# SUPPORT OF GAS FLOWMETER UPGRADE
# FINAL SUMMER FACULTY FELLOWSHIP REPORT

Final Report
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Johnson Space Center White Sands Test Facility

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**ABSTRACT**

A project history review, literature review, and vendor search were conducted to identify a flowmeter that would improve the accuracy of gaseous flow measurements in the White Sands Test Facility (WSTF) Calibration Laboratory and the Hydrogen High Flow Facility. Both facilities currently use sonic flow nozzles to measure flowrates. The flow nozzle pressure drops combined with corresponding pressure and temperature measurements have been estimated to produce uncertainties in flowrate measurements of 2 to 5 percent. This study investigated the state of flowmeter technology to make recommendations that would reduce those uncertainties.

Most flowmeters measure velocity and volume, therefore mass flow measurement must be calculated based on additional pressures and temperature measurement which contribute to the error. The two exceptions are thermal dispersion meters and Coriolis mass flowmeters. The thermal dispersion meters are accurate to 1 to 5 percent. The Coriolis meters are significantly more accurate, at least for liquids. For gases, there is evidence they may be accurate to within 0.5 percent or better of the flowrate, but there may be limitations due to inappropriate velocity, pressure, Mach number and vibration disturbances.

In this report, a comparison of flowmeters is presented. Candidate Coriolis meters and a methodology to qualify the meter with tests both at WSTF and Southwest Research Institute are recommended and outlined.

## INTRODUCTION

The NASA Johnson Space Center White Sands Test Facility (WSTF) currently conducts hydrogen and oxygen flow-rate measurements for the shuttle flow control valves (FCV's). Recent estimates have shown that these measurements have an uncertainty level of 2 to 5 percent, a level inadequate for certifying new FCV designs associated with using lightweight shuttle tanks. The new FCV's require flow measurements be performed to an uncertainty level of less than 1 percent. Currently, no facility is capable of qualifying the new shuttle FCV's without the use of costly gravimetric calibrations for hydrogen. A WSTF Center Director's Discretionary Fund (CDDF) project objective is to select an affordable flowmeter and method for testing the new FCV design.

In addition, the less accurate sonic-flow nozzles used for other calibrations in the WSTF Calibration Lab could be replaced by a Coriolis mass flowmeter (CMF) or calibrated on site using the CMF.

This CDDF project has an FY95 objective to complete a literature search and select a methodology for calibrating sonic gas flow meters. This Summer, this faculty fellow provided:

1. A review of the past work performed at WSTF on Coriolis gas meter testing
2. A literature review and summary
3. Communication with vendors to locate candidate flow meters
4. Identification of candidate Coriolis meters for testing in the WSTF High Flow Facility
5. Coordination of plans to test a candidate meter at Southwest Research Institute (SwRI) in San Antonio
6. A recommendation of relevant flow parameters to include in the test matrices for SwRI, the WSTF hydrogen test facility and the WSTF Flow Calibration Laboratory in the form of a preliminary test matrix. This is necessary to correlate the tests using different gases.
7. An extension of this Summer Faculty Fellowship project is being funded by the Center Director Discretionary Fund project. Its goals are to complete the test matrices, tour the SwRI's flow test facility and continue the search for applicable meters and testing facilities and literature.

## REVIEW OF PAST WORK ON THE WSTF CORIOLIS FLOWMETER STUDY

**Brandon Gabel's 1992 "A Study of the Use of a Coriolis Mass Flowmeter as a Gas Calibration Standard Calibrated in Liquid"** (Gabel, 1992)

The WSTF Flow Calibration Laboratory has an EG&G liquid flowmeter, a Cox sonic gas nozzle flowmeter, and a Brooks Bell Prover gas flow measuring device. WSTF tested an ABB K-Flow model K-20 Coriolis flowmeter using these three available flow measuring devices. The goal was to test the Coriolis meter against other WSTF meters and evaluate the potential for the Coriolis meter as a calibration device for the Cox sonic meter and possibly other gas flow meters.

The K-20 meter was tested first against the Cox nozzle using $GN_2$ at 7 to 75 g/s. Nearly all the data points landed outside the ABB Company specifications for their Coriolis meter, but mostly remained within the Cox nozzle error bands. This is not surprising, since the uncertainty in the Cox system is about 1% and the specifications on the K-20 show accuracy of about 0.6 to 0.2 % in the tested range. No relevant conclusions regarding the Coriolis meter were made from this set of data, although the meters showed better agreement at the higher mass flow rates (45 to 75 g/s) than at the lower end of the scale.

Next, the Coriolis meter was compared to the Bell Prover, which is only capable of low flows (< 7 g/s). Again, all the data was outside the ABB company error specified accuracy. For instance, the specifications show an error of about 1% at 7 g/s, but the test showed 2 to 4% error.

