# New Applications for Coriolis Meter-based Multiphase Flow Metering in the Oil and Gas Industries

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KEYWORDS : Coriolis Mass Flow Metering, Multiphase Flow, Oil and Gas Industry, Wet Gas, Net Oil , Bunkering

*The last decade has seen significant advances in Coriolis mass flow metering, widely regarded as the most accurate industrial flow meter. A key development has been the ability to maintain operation during multiphase flow (gas/liquid); with appropriate modeling techniques the mass flow and density readings can become new measurement principles available for difficult multiphase flow applications. This talk will describe three new applications for Coriolis multiphase flow metering in the oil and gas industries: net oil metering, wet gas metering and bunker fuel transfer.*

Manuscript received: January XX, 2011 / Accepted: January XX, 2011

## 1. Introduction

A Coriolis mass flow meter (Fig. 1) consists of an (essentially mechanical) vibrating flowtube through which the process fluid passes, and an (essentially electronic) transmitter. The transmitter maintains flowtube vibration by sending a drive signal to one or more drivers ($d_1$, $d_2$), and performs measurement calculations based on signals from two sensors ($s_1$, $s_2$). The phase difference between the signals from sensors $s_1$ and $s_2$ is used to calculate the mass flow rate. The frequency of oscillation varies with the density of the process fluid: its value is extracted from the sensor signals so that the process density can also be calculated. The design and material selection of the flowtube determine the frequency range of the meter: the so-called "bent" tubes (as shown in Figure 1) typically oscillate between 50 - 150 Hz, while the "straight" flowtube geometries may oscillate at up to 1 kHz. The flowtube temperature is also monitored to provide temperature-based corrections to the mass flow and density measurements.

Coriolis meters offer many benefits, including high accuracy (to 0.1% for steady flow rates), and good turndown (100:1 or better), while their limitations have included poor dynamic response and an inability to maintain operation when exposed to multi-phase flow. A user perspective on Coriolis as an "almost perfect" flowmeter is given by Reizner [1].

The exploitation of new technology, such as audio quality analog-to-digital convertors and digital-to-analog convertors (ADCs and DACs) and Field Programmable Gate Arrays (FPGAs), has facilitated the development of new capabilities for Coriolis meters, such as the

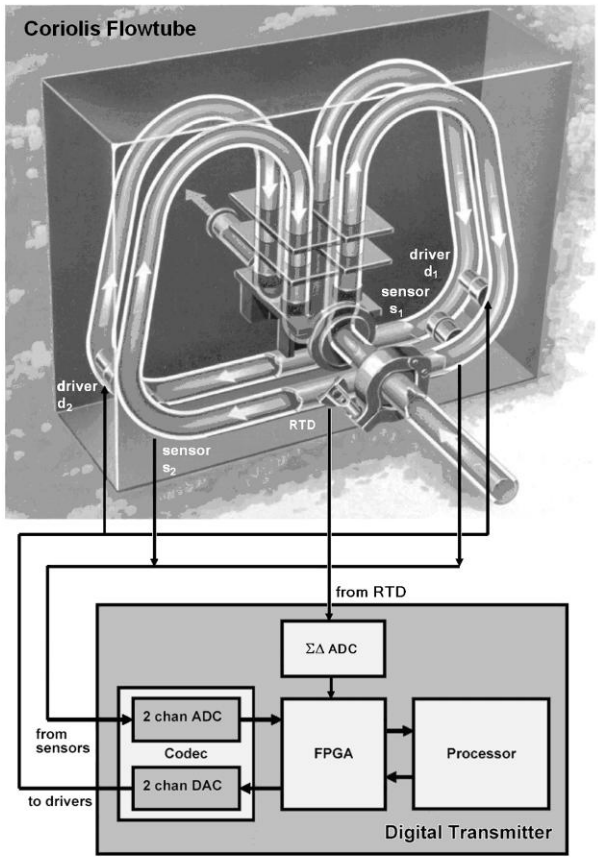


Fig. 1 Coriolis mass flow meter: flowtube and digital transmitter.

ability to deal with multiphase flows [2]. Multiphase flow introduces highly variable damping on the flowtube, up to three orders of magnitude higher than in single phase conditions, requiring agile and precise drive control, which only the latest technology can provide. In addition, the mass flow and density measurements generated under multiphase flow conditions are subject to errors, for which correction algorithms must be defined and implemented.

