Correcting a Coriolis Meter for Two Phase Oil & Gas Flow

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1 INTRODUCTION

In the oil & gas industry, the requirement for flow measurement of two phase oil and gas flow is prevalent. This stems from the fact that the output characteristics of production wells can alter significantly over time and the level of entrained gas within an oil flow can vary.

It is also common for flowmeters to be installed downstream of a two or three phase separator. If the well conditions change or the separator has been incorrectly sized, then it is possible that the oil liquid outlet may have some gas carry under. The effects of gas entrainment on the output of ultrasonic and Coriolis meters has been reported previously [1] [2]. It is already known that gas entrained in flowing liquids has the potential to lead to a substantial mis-measurement of the flow.

However, the utilisation of advanced diagnostics on the performance of flowmeters in two phase liquid/gas flow has not yet been explored. Coriolis flowmeters offer diagnostic capabilities that could potentially be used to predict and possibly even correct for the presence of a second phase within the flow. It is reasonable to predict that different Coriolis devices with their own diagnostic capabilities will be affected in different ways, but to date the diagnostic capabilities of these technologies for two phase flow measurement are not yet well defined.

To improve this situation, NEL have completed an investigative programme into the performance of a Coriolis flowmeter in two-phase liquid/gas flow. This paper reports on the diagnostic parameters of Coriolis flowmeters when operated in two phase liquid/gas flow. Furthermore, the author presents a method of correcting the liquid mass flow output from the device in the presence of a second gas phase.

2 FLOW MEASUREMENT CHALLENGES

Flow measurement of two phase flow presents additional technical challenges compared to single phase flow. Challenges such as signal loss, meter damage and pressure drop will be discussed in more detail in the sections below.

2.1 Effects of Gas Entrainment on Conventional Liquid Flow Meters

The effects of gas entrainment / two phase flow are complicated and will likely differ depending on metering technology applied.

A positive displacement (PD) meter is a volumetric device and as such, the measurement error will be directly related to the quantity of gas entrained within the fluid. As the measurement principle of a PD device is based upon the displacement of a known volume per revolution, any entrained gas could lead to
an over reading of the fluid liquid flow rate. For example, if the fluid has a gas entrainment level of 5% GVF then the volume of the fluid will be 5% gas and thus constitute at least a 5% error in the liquid volumetric flow rate measurement. The potential also exists for large pockets of gas to accumulate inside the measurement chambers, which may cause the device to over-spin which would ultimately damage the meter internals [3].

**Differential pressure** (DP) devices such as Venturi tubes or orifice plates make up a considerable proportion of the flow meters currently used in the world. These meters have been in operation for many years, and have been widely studied and characterised by correlations such as the Reader-Harris/Gallagher equation [4]. The correlations and standards assume ideal or stated ranges of operating conditions. However, the effects of gas entrainment on DP devices are not currently governed by any industry standard. The discharge coefficient (C_D) is known to be strongly dependent on Reynolds number for highly viscous fluids, however to date there has been little characterisation of the effects of gas entrainment on the DP meter’s C_D.

In **turbine** meters, gas entrainment within flow will cause the meter to misread the liquid volumetric flow rate. Without correcting for the void fraction, the degree of error and sign is dependent on the flow conditions and also which type of turbine meter is used [5]. Large slugs of gas travelling through the device at high velocities could cause the meter to over spin or even result in significant damage to the turbine blades within the device. The extent of the damage will be meter and condition dependent. It is possible that the blades could be bent out of plane or even broken off entirely. This would affect the k-factor of the device and thus the measured flow rate uncertainty, repeatability and reproducibility.

Compared to the other flow meters listed above, **ultrasonic** meters are viewed as being a relatively “modern” technology. They are volumetric devices and can offer diagnostic software that can monitor, trend and report on all of the information recorded. This can then theoretically be used to improve meter accuracy and performance. Gas entrainment within transit time ultrasonic meters could potentially result in ultrasonic paths “failing” which might result in inaccuracies in the flow measurement. Advanced diagnostics could potentially be used to determine if there are any issues within the fluid such as gas entrainment, which might adversely affect the ultrasonic flow meter response. A low signal to noise ratio alarm setting could indicate signal attenuation due to gas particles interfering with the ultrasonic beam [6]. Potentially the signal could deteriorate to such an extent that it is no longer detectable at the receiving transducer; with the result that the path “fails”. Most multipath meters are able to compensate for a failed path at the expense of an increase in uncertainty. However, gas entrainment could potentially result in multiple paths “failing”, possibly resulting in larger uncertainties in the recorded measurements.

