 study (T. Patten; North Sea Flow Workshop) using hot water. Within a few pipe diameters of the primary element, no effect of flow profile or swirl was found.

Gas testing at CEESI during product development of Micro Motion R-Series is shown below. Note the installation details: meters are mounted flange-to-flange and an ELITE® meter is used as a reference meter.

2. *Wet gas:* The industry is very interested to quantify the amount of entrained liquid Coriolis technology can handle, while maintaining good accuracy. Initial results from a consortium study in Canada indicate good tolerance for



entrained liquids, but additional testing is necessary and desired. Produced or wellhead gas are the target applications.

The AGA standard will focus on two "sweet spots" for Coriolis:

1. *Medium to high pressure distribution metering points.* These city-gates or industry-gates often have high turndown requirements, and new installations must meet the recently revised, more stringent AGA-3 straight run requirements, adding additional cost to using traditional measurement technologies. As well, Coriolis' proven stability over time offers reduced maintenance and field proving/verification.

2. *Wet gas measurement.* If Coriolis is capable of measuring wellhead or produced gas, prior to processing, significant operational savings are possible.

The AGA TMC#11 working group plans to publish a "technical note" by the end of the calendar year 2000, and a draft standard by year end 2001, pending results from testing. Industry, test labs, and of course Coriolis vendors are very excited and are actively supporting this effort to bring Coriolis technology to the natural gas industry.

Application examples

Coriolis meters have been used 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 these "sweet spots":

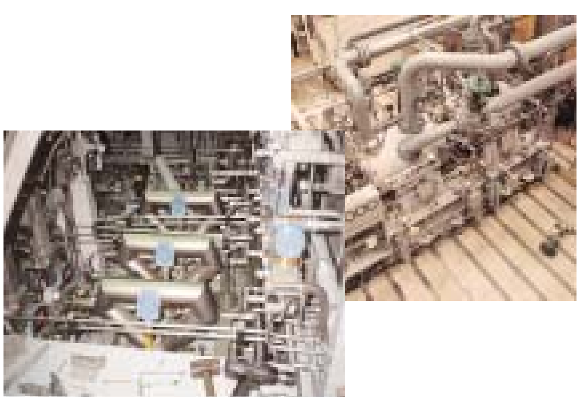
- Line sizes 6" and smaller
- High turndown requirements
- Dirty, wet, or sour gas where maintenance can be an issue with other technologies
- There is no room for long straight-runs
- Changing gas composition and density

Coriolis meters can be sized for very low-pressure drop (100" H_2O), but can also be installed upstream of the pressure regulator for increased useable turndown. For instance, in one application for custody transfer of nitrogen, a 50-psid drop (2000" H_2O) was taken through the primary element, and the pressure regulator adjusted accordingly. This allowed the use of a 1" primary element instead of a 3" element, and a 40:1 useable turndown (better than2% accuracy at minimum flow). The only other alternative was two to three parallel orifice runs at much greater installed cost ($8k vs. $20k)

Test/Production separators: The application shown below is a "before and after" scenario. Coriolis meters on both the liquid (oil/water) and gas streams streamlined the separator design, saving over $100k in design, engineering, and fabrication. As well, numerous parallel orifice runs were eliminated by the superior turndown of the Coriolis meter.

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

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 (fuel "rails"). The combination of 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 technology a perfect fit. Note that this fuel-consumption application is a non custody-transfer application, allowing the use of Coriolis meters in the field, without any formal AGA standard or guideline.



Coriolis meters on low NOx gas turbine for pipeline compressor.

Natural Gas Fiscal Transfer Example: 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".

The justification for using the Coriolis meters was based on installed and calibration / maintenance cost improvements over the more traditional turbine 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 much reduced due to the intrinsic reliability of Coriolis meters (i.e. no moving parts). Similarly, reliability improvements had a very positive effect on calibration and proving costs.

Internal checks by the customer have shown agreement to better than 0.1% on all gas transfers. The meters have been installed and operating for over four two years: 48 months of proving data is being requested from this utility as part of the AGA TMC#11 effort.

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. Custody transfer between utility and cogeneration project. 0.3 - 23 MMSCFD at 500 psia.

Proving: The data shown in Figure 1 (page 6) was taken on natural gas, but the meter was calibrated (i.e. the meter factor was established) on water at the factory. Based on an extensive database of water vs. gas calibration data, there is no change in calibration between water and gas. In addition, a history of over 250,000 installed meters on liquid and gas indicates no change in meter factor over time (barring corrosion or erosion issues).

Since proving any gas meter in-situ is difficult, the stability of Coriolis meters makes them ideal for use on gas. By utilizing the transferability of water calibration to gas and the meter stability over time, an extremely accurate and stable metering system can be established. The following methodology was proposed by the Australian utility in the previous example to establish traceability for high-value gas transfers:

1. Establish the meter factor on water
2. Validate the meter factor on gas (i.e. natural gas at Pigsar)
3. Periodically remove the meter from service and verify the meter factor on water

Although this methodology requires that the meter be removed from service, it defines very accurately the in-situ performance of the meter. Since steps 1 & 2 establish the meter traceability between water and gas, verifying water performance in step 3 automatically validates the meter in-situ (gas) performance. After some experience, it is likely that the period to repeat step 3 would be lengthened from every year to every two or three years.

