Application of a Coriolis Effect Mass Flow Meter in Obtaining Direct Measurement

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Abstract

A non-intrusive flow meter which directly measures mass has been commercially available for seven years. This meter, sometimes known as a Coriolis or gyroscopic flow meter, measures the force imparted to a vibrating tube by the mass of a fluid as it passes through the tube. This allows the measurement of mass flow without compensation for fluid properties. This paper will present the operating principles of this device and its applicability to the measurement of carbon dioxide, with methods and techniques for mass calibration.

Introduction

Mass, time, and length are the fundamental physical standards of measurement. Transfer of product in mass units is desirable because the accuracy of the amount transferred in then not dependent on the temperature, viscosity, or density of the product, or on line pressure or velocity. Since the beginning of flow measurement, volumetric meters have been used because a mass meter was not available. Some volumetric meters measure volume directly, as in a positive displacement meter, while others infer volume by measuring the velocity through a known cross section. Examples of this latter type would be turbine, magnetic, ultrasonic, and vortex shedding flow meters. Other inferred volume meters would include orifice plates and pitot tubes.

Numerous attempts have been made over the years to provide a means of mass measurement. Volumetric meters have been combined with a variety of methods for determining density to arrive at a calculated mass flow rate. This technique is limited in accuracy by the combination of the elements involved in the system. Thermal mass meters are limited by their ability to measure only gases with a constant heat transfer coefficient and have limited application. Intermittent weigh scales have been used to batch material and obtain the needed mass flow data, but this type of system is inefficient in most applications.

In 1978, a mass flow meter was introduced originally as a replacement for static weighing systems in batch processes. Application of this technology became more widespread than was originally envisioned and the meter was installed in the food, petrochemical, asphalt, pharmaceutical, photochemical, as well as oil and gas production industries.

Theory of Operation

Mass Flow Meter

The meter consists of a full line size sensor with a separate transmitter. As the flow enters the sensor, it is split into two parallel streams (see Figure 1). At the bend of the tubes a magnet and coil assembly drive the tubes at their resonant frequency as in a tuning fork. A mathematical description of the effects on this vibration by fluid flow through the tube can be derived using the following three well known formulae.

1) $\Delta d = V \Delta t$
2) $F = Ma$
3) $V_t = \omega d$

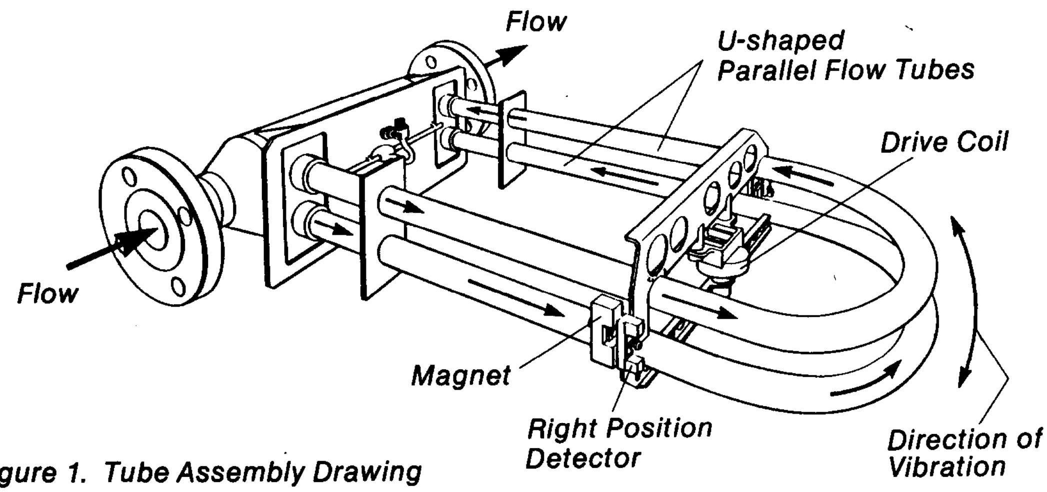

Figure 1. Tube Assembly Drawing

In the tube, a particle of mass is moving at a velocity, V, over a period of time, t, to change its distance from the tube vibration node by d. When the tube is vibrated, the particle has a vertical velocity, V_t, imparted to it that is equal to the angular velocity, ω, times the distance of the particle from the vibration node, d. Solving these equations, we find:

$$V_t = \omega V \Delta t$$

$$\text{or, } \frac{\Delta V_t}{\Delta t} = \omega V = a = \frac{F}{M}$$

Solving this equation for the force, F, we find:

$$F = \omega V M$$

This states that as the fluid passes through the tube, it exerts a force on the tube that is proportional to the mass velocity of the fluid. Looking at only one phase of the vibration cycle, the force is positive on the inlet and negative on the exit, creating a force couple which will cause the tube to twist with fluid flow (see Figure 2). The differential tube twist (i.e., up stroke versus down stroke) can be measured to determine the mass flow through the meter. The measurement is accomplished by mounting position detector coils on opposing corners of the bend on one tube with magnets in opposition on the other tube. The phase shift of

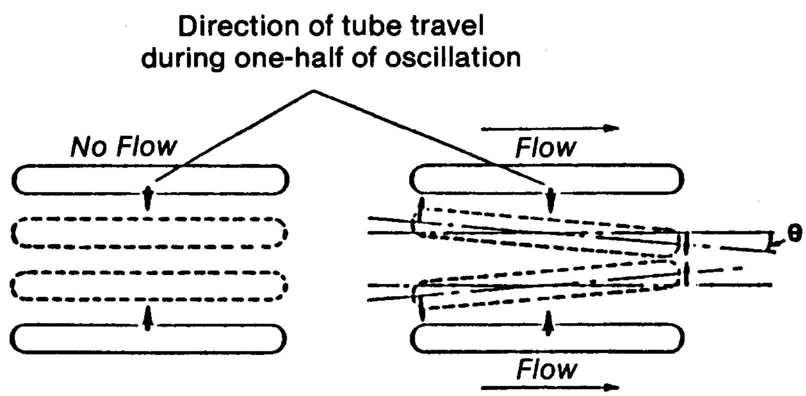

Figure 2. End view of the U-shaped tubes showing the parameters for calculating the torque and its relationship to the mass flow rate. The torque depends on the deflection angle, θ, of the pipe and its spring constant, K_s.

the signals from these detectors allows us to determine how much the tube is twisting so we may interpret the mass flow in the meter by measuring the time difference of the phase shift. As can be seen from the equations, the amount of tube twist, and the resulting phase shift, is linear with the mass flow rate. The interesting thing to note in the final equation is that the factors that cause the tube to twist do not include any of the fluid properties such as density, viscosity, temperature or pressure. A calibration of this type of meter is transferable from liquid to gas applications without adjustment.

The signal processing is accomplished in a remote transmitter device which provides linear output signals of either 4-20maDC or 15 V square wave pulse with displays available that can readout directly in pounds, MSCF, or any other mass units. The displays are also available with RS-232 interface output to communicate rate and total information to a remote receiver, such as a computer or RTU.

Density Determination

Density measurement is possible because the natural vibration frequency of the dual tube system varies with the density of the fluid in the tubes. The frequency can be measured and displayed in the form of density or specific gravity.

Performance

Direct mass flow measurement offers several advantages over conventional techniques:

1. The measurement is made independently of the density, viscosity, temperature, and pressure.

2. Sensing elements are non-intrusive so the pressure drop will be less for a given meter size because there are no in line obstructions.

3. Essentialy no moving parts.

4. No up or down stream piping required as in many meters. The measurement is not sensitive to velocity profile.

5. High turndown can be easily accomplished.

6. Strainers and, in many instances, gas eliminators are not required. Liquid carbon dioxide or other fluids with entrained gas and solids can be measured accurately in mass units without these accessory devices.

7. The flow rate accuracy is not affected by pulsating flow.

8. Fluid density information is also available through a technique unrelated to the mass flow measurement.

9. The flow rate accuracy is not affected by coating or buildup on the sensor tube walls. The flow rate in mass units will continue to be measured accurately.