In theory, the presence of entrained gas shouldn’t adversely affect the mass flow reading of **Coriolis** flow meters. However, gas entrainment within the flow tubes can result in spikes in the tube damping which can adversely affect both the mass flow and density measurement. Another issue could be non-homogenous mixing of the gas within the fluid. The consequence of this might be that there is an uneven distribution of entrained gas through the flow tubes which could cause mismeasurement of the flow and density. Similar to ultrasonic devices, Coriolis meters are also deemed as a “modern” technology and can offer advanced diagnostics [6]. The tube damping and operating frequency are both important...
diagnostic parameters and any fluctuations can be used to indicate the presence of solids, particles or gas within the flow tubes.

### 2.1.2 Pressure Drop

Pressure loss is a critical consideration since frictional losses increase with GVF. There is therefore an incentive to minimise flowmeter pressure drop to avoid excess pumping power requirement. If the differential pressure across a flowmeter is sufficiently high it could potentially lead to internal (and unmeasured) leakage of fluid through the device. In extreme cases its mechanical integrity might even be compromised.

Coriolis flowmeters are known to have a notable pressure drop due to the design of the measuring tubes within the device. To avoid a large pressure drop, some users might select a flowmeter that has a larger bore than the line size. For example, a 6-inch (152.4 mm) flowmeter for a 4-inch (101.6 mm) line size.

More likely, is that the pipe size is increased to reduce pressure loss and velocity in the main pipeline. The pipe size will then have to be reduced to ensure the flowmeter is within its operating range. Operating too far down the operating range can result in a higher flow measurement uncertainty through poor linearity and decreased repeatability. However, local pressure drops will then dominate with potential risk of flashing or cavitation.

### 2.2 Scope of Current Work

The effect that two phase flow has on the current generation of liquid flowmeters (Coriolis and ultrasonic) has already been reported [1] [2]. However satisfactory methods for correcting Coriolis devices in the presence of two phase oil and gas flow has not yet been defined. This follows partly from the scarcity of suitable test facilities capable of providing two phase flow in combination with accurate and traceable reference instrumentation.

The work completed in this project will detail the performance of a 4 inch Coriolis mass flowmeter in two phase oil & gas flow. Furthermore, the author will look at correcting the mass flowrate for single phase oil in the presence of a second gaseous phase.

Specific objectives of the present work were to:

- Zero the device and generate a flow calibration curve at a nominal viscosity of 25 cSt with a 12 point calibration (3 repeats at each flowrate).
- Test the device at 0 – 10 % Gas Volume Fraction (GVF) at a flow range of 10 – 40 kg/s (3 repeats at each test condition).
- Repeat the two phase flow tests to ascertain reproducibility.
- Log the diagnostics from the Coriolis device.
- Devise a method for correcting the mass flow output for single phase oil in two phase oil and gas flow.
3 TEST METER

3.1 Test Meter Description

The flowmeter evaluated in this test programme was a 4 inch (101.6 mm) Coriolis device. This project was not structured as an evaluation of any particular manufacturer or flowmeter model, but rather as a generic evaluation of whether the effects of two phase flow on Coriolis flowmeter technology can be corrected for by utilising the devices diagnostics. As such, the manufacturer of the flowmeter evaluated in this programme has not been named.

3.2 Coriolis Operating Principle

Coriolis flow meters provide a direct measurement of mass flowrate and product density with stated uncertainties as low as 0.1% and 0.05 kg/m$^3$ respectively for light hydrocarbons. The exact specification differs by manufacturer and model type. Advantages such as high accuracy, claimed insensitivity to installation and direct measurement of mass flow have led to wide scale adoption across a number of sectors, including the food, pharmaceutical and process industries.

