Wet Gas Performance of Coriolis Meters: Laboratory and the Field Evaluation

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Abstract
The rapid growth in unconventional gas production has brought with it increased demand for a method of measuring flow rates of both gas and liquid at the wellhead that is more cost effective and reliable than traditional methods (i.e. separator and/or compensated differential pressure), while remaining reasonably accurate. This paper describes research efforts to determine to what degree a single Coriolis meter is capable of measuring gas and liquid flow rates in wet gas processes, without compositional fluid analysis or other inputs beyond readily available process measurements. This paper will also discuss some of the potential impacts of meter design and best practices for installation and use in the field. This research builds on more than 10 years of development in Coriolis multiphase performance, although previous work has largely focused on small amounts of gas in a liquid process. Coriolis meters have the ability to measure multiple relevant variables: mass flow, density, temperature, tube damping (an indicator of phase fraction conditions), and time. By combining these variables with readily available process variables, such as density of liquid and gas, it is possible to make corrections to errors in Coriolis measurements due to multiphase process conditions and calculate the phase fraction, to apportion the overall mass flow to gas and liquid components.

1 Introduction

One of the greatest advantages of Coriolis flow meter technology is relative flexibility in specification and installation – generally no flow conditioning needed and high rangeability, and low sensitivity to secondary effects or fluid properties. Certainly, some designs offer a more robust flow measurement than others (a straight tube meter will be affected quite differently than a U-shaped meter to changes in temperature, pressure, viscosity, etc.) but all Coriolis meters, like all flow measurements, are affected by multi-phase conditions. For many years, the approach of treating all Coriolis meters as essentially equivalent representations of the technology has meant that Coriolis meters had been limited to strictly single-phase use [1], but research into the underlying physical behaviour that caused errors, such as decoupling [2] and compressibility of bubbles in a liquid [3], along with improved electronics have enabled new capabilities for Coriolis meters in liquid processes with some bubbles. This understanding of bubbly regimes and meter technology improvements have growth in the understanding and acceptance of Coriolis as a viable technology in limited, liquid-dominant multiphase conditions [4], but current literature tends to identify Coriolis technology as wholly unsuited for wet gas applications [5] [6]. More recent lab testing [7] and field experiences [8] have indicated that the technological improvements in Coriolis meters may provide better performance than indicated in existing industry guidelines and literature, and a path towards viable wet gas measurement systems with Coriolis meters.

2 Coriolis Technology Improvements

With the improved understanding of bubbly two-phase behaviour (some gas in mostly liquid flow) gained from research in the early 2000's, improvements were made to sensor designs with two-phase performance in mind. Modal separation, balance between flow tubes, vibration isolation and minimizing the natural frequency were elements in sensor design improvements.

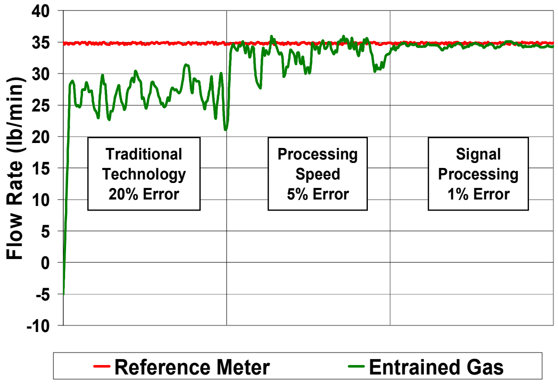


Figure 1: Improvements in bubbly two-phase due to electronics development

Faster processing speeds and improvements to signal processing (see Figure 1) and vibration control also made Coriolis technology better suited for service where liquid processes could have some gas phase contamination.

Many of the industry guidelines and best practices precede this development, or were written based on testing meters that had not been optimized for two-phase performance and therefore indicate “Coriolis meters can have an unpredictable behaviour in wet gas conditions but there is current research into their use in this area” [6], but have not yet been updated to reflect further research. The research into wet gas performance discussed in this paper shows that current Coriolis meter technology – the results of efforts in developing Coriolis meters for bubbly two-phase, have more stable and promising wet gas performance characteristics.