Finally, the Coriolis meter was used with liquid water and compared to the EG&G calibration system. Only for the higher flow range (over 60 g/s) was the data within the ABB Company specified accuracy. Below 60 g/s, most of the data was outside the specified accuracy.

The conclusion was that the meter did not perform as specified in low liquid or low gas flow. The accuracy at higher flows could not be determined with available WSTF measuring devices. It was not proven that the meter does not give the same readings in liquid as it does in gas. However, it was also not proven that the Coriolis flowmeter could be calibrated in liquid and then used as a calibration standard in gas.

## SUMMARY OF THE LITERATURE REVIEW

Genesi (April, 1991) focused on orifice-plate, segmental-wedge, venturi flow-nozzle, V-cone, target, and oscillating-vane flowmeters. In the following month (Genesi, May, 1991), he covered variable-area, vortex-shedding, magnetic, turbine, ultrasonic, Coriolis, and thermal-dispersion meters. Table 1 is a brief summary of his meter descriptions.

***The Coriolis mass flowmeter*** consists of one or more tubes that are vibrated at a natural resonance frequency by electromagnetic drivers. Their harmonic vibrations impart Coriolis (angular) forces proportional to the product of fluid density and velocity that act against the wall. This results in a secondary movement that is superimposed on the primary vibration, which varies proportionally with mass flowrate. A sensor measures the phase difference between inlet and outlet caused by the magnitude of this secondary vibration. They supposedly are capable of an accuracy to 0.2% of the flowrate.

The Direct Measurement Corp. (DMC) has developed a Coriolis mass flowmeter that vibrates in the radial mode (Hahn, 1994). The flow path is a single straight tube with no intrusive elements. The vibration is induced at the center of the length and flattens the tube by about one thousandth of an inch. As fluid flows through, the combination of the fluid velocity relative to the tube and the rotational component of the vibration creates a Coriolis acceleration of the fluid. The reaction forces in the tube cause the tube to distort differently than the no-flow distortion. The difference in tube distortion is a measure of the flowrate. According to the company, the vibrational frequency (2000 Hz and above) is higher than most other Coriolis meters use and also higher than most noise vibration that may be produced by other flow effects, such as sonic nozzles in the line. The meter was designed specifically for gas metering. There will be a distinct advantage over other Coriolis meters that have been shown to lose accuracy because of noise and/or high velocity in gas.

TABLE 1.-FLOWMETER COMPARISON

| Meter Type | Fluid Type | Accuracy (%) | Comments |
|---|---|---|---|
| **Square Edge Orifice** | Gas or Liquid | 0.5 to 3 by volume | Edge and tap wear |
| **Segment Wedge** | Gas or Liquid | 0.5 to 5 by volume | Good stability |
| **Venturi Tube** | Gas or Liquid | 0.5 to 1.5 by volume | Good stability |
| **Flow Nozzle** | Gas or Liquid | 1 to 2 by volume | Good stability |
| **V-Cone** | Gas or Liquid | 0.5 to 2 by volume | Good stability |
| **Oscillating Vane** | Liquid | 0.5 by volume | Sensor replacement |
| **Target** | Gas or Liquid | 0.5 to 2 by volume | Wear |
| **Variable Area** | Gas or Liquid | 0.5 to 5 by volume | Good stability |
| **Vortex** | Gas or Liquid | 0.5 to 1.5 by volume | Corrosion, Erosion , & Reynolds no. limit |
| **Ultra-sound Doppler** | Liquid with Suspended Solids | 1 to 5 by volume | Installation sensitivity |
| **Ultra- sound Transit Time** | Gas or Liquid | 1 to 5 by volume | Installation sensitivity |
| **Thermal Dispersion** | Gas | 1 to 5 by mass | Sensor buildup sensitivity |
| **Magnetic** | Liquid | 0.2 to 1 by volume | Good stability |
| **Turbine** | Gas or Liquid | 0.1 to 1 by volume | Bearing wear, viscosity, and installation sensitive |
| **Coriolis** | Liquid or Limited Gas Use | 0.2 to 2 by mass | Re-zero for various fluids, one vendor for gas |

Vogtlin and Txchabold (1994) gives a simple and clear explanation of Coriolis force and the principle applied to straight tube flowmeters. They also explain signal processing using photodiodes to measure change in frequency where the phase shift is proportional to mass flow. The drifts in the transmitters, receivers and amplifiers and are checked automatically at set intervals.

Vogtlin gives an interesting example of Coriolis forces: rivers flowing north to south exhibit heavier erosion on their western shores if in northern hemisphere and eastern shores if in southern hemisphere. Note in the northern hemisphere, the Coriolis acceleration of the river is toward the east but the corresponding reaction force (acting on shore) would be on west shore. They also derive the $F_{coriolis} = 2m\omega v$ based on two people standing on a rotating disk and one moving toward the other. Even though one moves through the original distance toward the other, the distance has changed because the innermost person on the disk does not move far as the outermos person in the tangential direction. This tangential distance requires a Coriolis acceleration to cover it in the required time to reach the radial distance.