![Figure 1: Example of Coriolis Flow Tube Configurations](image)

The principle measurement method used in Coriolis meters is the use of tubes that are vibrated at their natural frequency. When no flow is present, the tubes show no sign of twist and remain in phase. However, once flow is applied Coriolis forces produce twisting in the tubes. By measuring these twists, or more correctly the time shift in phase of oscillation of each measuring tube, a mass flowrate can be calculated.

No two Coriolis meters are identical and hence there are small variations in natural frequency of the oscillating tubes. This coupled with the wide range of process conditions any meter is expected to work in means that potential errors could be present. However, a simple zeroing process in operation is claimed to eliminate these issues leaving the meter able to achieve its stated uncertainty in all operating conditions. Consider equation 1 [1]:

$$Q_m = FCF(\Delta t_m + \Delta t_{live\_zero} - \Delta t_{stored\_zero})$$  \hspace{1cm} (1)

The mass flowrate, $Q_m$, can be calculated using equation 1 where FCF is the flow calibration factor, $\Delta t_m$ is the measured time difference caused by the mass flow of the fluid only, $\Delta t_{live\_zero}$ is the measured time difference due to the live zero value and $\Delta t_{stored\_zero}$ is the stored zero value from the meters previous use.
By zeroing a meter after installation, the stored zero value then equals the live zero value therefore eliminating any zero effect from the meter. The mass flowrate can then be calculated using equation 2 and any measured time difference is only due to the mass flowrate only.

\[ Q_m = \text{FCF} \times \Delta t_m \] (2)

By zeroing a meter at process conditions, the user is effectively calibrating out any effect of tube rigidity at those process conditions. This means that any variations in meter construction, thermal expansion or contraction of the meter body can be minimised.

Typically, the zero value is given as a mass flowrate i.e. the mass flow that the meter would record at zero flow conditions. There is a limit to the value that would constitute an acceptable zero. This differs by meter size and manufacturer.

A Coriolis flowmeter will also provide a density measurement. The density measurement is derived from the natural frequency of oscillation of the flow tubes, which varies with mass. A change in the mass results in a change in the frequency. As the volume of the flow tubes is constant, the oscillation frequency is a function of fluid density.

### 3.3 Coriolis Diagnostics

The following measurement parameters are available for diagnostics. The name of the system parameters may vary from one vendor to the other.

**System parameters**

- Frequency
- Operating frequency fluctuation
- Driver energy level (display of driver energy in percentage)
- Driver amplitude or oscillation amplitude
- Excitation current
- Tube damping (= excitation current / oscillation amplitude)
- Tube damping fluctuation
- Phase shift
- Strain (resistance of strain gauge in “Ohms”)
- Electro-dynamic sensor or sensor symmetry

Both process and system parameters are normally compared with reference values (finger print) saved in the flow meter system to ensure correct operation of the flow meter as described below.

**Reference Values (Finger Print)**

Reference values of the process and system parameters are recorded for trend analysis. These are determined under reproducible and constant conditions. The reference values are initially recorded during calibration at the factory and saved in the measuring device. Each Coriolis flow meter has a unique finger print due to the tolerances in the manufacture of the flow meter.

Reference data can also be ascertained under customer-specific process conditions, e.g. during commissioning or at certain process stages such as cleaning cycles.
4 EXPERIMENTAL PROGRAMME

4.1 Oil Flow Facility

The experimental programme was completed in 2011 at the UK National Standards Oil Flow Facility, located at NEL in Glasgow, Scotland. The facility consists of two separate flow circuits (A and B), each with a high capacity and a low capacity flow line. These can accommodate nominal pipe sizes from 0.5” to 10” (12.7 – 254 mm), and can operate at line pressures up to 10 bar. Test fluids can be delivered at flowrates up to 720 m³/hr.

Six test fluids are available in this facility – Kerosene, Gas Oil, Velocite, Primol, Siptech and Aztec – covering liquid viscosities from 2 to 1500 cSt. Figure 2 displays the kinematic viscosity of NEL’s test fluids for the Oil Flow Facility in 2011.

Figure 2: Kin. Viscosity of NEL test fluids

Figure 3 shows a schematic diagram of the flow circuits. The oil for each circuit is drawn from a 30 m³ supply tank, from where it is discharged to the test lines. A conditioning circuit, linked to each tank, maintains the oil temperature to within ± 0.5 °C of a pre-selected value (itself set in the range 10 – 50 °C).