There is great interest within the oil and gas industry for exploiting the new Coriolis metering technology in upstream applications, where the process fluids are inherently multiphase. A Coriolis meter measuring two parameters - mass flow and density - is theoretically able to resolve a two-phase (liquid/gas) mixture [3]. However, unless simplifying assumptions are made, a Coriolis meter cannot on its own resolve the general three-phase oil/water/gas mixture that characterises most oil well production. However, when used in conjunction with a third instrument, such as a water cut meter, which detects the proportion of water in the mixture being monitored, true three-phase metering can be achieved.

There are many parameters that can characterize multiphase flow (for example, the relative proportion of the three phases, pressure, flowrates, the presence of additional components etc.); the development of an entirely general purpose three-phase flowmeter is notoriously difficult. In our work with Coriolis meters, we have begun by dealing with more limited ranges of three-phase conditions suitable for economically useful applications. These include relatively low gas content (up to 35% by volume) net oil measurements, and high gas content (exceeding 95% by volume) wet gas measurements. Recent developments of each of these applications are described. Finally, a largely two-phase application is described in which Coriolis meters are being introduced for monitoring the transfer of bunker fuel oil for shipping. Here, the use of internal diagnostics enables the detection of even the lowest levels of gas content. Overall, the complexity of multiphase flow and the variations in measurement quality across the range of flow conditions suggest the use of on-line assessment of measurement uncertainty - SEVA.

## 2. Net Oil Measurement

A net oil real-time well testing system has been developed which combines three-phase metering with automated test scheduling for up to 30 wells. This system has been used in mature, high-water cut oil fields in Texas (Fig. 2). The automated test scheduler operates the valve network to select the well for testing, while the metering system measures the oil, water and gas flow rates from the selected well, without the need for separation. Figure 2 shows the net oil system.

One of the difficulties of assessing the performance of three-phase metering systems in the field is the limited availability of high accuracy reference measurements. Accordingly, it is common practice to develop and calibrate three-phase instrumentation at suitably equipped laboratories such as the UK's National Flow Laboratory TUV-NEL near Glasgow. Systematic tests of the coriolis meter response to three-phase mixtures have been carried out with Gas Void Fraction (GVF) levels - that is, the percentage of gas by volume in the multiphase mixture – of up to 50%. Figures 3 and 4 show typical results for the uncorrected mass flow and density errors for a 12mm flowtube where the water cut, or volumetric proportion of water in the bulk liquid, is 85%. Each point represents the mean measurement over a minute of steady flow at the conditions indicated. The x-axis shows the GVF: with no gas present the mass flow and density errors are typically less than 0.1%, but as the proportion of gas in the three-

Fig. 2. Net Oil metering system installed in Texas; the output of each of up to 30 wells is monitored in turn for 24 hours.

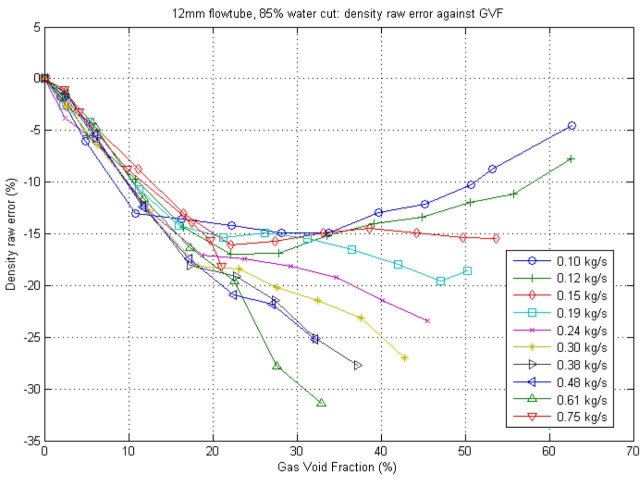


Fig. 3. Density errors for uncorrected Coriolis mass flow meter: 12mm diameter flowtube, 85% water cut

