**32nd International North Sea Flow Measurement Workshop**
**21-24 October 2014**

**Technical Paper**

# Coriolis Meter Testing Under Variable Water Cut, Oil Water Conditions

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## 1. INTRODUCTION

While multiphase flow is often considered to be a mixture of oil, water and gas, in oil production the flow is often predominately oil with water. Gas is usually present to a degree, but it can be readily removed. In marginal fields the use of large separators is cost prohibitive, so the measurement of the oil with water flows without separation is often necessary. The methods employed range from use of complex purpose designed multiphase meters to the adaption of standard liquid flow meters to this task.

This paper discusses the potential use of Coriolis meters for the measurement of oil with water flows. The Coriolis meter is potentially well suited to this adaption to oil with water metering. The physical principles on which it operates allow the meter to output multiple variables, i.e. mass flow rate, volume flow rate and fluid density.

The multi-variable functionality of the Coriolis meter has led to attempts to use the Coriolis meter to measure oil with water mixtures. The mass or volume flow rate output is used to find the total mixture flow rate. The density output is then used in conjunction with known base densities of the oil and water flows to predict the water cut. Combining the total flow rate and water cut information allows both the oil flow rate (typically the primary flow rate of interest) and water flow rate to be estimated.

In reality there are challenges to operating a Coriolis meter in an oil/water mixture flow application. Low uncertainty oil and water flow rate predictions are dependent on low uncertainty total flow rate and water cut predictions. In practice it is difficult to assure low uncertainty water cut predictions. The water cut uncertainty is dependent on the uncertainty of the oil and water base densities as well as the uncertainty of the average (or 'homogenous') density reading. The base oil and water densities can change during production. Scheers [1] gives a worked example showing the sensitivity of the Coriolis meter's water cut prediction to biases in water density input. Relatively small biases in the base oil or water density values used can have a large adverse effect on water cut prediction, and hence the oil flow rate prediction. Furthermore, the Coriolis meter measurement of the averaged (or 'homogenous') density is dependent on the mixing level. NEL [2] showed that two operational Coriolis meters in an oil with water flow application gave different averaged density measurements when their respective installations caused different mixing levels at the inlet to the meters. After 50% water cut laboratory tests with Coriolis meters mounted in different installations, with and without mixing devices, it was concluded by NEL that the velocity of the mixture flow should be as high as possible to promote good mixing. It was also shown that vertically upward mounting (promoting mixing) was the best installation for inducing mixing.

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The CEESI tests discussed in this paper continue this research for horizontal "flag down" installations with a greater range of water cuts. The potential errors in Coriolis meter water cut measurement for known base densities are also discussed.

## 2.    TEST EQUIPMENT & TESTING PROCEDURE

The two Coriolis meters tested (i.e. meters under test, or "MUT"), where 3" & 4" MicroMotion Elite Coriolis meters. Both meters were installed horizontally in the tubes (or "flag") down configuration, as shown in Figures 1 & 2. Some results from the 4" Coriolis meter have been previously discussed by Cousins et al [3]. The 3" Coriolis meter used a 1700 series transmitter while the 4" Coriolis meter used a 2400 series transmitter. The specifications of these transmitters are similar and it is therefore expected that they will perform similarly in oil with water flow applications.

The test facility has been described in detail in reference [3]. Only a brief overview is given here. Initially developed to test mixers at high water cuts the facility has always been capable of testing flow meters with varying water cuts to a low level of uncertainty. The facilities oil and water reference flow rates are known to < 0.28% uncertainty. A schematic diagram of the facility is shown in Figure 1.
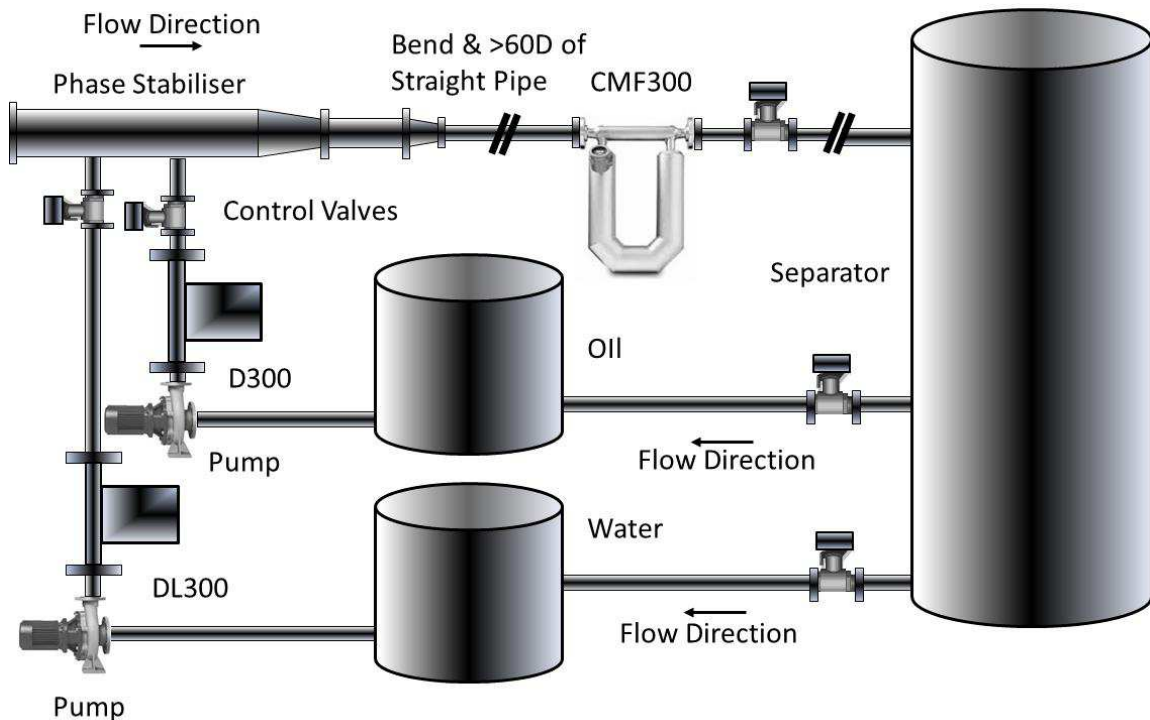


**Figure 1. Schematic of the Water/Oil Test Facility**

The oil and water are stored in separate tanks. Each has an outlet that goes into a phase stabilizer via centrifugal pumps, 3" D 300 (oil) and DL 300 (water) Coriolis meters and control valves. On exiting the phase stabilizer the oil and water mixing is solely dependent on the flow velocity. No active mixing device was installed between the stabilizer and the MUT. In the case of the 4" meter the pipe

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remains the same diameter around a bend and into the meter section. For the 3" meter, after the 4" bend the pipe is reduced to 3" before the meter section. In both cases there is > 60 pipe diameters of straight constant cross sectional area pipe upstream of the MUT. The piping is clear plastic, allowing the phase dispersion to be viewed and videoed. The installation deliberately represents a worst case scenario compared to most operational installations, as there are no close fittings to help mix the oil and water flow. (Mixers or fittings could be installed on request to simulate operational conditions.) After the MUT the flow enters a separator, where the water and oil are separated and then returned to their respective tanks. A photo of the system is shown in Figure 2.



**Figure 2. Photograph of CEESI Water/Oil Facility**

The nominal oil viscosity was 2.5 cS and the nominal oil density was 830 kg/m$^3$. The nominal water viscosity was 1.0 cS and the nominal oil density was 997 kg/m$^3$. Temperature is measured at the reference meters and the MUT to allow for correction of the meter density and volume flow rates. Over the tests there were differences in temperature between the water, oil and water/oil mixtures of up to 1.5$^o$F. The pumps allowed for nominal maximum velocities of 2.5m/s for the 4" line and 6.5m/s for the 3" line.

The facility is a single pass system where the oil and water are pulled from their respective storage tanks through pumps and reference meters, mixed, flown down the test section through the MUT and gathered in a separator. The test can continue until one of the supply tanks empties. The test is then stopped and the mixture separated by separator retention time. The oil and water are then returned to their storage tanks to prime the system for a new test. During testing there is adequate time for the process to stabilize (i.e. reach steady state flow) before data is logged. This, in combination with the Coriolis meter damping factors being set to a minimum, ensured that the meters were reading the correct flow rate during the tests. Once flow stability was achieved 30 second data points were automatically logged.

During commissioning of the facility the oil and water lines had samples taken at the reference Coriolis meters. These samples were taken across the facilities full

range of water cut and flow rates. No cross contamination of phases was noted in the samples. A certified hydrometer was used to measure the oil and water

sample densities. The Coriolis water reference meter density prediction was within 0.2% of the sample water density values. This was within the system uncertainty and no correction was applied. The Coriolis oil reference meter density prediction had an offset with the sample oil density values of approximately 0.8%. This was an offset greater than the system uncertainty and a correction was applied to the oil density reference measurement.