The main test line can accommodate up to 30 m of horizontal straight lengths or alternative configurations as required. The test line can also accommodate 1 metre long sections of Perspex pipe work to enable flow visualisation. At the outlet of each test section, a manifold directs the test fluid back to the storage tank or to one of the calibrated weigh tanks.
Line temperature and pressure are monitored both upstream and downstream of the test section. The flow lines share a common primary standard weighbridge system consisting of four separate weigh tanks of 150, 600, 1500 and 6000 kg capacity. The facility is fully traceable to National Standards and is accredited by the United Kingdom Accreditation Service (UKAS) to ISO 17025.

4.2 Reference System

For ‘primary’ calibrations, a gravimetric ‘standing-start-and-finish’ method is used to determine the quantity of fluid (volume or mass) which has passed through the flowmeter under test and into the selected weigh tank. The gravimetric weigh tanks constitute the primary reference standard of the NEL oil flow facility.

Using the above technique, the overall uncertainty in the quantity of fluid passed, expressed at the 95% confidence limit is ± 0.03 % (k = 2). For a ‘secondary’ calibration, the quantity of oil passing through the test meter is measured using a pre-calibrated reference meter, installed in series. The reference meters used at NEL have a history of previous calibrations and typical uncertainties in the quantity of fluid passed of the order of ± 0.08 % (k = 2). This applies to oils with a kinematic viscosity between 2 – 30 cSt.

In this evaluation programme, the oil flow facility was operated in ‘re-circulation’ mode and the test meter compared against secondary reference standards – in this case a pre-calibrated volumetric device. The reference meter was installed upstream of the gas injection point for these tests to ensure that it monitored the liquid flowrate only.

The reference meter used in the present test programme consisted of one 8 inch rotating-vane Positive Displacement device (Smith Meters™), manufactured by FMC Technologies. The “K-factor” for this type of PD meter can be considered to be a function of three main parameters: the volumetric flowrate (Q), the liquid viscosity (ν) and the fluid temperature (T).
The PD meter was calibrated (as a function of flowrate only) for the fluid temperature and fluid type detailed in the test matrix. This provided the most accurate reference for testing and produced a K-factor curve of the form:

\[ K_{F,T} = f_{F,T}(Q) \]  

where F and T denote the fluid type or test temperature respectively. The resultant uncertainty of the PD meters in service was of the order of ± 0.08 % at the 95% confidence level.

### 4.3 Test Matrix

The investigative programme used mineral oil Velocite as the test fluid and was based around 4 inch schedule 40 pipe work. Before the effects of two phase oil & gas flow were evaluated, the devices were zeroed and calibrated in single phase oil flow at 20 °C across a range of mass flowrates. The nominal test matrix of Table 1 details the work proposed.

<table>
<thead>
<tr>
<th>Flow m³/hr</th>
<th>Gas Volume Fraction %</th>
<th>Flow kg/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>x x x x x</td>
<td>10</td>
</tr>
<tr>
<td>85</td>
<td>x x x x x</td>
<td>20</td>
</tr>
<tr>
<td>127</td>
<td>x x x x x</td>
<td>30</td>
</tr>
<tr>
<td>169</td>
<td>x x x x x</td>
<td>40</td>
</tr>
</tbody>
</table>

Tests were conducted at a kinematic viscosity of 25 cSt and a fluid temperature of 20 °C.

To investigate the sensitivity of the Coriolis flowmeter to the presence of entrained gas, a short series of tests were conducted on both flowmeters in which Nitrogen was injected at a controlled and monitored rate, upstream of the test meter location. One PD reference meter was installed upstream of the gas injection point for these tests to ensure that it monitored the liquid flowrate only.

The injection system consisted of a pressurised gas inlet stream and a series of reference flowmeters – one small and one large variable area meter and three gas turbine meters (½ inch, ¾ inch and 1 inch) – together with pressure and temperature sensors.

Pressure transmitters were located at the inlet of both test meters to allow offline calculation of the local gas volume fraction. The temperature sensor was located as close to the flowmeters as possible.