Keita (1994) emphasized that Coriolis meters can be unduly influenced by fluid properties and process parameters. The linear approximation of the meter response as a function of the fluid velocity, legitimate for a liquid, remains to be ascertained for a gas. Like most mechanical systems, CMF's are truly non-linear. The meter sensitivity and resonance frequency can suffer from non-linear effects because of the stress induced by a process parameter, such as the line pressure. A list of the process parameters to consider in a liquid to gas comparison:

1. Temperature effect: elastic properties and thermal expansion render temperature correction necessary. All CMFs contain a temperature sensor and the correction algorithm is implemented in the instrument's software.
2. Pressure effect is due to the stress stiffening of the mechanical oscillator. Generally the manufacturers neglect this and no correction is applied. However, with gas under high pressure it must be accounted for. Fortunately, with straight pipe design, a theoretical estimate can be made.
3. The fluid velocity effect is a true non-linearity of the sensor. This is computable in a straight-pipe design.
4. It is common practice to calibrate a CMF with water. However, it is believed that for a gas the sound velocity or compressibility effect could be significant, as has been found for the vibrating element gas densitometer.

Keita concluded the following:

1. The main contribution to the shift in the meter factors is due to the pressure.
2. The compressibility effect can be smaller than the experimental uncertainty for a high-frequency CMF if the pipe diameter is small enough.
3. The pressure effect and compressibility effect partly compensate for each other.
4. Despite their high resonance frequency, straight pipe CMF's are suitable for gas measurement, and their behavior is predictable.

Carpron (1994) reported on tests that were performed at the Colorado Engineering Experiment Station, Inc. (CEESI) to compare discharge coefficients for ***sonic flow nozzles*** in ***$GH_2$*** to ***air***. Two systems were used to measure flowrates of air. One was a direct gravimetric scale reading (Primary B); the other was a volume-pressure-temperature calculation (Primary C) for mass of air. The $GH_2$ was only measured with the Primary C system. All three correlated mostly within their 95% confidence interval. The most deviation appeared to be for $GH_2$ at low and high Reynolds numbers.

Blickley (1990) focused on the shapes and specialty designs of Coriolis flowmeters to reduce the effects of fatigue stress in the meter tubes. Torsional twisting of the meter tube does not create localized high concentrations of stress that can result from pure bending. Instead, it distributes the stress along the whole length of tube. The effects of pipe vibration on the readings can be reduced by operating at higher oscillation frequencies (700-1100 Hz Vs 40-120 Hz) according to the Endress & Hauser, Inc., located in Greenwood, Indiana.

Babb (1992) reported that Exac Corporation had an SX series flowmeter that costs about the same as a good volumetric meter. The company surveyed customers and found most flow applications require about 0.5% accuracy. Exac Corporation has since merged with Micro Motion, Inc. and all their meters are sold under the Micro Motion name.

## TESTING FACILITIES

### The Institute of Gas Technology

The Institute of Gas Technology (IGT) has a multi-purpose meter testing facility capable of testing metering technologies for high flow rate and high-pressure natural gas applications (Rowley, et al). The testing and facility is supported by a consortium of utilities under IGT's Sustaining Membership Program (SMP). Meters are being evaluated that could, potentially, be applied to natural gas vehicles (NGV) at fueling station operating conditions. Two Coriolis meters have been evaluated:

1. The Micro Motion Model DH025S which is commonly used in NGV dispensing
2. The Micro Motion Model DH038S which has a higher flow capacity and is a modification of the DH025S.

The test facility consists of piping, control components and storage vessels mounted on a high-precision scale. The test loop is configured with two high-pressure storage vessels rated at 3600 psig and volume of 7 cu. ft. The loop is designed to accommodate flow rates up to 1700 scfm at 3000 psig. Before the test begins, the test stand piping on the scale is pressurized to the equilibrium pressure, and the scale is tared. The gas flow is directed through the meter and into high-pressure storage vessels mounted on the precision balance.

<u>Micro Motion DH025S test results</u>:
This meter was tested at 3000 psig and flow rates from 15 lb/min to 40 lb/min (875 scfm of NG). The meter was very unstable at flow rates over 25 lb/min but was very stable at flow rates of 23 lb/min and below. It appears to be have uncertainty of less than 0.3% at 23 lb/min and lower, but at 33 lb/min the uncertainty jumped to nearly 15% even though the meter is rated for as much as 40 lb/min.

<u>Micro Motion DH038S test results</u>:
Micro Motion developed a larger meter which has a 0 to 50 lbs/min and 5200 psig pressure capability. Tests were conducted at various line pressures and flow rates. The threshold flow rate at each pressure was determined based on the flow output stability from the meter and the overall error of the meter total compared with the high-precision scale. In general, the pattern of performance was similar to that of the DH025S.