Diagnostics for identifying phase contamination were also further developed during this time, and although Coriolis manufacturers developed these primarily with bubbly two-phase conditions in mind, they can be quite sensitive to liquid phase contamination in gas processes [9].

3 Effects of Multiphase Conditions on Coriolis Meters

Coriolis meters are, like most other flow measurement technologies, designed to measure single-phase processes. Coriolis technology is unique in that it measures the mass flow and density of the process fluid simultaneously and independently. If there are only two phases that need to be independently measured in a process (i.e. liquid and gas) and the densities at process conditions of the two phases are known, this would be enough information to provide an overall mass flow rate along with phase fraction. However, when multiple phases are present, some of the basic assumptions made in Coriolis measurement break down. Primarily, the fluid no longer vibrates in sync with the flow tubes, resulting in measurement errors. This section focuses on the describing primary error sources in multiphase Coriolis measurement, to build the case that different Coriolis meter designs react differently enough in multiphase conditions that the technology cannot be treated uniformly across designs. These errors and their sources are only briefly discussed in this paper; additional discussion can be found in Weinstein [2]. The decoupling examples in this paper and cited references focus on liquid-continuous flow regimes. Although more study is needed in gas-continuous flow regimes, there is no indication in studies to date that suggest that decoupling is substantially different in gas-continuous processes.

3.1 Slip and Imbalance

Depending on the orientation of the meter, this error can be either positive or negative. For example, if a meter is installed tubes down, then because of gravity, more gas will be trapped on the inlet side of the meter, Figure 2. This will result in more mass on the outlet side of the meter and increased damping on the inlet side of the meter. Both of these conditions will result in mass flow error.

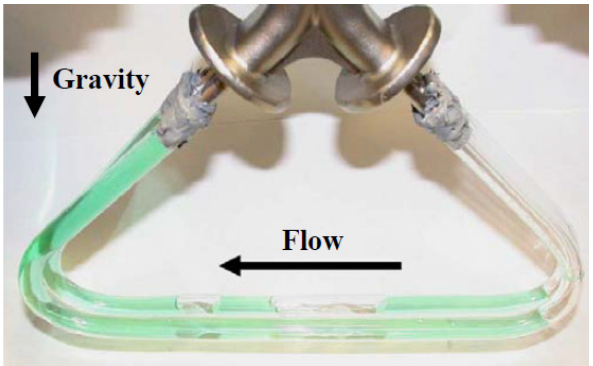


Figure 2: Asymmetric phase distribution

With high enough velocity, the turbulence will homogenize the phases and practically eliminate the effects of inlet-to-outlet imbalance, but this would effectively reduce the turn-down of the meter. Installing the meter in a vertical orientation, with flow down for wet gas applications, means that gravity and the gas velocity are working in the same direction and uniform distribution of phases will be less dependant on velocity.

3.2 Decoupling effects

During Coriolis sensor operation, if a single-phase gas or liquid moves in the transverse direction exactly with the flow tubes, the center of gravity of the fluid remains fixed in the middle of the tube. However, the presence of two phases with different densities causes a decoupling of the transverse fluid motion from the tube motion. This causes mass and density measurement errors due to changes in the location of the center of gravity of the fluid mixture inside the tube. The term "decoupling" refers to relative motion between two components of differing density in the direction of tube oscillation, which is perpendicular to the direction of bulk fluid flow, as shown in Figure 3

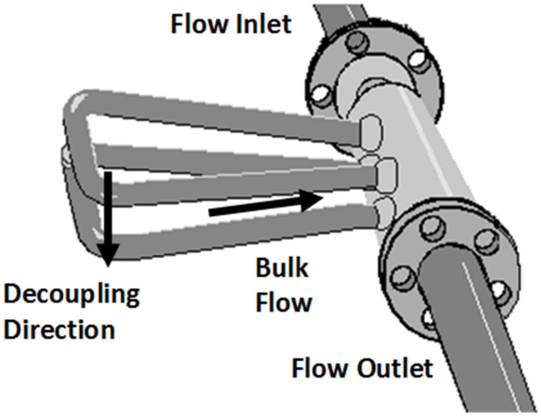


Figure 3: Direction of decoupling and bulk flow

Figure 4 shows a cross-sectional view of a single vibrating tube at two instances during a vibration cycle. At the point of maximum deflection, the bubble has moved further than the liquid, by a factor defined as the decoupling ratio: A_p/A_f. The amplitudes are defined with respect to the distance from the midpoint of tube oscillation. In the example of a sand particle, where the density of the particle is greater than that of the fluid, the particle would move less than the fluid, also imparting decoupling.