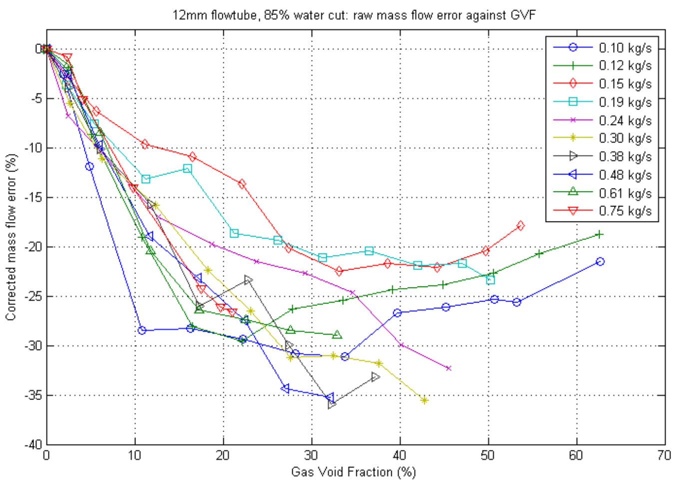


Fig. 4. Mass Flow errors for uncorrected Coriolis mass flow meter: 12mm diameter flowtube, 85% water cut

phase mixture increases, a structured and repeatable pattern of errors emerge, which can be modeled and inverted.. By collecting such data at varying water cuts, it is possible to develop a three-dimensional model of meter behavior. Using Neural Net to implement the models [3], on-line corrections are provided for the effects of multi-phase flow on the Coriolis meter measurements. For example, Fig. 5 shows the residual errors for the mass flow rate measurement at 85% water cut after the correction has been applied. Here, the errors have been reduced to lie mostly within ±1.5%. Of course Fig 5 only shows the results of off-line modeling.

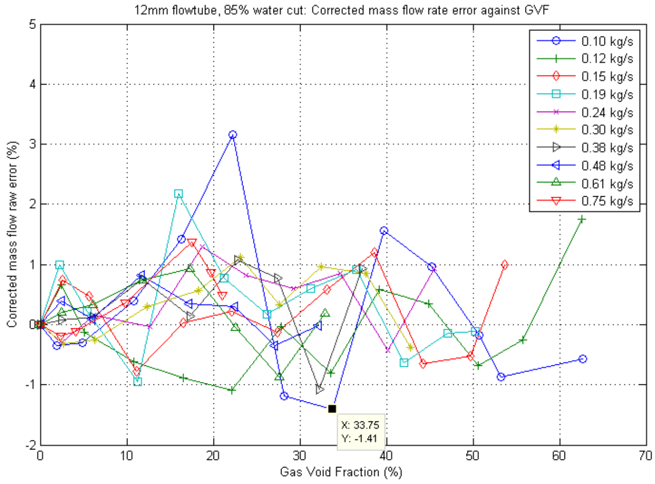


Fig. 5. Mass Flow errors for corrected Coriolis mass flow meter: 12mm diameter flowtube, 85% water cut.

However, using the coriolis meter in combination with a water cut meter, it is possible to deduce in real time the mass flow of the oil, water and gas respectively. This functionality is provided in an integrated system that combines the measurements, applies the necessary corrections, and records and transmits the oil, water and gas readings (Fig. 2)

Accuracy requirements for multiphase metering vary by country; some of the most stringent are for Russia, where the latest GOST standard [4,5] specifies the following accuracy requirements:

- Total liquid (oil + gas) flow rate: accurate to within ±2.5%
- Gas flow rate: accurate to within ±5.0%
- Net Oil flow rate (i.e. oil only)
    - For water cuts < 70%: oil flow rate ±6.0%
    - For water cuts < 95%: oil flow rate ±15.0%

At the time of writing, formal trials are planned for demonstrating this level of three-phase measurement performance at the TUV-NEL flow laboratory, starting in May 2011. These will cover a broad range of three-phase flow conditions suitable for net oil applications. Results will be reported at the Symposium.

## 3. Wet Gas Metering

In wet gas applications, the requirements are similar to net oil, namely, the measurement of oil, water and gas flow rates, but under entirely different three-phase flow conditions, with gas constituting at least 95% by volume. Given the relative densities of gas and liquid, the 5% of liquid by volume may still amount to 50% or more of the mass of the flow stream. The same basic techniques used for net oil have been applied in the development of a wet gas metering skid (Fig 6) consisting of a Coriolis mass flow meter and water cut meter. Data collected at the CEESI standards laboratory wet gas metering facility in Boulder Colorado has been used to develop models of the response of a Coriolis meter to wet gas conditions. On-line measurements from the Coriolis meter and a wet gas meter (together with temperature and pressure readings), have been successfully combined to generate on-line measurements of gas, water and oil.

Fig. 6. Wet gas metering skid combining Coriolis mass flow meter and water cut meter.