In addressing the high flow rate problem, Micro Motion said the test results identified gas flow effects that disturb meter performance above some threshold flow rate. They determined that the threshold flow rate is closely related to gas velocity. Therefore, higher gas flow rates need to be measured at higher pressures. Note that the higher pressure increases the density, resulting in a corresponding decreased velocity.

IGT is currently expanding its facility to handle higher pressures and flow rates. The program has been accelerated by a recently awarded contract from the Gas Research Institute (GRI).

Chris Blazek, of IGT, said they have an 8000 cu ft scale for gravimetric analysis (about 3000 lbs). They can add 200 to 300 lbs $N_2$ gas. It can measure to 2 grams. Gases used are CNG and $GN_2$, says they can probably measure helium but have never done it. He thinks they can even measure $H_2$ but not classified for $H_2$ service. Blazek has 1000 psi $H_2$ experience. They have 40,000 cubic feet of gas storage capacity. Patricia Rowley said the scales are "Metler Scales" accurate to 0.05 lbs. used in their gravimetric analysis and the system may be adapted to $H_2$.

**Southwest Research Institute (SwRI) in San Antonio**

John Gregor at the Gas Research Institute said they are developing a flow calibration lab at SwRI. They have three test loops:

Distribution test loop: 0-40 psig, 2500 acfh (42 acfm)
Low pressure test loop: 0-210 psig, 36,000 acfh (600 acfm)
High pressure test loop: 185- 1440 psig, 120,000 acfh (2000acfm)

They can achieve a level of accuracy of 0.1% using a tank on a gyroscopic scale (made in Germany).

GRI is a private, not-for-profit membership organization that plans, manages, and develops financing for a cooperative research and development program in gaseous fuels and their use. SwRI is an independent, nonprofit, applied engineering and physical sciences research and development organization.

In 1987, GRI contracted with SwRI to develop a world-class Metering Research Facility (MRF) with the objective of improving the state-of-the-art in gas flow measurement at field installations. The MRF includes three independent, natural gas systems: a low-pressure loop (LPL), a high-pressure loop (HPL), and a distribution test stand (DTS). The research there has involved installation and pulsation effects for orifice and turbine meters as well as gas sampling, electronic flow measurement, ultrasonic meters, field meter provers, and distribution measurement using diaphragm, rotary, and compact gas meters. The MRF is available for third party use to perform metering research and development, equipment calibration and testing, and personnel training. The specifications for the MRF are shown in Tables 2 and 3.

The primary mass flow standard for each MRF test system is a gravimetric system that weighs the gas collected during a precisely measured time interval. The scales are gyroscopic balance systems and are considered the most sensitive weighing systems available for MRF applications. The scales are calibrated using mass standards traceable to the National Institute of Standard Testing (NIST). The HPL and LPL are re-circulating flow loops. Constant flow conditions in the test section during a primary calibration are maintained by adding gas to the re-circulating portion of the loop at the same rate it is drawn off to the weigh tank. Special fast-acting hydraulically powered diverter valves are installed in both the HPL and LPL to control the flow of gas to the weigh tank and from the makeup bottles. They are computer controlled and independently actuated, with a full stroke response time of less than 50 milliseconds. The DTS is a blowdown type or single-pass flow system, rather than a re-circulating system.

The secondary flow calibration standards in the HPL and LPL consist of ASME/ANSI MFC-7m critical flow nozzles and industrial turbine meters. The secondary flow calibration standards for the

DTS are laminar flow elements (LFEs). This secondary capacity ranges from 8 to 920 acfm of gas flow at considerably faster turn around time than the primary system.

The SwRI Coriolis meter experience is only with Natural Gas Vehicles and is useful because of the high velocity and pressures encountered in that application. SwRI is testing the meter in another of their test facilities.

In response to a request for a quotation, SwRI will prepare and submits a letter proposal to the client. The contractual arrangements can be tailored to meet the client's normal procedures for doing business. They serve in a consultant capacity for outside organizations. They cannot test $H_2$, but they are willing to develop the capacity. NOVA in Canada does some similar work, but probably not at our flow high flow rates; Astleford did not know if NOVA could test $H_2$. There are about a half-dozen other labs in world that do similar calibration work but none have the capacity of SwRI's HPL. The weigh scale is Vala Vagabaugh with a 24,000 lb tare on the tank. The gas weighs about 2200 pounds and the scale is accurate to 21 grams.