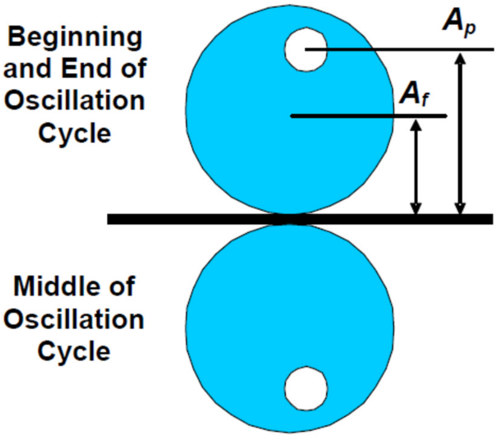


Figure 4: Decoupling ratio definition

Decoupling causes some of the liquid mass in the tubes to move so that it is undetected by the flow meter. This causes the density to read lower than the mixture density in the case of a bubbly fluid. For example, if a mixture consists of 10% volume fraction gas in a liquid of density 1000 kg/m^3, then the meter density should read 10% lower than the liquid, or 900 kg/m^3, assuming the gas density is negligible. However, due to decoupling, the meter erroneously measures perhaps 898 kg/m^3. The further the bubbles or particles decouple from the fluid on each oscillation of the tubes (i.e. greater A_p/A_f), the larger the undetected mass of fluid will be and the larger the resulting density error.

Mass flow is also affected by decoupling. Mass flow errors are the result of asymmetric damping and mass between the two sides of the meter caused by two-phase conditions.

To better understand where decoupling errors come from and how to better mitigate them, the density ratio and inverse Stokes number, as it applies to bubbles in a liquid process, is considered. It is anticipated that wet gas processes will differ somewhat, but at the time of writing, wet gas decoupling has not been studied to the degree that liquid-dominant conditions have. It is expected that the decoupling of centers of mass occur similarly but are more dependant on interactions with the pipe wall than particle size.

The inverse Stokes number and density ratio are non-dimensional numbers used in the equation that describes oscillatory motion of a spherical particle in a viscous fluid. The density ratio is the ratio of fluid and particle densities, equation 1, where ρ_f represents the fluid or liquid phase, and ρ_p represents the particle or gas phase. The density ratio indicates the importance of the inertial difference between the phases which is the driving force for decoupled motion. The inverse stokes number, equation 2, represents the viscous effects of the fluid where, ν_f is the kinematic viscosity of the fluid, ω is the frequency of the fluid oscillation or the drive frequency of the flow meter, and a^2 is the radius of the particle, liquid droplet, or gas bubble.

$$Density\ Ratio = \frac{\rho_f}{\rho_p} \qquad 1$$

$$Inverse\ Stokes\ Number, \delta = \sqrt{\frac{2\nu_f}{\omega a^2}} \qquad 2$$

Figure 5 below relates the decoupling ratio to the density ratio and inverse Stokes number.