The required total flow rate and water cut were decided before the test commenced. The oil and water reference meters were monitored as the oil and water pumps were altered to supply the required oil and water flow rates. When the flow settled to the constant required values, and the temperature and pressure were noted as constant, data logging from the MUT commenced. During the tests oil and water samples were periodically taken to check the densities. The data collected from the MUT included the mass & volume flow rates, flowing density, and diagnostic outputs (in particular the gain).

As there are potential errors in determining the mixture expansion coefficient it was problematic to convert flowing conditions to standard conditions. Furthermore, as the test pressure was < 100 psi both fluids could be considered effectively incompressible, so no pressure correction was applied. The density and volume flow rate were therefore referred to the flowing conditions at the MUT. The facilities oil and water density and flow rate reference information can be used with the ASME [4] Equations 1 & 2 to predict the oil and water mixture flow's average / homogenous density.

$$\rho_{\mathrm{hom}ogenous} = \frac{\rho_w \rho_o}{\rho_o x_l + \rho_w (1 - x_l)} = \frac{\rho_w Q_w + \rho_o Q_o}{Q_o + Q_w} \qquad \text{--- (1)}$$

$$x_l = \frac{m_w}{m_o + m_w} \qquad \text{--- (2)}$$

Note that:

| | |
|---|---|
| $\rho_{homogeneous}$ | is the mixture density |
| $\rho_w$ | is the water density |
| $\rho_o$ | is the oil density |
| $Q_w$ | is the water volume flow rate |
| $Q_o$ | is the oil volume flow rate |
| $m_w$ | is the water mass flow rate |
| $m_o$ | is the oil mass flow rate |
| $x_l$ | is the mass water liquid ratio |

The uncertainty of the individual oil and water reference mass flow rates was 0.2%. The uncertainty of the oil and water reference volume flow rates, the combined uncertainty, was better than 0.5%. The uncertainty of the combined oil and water densities was 0.5%.

## 3.    TEST RESULTS

The average flow velocity heavily dictates the level of mixing between the oil and water phases which in turn dictates the Coriolis meter's performance in oil with water flow metering applications. As such, the data has been plotted relative to average flow velocity.

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### 3.1    4" Coriolis Meter Mass Flow Rate Prediction Results

The 4" Coriolis meter (MUT) had to be corrected for a 1% offset found during the initial single phase oil & then water flow meter calibrations. All 4" Coriolis mass flow rate data presented has this 1% offset applied. Figure 3 shows the difference between the facilities reference meter system and the 4" Coriolis MUT total flow rate prediction for all water cuts tested. That is, Figure 3 shows the total mass flow rate prediction error vs. average flow velocity. This error (and spread of data) increased as the velocity reduced below 1 m/s. As the flow reduces to 0.4 m/s the error increases to 10%. This is almost certainly due to the oil and water being separated in the meter. Figure 3 shows that at lower average velocities with lower water cut flows the 4" Coriolis meter tends to over predict the total mass flow, for the higher water cut flows the 4" Coriolis meter tends to under predict the total mass flow. Figure 4 shows the scale expanded to +/-2%. The spread of data above 1m/s averages +/- 0.6%.
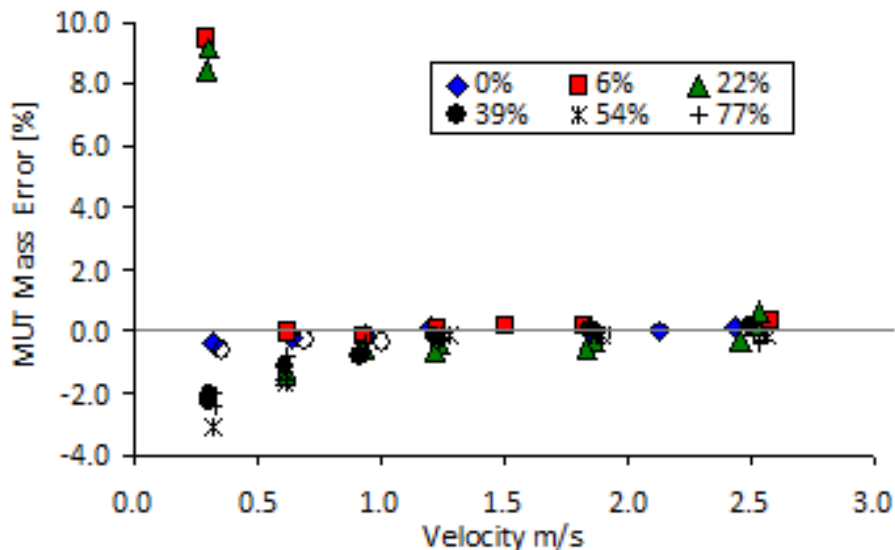


**Fig 3. 4" Coriolis Meter Total Mass Flow Rate Prediction Error vs. Average Velocity**
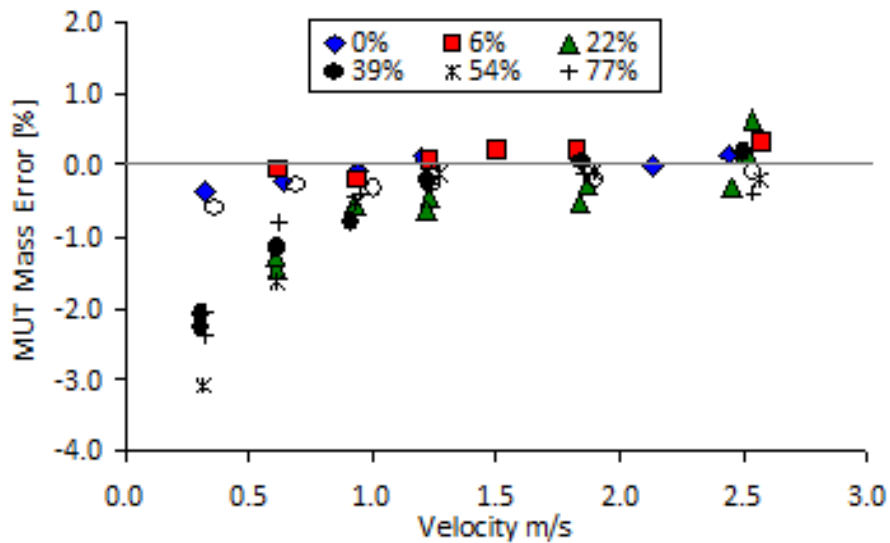
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**Fig 4.  4" Coriolis Meter Total Mass Flow Rate Prediction Error vs. Average**

### 3.2    3" Coriolis Meter Mass Flow Rate Prediction Results

The oil and then water single phase flow calibration results, figure 5, showed that the 3" Coriolis meter and the facility reference meters had an offset of approximately 0.3%. This difference was within the combined uncertainties of the Coriolis meters and therefore no correction / offset was applied to the MUT.
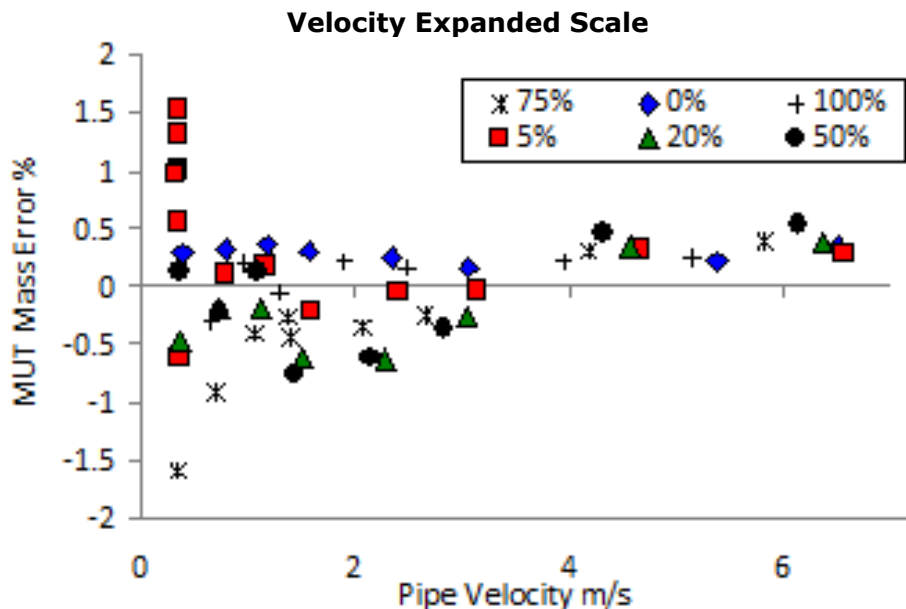


**Fig 5.  3" Coriolis Meter Total Mass Flow Rate Prediction Error vs. Average Velocity**

Due to pump capacity the 3" meter was tested over a wider velocity range than the 4" meter. Above 3m/s the data spread is nominally 0.2% spread around the above mentioned 0.3% offset. For average flow velocities down to 2 m/s the spread of the 3" meter data is very similar to the 4" meter data, i.e. the data spread is within +/-0.6%. Below 1 m/s the 3" Coriolis meter results are similar to the 4" Coriolis meter results. As found with the 4" meter, below 0.5 m/s there is a

significant increase in the data spread. Again, this is probably due to the oil and water phases being separated in the meter. At lower average velocities for the lower water cut flows the 3" Coriolis meter tends to over predict the total mass flow, for the higher water cut flows the 3" Coriolis meter tends to under predict the total mass flow.

