# Wet Gas Performance of Coriolis Meters: Laboratory and the Field Evaluation of a New Method

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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 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 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, this meant that Coriolis meters had been limited to strictly single-phase use, but research into the underlying physical behaviour that caused errors, such as decoupling [1] and compressibility of bubbles in a liquid [2], 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 [3], but current literature tends to identify Coriolis technology as wholly unsuited for wet gas applications [4] [5]. More recent lab testing [6] and field experiences [7] 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.

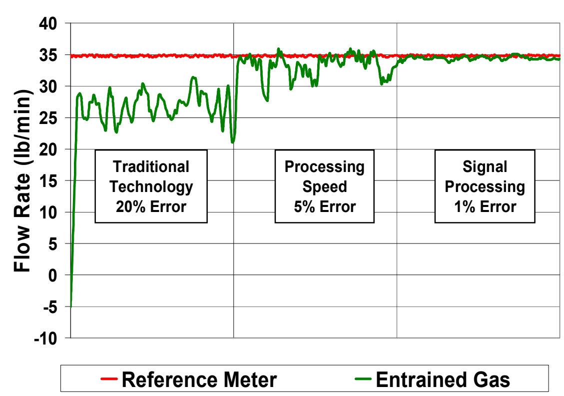



**Figure 1:** Improvements in bubbly two-phase due to electronics development

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” [5], 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 [8].

## 3. Common Technology in the Field

*3.1 Periodic Separator Testing*

The most common method by far of monitoring well performance is periodic testing using a 3-phase separator. The most common form of separator is a tank with one or more weirs that uses gravity and time to separate oil, water and gas. The level of each phase must be controlled to achieve perfect separation efficiency. Wells are diverted to the test separator, which may be mobile or permanently installed, for a period of time and results for that period are averaged to create a single flow rate data point for each phase. A typical testing period and interval would be one day-long test per month. A separator is a simple, easy to understand method of flow rate for each phase.

Separators are often quite large and expensive, especially for high flow rates or emulsions that require long residence times to separate. In order to reduce capital expenditure and footprint, separators are kept as small as possible, but under sizing can cause incomplete separation and measurement errors. The valve and level control systems also require maintenance to avoid cross contamination of phases. The end result is a large, expensive piece of equipment that can require frequent attention and still may not provide desired accuracy.

*3.2 Multiphase Flow Meters (MPFMs)*

The term MPFM can encompass a wide array of technologies, combining flow meters, densitometers, fluid analysis inputs, and/or partial separation. The MPFM may be one self-contained device, or a small skid with various measurement devices, but the central theme is that they are meant to have much small footprint, less maintenance needs, and lower overall cost.

As attractive as a self-contained multiphase meter measurement can be, multiphase meters represent a significant investment for the average asset in both initial spending and in maintenance (particularly for nuclear based devices) and tend to have higher uncertainties than 3-phase separators. To date, the adoption rate of multiphase measurement has been significantly higher for subsea applications thanks to the greater initial investment and expected rate of return. While partial separation skids can offer reasonable accuracy, these meters often have a narrow operating range and represent a significant footprint and investment.

*3.3 Differential Pressure with Correction*

Differential pressure is a ubiquitous and relatively straightforward technology for continuously monitoring gas wells. When the process is dry gas, differential pressure can provide an accurate gas flow rate, but when differential pressure is used in wet gas measurement, they have errors (referred to as ‘overread’). This overread is due to the flow measurement now including the liquid, as well as errors in the bulk (gas and liquid combined) flow rate.

The magnitude of these overread errors varies with the amount of liquid, pressure, flow rate, flow regime, etc [9]. There is a large body of empirical data regarding overread in differential pressure measurement of wet gas, which has been used to generate correction algorithms. Single differential pressure meters require an input of Lockhart-Martinelli Parameter for the correction algorithms, but with the addition of a third pressure measurement the meter effectively becomes 3 differential pressure measurements in one, allowing for additional diagnostics and empirical correction algorithms that do not require additional inputs from sampling.

Differential pressure meters are fundamentally simple and compact instruments but require straight runs upstream and downstream that can greatly increase the cost and footprint of installations and in wet gas conditions, they rely heavily on complex empirical correction algorithms that have a narrow range of applicability that can result in higher than expected errors or even non-convergence (no output) when in operation in the field. With limited diagnostics available, it can be difficult to validate the accuracy of the meter in-situ.