### 4.4 Test Meter and Set-up

The test meter used in this experimental programme was supplied by the manufacturer and was installed, set up and tested by NEL.
The test meter was a nominal 4 inch Coriolis mass flowmeter device. The meter was supplied with 4 inch ANSI 150 flanges. The device also had the latest electronics installed.

The meter was installed horizontally as recommended by the manufacturer for measuring liquid flows. The PD liquid reference meter was installed 40 Diameters (D) upstream of the Coriolis flowmeter. The gas injection point was located 30 D downstream of the PD meter and 10 D upstream of the Coriolis test flowmeter. A bellows was installed 3 D downstream of the Coriolis flowmeter. After installation the bellows and sliding joint were locked to provide a rigid pipe installation.

4.5 Test Procedures

In this test programme, the oil flow facility was operated in ‘re-circulation’ mode and the test meters compared against secondary reference standards – in this case pre-calibrated volumetric.

The test line was filled with the test fluid and circulated at 20 °C before the slide and bellows were locked up to provide a rigid installation to relieve line stress.

The first phase of the test programme was to zero the Coriolis flowmeter at 20 °C at zero flow conditions. The flow in the test line was stopped and ‘locked in’ by closing the valves upstream of the Coriolis flowmeter. The flowmeter was then zeroed according to the manufacturer’s guidelines.

After a stable and acceptable zero had been established, the fluid flow within the test line was restarted and the fluid temperature in the line maintained at 20 °C. The flowmeter was then calibrated with three test points across a mass flow range of 10 – 40 kg/s. The results for the calibration are provided in Table 2.

The second phase of the test programme was to inject gas into the test line to enable the response of the flowmeter at various GVFs to be recorded. The fluid temperature was maintained at 20 °C. The flowmeter was then tested at a GVF range of 1 – 10 % across a mass flow range of 10 – 40 kg/s. The two phase oil and gas tests were then repeated the following day to assess reproducibility. The results for these tests are provided in Tables 3 and 4 respectively.

5 TEST RESULTS

5.1 Single Phase Mass Flowrate Results

The first set of results in the test programme was the initial calibration of Meter Z at 20 °C in the NEL oil flow facility. The purpose of this test was to achieve a satisfactory baseline calibration. Figure 4 displays the 20 °C baseline calibration with a 2nd order polynomial curve fit applied. The device is slightly out of the manufacturer’s specification of ± 0.1 %. 95% of the data is within ± 0.173 %.
The repeatability of the device was assessed simply by comparing the percentage difference between the errors in the total mass for three successive runs at the same nominal flowrate.

\[ r = \sigma \cdot t \cdot \sqrt{2} \]  

(1)

Where:
- \( r \) = Repeatability
- \( \sigma \) = Standard Deviation
- \( t \) = Students’ t

### TABLE 2
SINGLE PHASE FLOW REPEATABILITY

<table>
<thead>
<tr>
<th>Nominal Mass Flow [kg/s]</th>
<th>Repeatability [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.038</td>
</tr>
<tr>
<td>20</td>
<td>0.014</td>
</tr>
<tr>
<td>30</td>
<td>0.017</td>
</tr>
<tr>
<td>40</td>
<td>0.024</td>
</tr>
</tbody>
</table>
5.2 Two Phase Mass Flowrate Results

The second set of results in the test programme was the two phase oil and gas tests on Meter Z at 20 °C in the NEL oil flow facility. Figure 5 displays the deviations in the mass flow error for all of the test data. Meter Z under reads the mass flow rate for all the test conditions. 95% of the data is within ± 5.76 %.

Figure 5: Two Phase Oil & Gas Tests for Meter Z Day 1

Figure 6 displays the deviations in the mass flow error for all of the test data separated by GVF. It can be seen that for the majority of test conditions, the meter under read increased as the GVF increased.
To evaluate the effect of increasing GVF on the performance the Coriolis device, Figure 7 displays the test data, separated by mass flowrate, plotted against GVF.

Table 3 below summarises the standard deviation repeatability of the three repeat points at each test condition. At higher GVFs the scatter in the data increases.
This could be due to different flow regimes occurring and irregular slugs of gas forming.