### 3.3    4" Coriolis Meter Density Prediction Results

Figure 6 shows the difference in the ASME average (or "homogenous") density value and the 4" Coriolis meter's density prediction value vs. average flow velocity. That is, Figure 6 shows the average density prediction error vs. average flow velocity. At average flow velocities of < 0.5 m/s there is a significant density prediction error of up to 8%. At < 0.5 m/s lower water cuts give significant density prediction positive biases. The high average density prediction errors at < 0.5 m/s is suspected to be due to phase separation in the Coriolis meter. As mixing improves as the average velocity increases, by 1 m/s the average density prediction error is relatively small. However, as the velocity increases from 1 m/s to 2.5 m/s the density prediction error again increases. By 2.5 m/s the 4" Coriolis meter's average density prediction error has a significant error of between 1 & 4%. The reason for this increase is not known.
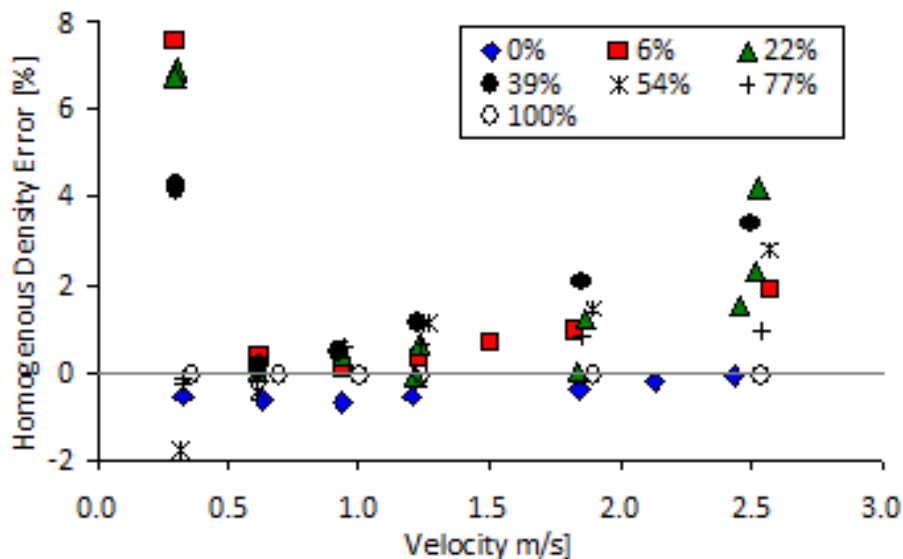


**Fig 6. 4" Coriolis Meter Density Prediction Error vs. Average Velocity**

### 3.4    3" Coriolis Meter Density Prediction Results

The 3" Coriolis meter's density output performance was found to be similar to that of the 4" Coriolis meter. Figure 7 shows the average density prediction error vs. average flow velocity. At average flow velocities of < 0.5 m/s the lower water cuts give significant density prediction positive biases. However, for the 3" Coriolis meter this was found to be up to 2% (compared to the 4" meters to 8%). Again, these high average density prediction errors are suspected to be due to phase separation in the Coriolis meter. As mixing improves as the average velocity increases at >1 m/s the density prediction is within 0.7% of the reference, and at > 2 m/s the density prediction is within 0.5% of the reference.
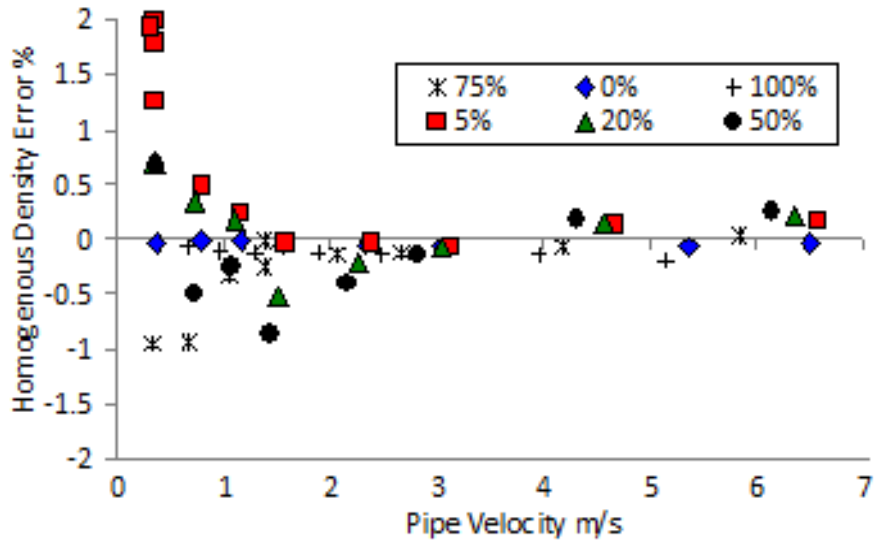
**Fig 7. 3" Coriolis Meter Density Prediction Error vs. Average Velocity**

### 3.5    Volume Flow Rate Prediction

The 4" Coriolis meter tested was not configured to supply a volume flow rate output. Only the 3" Coriolis meter gave a volume flow rate prediction. Figure 8 shows the 3" Coriolis meter volume flow rate error (i.e. the difference between the reference system & MUT volume flow rate predictions) vs. average velocity. A Coriolis meter derives volume flow rate from its primary mass flow rate and density measurements. It is therefore no surprise that the meter's oil with water volume flow rate prediction is similar to the mass flow rate and density predictions.
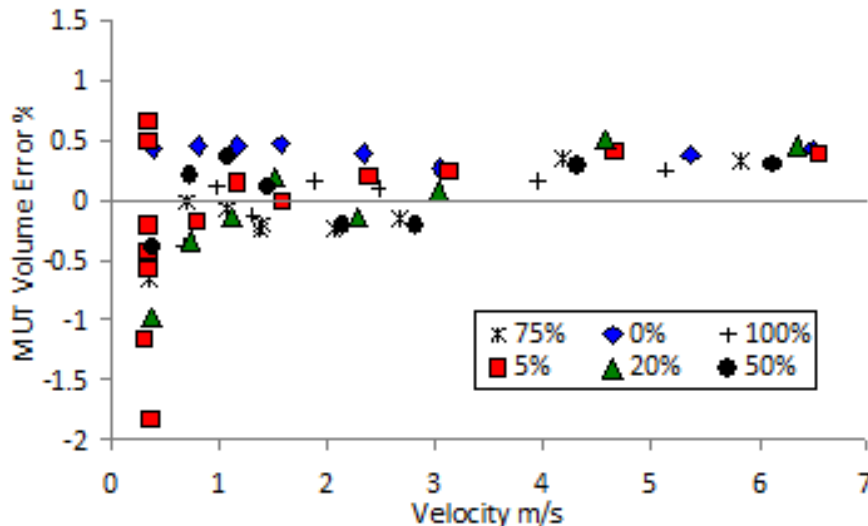


**Fig 8.  3" Coriolis Meter Volume Flow Rate Prediction Error vs. Average Velocity**

Figure 8 shows that at < 0.5 m/s for lower water cuts there is a significant error up to -2% in the volume flow rate prediction. At 0.5 m/s to 3 m/s the volume flow rate was predicted to ±0.5%. At > 3 m/s the volume flow rate prediction error closely agreed with the facility reference value, with a positive bias that is inside the limit of the MUT and reference meter combined uncertainties. These results

are directly related to the 3" Coriolis meter's mass flow rate and average density performance as shown in Figures 5 & 7.