**TABLE 2.-DESIGN PERFORMANCE SPECIFICATIONS OF THE MRF**

| | HPL | LPL | DTS |
|---|---|---|---|
| Flow Rate, scfm | 115,000 | 7,700 | 42 |
| Flow Rate, acfm | 2,000 | 600 | 42 |
| Pressure, psig | 185 to 1440 | 0 to 210 | 0 to 40 |
| Gas Temperature, °F | 20 to 100 | 40 to 120 | Ambient |
| Pipe Size, in. | 6 to 16 | 1 to 8 | up to 2 |
| Specific Gravity | 0.55 to 0.97 | 0.55 to 1.0 | 0.55 to 1.0 |
| Test Fluid | Natural Gas/N2 | NG/N2/Air | NG/N2/Air |
| Flow Standard | Weigh Tank | Weigh Tank | Weigh Tank |

**TABLE 3.-MRF CONTROLLABILITY AND ACCURACY**

| | HPL Controllability | LPL Controllability | DTS Controllability | Measurement Accuracy |
|---|---|---|---|---|
| Flow Rate | 1.0% | 0.5% | 1.0% | 0.1 to 0.25% |
| Pressure | 1.0 psi | 0.2% | 0.2 psi | 0.015% |
| Temperature | 1 F | 1 F | Ambient | 0.1 F |
| Pipe size | Pipe Sch. 0.05 in. | Pipe Sch. 0.02 in. | Pipe Sch. | 0.001 in. |
| Specific Gravity | 0.005 | 0.005 | 0.005 | 0.001 |
| Reynolds No. | 1.0% | 1.0% | 2.0% | 1.0% |

**Calibron Systems, Inc. in Scottsdale, AZ**

Gary Cohrs (602/991-3550) was called on 6/30/95. He said they have used tanks on scales with 0.01 lb. resolution to test gas flow in the past at higher flow rates, but it is not a standard procedure. They calibrated the K- 20 meter on a 1.0-acfm bell prover. They cannot perform a gravimetric calibration at high flowrates.

## POTENTIAL VENDORS

**Krohne America; Peabody, MA; Warren Ellisin; 713/464-5454**
**Control Engineering** referred to Krohne in an article: "Coriolis Flowmeter Measures Mass Flow Directly," in Jan., 1990. The claim by the Krohne America was that their "Corimass" system had a repeatibility of 0.1% of flowrate and an error of less than 0.2% of the value. The design used torsional stress, not bending stress. Rates are from 0.2 lb/min to 3600 lb/min. Average cost was $5000. The specs were for liquid. According to Warren Ellisin , Krohne America makes variable area flowmeters (rotameters) and Coriolis meters for liquids only (6/30/95).

**Stork Ultrasonic Technologies, Inc.; Shelby Morley; 800/795-7512**
Shelby Morley thinks his ultrasound meteres may have application in our $H_2$ flow control valve tests. Note: these ultrasound meters are not accurate enough for this project.

**Daniel Flow Products, Inc.; Kevin Warner; 713/827-5067**
Kevin Warner says ultrasonic meters for gas are less accurate than sonic nozzles (6.23/95).

**Endress and Hauser Instruments (E & H) in Greenwood, IN; 800/428-4344**
Marcel Woiton (a research engineer) said E & H makes Coriolis meters but they only have done limited gas testing with CNG. They usually calibrate with water and assume no change with gas. Their meter measures the phase shift. They have sent catalogs to WSTF.

Greg Harker, of E & H, said the M-point model is being replaced by Promass 60/63 models. The promass F is for higher temperatures (392F compared to 300F for the Promass M). The cost is about $6500. Delivery is as short as 3 days for a 1-in. Promass M. There are two tubes so the sensor can reference motion of one tube with respect to the other; this gives the measurement stability. Their velocity limitation is recommended mainly for viscous fluids that would produce too large of a pressure drop.

Woiton at E & H said it would cost about $1 million to develop a meter at 5000 psi and 980 F. The 1000/1 turndown refers to the electronics capability. They have a meter now being used for CNG at 3600 psi. High-pressure changes require new calibration for a meter. The high-pressure effect is to change the internal diameter (ID), thus the volume of the meter. Therefore, a new calibration is required. The pressure change does not affect the resonance frequency. The density influences the resonance frequency. For instance their meter resonates at 1000 Hz in air but at 700 Hz in water. The mass flow is measured by the delta time in the phase shift from inlet to outlet sensor.

According to Woiton, the mass flowrate errors at are probably due to sonic effects. They do not have much data to go on for gas, but in liquid a high upstream velocity causes interference in the meter. He recommended a 3/8 in. meter for calibration lab and a 1/2 in. meter for the high flow facility. He thinks the pressure drop may be too high at high flowrates to install two meters in series. They want to work with WSTF to get data. They will send us a meter to test but I think they need a purchase order and then for us to either return the meter or pay for it if we are satisfied.

**Schlumberger-Neptune; Chandler, AZ; Marty Brickner**
Schlumberger makes an omega shape for gas, but they cannot guarantee published accuracy for gas. They are quoting liquid accuracy. They are discontinuing their straight pipe version, which was used only for liquids.

**Bailey-Fischer & Porter;**
We have been unable to get the technical people here to talk to us to date (6.30/95 to 8/3/95).