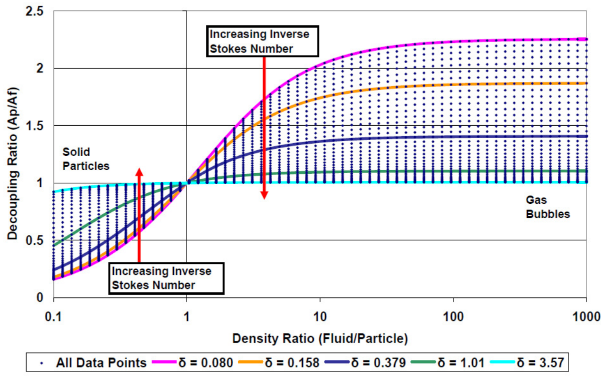


Figure 5: Decoupling Ratio vs. Density Ratio vs. Inverse Stokes number

The inverse Stokes number, *δ*, shows that it is the balance between fluid kinematic viscosity, particle size, and frequency that is important, not any one of these variables alone. By increasing inverse stokes number the decoupling ratio can be significantly reduced, resulting in smaller mass and density errors. While viscosity is often not under a user's control, meter frequency and bubble or droplet size are. Equation 2 shows that low frequency Coriolis meters are less prone to decoupling errors and should be used in applications where two-phase conditions may be expected. Equation 2 also shows that because particle size is the only variable that is squared, small changes in bubble or droplet size overwhelm changes in viscosity or frequency.

Increasing pipe pressure by adding a pump or increasing back pressure will decrease bubble size, and in liquid-continuous applications, may even force gas back into solution and return the process to single-phase. In gas-continuous processes, increasing the pressure will bring the density ratio closer to unity and increase the gas (carrying fluid) viscosity somewhat. Generally, higher pressures are beneficial to Coriolis multiphase performance.

Also, keeping pipe velocities high and using mixing devices can effectively decrease bubble or droplet size and dramatically improve measurement performance.

3.3 Velocity of sound effects

In addition to problems caused by the relative motion of bubbles, droplets, and particles, Coriolis meters experience velocity of sound effects when the sonic velocity of the measurement fluid is low or the oscillation frequency of the meter is high. Gases have lower sonic velocities than liquids, but the lowest velocities result from a mixture of the two. The addition of even a small amount of gas to a liquid results in a dramatic reduction in the velocity of sound of the mixture below that of either phase.

The oscillation of the flow tube produces sound waves that oscillate in the transverse direction at the drive frequency of the meter. When the velocity of sound of the fluid is high, as in a single-phase fluid, the first acoustic mode for transverse sound waves across the circular conduit is at a much higher frequency than the drive frequency. However, when the velocity of sound drops due to two-phase conditions, the frequency of the acoustic mode also drops. When the frequency of the acoustic mode and the drive mode are close, meter errors result due to the off-resonance excitation of the acoustic mode by the drive mode. For low frequency meters and typical process pressures, velocity of sound effects are negligible with respect to the specified accuracy of the meter. However, for high frequency Coriolis meters, the velocity of sound can be low enough to cause significant measurement errors due to interaction between the drive and fluid vibration modes.

A more physical explanation of velocity of sound effects in Coriolis meters is that the fluid in the tube is compressed against the outside wall of the tube on each oscillation when the compressibility of the mixture is high enough to allow for such motion. In this way, velocity of sound effects are similar to decoupling effects in that the actual error is caused by movement of the location of the center of gravity. The difference is that velocity of sound effects result in heavier fluid pushed to the outside walls of the tube while decoupling results in heavier fluid pushed to the inside walls of the tube. For this reason, velocity of sound errors are positive and decoupling errors are negative. This is confirmed by a recent model by Hemp & Kutin [1], which quantifies density and mass flow errors due to velocity of sound effects. The closed form expressions are given as percentage increases from true mixture values, where d is the inner diameter of the Coriolis meter flow tube, ω is the angular oscillation frequency, and c_m is the mixture velocity of sound.

$$\rho_{vos,err} = \frac{1}{4}\left(\frac{\omega d}{2c_m}\right)^2 * 100 \qquad 3$$

$$\dot{m}_{vos,err} = \frac{1}{2}\left(\frac{\omega d}{2c_m}\right)^2 * 100 \qquad 4$$

4 Significance of Meter Design

There are several factors that contribute to the errors in Coriolis measurement caused by multiphase conditions outlined above that are affected by the design of the meter. Because the meter manufacturers have designs that are so varied, even though the underlying measurement concept is the same, it is not practical to treat them all as equal in multiphase applications, as one would differential pressure measurement elements of a similar type. Sensor frequency has an effect on the magnitude of the decoupling effect, as shown in equation 2. Lower frequency is preferable and typically, that is achieved with a large “U” shape. This can have drawbacks in avoiding imbalance at low velocities, if installed in horizontal orientation, however.