### 3.6    Comparison of Water Cut & Density

It is theoretically possible to predict an oil with water flow's water cut by use of a Coriolis meter and accurately known base oil and water densities. The base oil and water densities must be supplied to the metering system from a source external to the Coriolis meter. The general concept was discussed in passing by Weinstein [5] but the authors cannot find any published water cut prediction uncertainties for this method.



$$X_l = \frac{\rho_{homogenous} - \rho_o}{\rho_w - \rho_o}$$

$$m_{oil} = m_{total} * (1 - X_l)$$
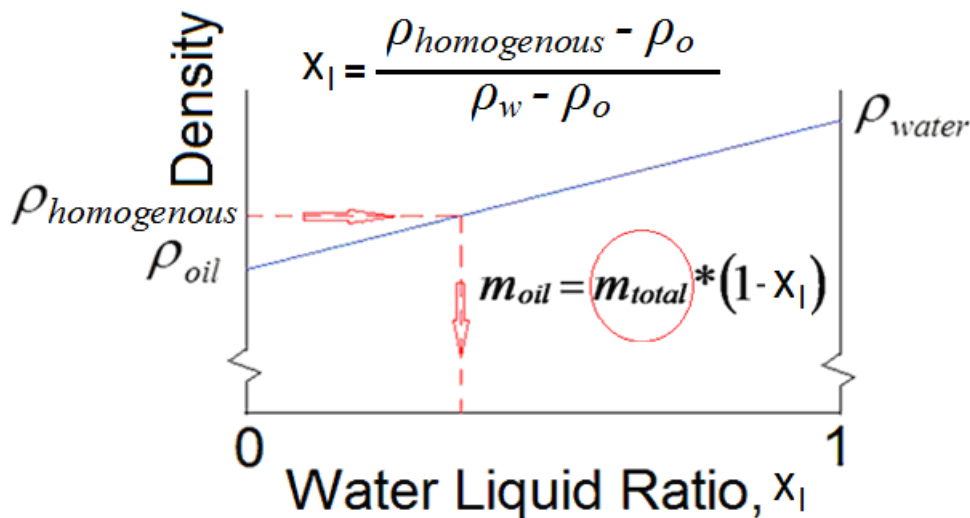
**Fig 9.  Sketch Showing the Coriolis Meter Water Cut Measurement Operating Principle**.

The theoretical concept on which a Coriolis meter can measure the 'water cut' is now described. The water cut refers to the water and oil relative volumes at standard conditions.  As the meter actually sees and reads at line conditions the Coriolis meter will not directly read the water cut. The Coriolis meter directly reads the mass water liquid ratio (or 'WLR', denoted here as $x_l$), i.e. the mass of the water to total mass of the liquid. Once the WLR is read that value can then be converted to a water cut value independently of the meter operation. Equation 3 shows the definition of the WLR and how the Coriolis meter can theoretically predict the WLR by the measured average or "homogenous" density and known base oil and water densities. Figure 9 shows Equation 3 in graphical form. The uncertainty of the Coriolis meter WLR measurement therefore depends on the uncertainty of the base density values used and how precisely the real meter performance fits the theoretical Equation 3.

$$x_l = \frac{m_w}{m_o + m_w} = \frac{\rho_{homogenous} - \rho_o}{\rho_w - \rho_o} \quad \text{---- (3)}$$

In 2010 Scheers [1] used this concept to carry out a hypothetical worked example to indicate the importance of multiphase meters having correct fluid property inputs. By making the simplifying assumption on this desk top exercise that the Coriolis meter will behave precisely according to Equation 3, Scheers then showed the sensitivity of the water cut prediction to even slight errors in the base oil and

water density inputs. Scheers was not inferring the Coriolis meter would in reality agree exactly with the hypothetical Equation 3. The assumption simply allows the effect of base oil and water density biases on water cut prediction to be isolated and studied.
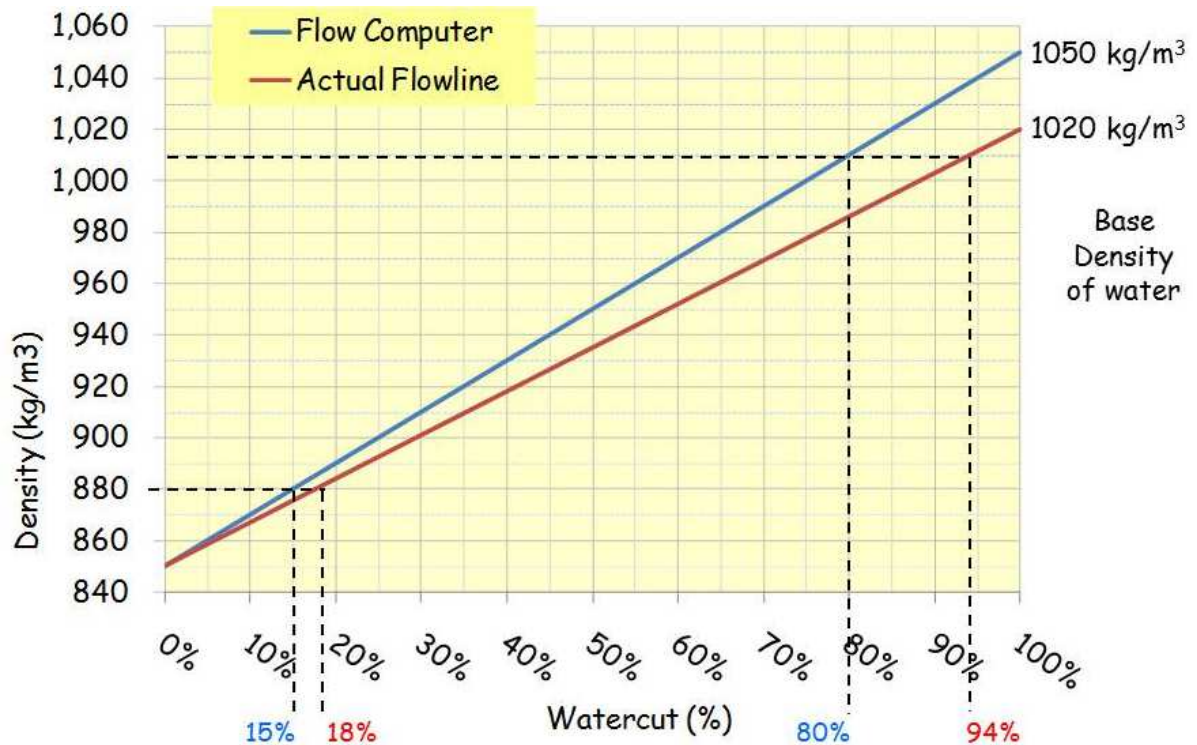


**Fig 10. Scheers [1] Hypothetical Example Showing Corilois Meter Water Cut Prediction Sensitivity to Base Oil or Water Density Biases**.

Figure 10 reproduces the Scheers [1] graph. (In this example Scheers makes the simplifying reasonable assumption that WLR and water cut can be considered approximately the same.) The correct oil and water base densities are 830 kg/m$^3$ and 1020 kg/m$^3$ respectively. If the Coriolis meter behaved precisely as predicted by Equation 3, then for the correct base oil and water densities the correct water cut would be predicted. In this example for the correct fluid densities (i.e. the 'Actual Flowline' red line) an average / homogenous density of 1010 kg/m$^3$ indicates a 94% water cut, or an average / homogenous density of 880 kg/m$^3$ indicates a 18% water cut. However, Scheers then showed the effect just one fluid density input being slightly incorrect. If the water density was not the keypad entry value of 1020 kg/m$^3$ but in reality 1050 kg/m$^3$ (i.e. as shown in the 'Flow Compute' blue line) then the water density input would be approximately 3% high. The knock on induced bias on the water cut prediction is significant. Figure 10 shows that this slight inaccuracy in base water density would mean that an average / homogenous density of 1010 kg/m$^3$ would indicate 80% water cut instead of 94% water cut, or an average / homogenous density of 880 kg/m$^3$ would indicate a 15% water cut instead of 18% water cut. Therefore, when using a Coriolis meter to determine the water cut it is imperative that the two fluid densities are known precisely. The similarity in oil & water densities are such that the density vs. WLR gradient is low and there is very little room for error in the flow computer keypad entry values. The Coriolis meter water cut prediction is very sensitive to base oil and water density biases. 0.5

This exercise by Scheers is very important when considering the uncertainty of a Coriolis meter water cut measurement. However, it is not the only issue. The other issue not addressed by Scheers (as it was separate to his main point) is how realistic is it to assume that the Coriolis meter performance in oil with water flow applications follows Equation 3 precisely? The average / homogenous density output of the 3" & 4" Coriolis meters are now examined to investigate this issue.