A wet gas metering system has been trialed in an enhanced oil recovery (EOR) application in Alberta, Canada. Enhanced oil recovery is a technique used to maintain pressure and hence productivity in a mature oil and gas reservoir by injecting liquid or gas into the reservoir. As the reservoir concerned produces sour gas (about 20% $H_2S$), undesirable waste gases ($H_2S$ and $CO_2$) are re-injected into the reservoir. The producing well to be monitored thus generates a mixture of sour gas, water and condensate (light oil).

The only reference measurement system available to validate the wet gas metering performance against was a test separator, some 4 kilometers distant. A test separator is a vessel designed and sized to allow the gas, oil and water to separate mechanically, so that each stream can be extracted separately and metered using conventional single phase flow instrumentation. As with the net oil application, such test separators are typically used to monitor the output of one well over a 24 hour test period, and each well is only monitored for example one day each month. Furthermore, the integrating action of the test separator means that all dynamic information, such as the pattern of liquid and gas flow, is lost. All that can be provided is the totalized flow of each of the three components over the test period.

By contrast, the wet gas metering system is able to provide dynamic monitoring of the well output on a second-by-second basis. For example, figure 7 shows data from the Alberta trial over the course of one hour. The top two graphs show the (corrected) density and mass flow readings from the Coriolis mass flow meter. The system is able to calculate the expected density of the gas mixture, given its composition, density and temperature, and so it is able to partition the observed density into two parts: what is gas (shown here

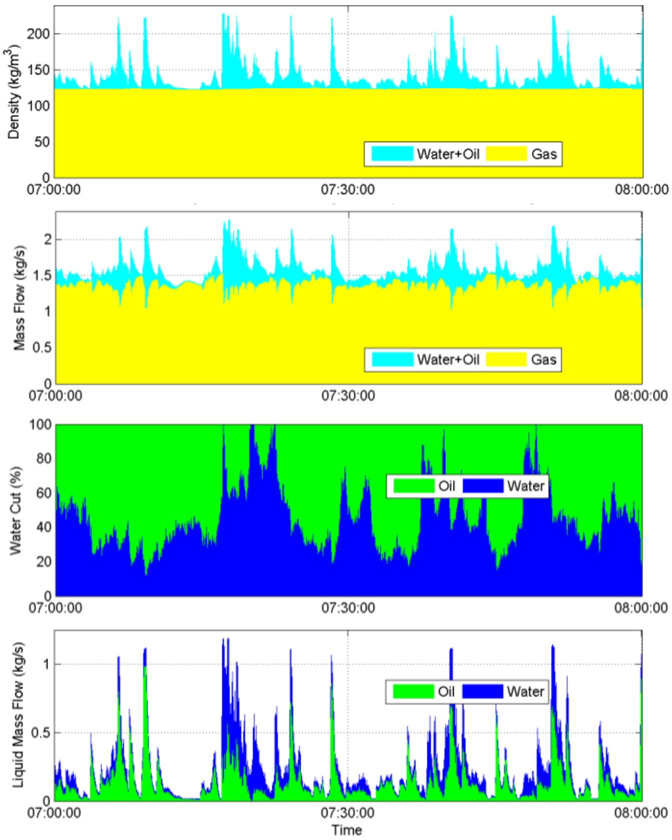


Fig. 7. Data from wet gas metering skid.

in yellow), and what is liquid (shown here in cyan). This ratio can be applied to the observed mass flow reading, in order to determine the mass flow of the gas, and of the liquid respectively. The third graph shows the water cut reading, which indicates the proportion of oil (green) and water (blue) in the liquid. Based on this data, the lowest graph shows the liquid mass flow rate partitioned into oil and water. The information provided by this real-time system gives a detailed picture of the patterns of flow emerging from the well, which can assist in reservoir management, for example in assessing the effectiveness of strategies to optimize oil yield, or in the detection of significant changes of behavior such as the occurrence of significantly longer slugs of liquid. Note that where longer slugs of liquid occur so that the multiphase fluid is no longer in the wet gas region, the metering system switches to an alternative model to optimize measurement accuracy.

In the trial, the 4km distance between the wellhead and test skid on the one hand, and the test separator on the other, limited the scope of liquid measurement comparison. For example, the weekly practice of pigging the line could result in the liquid transport down the pipeline never being in equilibrium. However, good correspondence between the gas readings was expected and achieved – over a period of 9 days, the maximum difference in the daily gas total flowrate between the test skid and the test separator was 1%.