Mode separation can be controlled to a certain degree by varying the flow tube diameter and / or wall thickness as well as with material properties affecting tube stiffness. Together with the structural design of the meter, the digital signal processing will play a key role in reducing the flow and density errors resulting from wet gas applications. Electronics that have memory, processing and flexibility to run correction algorithms or house more complex ‘calibrations’ for multiphase are also required for stable and reasonably accurate performance. In addition to having the hardware needed to run algorithms to deal with different flow regimes or process conditions, those algorithms must obviously also be developed.

5 Remediation for Different Flow Regimes

When addressing multiphase conditions in a Coriolis meter, it can be helpful to divide the problem into two parts: intermittent, irregular phase contaminations, including slugging flow regimes; and continuous, dispersed phase contamination. This approach is practical because in many applications, the distribution of phase contamination is known and knowing that reduces the complexity of the solution required. In the case of processes that are predominantly single phase (all liquid or all gas – for this paper, consider two-phase to be gas-liquid mix) with intermittent two-phase conditions, such as separators with dump valves or plunger lift wells, using an approach that categorizes data as single phase or two-phase in real time and treats that data as such is an effective way to greatly improve Coriolis volume and liquid measurement performance [10].

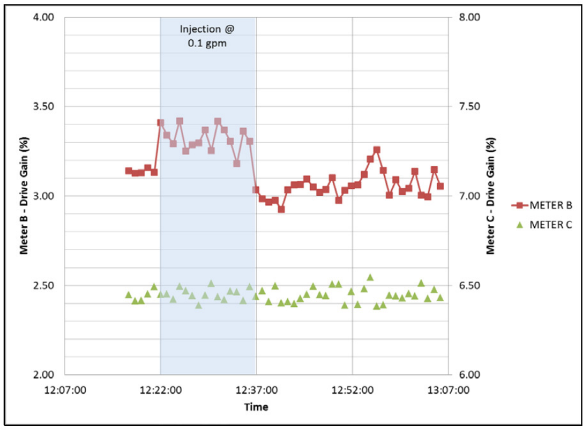
5.1Intermittent Two-Phase Detection and Remediation

Performance of Coriolis meters in two-phase flow is not necessarily limited by the improvements discussed in section 2. Correction techniques can be applied to improve their performance in limited two-phase applications. The first step in remediating gas measurement errors in two-phase conditions is identifying when single-phase and two-phase conditions occur within the sensor. With the sensitivity to detection of two-phase conditions, the correction algorithm can use real-time data validation to employ different methods for single-phase conditions, intermittent two-phase (slugging), and continuous two-phase. Additionally, diagnostic and trending information can be derived from the meter to help customers better understand their application.

5.2 Improving gas measurement

Similar techniques to those used to detect entrained gas in a liquid process can be used to detect liquid mist in a gas process, with certain Coriolis sensor designs. Testing at Southwest Research Institute [9] shows drive gain in Coriolis meters with a large “U” shaped geometry are very sensitive to even small amounts of liquid.

Figure 6 shows that with as little as 0.013% liquid by volume, drive gain is a clear and immediate indicator in one Coriolis meter but does not register with the other.



Drive Gain Results for Meter B at 100 acfm and 0.1 gpm

Figure 6: Drive gain response, 0.013% liquid

Once liquid is detected, the algorithm described below can be used to remediate gas flow rate measurement. Equation 5 showed that it is very easy for the mass flow rate of liquid to overshadow the mass flow rate of gas:

Equation 5

$$\dot{M}_{mixture} = \dot{M}_{liquid} + \dot{M}_{gas}$$

$$\dot{M}_{gas} \ll \dot{M}_{liquid}$$

$$\dot{M}_{mixture} \sim \dot{M}_{liquid}$$

In a gas process, this is detrimental to the measurement, since the desired output is often gas volume at standard pressure and temperature, which is simply:

Equation 6

$$\dot{\boldsymbol{V}}_s = \dot{\boldsymbol{m}} \cdot \boldsymbol{\rho}_s$$

where $\dot{V}_s$ is the volume rate flow at standard condition, $\dot{m}$ is the mass flow rate at line conditions, and ρ_s is the density of the gas at standard conditions. The standard density of the gas is constant, provided the gas composition doesn’t change, so mass flow rate is the critical measurement for gas processes.