Tests by manufacturer and user have shown accurate results for gases, liquids, and slurries over a density range of 0.001 to 2.50 SGU, and flow rates from 1 to 1,000,000 pounds per hour, for both Newtonian and non-Newtonian fluids. Accuracy has been shown to be ± 0.4% of rate (see Figure 3) over a 20:1 range with 0.1% repeatability. The density measurement accuracy is ± 1.0% in smaller meters and ± 0.5% in sensors one inch or larger.

The flow sensors are available in various configurations designed for specific applications with pressure ratings up to 15,000 psi. The sensor can perform over a temperature range from −400 degrees F to +400 degrees F.

Application in CO_2 Measurement for Coriolis Mass Flow Meters

Several major oil companies have serious questions regarding their ability to accurately measure carbon dioxide with conventional metering techniques. Custody transfer metering stations can cost up to $1 million and still measuring errors are producing billing discrepancies between $45,000 and $225,000. Some

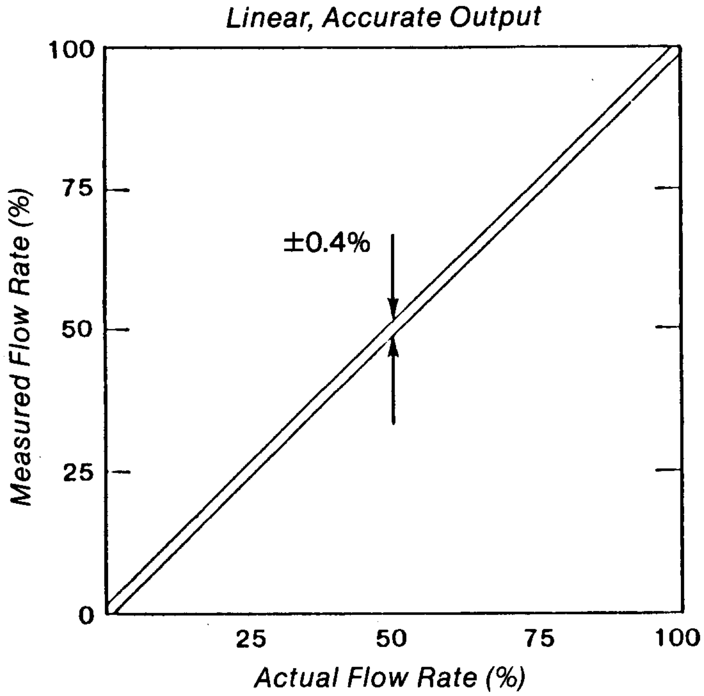

Figure 3. Accurate, Linear Output

producers have reported imbalances up to 50% between turbine meters and orifice meters. The direct mass method can offer substantial benefits for both the custody transfer and well injection applications. This technology offers a single element mass flow measurement avoiding the complexities and expense of installing and maintaining a measurement system consisting of numerous elements for determining the volume rate in combination with temperature, pressure or density and calculation of the mass rate.

The sensor element construction will allow installation in carbon dioxide flood operations that are alternated with water flood. The meter, if properly sized, can be used to measure the injection rate of both fluids.

Calibration

Mass flow meters can be calibrated by conventional methods. The meter has been calibrated using weigh time techniques by Utah Water Research Laboratory in the College of Engineering at Utah State University. The results of one calibration are shown in Table 1 and graphically displayed in Figure 4. This method is employed in an installation in North Dakota to check meter calibration on a monthly basis using a portable weigh scale. Volumetric provers may be used to verify the calibration of mass meters providing the calibration medium has an easily ascertainable density. Water is suitable for such calibrations, as the calibration is directly transferable to any other process fluid. One customer extensively tested this technique using water and a compact portable meter prover and "confirmed the performance and [that] a volumetric prover is a viable means of identifying problems and making regular provings."

Mass provers for direct calibration on gas have been constructed for test purposes and are currently being evaluated for construction to regularly prove meters used in gas service. These tests have shown the water calibration to be transferable to nitrogen gas within the accuracy limits of the weighing devices employed in the tests. The results are displayed in Figure 5. As gas prover devices are not yet commercially available, field proving can be performed for mass meters using the liquid prover techniques outlined above.