### 3.6.1 Coriolis Meter Water Liquid Ratio Prediction

Figure 11 shows the 4" Coriolis meter's oil with water homogenous (MUT) density reading vs. the flow facilities reference WLR values. Clearly the actual data does not precisely fall on the theoretical line stated by Equation 3. The 4" Coriolis meter tests were carried out with oil and water densities of 820 kg/m$^3$ and 997 kg/m$^3$ respectively. As expected, at the extremes of 0% & 100% WLR the Coriolis meter predicted the densities to low uncertainty (<0.5%). However, there is considerable scatter in the 4" Coriolis meter data, particularly at low WLR values. The very low velocity of a nominal 0.3 m/s has very large errors, the nominal velocity range of 0.6 < velocity, V (m/s) < 1.2 had moderate errors, and then the errors increased again as the velocity continued up to a nominal value of 2.6 m/s.
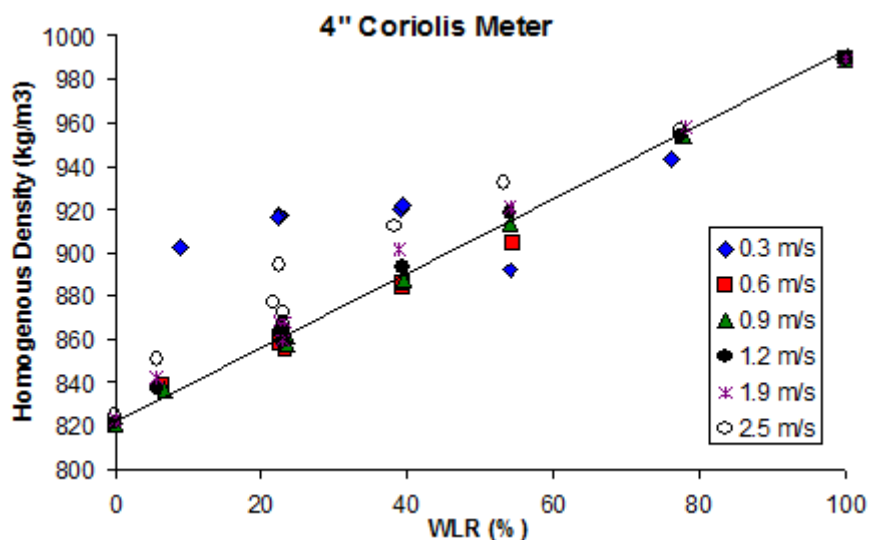


**Fig 11. 4" Coriolis Meter Homogenous Density Measurement vs. WLR%.**
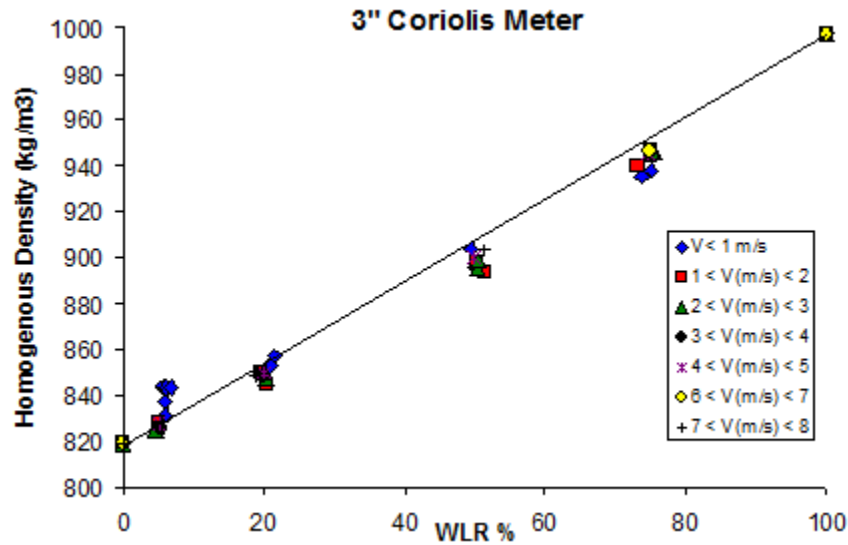
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Fig 12. 3" Coriolis Meter Homogenous Density Measurement vs. WLR%.

Figure 12 shows the 3" Coriolis meter's oil with water homogenous (MUT) density reading vs. the flow facilities reference WLR values. Again, clearly the actual data does not precisely fall on the theoretical line stated by Equation 3. The 3" Coriolis meter tests were carried out with oil and water densities of 820 kg/m$^3$ and 997 kg/m$^3$ respectively. As expected, at the extremes of 0% & 100% WLR the Coriolis meter predicted the densities to low uncertainty (<0.5). However, for oil with water flows the 3" Coriolis meter acts similarly to the 4" Coriolis meter. The homogenous density predictions have moderate biases. Very low velocities at < 1 m/s coupled with low water cut produced the greatest errors. In general, across the velocity range of 1 < Velocity V (m/s) < 8 m/s the 3" Coriolis meter's homogenous density prediction was slightly low. Compared to the 4" Coriolis meter the 3" Coriolis meter data has a smaller homogenous density prediction error, but this must be taken in context. The 3" Coriolis meter data is for a much higher average velocities, and hence much more oil and water mixing. At similar average flow velocities there is little difference between the 3" & 4" Coriolis meters.

Unfortunately the Coriolis meter's WLR prediction is very sensitive to homogenous density measurement biases. Therefore, for both the 3" & 4" Coriolis meters, these moderate homogenous density biases produce significant WLR (and therefore water cut) biases, even if the base oil and water densities are known precisely. This is now highlighted by a worked example.

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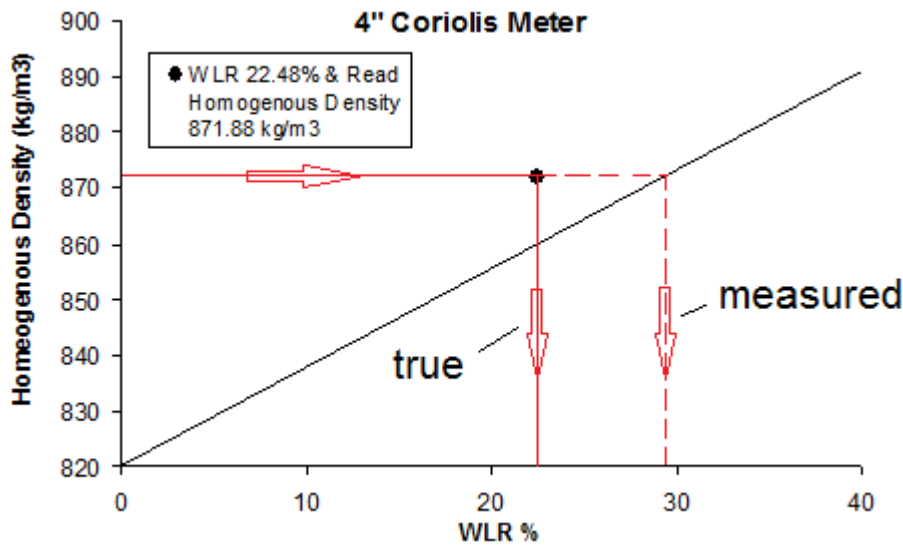


**Fig 13. An Isolated 4" Coriolis Meter Water with Oil Data Point For Use as Example.**

Figure 13 shows a single CEESI test result from the 4" Coriolis meter test matrix. A relatively low flow velocity (of 1.2 m/s) and WLR (of 22.5 %) were chosen along with a modest WLR prediction error (relative to the range of errors shown in Figure 4). This ensures the example does not show unusually large mis-measurements.

The facility reference meters state that the actual oil flow rate was 6.72 kg/s and the actual water flow rate was 1.95 kg/s, i.e. an actual WLR of 0.225 (i.e. 22.5%). The reference facility total liquid mass flow rate measurement was 8.67 kg/s. The Coriolis meter under test predicted a total liquid flow rate of 8.72 kg/s. This is a difference of < 0.6%, which is a good oil with water flow rate prediction. The Coriolis meter homogenous density prediction is 871.9 kg/m$^3$. For correct oil and water base densities of 820 kg/m$^3$ and 997 kg/m$^3$ Equation 3 predicts a WLR of 0.293 (i.e. 29.3%).

$$ x_l = \frac{m_w}{m_o + m_w} = \frac{\rho_{\mathrm{hom}ogenous} - \rho_o}{\rho_w - \rho_o} = \frac{871.9 - 820}{997 - 820} = 0.293 $$

Hence, the measured total liquid mass flow rate of 8.72 kg/s is split into 29.3% water and the remainder of 70.7% oil. Therefore the meter predicts 6.16 kg/s of oil and 2.56 kg/s of water. As the reference oil flow meter stated the oil flow rate was 6.72 kg/s the oil flow rate error from the 4" Coriolis meter under tests is approximately -8.3% (i.e. a loss of 0.56 kg/s). In this example the Coriolis meter is under-reading the oil production by 48,384 kg/day, or approximately 370 barrels per day. Note that this example assumes the precise base oil and water densities are used in the calculation. The oil flow rate prediction bias may be higher if one or both of the base densities also have a bias.

It would not be a fair comparison to simply compare the Coriolis meter performance to the test facility reference meters. It is not reasonable to assume

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test facility uncertainties in the field. A fair comparison requires the Coriolis meter performance be compared to the typical industry metering alternative. Only then is the performance of the Coriolis meter seen in context. Industry practice is to use a liquid meter to predict the total volume (or mass) flow rate. In this respect the Coriolis meter's performance is very good, e.g. in this example the 4" Coriolis agreed with the reference facility total flow rate to <1%. However, the WLR prediction had a larger error of about -8.3%. In the field industry usually uses mixer / sampler systems to measure the WLR. Although these are spot checks they look to give WLR values with <1% uncertainty. Hence, to see the performance of the Coriolis meter WLR prediction in proper context it should be compared against the sampling system WLR uncertainty (and not the facility reference system).