*3.4 Coriolis Meters*

Coriolis meters offer multi-variable measurement, often at a lower installed cost than the technologies mentioned above, since they don't require straight runs or flow conditioning. Coriolis meters can independently measure mass flow rate and density, and some manufacturers have variables that indicate severity of multiphase conditions by monitoring tube damping. There are also diagnostics available that verify the sensor calibration in-situ. With all of this data available in a technology that has been widely accepted as robust and reliably accurate in single phase measurement, it seems there should be potential for viable 2-phase applications.

As it will be shown in this paper, Coriolis meters have the potential to produce accurate measurements on wet gas conditions without the need for laboratory or field calibration on specific wet gas applications or need for correction factors obtained from field test separators or additional equipment.

## 4. Applicable 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].

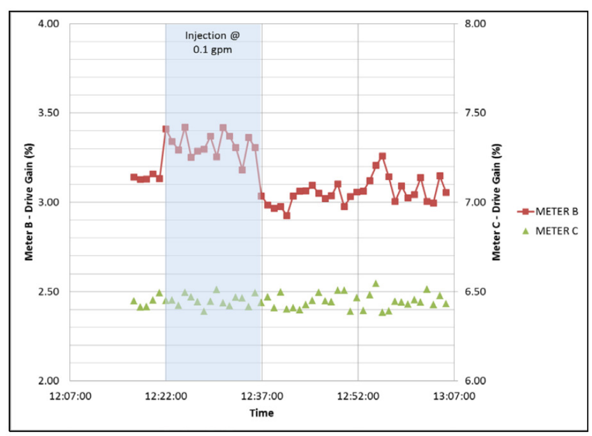
*4.1 Intermittent Two-Phase Detection and Remediation*

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.

*4.2 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 [8] shows drive gain in Coriolis meters with a large "U" shaped geometry are very sensitive to even small amounts of liquid.

Figure 2 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 2:** Drive gain response, 0.013% liquid

Once liquid is detected, the algorithm described below can be used to remediate gas flow rate measurement. Equation 1 showed that it is very easy for the mass flow rate of liquid to overshadow the mass flow rate of gas:

**Equation 1**

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

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

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

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 2**

$$\dot{\boldsymbol{V}}_{\boldsymbol{s}} = \dot{\boldsymbol{m}} \cdot \boldsymbol{\rho}_{\boldsymbol{s}}$$

where $\dot{V}_s$ is the volume rate flow at standard condition, $\dot{m}$ is the mass flow rate at line conditions, and $\rho_s$ 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 3) 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.

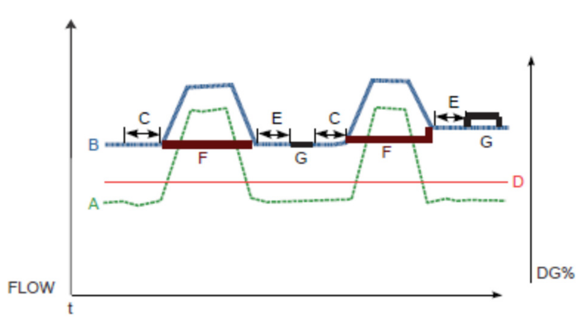



**Figure 3:** Gas remediation method for intermittent two-phase flow

In Figure 3, 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.

*4.2 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 4 shows condensate/gas ratio (CGR) versus measured density from 5 meters with large "U" shape, in a field in Qatar [7]. 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.

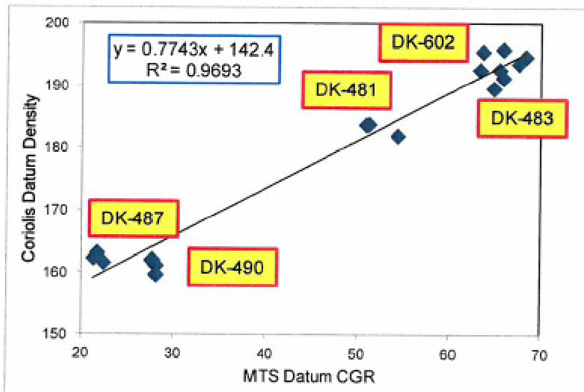



**Figure 4:** CGR vs Measured Density

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 [1].