## 4. Bunkering

The $150 billion ship fuel (bunkering) industry still uses largely manual methods for determining the transfer of fuel from the bunkering barge to the receiving ship. These techniques are prone to error and potential fraud, with Maersk, the world's largest ship operating company, estimating it is defrauded of 1.5% of its $7 billion annual spend of fuel [6]. Conventional flow metering does not work because of entrapped air in the viscous fuel. However, the new generation of Coriolis meters is able to detect and correct for this condition. The detection of air can in turn improve the operation of the barge leading to better asset utilisation. This is primarily a two-phase (oil and air) measurement problem, as standards limit the water content of the fuel oil to less than 0.5%.

Bunker transfers typically take place at flowrates of several hundred tonnes per hour, with pipe diameters of 200mm or higher, requiring significantly larger Coriolis meters than the upstream oil and gas applications discussed earlier. For example, Fig. 8 shows an 8” Coriolis meter used in a trial on a Singapore bunker barge. During the trial, some 80 commercial bunker transfers were monitored, valued at over $30 million in total. As with the previous two examples, models of the two-phase performance of the 200mm flowtube were developed using high viscosity oil (around 200 cSt), at a standards laboratory, in this case TUV-NEL in Glasgow, and satisfactory two-phase performance was obtained in laboratory trials.

In the field trials in Singapore, the level of aeration in the fuel came as a surprise, given that the conventional measurement technique, via manual tank dipping, gives no indication of the presence of air in the fuel. However, it is possible to demonstrate that internal diagnostics within the coriolis meter are able to detect very low levels of air entrainment, which cannot be attributed to, for example, an inaccurate density reading. This is illustrated in figure 9, which shows data from an actual bunker transaction recorded during the Singapore trial.

The top graph in figure 9 shows the mass flow rate of fuel during the bunker transfer from the barge to the receiving ship, over the course of seven hours, as observed by the Coriolis mass flow meter. The second graph down shows the observed density of the fluid, again as measured by the Coriolis mass flow meter. Where there is no possibility of any air or gas being entrained in the fuel, then the density reading can be used as a further indication of the quality of the fuel – there are fairly strict limits placed on the permitted densities of bunker fuels, so that for example a 380 cSt grade fuel oil should be expected to have a density close to 980 kg/m3. It can be seen that prior to the start of the batch the density reading is low – the meter has been incompletely drained at the end of the previous bunker transfer - but once the new batch begins the density reading rises to approximately 1000kg/m3. Later in the batch, at about 2:30am and then at 04:00am, the density drops significantly, indicating the presence of air in the fuel.


Fig. 8. Coriolis meter installed on bunker barge.