**The Direct Measurement Co. (DMC) in Longmont, CO; Dave Hahn**
Within the last year, the Direct Measurement Corporation (DMC) has marketed a "radial mode meter" specifically for gaseous flow. The flow sensor is a single straight tube as opposed to the bent tubes found in most Coriolis flowmeters. The vibration is in the radial mode as opposed to the bending mode or torsional mode. Also, this arrangement can achieve higher frequencies (5000 Hz) than the bending mode. They claim 0.5% accuracy of the rate plus 0.025% at the upper range limit. Meters are available for 0 to 60,000 or 0 to 240,000 lbs/hr.

Dave Hahn discussed obtaining their 1-in. meter to test in our Calibration Lab. He said the problem is freeing up a meter. He expressed some concern about publicizing the results particularly at certain flowrates or in liquid. I faxed three proposed test matrices for his inspection. One was for Brooks Prover, another for Cox Sonic Nozzles, and the third was for liquid calibrations (7/5/95). He said they intend to test at SwRI when SwRI finishes with another customer. I mentioned we may cost share to get data. He seemed agreeable (7/8/95).

Don Cage it would take 10 weeks to deliver a 1-in. meter. I have a feeling it will be longer.

Hahn said their prototype 4000 psi meter is chromoly. There may be a provision for a one-time overpressure in the code B31.3 so that we could place it upstream of the FCV in Hydrogen flow facility. He has only investigated density and mass flow as opposed to effects of other variables and parameters. Angular velocity is function of frequency and geometry only. In the Coriolis force equation ($F_{cor}=2m\omega xV$), "m" is point mass, not mass flow. Therefore the "m" is unknown.

**Foxboro Co. (Foxboro, MA); Carl Annromo**

Foxboro Co. stated accuracy for their I/A series mass flowmeters is 0.2% over the top 90% of the entire range but only for liquids.

Carl Annromo has Coriolis experience testing a DMC meter at CEESI. He said Coriolis meters are just not made for gases because electronics are tuned for liquid flow ranges. We will be lucky to get 1% accuracy for gas flow in the DMC meter. Foxboro and other companies besides DMC only make them for liquids.

Jim Vignos (R&D at Foxboro: 508/549-2065) recommends Vortex meters no. 83F or 83D. The F-series is purely analog 4-20 mA output or pulse ouput; The D-series is a digital 4-20 mA or a total output, not flowrate. They come in flange or wafer. Specs are 1% in gas but 0.5% accuracy can be achieved. They just cannot calibrate that accurately. Summit Controls in Lubbock sent literature (Sheila 806/792-2072) (7/28/95).

Tables 4 and 5 summarize details regarding potential Coriolis flowmeter vendors.

TABLE 4.-CORIOLIS MASS FLOW METER COMPARISON (8/2/95)

| **Manufacturer and Model -->** | **DMC Radial Mode CMF 303/535-4864 Dave Hahn** | **E & Hauser Promass M or Promass F 800/428-4344 Greg Harker MarcelWoiton** | **Krohne America Corimass 713/464-5454 Herb Wilson** | **Fischer & Porter Tru-mass 800/326-1786 Peter Belevich** | **Micromotion (Formerly Exac Corp) Model D 100 408/365-3300** |
|---|---|---|---|---|---|
| **Construction material** | 316 SS | Ti Gr.6 or 904L SS | | 316L | 316L SS or Hastelloy |
| **Gas** | yes | limited testing | no | ? | ? |
| **Liquid** | not tested | yes | yes | yes | yes |
| **Nominal size** | 1 or 2" | 3/8, 1/2, 1, 1.5, 2" | | 1/8 - 1.5" | 1" and other sizes available |
| **No. of tubes and diameter** | 1 straight @1" 1 straight @2" | Straight split into 2 | 1 straight or z-tube torsional vibration | 1 Helix tube | Dual U- tubes |
| **Accuracy (%)** | 0.5% +/- 0.025% of hi range in gas | 0.2% +/- .005% of full scale in liquid | 0.2% | .25% | 0.5% |
| **Rangeability** | 60:1 | 1000:1 | | | |
| **Cost ($)** | 7K | 7K | 5K | | |
| **Flow rate range (lb/s)** | 0-0.3 or 0- 17 0-1.1 or 0- 67 | 0-1.23 (3/8") 0-42.8 (2") | .003 - 60 | .083 to 20.5 | |
| **Fluid Temp (F)** | -238 to 302 | -58 to 302 (Ti) -58 to 392(SS ) | | -40 - 400 | |
| **Pressure range (psig)** | 1440 std. 4000 prototype | 580 (1450 opt.) 360 (580 opt.) | | 1450 - 1700 | |
| **Comments** | 10 week min. delivery. Designed for gas. | Some units available in 3 days | | | WSTF HFF used one:no success. IGT tests in CNG showed instab. at high veloc. |