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.

## 5. 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 5.

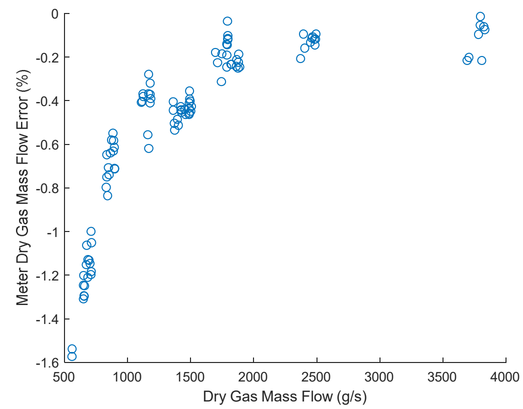



**Figure 5:** Dry gas performance of CMF300 at 25 and 50 bar

As shown in Figure 6, 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.

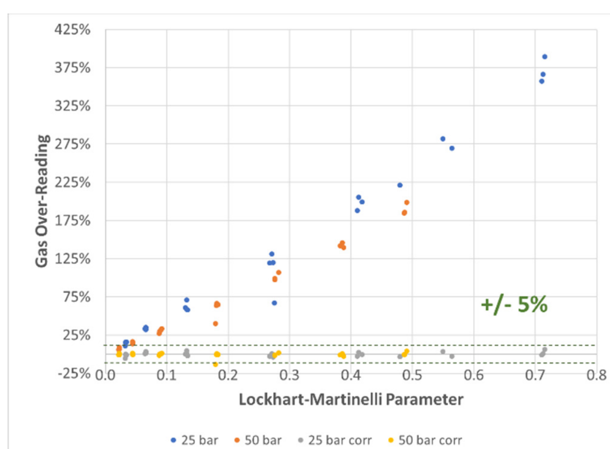



**Figure 6:** Unremediated and corrected dry gas overreading from CMF300 mass flow measurement on wet gas conditions

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 7 and Figure 8 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.

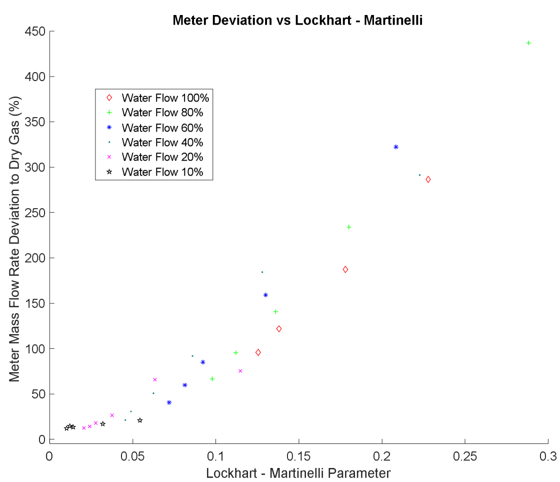



**Figure 7:** CMF100 overreading as a function of Lockhart-Martinelli parameter and water flow rate

Figure 7 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.

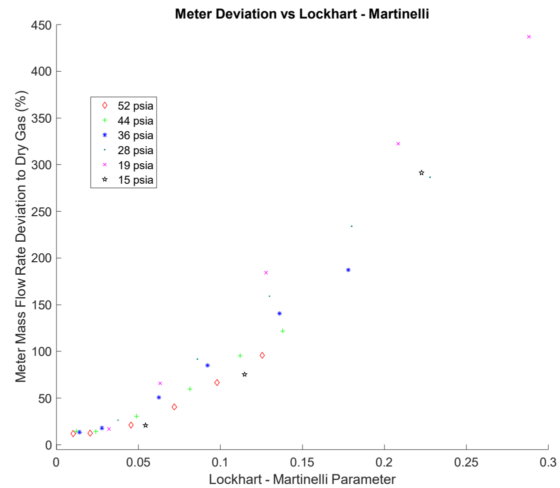



**Figure 8:** CMF100 overreading as a function of Lockhart-Martinelli parameter and pressure

Figure 8 shows the meter response at different line pressures, this data was obtained from the same test matrix as Figure 7 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.

## 6. 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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