### TABLE 3
**TWO PHASE FLOW REPEATABILITY DAY 1**

<table>
<thead>
<tr>
<th>Nominal Mass Flow [kg/s]</th>
<th>GVF [%]</th>
<th>Repeatability [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1</td>
<td>0.468</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.000</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.450</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.139</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>0.178</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.044</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.147</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.459</td>
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<tr>
<td>30</td>
<td>1</td>
<td>0.251</td>
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<td>3</td>
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<td>10</td>
<td>4.319</td>
</tr>
<tr>
<td>40</td>
<td>1</td>
<td>0.187</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.400</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>4.159</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>3.420</td>
</tr>
</tbody>
</table>

The third set of results in the test programme was the two phase oil and gas tests on the Meter Z at 20 °C in the NEL oil flow facility that assess the reproducibility of the device. These tests were completed the day after the second set of results and were completed using an identical test matrix.

Figure 8 displays the deviations in the mass flow error for all of the test data. It can be seen that the data follows a similar trend to the previous data. Meter Z under reads the mass flow rate for all the test conditions. 95% of the data is within ± 6.69 %.
Figure 8: Two Phase Oil & Gas Test Data for Meter Z Day 2

Table 4 below summarises the standard deviation repeatability of the three repeat points at each test condition. As before, at higher GVF the scatter in the data increases.

### TABLE 4

TWO PHASE FLOW REPEATABILITY DAY 2

<table>
<thead>
<tr>
<th>Nominal Mass Flow [kg/s]</th>
<th>GVF [%]</th>
<th>Repeatability [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1</td>
<td>0.059</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4.871</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.062</td>
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<tr>
<td></td>
<td>10</td>
<td>1.868</td>
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<tr>
<td>20</td>
<td>1</td>
<td>0.459</td>
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<td></td>
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<td></td>
<td>5</td>
<td>1.584</td>
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<td>0.529</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>4.176</td>
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<tr>
<td></td>
<td>0</td>
<td>1.298</td>
</tr>
<tr>
<td>40</td>
<td>1</td>
<td>2.579</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.511</td>
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<td></td>
<td>5</td>
<td>3.020</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>4.943</td>
</tr>
</tbody>
</table>
Figure 9 displays the deviations in the mass flow error for both Day 1 and Day 2. It can be seen that two phase test data from the two calibrations looks both repeatable and reproducible.

![Figure 9: Two Phase Oil & Gas Test Data for Meter Z Day 1 & 2](image)

### 5.4 Diagnostic Results

The diagnostic measurement drive gain is displayed in Figure 10 at a liquid mass flowrate of 10 kg/s at 1 – 10 % GVF with respect to log time. The log time was 180 seconds for each test point. To present a usual visual, a 100 second snapshot has been displayed in Figure 10.
Drive gain is often regarded as being a useful parameter for identifying gas entrainment. The results show that this is the case and that when gas entrainment occurs, the drive gain increases from the ‘baseline’ value of 5 % to 100 %. As discussed in Section 3.3, the drive gain represents how much energy is required to oscillate the Coriolis tubes at their resonant frequency. When a second gaseous phase is present, the tubes must work harder and as such the drive gain increases.

Figure 10 suggests that drive gain is a qualitative diagnostic in that it can indicate when gas is present but not the quantity of gas or the deviation caused by the secondary gaseous phase. Figure 11 below displays the drive gain plotted against GVF.
The diagnostic measurement ‘normalised tube frequency’ from Meter Z is displayed in Figure 12 below with respect to logging time. The normalised value is the recorded tube frequency value divided by the raw tube frequency when only filled with the test fluid. This value could be recorded with the ‘finger print’ data and then used as a key diagnostic parameter.
The tube frequency increases as the presence of gas increases within the oil phase. This is because the frequency of oscillation is related to the mass and stiffness of the measuring tubes. As gas has a low density, the tubes are lighter and the natural frequency is greater than with single phase oil. This results in a higher tube frequency being recorded.

Figure 12 suggests that tube frequency could be used as a quantitative diagnostic as there is a definitive relationship between the tube frequency and the GVF. Figure 13 displays how the normalised tube frequency could be used to predict the GVF of the flow within the Coriolis flowmeter. The relationship is linear and repeatable.