A variation of this proving methodology is to use a Coriolis meter as a master meter. By establishing the traceability between water and gas measurement on the master meter, it can be used to prove other meters (of any type). Figure 3 shows a 1" Coriolis meter being used as an in-situ master to prove an in-line turbine meter. Since in this example the master meter is moved from one installation to another validating the measurement on water periodically can be easily accommodated.

Figure 3. Master meter proving of a turbine meter using a 1" Coriolis meter.

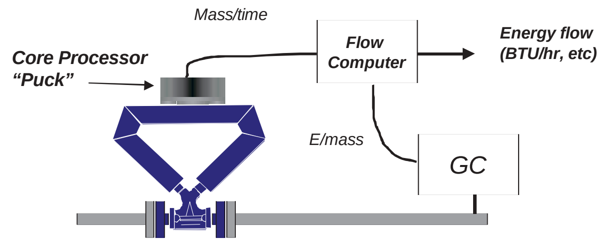
Distribution metering: Of special interest to the AGA working group are medium to high-pressure distribution applications as shown below. In this example, natural gas at 1000 psig is transferred, and requires Modbus communications protocol.

Distribution metering: 3.5MMscfd, 1000 psia, ModBus, high turndown.

Energy Metering: Coriolis meters have the potential to be excellent energy meters, with or without on-line chromatography. Three basic levels of energy metering exist, as follows:

1. Small lines, where volumes do not justify on-line GC. Coriolis meter alone can be used to measure energy content typically within 1-3%.
2. Medium lines, where volume justifies an on-line GC. Single or parallel Coriolis meters can be tied to the GC, per the sketch below:
3. Large lines, with on-line GC and multipath ultrasonic meter.

Energy per scf varies tremendously, depending on molecular weight, with ethane having almost twice the energy content of methane. If energy is measured per unit mass, it can be seen that energy varies only 4%. For natural gas energy metering, if composition is relatively constant (especially of inerts such as nitrogen), the Coriolis meter by itself offers a very affordable method of measuring energy transferred. In this application, the meter's output is configured to represent energy per time (e.g. BTU/hr) instead of mass or standard volume (lb/hr or scfh).



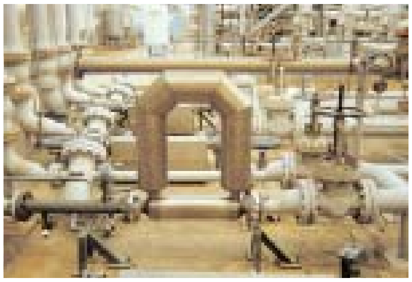
Key advantage is that mass measurement is more accurate

	Heat of Combustion		Air required for Combustion	
	BTU / scf	BTU / lb	scf air / scf fuel	lb air / lb fuel
Methane	911	21600	9.6	17.2
Ethane	1630	20500	16.8	16.1
Propane	2360	20000	24.3	15.7
n-Butane	3110	19700	32.1	15.5
Hydrogen	273	51900	2.4	34.3

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 (standard volume) ration between the natural gas and combustion air, over wider turndowns with no flow conditioning.

Check metering: An emerging application is in the use of Coriolis meters to "check" the billing from utility companies. In this application, a major US specialty chemical manufacturer on the West Coast used a large amount of natural gas for process boilers and furnaces. When plant energy balances did not match utility company billing, check meters were installed. Note that this user relied on the NIST-traceable water calibration factor transferring to gas applications in their discussions with their utility supplier.

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, helping to meet both unit mass-balance goals, as well as reactor feed rate requirements. Ethylene is fed continuously to a polymerization reactor, where various grades of polyethylene (LDPE, etc) are made.



Summary

Although relatively new technology for natural gas applications outside of compressed natural gas (CNG), Coriolis have gained worldwide acceptance for other fluids and other industries. With a worldwide installed base of around 300,000 units, Coriolis technology is seeing expanded use for both liquid petroleum and natural gas. A number of countries and groups have either drafted standards or are in the process of studying the technology.

Technology limitations of earlier designs have been largely overcome, with high accuracy measurement now possible at low-pressure drop, typically 90" H_2O. Coriolis "sweet spots" are mainly in lines of 6-8" and smaller, where high turndown is needed, flow conditioning to meet new AGA-3 requirements is costly, and/or the gas is of dirty, sour, or of changing composition. Also, good potential exists for "simple" energy metering, using the Coriolis meter output directly, scaled for energy units.

Third-party data from CEESI, Pigsar, SwRI, and others show little if any effect of flow profile, and little if any shift in meter factor from factory calibration to natural gas application. This is a key area of study for an AGA working group.

Common Coriolis gas applications range from wellhead and separator gas to turbine and boiler combustion control to medium/high pressure distribution metering.

Several Coriolis vendors are actively involved in supporting the AGA's work to develop a Technical Note for Coriolis. Hopefully, based on acceptable third party testing for swirl effects and flow profile, plus wet-gas testing, an AGA standard will be forthcoming in 2001. Until then, Coriolis technology merits serious consideration as a bona fide technology for natural gas applications.

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