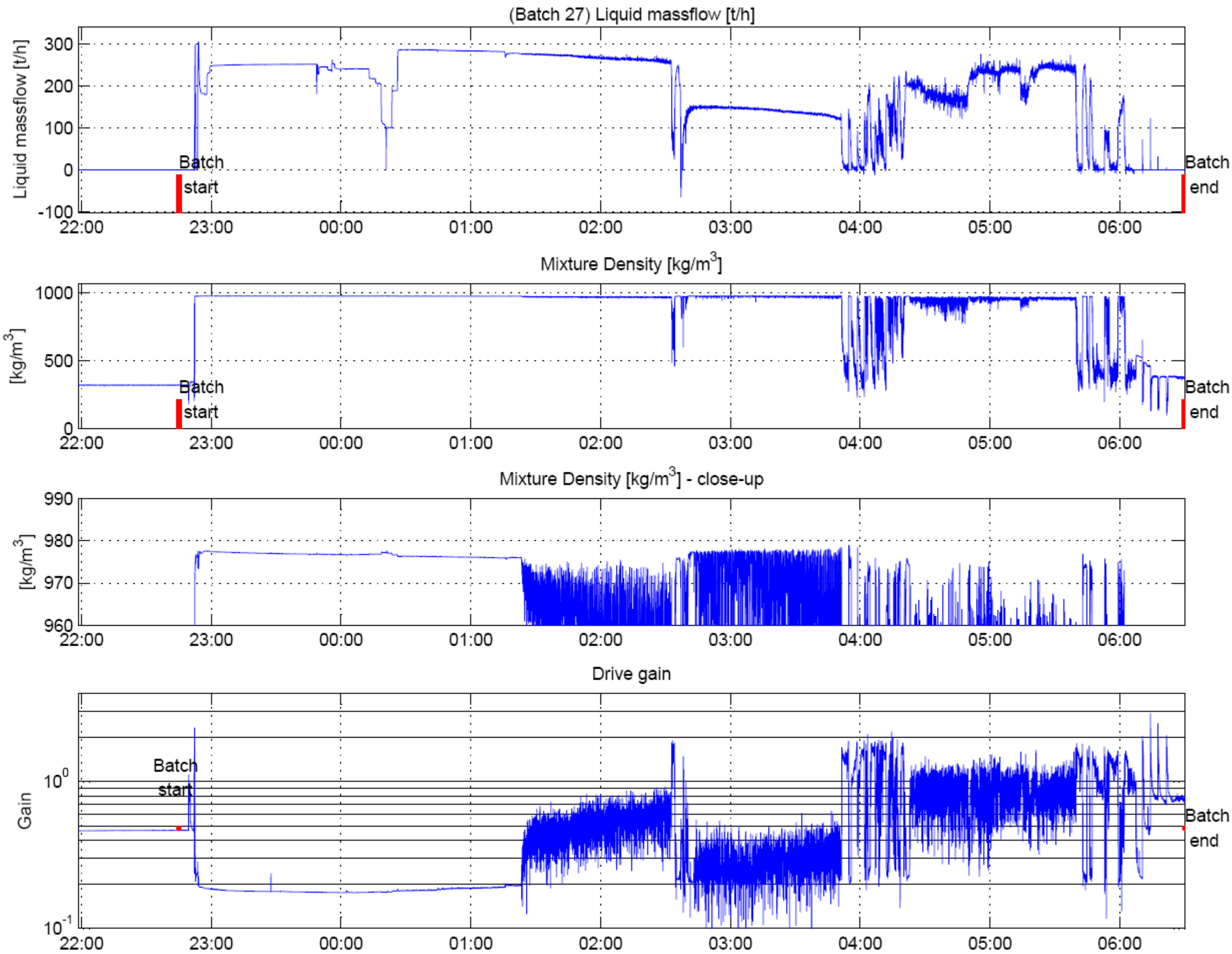


Fig. 9. Coriolis meter record of commercial bunker fuel transfer from Singapore-based barge

The third graph in Fig. 9 shows the same density data, but on a restricted y-axis scale. Note that the difference between 980 kg/m3 and 970 kg/m3 is approximately one percent. The characteristics of the density reading become more readily apparent on this scale. Between the start of the batch and approximately 01:20am, the density reading is very smooth and relatively steady, although a slight decline is evident. At around 01:20am however, there is a clear change in behaviour: the density reading becomes much noisier and its mean value drops by about one percent. This is one indication of the presence of air in the fuel. The lowest graph in figure 2 shows the drive gain, an indication of the energy required to maintain flowtube oscillation and hence of the damping on the flowtube, a measure which is entirely independent of the mass flow and density readings. The drive gain can vary by up to two orders of magnitude, and so is plotted on a logarithmic scale. It is clear that from the start of the batch until about 01:20am, the drive gain, like the density reading, is also steady, but the subsequent 1% drop in density is associated with a doubling or more of the drive gain. This provides an independent confirmation that the drop in density is associated with entrained air in the bunker fuel, rather than simple a change in the density of the fuel itself.

With the backing of several large users (most notably Maersk) and vendors, the Singapore Port Authority is now drawing up a standard for the use of Coriolis metering in the bunkering industry.

## 4. Conclusions

Extending the application of Coriolis mass flow metering to multiphase flow offers many opportunities for improving measurement in the oil and gas industry. Three examples have been provided in this paper: net oil, wet gas, and bunkering.

Given the multi-dimensional characteristics of multiphase flow and the complexity of the modeling necessary to provide measurements, it is difficult for users and suppliers to assess the quality of the measurements generated at different operating points. For example, a Coriolis meter mass flow reading is likely to be accurate to 0.1% over a 100:1 turndown. However, in multiphase flow conditions, the mass flow accuracy is likely to be at least an order of magnitude worse, and this is likely to vary dynamically with changes in the multiphase flow conditions. The use of the drive gain to confirm the presence of gas in the bunker fuel oil is an example of applying internal diagnostics within an intelligent sensor system to detect key changes in the behavior of the process fluid or possibly of the sensor system itself. The self-validating sensor or SEVA concept [7] is a logical extension of this approach, whereby a complex, intelligent instrument such as a multiphase meter is able to assess online the uncertainty of each of its measurements, based on internal diagnostics as well as the quality of its models and the current operating point. This appears an attractive way ahead to offer users an indication of measurement quality as it varies across the multiphase flow domain.

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