5.4 Corrected Two Phase Mass Flowrate Results

One of the objectives of this project was to derive a method of correcting for the presence of a second phase gas in single phase liquid flow measurement. The author of this report has developed a method of predicting the GVF at the test meter and then correcting the mass flowrate of the device. The process can be performed live and doesn’t require post processing. The steps are summarised below.

1. Monitor the uncorrected mass flowrate output of the Coriolis device along with tube frequency.
2. Convert the tube frequency into normalised tube frequency by using the ‘finger print’ data.
3. Predict GVF at test meter using normalised tube frequency.
4. Correct Coriolis mass flowrate output using predicted GVF.
Figure 14 displays the uncorrected and corrected data for the two phase oil and gas flow tests completed on Day 1. The correction was derived using Day 1 data so it is realistic to expect the performance of the correction on Day 1 to exceed Day 2.

![Coriolis Oil & Gas Tests Day 1](image)

**Figure 14: Corrected and Uncorrected Two Phase Oil & Gas Test Data for Day 1**

Figure 15 displays the uncorrected and corrected data for the two phase oil and gas flow tests completed on Day 2. The results show that the device is repeatable and reproducible and that the correction is robust.
Figure 15: Corrected and Uncorrected Two Phase Oil & Gas Test Data for Day 2

Table 5 summarises the standard deviation repeatability of the corrected test points at each test condition for both Day 1 and Day 2. Interestingly, the repeatability of the corrected results doesn’t differ much between Day 1 and Day 2. On Day 1, 95% of the data is within ± 1.46 %. On Day 2, 95% of the data is within ± 1.87 %.

TABLE 5
TWO PHASE FLOW CORRECTED REPEATABILITY DAY 1 & 2

<table>
<thead>
<tr>
<th>Nominal Mass Flow [kg/s]</th>
<th>GVF [%]</th>
<th>Day 1 Repeatability [%]</th>
<th>Day 2 Repeatability [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1</td>
<td>0.473</td>
<td>0.120</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4.018</td>
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5.4 Density Results

The density output from Meter Z was also recorded throughout the test programme. Figure 16 displays the fluid density measurements for the two phase oil and gas flow tests for Day 1 and 2. The density error is displayed with respect to mixture density.

The results from Day 1 and Day 2 display a good overlap which suggests that the density response from the Meter Z is also repeatable and reproducible. The Meter Z appears to under read the mixture density as GVF increases. This could possibly be due to the range of the density calibration of the device or gas persisting in the flow tubes and resulting in a lower mixture density being recorded at the device.

![Coriolis Oil & Gas Tests Aug 2014](image)

**Figure 16: Two Phase Oil & Gas Tests for Meter Z**

Figure 17 displays the deviations in the density response for all of the test data, plotted against GVF. The density error is displayed with respect to mixture density.
The main conclusions for the Coriolis flow meter, Meter Z, when tested in two phase oil & gas flow at NEL's oil flow facility are:

- The presence of a secondary gas phase produced deviations in the liquid mass flow output of the device. An increase in GVF caused an increase in the under-reading of the liquid mass flowrate. An under-reading of -14.55 % was recorded at 10 % GVF at 10 kg/s. The largest errors occurred at the lowest mass flow.

- As the velocity of the oil flow increased, the mass flow response improved slightly. However the meter still significantly mis-measured the mass flow.

- Small levels of gas entrainment appear to have a significant effect on the density output from the Coriolis device. As the GVF increases, the under-reading of the density increased.

- Both the mass flowrate and density outputs from the device are repeatable and reproducible.

- By monitoring the tube frequency, the liquid mass flowrate can be corrected for the presence of a second gas phase. The author used this method for two sets of data. For the first set of data, 95% of the data was corrected to within ± 1.46 %. For the second set of data, 95% of the data was corrected to within ± 1.87 %.
7 FURTHER WORK

This test programme was carried out according to a fixed schedule at NEL’s oil flow facility. There is scope for further research work into the performance of Coriolis flowmeters in two phase oil & gas flow using the correction outlined by the author.

The correction appears robust however more work should be completed to assess whether the correction would be robust for a different installation. For example, the device should be installed at a different distance from the gas injection point to ascertain if gas slugging affects the correction. The device should also be installed vertically to ascertain if gas / liquid distribution affects the correction.

8 REFERENCES