TABLE 5.-CORIOLIS MASS FLOW METER COMPARISON (CONT.) (8/2/95)

| Manufacturer and Model --> | Honeywell IA&C Phoenix 602-789-4040 Dick Verville | Foxboro Co. 508/549-6387 Carl Annromo 508/549-2065 Jim Vignos | Hersey Measurement Co. 803/574-8960 Strain Gage Mass Flowmeter (from KSC FAX) | ABB K-Flow "B-Tubes" 800/82k-flow | Schlumberger M-dot 2 tube 800/833-3357 Greg Nortz (engineering) |
|---|---|---|---|---|---|
| Construction material | | | | 316L SS | 316L SS and others |
| Gas | | no | yes | yes | yes |
| Liquid | | yes | | | yes |
| Nominal size | | | | 1/4 - 2" | 1/8 to 8" |
| No. of tubes and diameter | Straight-split dual tubes | Inverted U-tube | | B tubes 1 @ .078" to 2 @ 1.084" | Dual omega |
| Accuracy (%) | | | | 0.2% | 0.15% M-dot |
| Rangeability | | | | | 100:1 & 20:1 |
| Cost ($) | | | | | |
| Flow rate range (lb/s) | | | 400 SCFM - 5600 SCFM | .03 to 42 | .003 to 250 |
| Fluid Temp (F) | | | | -140 to 356 | -50 to 400 |
| Pressure range (psig) | | | 3000 - 5600 | 1000 - 1800 | 290 - 3600 |
| Comments | | Recommends Vortex meter for H2, N2. Mod. 83-F or Mod. 83-D Believe accurate to 0.5% | Apparently considered for use on FCVs by Rockwell FAX from KSC | WSTF cal lab tested K-20 by Gabel did not meet specs except for liq. at high flows | Accuracy is for liq. only |

## SUMMARY AND RECOMMENDATIONS

Table 1 shows that only thermal dispersion and Coriolis meters measure mass directly, and that using the thermal dispersion meter would be a step backwords in accuracy. Possible alternative meters for this project are turbine or vortex shedding meters, which measure volume flowrate. To obtain mass flowrate, the pressure and temperatures are required, which leads to additional error.

Based on the information collected during this Summer Faculty Fellowship, the following action is recommended to the project leaders:

#1. Obtain a 1-in. Coriolis Meter from DMC and calibrate it in CNG at SwRI using their high-pressure gravimetric primary calibration system. A test matrix should be developed to cover the appropriate range of parameters as described in the next section on "Test Matrices." The tests will identify the limitations of the meter within the chosen conditions in CNG.

#2. Test the same DMC meter against the EG&G liquid system and the Brooks Bell Prover. This will identify limitations as a liquid flowmeter, limitations in the very low range of the meter using $GN_2$.
#3. Obtain an Endress & Hauser Coriolis meter or Foxboro vortex shedding meter. Install it in series with the DMC meter in the Flow Calibration laboratory's $GN_2$ system and compare the readings. Another test matrix should be developed to cover the appropriate range of parameters as described in the next section on "Test Matrices." The purpose is to establish confidence in the Coriolis meter technology for gaseous flow.
#4. Based on the tests, WSTF could:

(a) cost share and work with the appropriate manufacturer to design a meter appropriate for the conditions of $GH_2$ in the WSTF high flow facility during the FCV tests, or

(b) install the appropriate meter in the hydrogen flow facility and calibrate it against the sonic flow nozzles to locate limitations and establish confidence as a calibration device for the FCV's.

**Test Matrices**

Experience with CMF's for measuring gaseous flowrates has revealed errors not found in liquid measurements. However, within certain limitations, some tests such as the CEESI testing of the DMC meter in air show uncertainties of less than 0.25%. The recommended approach here is to uncover the sources of error and the candidate meter limitations so that it is designed, sized, and used appropriately. Velocity, pressure, Mach number, and Reynolds number as well as flowrate are suspected limiting variables.

An example of the test matrix for pure methane is shown in the Appendix. The idea is to identify the $GH_2$ conditions, as shown in the first section of the table, used in the FCV tests. The following sections in the table will correlate relevant parameters for CNG, that will be used at the SwRI, or $GN_2$, that will be used at the WSTF Flow Calibration laboratory. The values in the table were computed based on ideal gas properties of hydrogen and methane. More accurate test matrices need to be developed based on real gas properties of the CNG mixture used at SwRI as the project progresses.