To avoid the large errors in gas mass flow measurement that would be incurred by measuring liquid as well (often called “overread”), when two-phase conditions are detected by increases in drive gain, the mass flow rate from a few seconds before the two-phase conditions can be substituted for the bulk measurement, until the process returns to single phase gas. If the mass flow rate of the dry gas before and after the wet gas period is different, then a small adjustment can be made (see G in Figure 7) to the flow rate, so that the total will reflect a linear change in dry gas flow rate during the two-phase period, rather than a step change as the process transitions back to single-phase gas.

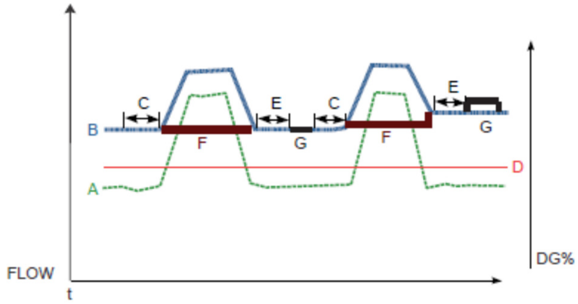


Figure 7: Gas remediation method for intermittent two-phase flow

In Figure 7, the letters represent the following:

A – Drive Gain
B – Bulk Mass Flow Rate
C – Pre-Mist averaging of flow rate
D – Drive Gain Threshold
E – Post-Mist Delay
F – Held Mass Flow Rate
G – Post-Mist Adjustment

For the algorithm to work properly, the process should have a flow regime that has periods of single-phase gas and periods of two-phase or wet gas conditions. These conditions were created in the 4-inch wet gas test facility at Colorado Experiment Engineering Station, Inc (CEESI) [11] by installing a liquid injection point directly upstream of the meter, so that the flow regime could quickly transition from dry to wet and back to dry. Test points consisted of a dry period, a two-phase test point and followed by another dry period. Data points represent a 2-minute average of the two-phase test point. Gas flow rate error falls largely between 0% and -2%, regardless of pressure. This contrasts quite starkly with the gas ‘overread’ if the standard mass flow output is used. Since the algorithm detects and ignores liquid in the process, much of the ‘overread’ can be avoided.

5.3 Continuous Two-Phase Detection and Remediation

When the process condition consists of continuous wet gas conditions, a new challenge consists on the ability of the Coriolis meter to quantify the liquid to gas ratio first, and then to correct the overall mass flow error without periods of dry gas conditions to allow adjustments. The latest advances in Coriolis technology allows for more repeatable and reproducible behavior on wet gas conditions which in turn allows for the characterization of ‘overreading’ which can be corrected with empirical methods, with similar success as current dP meters, but with the benefit of having additional variables or sensor responses available from a Coriolis meter to correlate liquid loading.

Some Coriolis users are already successfully using this technique in the field. Figure 8 shows condensate/gas ratio (CGR) versus measured density from 5 meters with large “U” shape, in a field in Qatar [8]. The liquid/gas ratio can be calculated directly from the density measurement, using input densities of gas and liquid phases. Errors in density measurement from decoupling will cause a negative bias, but since it is expected for there to be well test data when a well is brought on line, the density measurement from the Coriolis meter can be correlated to the liquid/gas ratio from well testing to give a repeatable and reasonably accurate indication of liquid flow rate and a way to correct the bulk rate to reflect the dry gas flow rate.