In the field where sampling is carried out the actual WLR of 22.5% would be found to within 1%. So we can reasonably use a WLR of 23.5% in this example. The Coriolis meter's total liquid mass flow rate of 8.72 kg/s would be split into 23.5% water and the remainder of 76.5% oil. Therefore the meter predicts 6.67 kg/s of oil and 2.05 kg/s of water. As the reference oil flow meter stated the oil flow rate was 4.93 kg/s the oil flow rate error from the 4" Coriolis meter coupled with the typical sample system WLR prediction is approximately -0.76% (i.e. a loss of 0.05 kg/s). In this case the Coriolis meter is under-reading the oil production by 4,406 kg/day, i.e. approximately 34 barrels per day. Therefore, in this example the increase in oil flow rate error between using the Corilois meter WLR prediction and using the traditional sample system in conjunction with the Corilois meter total mass flow rate prediction is 370 – 34 = 336 barrels of oil per day. Foe example if this was Brent crude at US$100 per barrel that is US$33,600 lost per day.

This example was not chosen to show a worst case scenario. The data point was chosen as the oil flow rate and WLR prediction error was seen as modest compared to some data points. There is little doubt that Coriolis meters are excellent single phase oil flow meters. Furthermore, it has been shown here that Coriolis meters exhibit very good total oil with water flow rate prediction performance across the full WLR range (at > 1 m/s). However, these test results indicate that the current Coriolis meter technology does not predict an oil with water WLR (or water cut) to the same low uncertainty as the traditional mixer / sampling arrangement. It is noteworthy that although Coriolis meter manufacturers mention the meters ability to monitor water cut no measurement uncertainty is stated. It appears that the current state of technology is such that Coriolis meters are a good choice for metering the total flow rate of oil with water flows, but they should be used in these applications in conjunction with mixer / sampler systems to find the WLR / water cut. The Coriolis meter WLR / water cut prediction method is a good continuous on-line WLR monitor, but it is not a precise measurement suitable for fiscal measurement.

## 4.      CORIOLIS METER DIAGNOSTICS AND OIL WITH WATER FLOW

During these tests both the 3" & 4" Coriolis meters had their full diagnostic output recorded. The tube amplitudes and time difference diagnostics showed little WLR information. However, the drive gain showed some relationship with WLR. The Coriolis meter drive gain is a measure of the power required to excite the flow tubes. The tubes are driven at resonance mode (i.e. at a tube bending natural frequency) in order to minimize the power required to excite the tubes. Single phase / homogenous flows do not produce much of a damping effect and hence

do not significantly shift the resonance frequency. However, two-phase / non-homogenous flows may create a significant damping effect which will significantly shift the tube bending resonance frequency. In this case, as the excitation frequency is set as a constant value, the shift of the resonance frequency away from this set frequency results in an increase of power required to excite the tubes. This is indicated by an increase in drive gain.

The Coriolis meter drive gain vs. WLR results are analogous to the Coriolis meter wet gas flow response described by Stobie et al [6]. Stobie stated that for a wet gas flow "… drive gain increase significantly when liquid fraction increases. The increase in drive gain is quite steep with a very small amount of liquid. The key observation here is that in dry gas conditions the drive gain is very low and stable. When liquid is introduced to the stream, the drive gain increases dramatically and also becomes more variable. Hence drive gain is a good indicator of liquid presence in wet gas streams for the Coriolis meter. The capability can be very useful in stopping the unintended receipt of liquids in a customer's gas system, and possibly mitigating the liquid loading of non-valuable liquids in a gas stream".

Figures 14 & 15 show the drive gain vs. WLR for the 4" & 3" Coriolis meters respectively. The single phase oil or water flows have low and relatively stable drive gains. The 4" Coriolis meter's single phase drive gain was approximately 11%, while the 3" Coriolis meter's drive gain was approximately 5%. Drive gain can vary slightly between Coriolis meters and these results are within the normal range. For both meters as WLR increased from 0% there was a significant increase in drive gain. This increase was heavily influenced by the average flow velocity although the precise relationship was complex. It is a curious point that for either meter with any given WLR the drive gain increase is least at the lowest average velocity. That is, for either Coriolis meter the drive gain shift is least where the oil and water flow at the meter inlet was most separated.
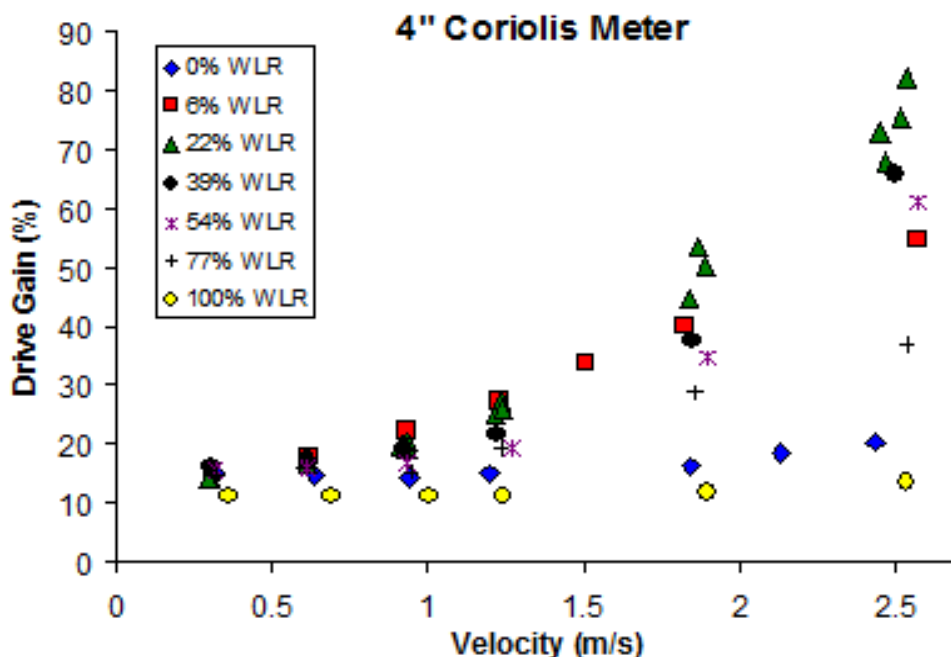


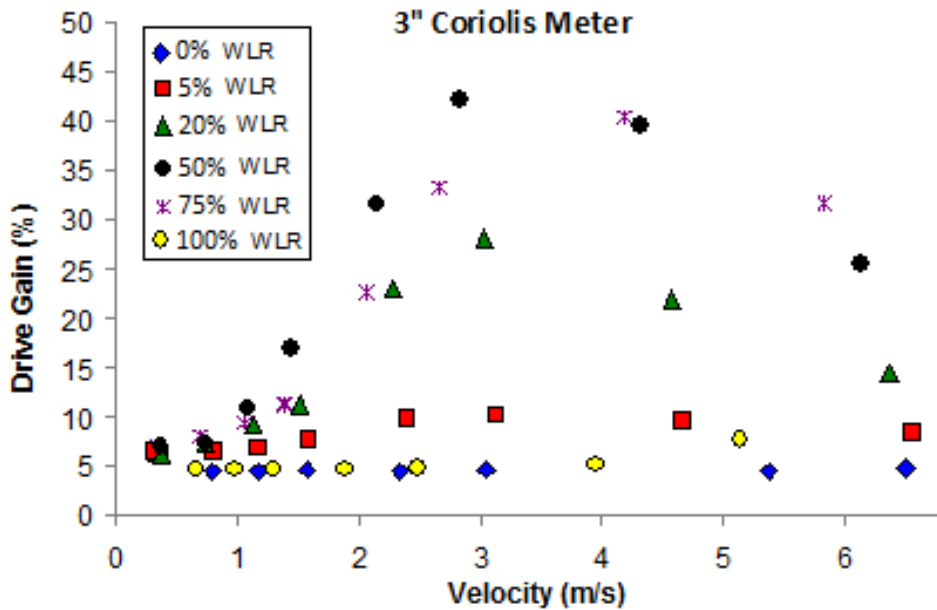**Fig 14. 4" Coriolis Meter Drive Gain vs. Average Velocity**.