Summary

The Coriolis/gyroscopic direct mass flow meter is very well suited for carbon dioxide measurement. Industry analysts have stated that "this device represents a real advance in the measurement of process streams" and that the "performance is within the requirements for [custody transfer] metering." It is replacing a variety of conventional meter types in virtually every application, with over twentyfive thousand meters as an installed base and more being installed at an increasing rate. This technology has decided economic advantages in many applications. The cost of ownership is very low when compared to more traditional methods of obtaining mass flow data.

Control of the flood process to optimize production depends upon accurate injection rate information. Direct mass flow measurement will yield the required accuracies while avoiding some of the difficulties involved with the more complex conventional techniques.

MASS FLOWMETER STUDY
STEADY STATE WATER CALIBRATION

MICRO MOTIONS

Meter D-150 SN 35810 Water Temp. ________ Meter Dia. 1.5 Date 10-22-84

Wt. Tank	Micro Motion Meter		% Discrepancy	Comments
Wt lb	Rate lb/min	Total mass lb	Total mass	Water Temp. meter / hg therm.
811.0	254	807.2	-.42%	10.5°C
901.6	354	899.5	-.23%	10.2°C
917.8	398	915.8	-.22%	9.3°C 9.2
862.0	460	861.3	-.08%	6.5°C 6.4
867.6	786	866.5	-.13%	6.9°C
890.5	1304	887.7	-.31%	
10085	1220	10098.2	+.13%	4.8°C
10788	1525*	10785.5	-.02%	
15475	1836	15484.8	+.06%	4.5°C
15373	2133	15375.6	-.02%	4.3°C
23853	2820	23799.1	-.2%	heavy cavitation