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# APPENDIX

## TABLE A1.-SAMPLE TEST MATRIX BASED ON PURE METHANE

| Flowrate (lb/s) | Pressure (est. psia) | Temp. est. F | Molar mass | Viscosity (lb-s/sqft) | Density (lb/cuft) | Meter ID (in) | Flow (sqin) | Velocity (ft/s) | Sonic velocity | Reynolds no. | Mach no. | Vdot acfh |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1"-DMC-HYDROGEN FACILITY FCV TEST RANGE** | | | | | | | | | | | | |
| 0.21 | 93 | 102 | 2.016 | 2.20E-06 | 0.031262 | 1 | 0.78539 | 1232 | 4410 | 1.75E+09 | 0.28 | 24182 |
| 0.40 | 176 | 102 | 2.016 | 2.20E-06 | 0.058778 | 1 | 0.78539 | 1248 | 4410 | 3.33E+09 | 0.28 | 24499 |
| 0.60 | 262 | 102 | 2.016 | 2.20E-06 | 0.087743 | 1 | 0.78539 | 1254 | 4410 | 5.00E+09 | 0.28 | 24617 |
| 0.80 | 349 | 102 | 2.016 | 2.20E-06 | 0.116707 | 1 | 0.78539 | 1257 | 4410 | 6.67E+09 | 0.29 | 24677 |
| 1.08 | 470 | 102 | 2.016 | 2.20E-06 | 0.157258 | 1 | 0.78539 | 1259 | 4410 | 9.00E+09 | 0.29 | 24724 |
| 1.30 | 565 | 102 | 2.016 | 2.20E-06 | 0.189119 | 1 | 0.78539 | 1260 | 4410 | 1.08E+10 | 0.29 | 24746 |
| **DMC-METHANE TEST MATRIX 1-MASSFLOW & REYNOLDS NO. EQUIVALENCE** | | | | | | | | | | | | |
| 0.21 | 200 | 102 | 16.04 | 2.60E-06 | 0.532296 | 1 | 0.78539 | 72 | 1563 | 1.48E+09 | 0.05 | 1420 |
| 0.40 | 200 | 102 | 16.04 | 2.60E-06 | 0.532296 | 1 | 0.78539 | 138 | 1563 | 2.82E+09 | 0.09 | 2705 |
| 0.60 | 262 | 102 | 16.04 | 2.60E-06 | 0.698117 | 1 | 0.78539 | 158 | 1563 | 4.23E+09 | 0.10 | 3094 |
| 0.80 | 349 | 102 | 16.04 | 2.60E-06 | 0.928569 | 1 | 0.78539 | 158 | 1563 | 5.64E+09 | 0.10 | 3102 |
| 1.08 | 470 | 102 | 16.04 | 2.60E-06 | 1.251202 | 1 | 0.78539 | 158 | 1563 | 7.62E+09 | 0.10 | 3107 |
| 1.30 | 565 | 102 | 16.04 | 2.60E-06 | 1.504700 | 1 | 0.78539 | 158 | 1563 | 9.17E+09 | 0.10 | 3110 |
| **DMC-METHANE TEST MATRIX 2-VELOCITY EQUIVALENCE** | | | | | | | | | | | | |
| 3.58 | 200 | 102 | 16.04 | 2.60E-06 | 0.532296 | 1 | 0.78539 | 1232 | 1563 | 2.52E+10 | 0.79 | 24190 |
| 4.77 | 262 | 102 | 16.04 | 2.60E-06 | 0.697308 | 1 | 0.78539 | 1254 | 1563 | 3.36E+10 | 0.80 | 24622 |
| 6.37 | 349 | 102 | 16.04 | 2.60E-06 | 0.928856 | 1 | 0.78539 | 1257 | 1563 | 4.49E+10 | 0.80 | 24681 |
| 8.59 | 470 | 102 | 16.04 | 2.60E-06 | 1.250896 | 1 | 0.78539 | 1259 | 1563 | 6.06E+10 | 0.81 | 24720 |
| 10.33 | 565 | 102 | 16.04 | 2.60E-06 | 1.503736 | 1 | 0.78539 | 1260 | 1563 | 7.29E+10 | 0.81 | 24740 |
| **DMC-METHANE TEST MATRIX 3-MACH NO. EQUIVALENCE** | | | | | | | | | | | | |
| 0.91 | 200 | 102 | 16.04 | 2.60E-06 | 0.532296 | 1 | 0.78539 | 313 | 1563 | 6.40E+09 | 0.20 | 6139 |
| 1.13 | 200 | 102 | 16.04 | 2.60E-06 | 0.532296 | 1 | 0.78539 | 391 | 1563 | 8.00E+09 | 0.25 | 7674 |
| 1.66 | 262 | 102 | 16.04 | 2.60E-06 | 0.697308 | 1 | 0.78539 | 438 | 1563 | 1.17E+10 | 0.28 | 8595 |
| 2.38 | 349 | 102 | 16.04 | 2.60E-06 | 0.928856 | 1 | 0.78539 | 469 | 1563 | 1.68E+10 | 0.30 | 9209 |
| 5.33 | 470 | 102 | 16.04 | 2.60E-06 | 1.250896 | 1 | 0.78539 | 782 | 1563 | 3.76E+10 | 0.50 | 15348 |
| 8.98 | 565 | 102 | 16.04 | 2.60E-06 | 1.503736 | 1 | 0.78539 | 1094 | 1563 | 6.33E+10 | 0.70 | 21487 |