**Fig 15. 3" Coriolis Meter Drive Gain vs. Average Velocity.**

The 4" & 3" Coriolis meters did not exhibit the same drive gain vs. WLR relationships, but they were not tested over the same average flow velocity range. The 4" meter tended to have a drive gain that increased up to about 50% and then reduced again until the 100% WLR water flow was similar to the 0% WLR oil flow. The 3" meter tended to have a drive gain that increased as soon as water appeared in the oil, and was affected by the average flow velocity, but between the range of 6% ≤ WLR ≤ 75% the relationship was more complex. It may be possible for a R&D project to characterize such behaviour but such work is out with the scope of this paper. However, from these results we can now modify Stobie's comments on wet gas flow to cover oil with water flow:

The drive gain increases significantly when water is present in an oil flow. The increase in drive gain is quite steep as the WLR increase slightly above 0%. The key observation here is that for single phase oil flow conditions the drive gain is very low and stable. When water is introduced to the oil stream, the drive gain increases dramatically and also becomes more variable. Hence drive gain is a good indicator of water presence in an oil production flow. This capability can be very useful in stopping the unintended receipt of water in a customer's oil flow system, and possibly mitigating the presence of non-valuable water in an oil stream.

## 5.0    Discussion of Results

A superficial glance at the 3" & 4" Coriolis meter results may suggest that their oil with water flow performances were different. However, the meters were tested over different average pipe velocities. Figure 16 shows total mass flow prediction data from both meters plotted on the same graph. Figure 17 shows homogenous density data from both meters plotted on the same graph. When accounting for average velocity the 3" & 4" Coriolis meter's oil with water flow performance look very similar. For the total mass flow rate prediction there are three general phases:
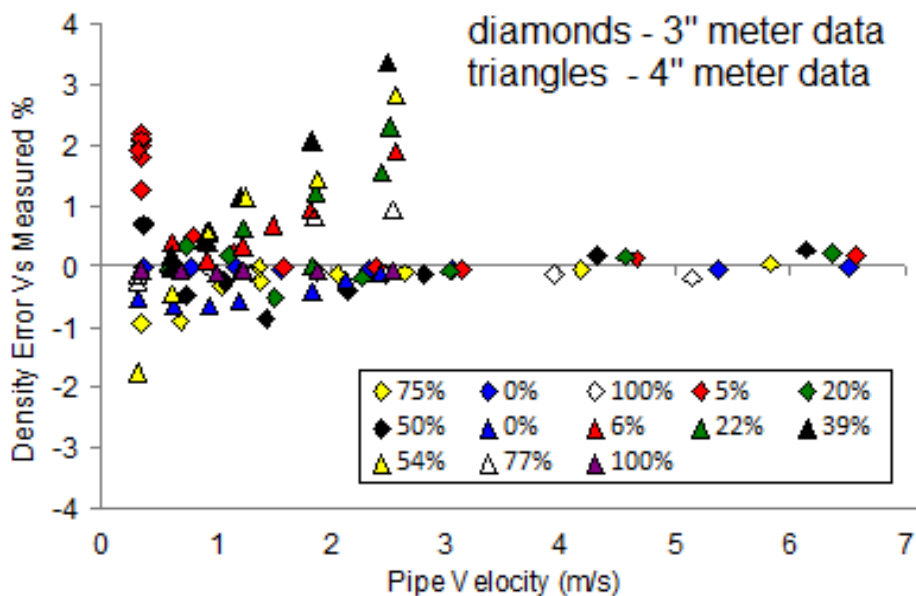
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- At the lowest velocity, < 0.5m/s, the oil and water flow were separated at the inlet and the meters total mass flow rate predictions show relatively large variations with WLR.
- At 0.5< V(m/s) <3m/s where there is some phase mixing the total mass flow rate predictions improves, but it is still significant at +/-0.7%. The scatter reduces towards 3m/s.
- At > 3 m/s where the phases are well mixed the Coriolis meters predict the total mass flow rate, assuming the offset is a calibration difference, to +/-0.2% (meaning there is no significant difference between the MUT and the reference meters).
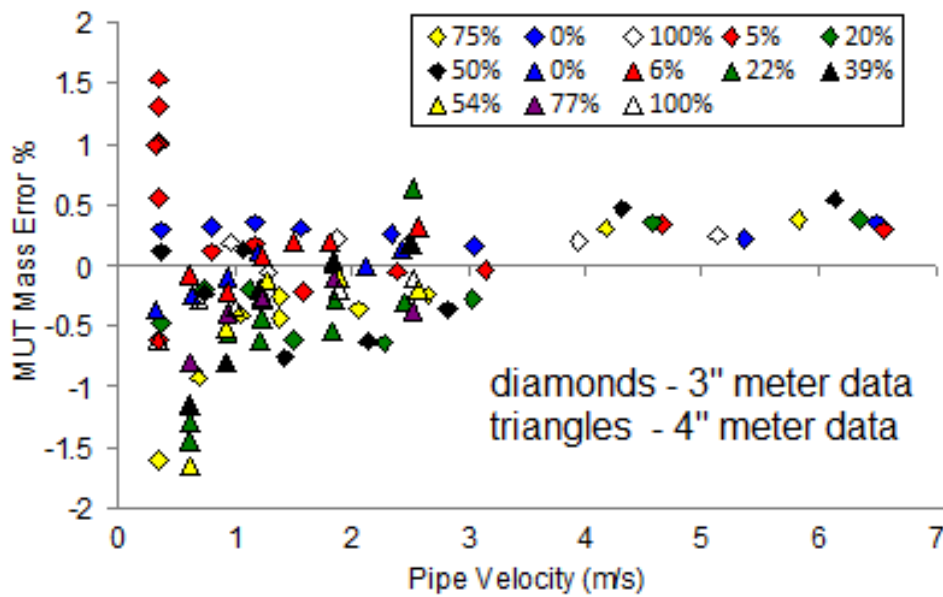


**Fig 16. Both Meters Under Test Total Mass Flow Rate % Error vs. Average Pipe Velocity.**



**Fig 17. Both Meters Under Test Homogenous Density vs. Average Pipe Velocity.**

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The homogenous density results are not as clear as the total mass flow rate prediction results. The 3" & 4" Coriolis meters may show different homogenous density prediction performance. The 3" Coriolis meter's homogenous density prediction has three general phases in line with the total mass flow rate prediction performance:

- At the lowest velocity, < 0.5m/s, the oil and water flow were separated at the inlet and the 3"meters homogenous density prediction has a large variations with WLR.
- At 0.5 < V(m/s) < 3m/s where there is some phase mixing the 3"meters homogenous density prediction scatter is less, but it is still significant at +/- 1%. The scatter reduces towards 3m/s.
- At > 3 m/s the 3" Coriolis meters predict the total mass flow rate to +/- 0.3%.

The 4" Coriolis meter was only tested up to an average flow velocity of 2.5 m/s. At < 0.5 m/s, where the oil and water were separated, the meters homogenous density prediction performance was similar to the 3" meter, with large variations with WLR. Figure 17 has the homogenous error range capped at 4% to allow resolution of the main data set, but Figure 6 shows < 0.5 m/s homogenous density errors at > 4%. However, by 1 m/s the 4" Coriolis meter's homogenous density prediction becomes very good (at < 1%) but then has an increasing scatter as the velocity increase to 2.5 m/s. This performance is not the same as the 3" Corilois meter and is contrary to the performance expected as the average velocity and associated level of mixing increases. It could be assumed that as the average velocity increases further the homogenous density prediction uncertainty will reduce, but that has not yet been shown. Therefore, the Coriolis meter has been shown to predict the total mass flow of oil and water mixture flow well at > 1 m/s, but the Coriolis meter homogenous density prediction at > 1 m/s is still in question.

These results are very similar to Ultrasonic meter oil and water mixture flow test results given by Cousins et al [7]. Just as stated here regarding the Coriolis meter performance with oil and water mixture flows, Cousins showed that during Ultrasonic meter horizontal clear pipe tests the average flow velocity dictated the level of oil and water mixing and therefore the Ultrasonic meter performance. Figure 18 shows stills of this phenomenon.