*meter cavitating

*Table 1. Mass Flowmeter Study. Steady State Water Calibration.**

**Utah Water Research Laboratory, College of Engineering, Utah State University, Report No. 112.*

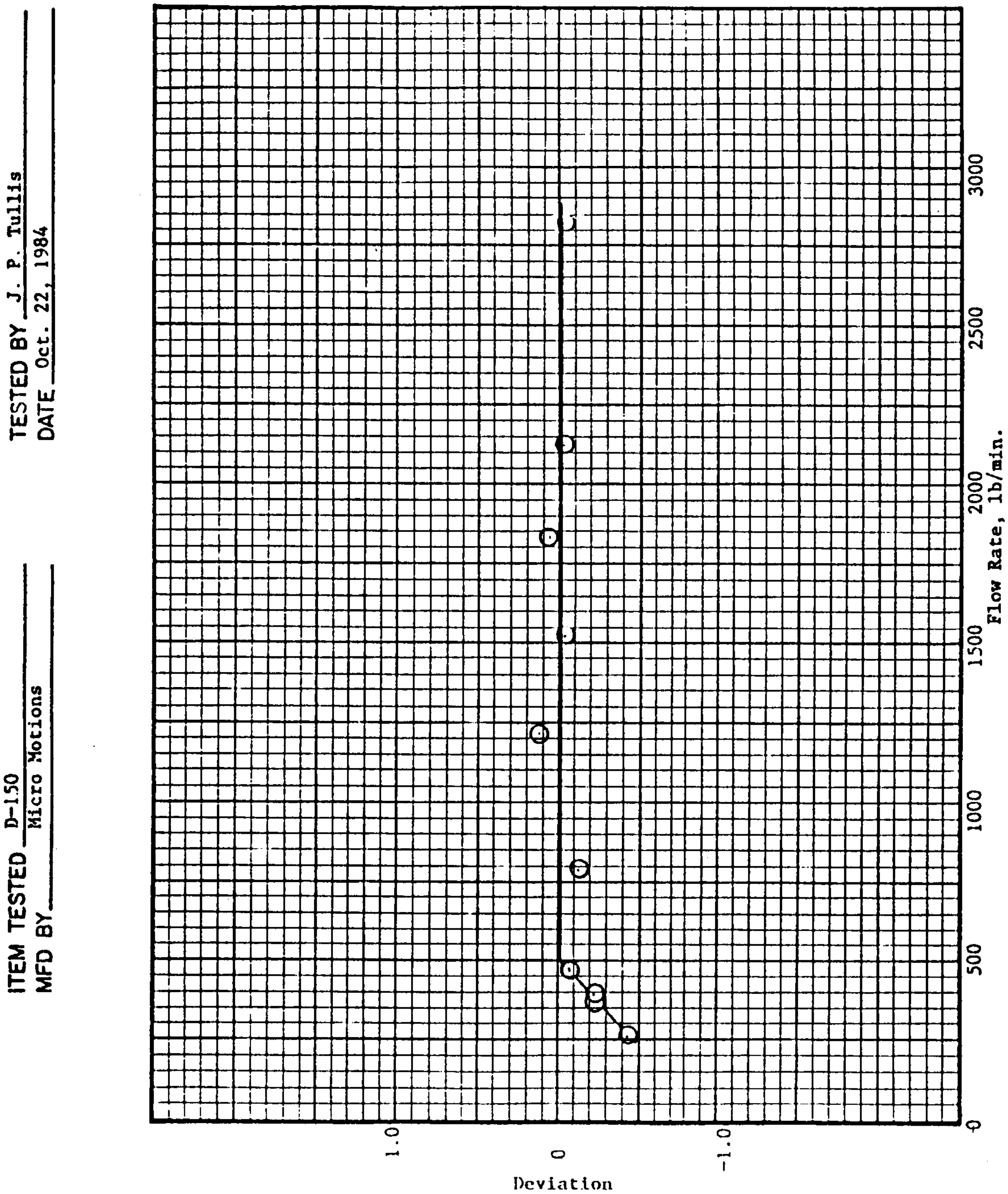

*Figure 4. Percent Deviation Versus Flow Rate.**

****Utah Water Research Laboratory, College of Engineering, Utah State University, Report No. 112.***

Test Results

The test result data points were used to plot a linear regression curve. The equation of the curve is:

$$y = mx + b$$

where m (slope) is the meter factor and b (y intercept) is the zero offset.

Water:

Rate	**Meter**	**Scale**	**Error (%)**	
10.0 lbs/minute	9.898	9.901	−0.03	m = 1.0011
10.0 lbs/minute	10.130	10.136	−0.06	b = 0.009
7.5 lbs/minute	7.661	7.666	−0.07	
7.5 lbs/minute	7.796	7.787	+0.12	
5.0 lbs/minute	5.120	5.112	+0.16	
5.0 lbs/minute	5.040	5.029	+0.22	
2.5 lbs/minute	2.511	2.509	+0.08	
2.5 lbs/minute	2.510	2.507	+0.12	

Air

Rate	**Meter**	**Scale**	**Error (%)**	
2.8 lbs/minute	2.965	2.974	−0.30	m = 1.0025
2.8 lbs/minute	2.859	2.864	−0.17	b = 0.006
2.0 lbs/minute	2.126	2.142	−0.28	
2.0 lbs/minute	2.020	2.024	−0.20	
1.5 lbs/minute	1.503	1.506	−0.20	
1.5 lbs/minute	1.520	1.521	−0.06	
1.0 lbs/minute	1.021	1.024	−0.29	
1.0 lbs/minute	1.020	1.023	−0.29	

Nitrogen Gas

Rate	**Meter**	**Scale**	**Error (%)**	
5.0 lbs/minute	5.038	5.050	−0.24	m = 1.003
4.0 lbs/minute	4.068	4.086	−0.44	b = 0.006
3.0 lbs/minute	3.026	3.034	−0.26	
2.0 lbs/minute	2.054	2.059	−0.24	
2.0 lbs/minute	2.020	2.025	−0.25	
2.0 lbs/minute	2.016	2.022	−0.29	
1.5 lbs/minute	1.509	1.514	−0.33	
1.5 lbs/minute	1.512	1.518	−0.39	
1.0 lbs/minute	1.010	1.012	−0.19	

Data collected at flow facilities of Micro Motion, Inc., Boulder, CO. on 9/30/84 on a D25 Meter.

Figure 5. Test Results