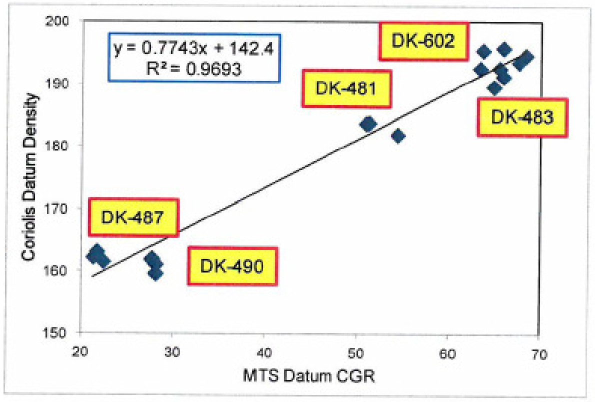


Figure 8: CGR vs Measured Density

With the understanding of liquid content gained by using the density measurement and input from a pressure measurement, there are two methods to obtain a separate liquid and gas output from a single Coriolis meter, which can operate simultaneously. Having an indication of the wetness of the process also provides a basis for flow measurement correction that responds to changing conditions in real time, without the need for additional sampling.

There is an ongoing research program by the authors to develop a more robust model based on the wet gas physics that would allow for digital processing of the sensor behavior in a similar fashion as previous work on decoupling for small amounts of gas in liquid phase [2].

Using this previous knowledge on entrained gas model it can be inferred that decoupling in wet gas conditions causes some of the liquid or gas mass in the tubes to move so that it is undetected by the flow meter. The further the particles decouple from the carrier fluid on each oscillation of the tubes (i.e. greater particle amplitude to fluid amplitude ratio), the larger the undetected mass of fluid will be and the larger the resulting flow error. The wet gas physical model will build from and complement the current entrained gas theory.

6. A New Method

Recent advances in wet gas metering using Coriolis meters have resulted in better prediction of liquid loading and flow measurement deviation from dry gas. A new method that relies on multivariable analysis correlations can produce wet gas measurements in the order of +/- 5% flow overreading with respect to dry gas. This improved accuracy is significant considering the unremediated overreading can be as high as 400% with respect to dry gas.

The new method was tested using an Emerson Micro Motion CMF300 meter at CEESI [11] with natural gas at 25 and 50 bar (absolute pressure) and Exxol D80 at different oil loadings. The meter was initially tested on dry gas conditions producing the mass flow error curve shown in Figure 9.

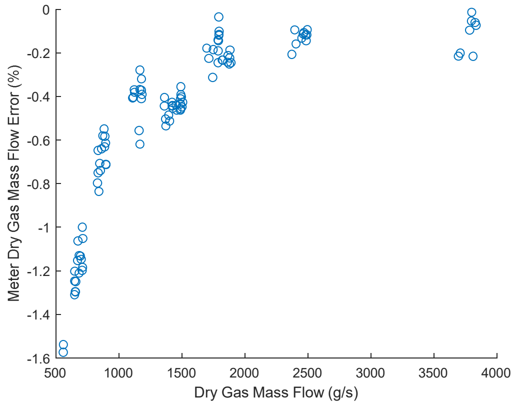


Figure 9: Dry gas performance of CMF300 at 25 and 50 bar

As shown in Figure 10, there is a linear correlation between dry gas overreading as a function of the Lockhart-Martinelli parameter. This dry gas overreading corresponds to the unremediated or total mass flow rate measured by a CMF300 on wet gas conditions at 25 and 50 bar. The new method can then correct the meter's mass flow and predict dry gas mass flow within 5% error.

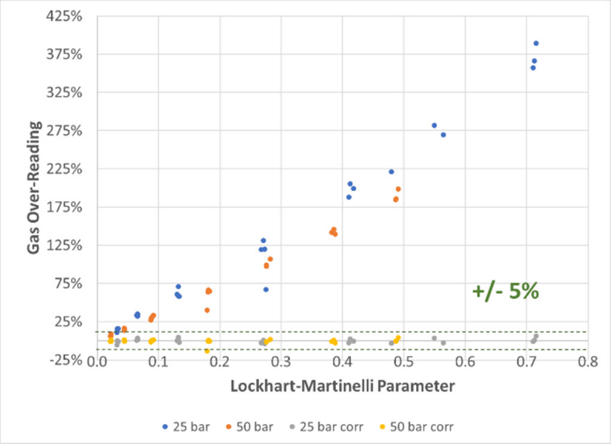


Figure 10: Unremediated and corrected dry gas overreading from CMF300 mass flow measurement on wet gas conditions

This is a significant achievement considering the dry gas performance of the meter itself is within 1.6% error and the corrected performance is linear on a wide range of wet gas conditions including multi-phase region where the Lockhart-Martinelli parameter is greater than 0.3.