- Below 1m/s the water dropped out of the oil and traveled along the bottom of the pipe as a separate stream. There was very little mixing.
- Between 1 & 3m/s the oil and water flowed separately, but with a wide mixing layer between the oil and water streams. This is a partially mixed transition region.
- At > 3m/s the oil and water looked to be well mixed.
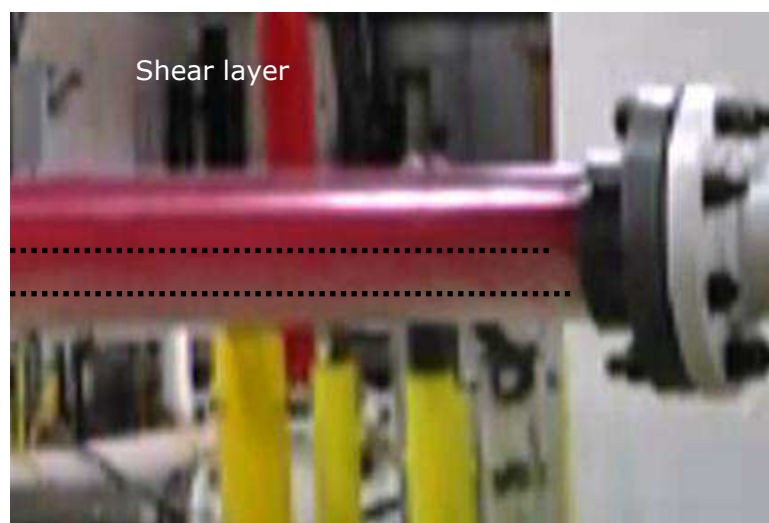
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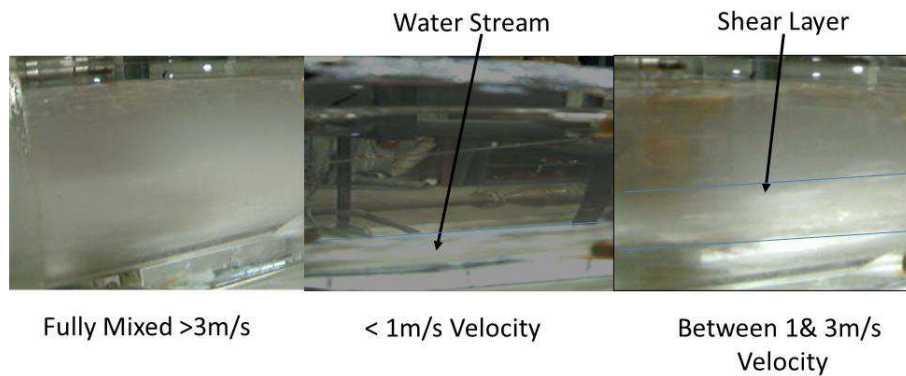


**Fig 18.  Photographs of Three Distinct Regions of Velocity Driven Oil & Water Mixing**.

The clear piping of the CEESI oil and water test facility allowed CEESI to view the level of mixing at the inlet to the test meters. Similar mixing levels were seen at CEESI as shown in Figure 18. Figures 19 to 21 show separated flow at <1 m/s, partially mixed transition flow at 1.2 m/s and fully mixed flow at >2.5 m/s.
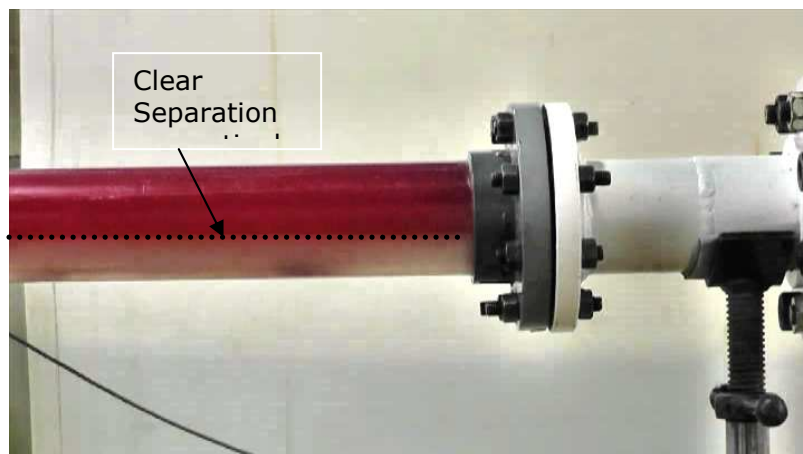


**Fig 19. Separated Flow at 0.3/s and 35% WC**



**Fig 20. Partially Mixed Transitional Flow at 1.2 m/s and 35% WC**

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**Fig 21. Fully Mixed Flow at 2.5 m/s**

The smaller cross sectional area of Coriolis meter tubes compared to the inlet pipe will cause the average flow velocity in the Coriolis meter to be higher than the inlet velocity. Nevertheless, for the Coriolis meter design tested here at least, the test data indicates that it is the inlet average flow velocity that dictates the meters performance with oil and water mixture flows. In later tests it would be interesting to view the flow in the tubes with a Perspex tube model.

The common term in multiphase and two-phase flow technology to describe the dispersion of two phases within a pipe flow is the "flow pattern". The flow pattern is a description of the physical dispersion of the phases in the flow. Hence, the flow pattern describes the level of mixing of an oil and water flow.

It is possible that different Coriolis meter designs will exhibit different sensitivities to oil and water mixture levels (or "flow patterns"). That is, different Coriolis meter designs may show performance shifts at different average velocities and associated mixing levels / flow patterns than the meters tested in this project. The flow pattern produced by an oil and water flow of a given velocity may be influenced by other parameters, such as oil viscosity, pipe orientation, line size etc. For example, the higher the oil viscosity the more resistant to mixing the oil and water flow will be. Therefore, the test results in this paper are sample results only, and only directly applicable to the meter design tested, the meter size tested and for the fluid properties tested. Nevertheless, these results confirm an important link between the Corilois meter's total mass flow rate and homogenous density prediction performance and the level of mixing at the inlet to the meter.

## 7.    CONCLUSIONS

The Coriolis meter is a very good single phase liquid meter. With good single phase liquid mass flow rate and density measurement capability the Coriolis meter is a popular choice for single phase processed oil flow metering applications. However, an oil and water mixture flow is an adverse flow condition for all flow meters, including the Coriolis meter. Nevertheless, Coriolis meters are promoted as viable metering technology for this adverse flow metering application.

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As CEESI has built an oil with water flow facility CEESI decided to independently test 3" & 4" Coriolis meters in this adverse flow condition. After confirming the meter types good performance with single phase oil and water flows the meters were tested in oil with water flow conditions. It was found that the level of oil and water mixing influenced the Coriolis meters performance. At > 1 m/s the 3" & 4" Coriolis meters total mass flow rate prediction was < 1%, which matches or exceeds the performance of competing technologies (see Cousins [3]). At < 1 m/s the oil and water flow became separated and the Coriolis meter total mass flow rate prediction becomes erratic. However, the Coriolis meter's density prediction uncertainty was significantly higher with oil and water flows than single phase liquid flows. As with the total mass flow rate prediction, the Coriolis meters average / homogenous density prediction was poor for both meters tested when the phases were separated at < 1 m/s. The performance was better at > 1 m/s but the 3" & 4" meters results differed. The 3" Coriolis meter predicted the homogenous density to <1% at > 1 m/s, but the 4" Coriolis meter predicted the homogenous density to only < 4% % at > 1 m/s.

The homogenous density is used to predict the WLR (and therefore water cut) in conjunction with known base oil and water densities. Unfortunately there is a relative shallow gradient between the density difference (between oil & water) and WLR. This means that the Coriolis meter method of predicting WLR is highly sensitive to both base density errors and homogenous density prediction errors. As such, even the 3" Coriolis meter with a <1% homogenous density error and correctly known base oil & water densities produced significant errors in WLR. In fact the testing carried out was with oil of a density that gave a reasonable slope. The heavier oils will have an even smaller gradient. This relatively high uncertainty WLR prediction coupled with the relatively low uncertainty total mass flow rate prediction produces a high uncertainty oil flow rate prediction. It is therefore not advisable to rely on a Coriolis meter to predict the WLR when low uncertainty oil metering is required.

It is advisable when using a Coriolis meter with oil and water mixture flow to keep the average flow velocity as high as possible. This facilitates mixing and reduces the meters total mass flow rate prediction uncertainty. It is then advisable to predict the oil flow rate from combining this information not with the meter's high uncertainty WLR prediction, but with an externally sourced WLR reading (such as from a mixer / sampler system) of low uncertainty. However, although the Coriolis meter does not appear to have a WLR prediction of low enough uncertainty for custody transfer metering, the WLR prediction method is still potentially valuable as a WLR monitor. Most low uncertainty WLR predictions come from spot check technology, i.e. mixer / sampler systems. This means between samples the operator is blind to changes in WLR. A Coriolis meter WLR monitor (even of relatively high WLR prediction uncertainty) could still see shifts in WLR if not measure them accurately. This in itself is potentially beneficial.

Furthermore, the Coriolis meter drive gain diagnostic is another beneficial tool. Operators who do not believe they have water in their oil flow, but consider it a possibility that needs to be monitored for could find the drive gain information important.

In summary, the Coriolis meter is a viable choice as an oil and water mixture flow meter. The Coriolis meter's performance at low flow velocities is poor, but so are the other competing meter technologies (see Cousins [3]). As long as the average velocity is high enough to cause significant oil and water mixing then the Coriolis meter total mass flow rate prediction is comparable to or better than competing

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technologies. The Coriolis meter WLR prediction is not accurate enough to be used as a custody transfer measurement, but nevertheless, the WLR prediction is a viable WLR monitor (if not meter) and the drive gain diagnostic is a viable water presence alarm system. Coupled with an independent WLR measurement system the Coriolis meter is a good choice for oil and water mixture flow metering applications.

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