The correction factors from this new method are obtained using direct measurements from the Coriolis meter and it doesn't rely on the Lockhart-Martinelli parameter. This allows for direct wet gas measurements using a single Coriolis meter without the need for periodic measurements of liquid loading as other instruments rely on for corrections. Additionally, the total mass flow rate output can be corrected for decoupling errors and separated into individual gas and liquid flow rate outputs.

Figure 11 and Figure 12 show additional wet gas data on a CMF100 from a new research pilot unit at one of Micro Motion's experimental facilities. The wet gas research program has provided valuable information on the physics behind the wet gas conditions and the behaviour of Coriolis meters with the ultimate goal of developing digital processing technique that enables higher accuracy on wet gas conditions based on physical models.

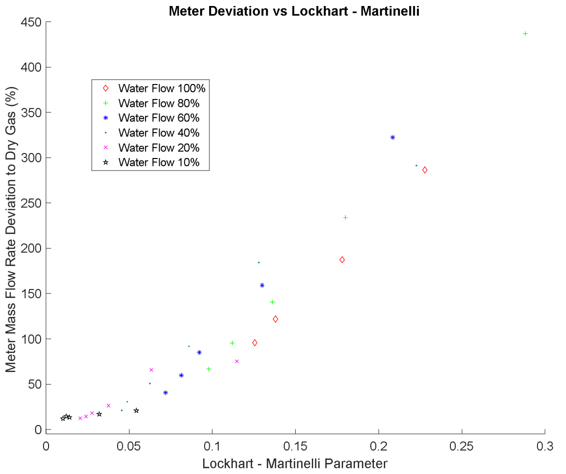


Figure 11: CMF100 overreading as a function of Lockhart-Martinelli parameter and water flow rate

Figure 11 shows the meter mass flow deviation (or overreading) at different Lockhart-Martinelli values within the wet gas region (lower than 0.3). As the percent of liquid flow varied there seems to be a linear response with Lockhart-Martinelli parameter. The water flow percent indicates the amount of liquid flowrate that was kept constant for various gas flow rates, and the percentage indicates the different liquid flow points on the test matrix.

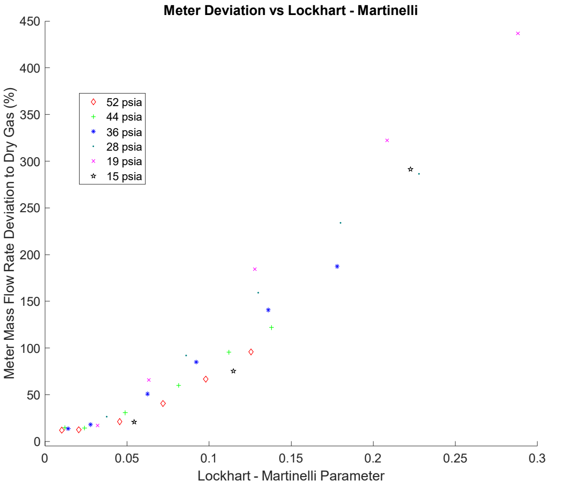


Figure 12: CMF100 overreading as a function of Lockhart-Martinelli parameter and pressure

Figure 12 shows the meter response at different line pressures, this data was obtained from the same test matrix as Figure 11 and it shows a dependency to pressure and Lockhart-Martinelli parameter.

Additional to the data presented, the wet gas research station at Micro Motion allows for inexpensive testing with the flexibility for testing different meter designs and it includes flow visualization ports that facilitates the physical model development.

7. Conclusions

The perception that all Coriolis meters are unpredictable in wet gas conditions should be updated with further research, using meters that have been designed to handle multiphase conditions. There are several methods that could be used to drive further improvements in performance. Each approach has application spaces that they can work in. As the methods are developed, it is critical to understand the limitations and appropriate operating envelope.

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