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# The Performance of Coriolis Meters in Two-Phase Liquid/Gas Flows

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## 1 ABSTRACT

A wide variety of industrial products are measured and traded on the basis of volumetric flowrate, but a disadvantage of this approach is that fluid volume is not a "conserved" physical quantity; varying with both the pressure and temperature of the product. Conversion of the measurements to a common standard (such as "base" or "stock-tank" conditions) requires input of the fluid's PVT behaviour, which itself introduces an additional uncertainty. Furthermore, the presence of secondary components – such as entrained gas within a liquid stream – can further distort the volumetric flow measurements.

Coriolis flow meters offer the advantage of direct mass flow measurement (as well as independent density information), which has led to their increasing adoption across a variety of industrial sectors. In particular, the technology has gained widespread acceptance within the food, pharmaceutical and process industries. In the hydrocarbon sector, the apparently low sensitivity of Coriolis meters to increasing fluid viscosity positions them as a key enabling technology in the worldwide shift from light to heavier crude oil production.

The development of liquid Coriolis meters is well advanced for single-phase flows, but an area of concern has been their accuracy and reliability in the presence of gas; and this can rarely be totally excluded. Two applications of Coriolis meters where the presence of gas is a possibility for the oil & gas industry are entrained gas in oil lines, and gas carry-under in separators. The major manufacturers are therefore focusing efforts on the development of meters for two-phase applications to address this specific need. However, there is little independent data available on the performance of these recent developments.

NEL undertook an independent evaluation of three 3-inch Coriolis meters, each with a different tube configuration, in two-phase oil/gas flow using the UK National Standards Oil Facility. This paper examines the performance of the Coriolis meters and gives recommendations on the expected errors.

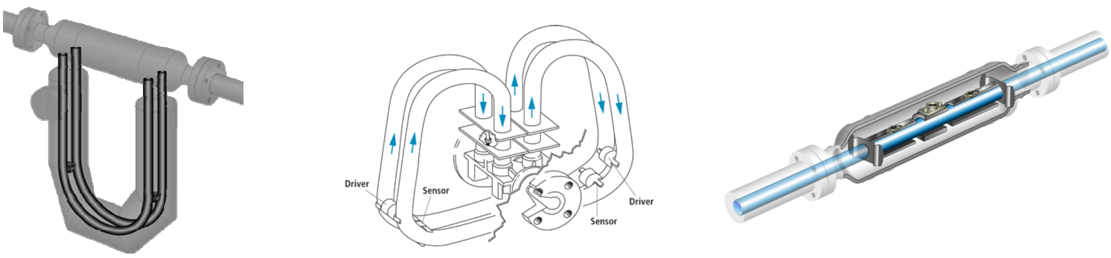
## 2 INTRODUCTION

### 2.1 Description of Operation

Coriolis forces are present when both translational (straight line) and rotational (revolving) movement occur simultaneously. The amplitude of the Coriolis force depends on the moving mass and its velocity in the system, and therefore its mass flow. The measuring principle of a Coriolis mass flow meter is based on the controlled generation of Coriolis forces. The sensor contains a flow tube (or tubes) oscillated (normally at their resonant frequency) such that, in the absence of flow, the inlet and outlet sections vibrate in phase with each other. When fluid is flowing, inertial (Coriolis) forces cause a phase shift between inlet and outlet sections. Two sensors measure the phase difference, and this is directly proportional to the mass flow. The natural frequency of oscillation will vary with the mass of the flow tube and since the mass and volume of the tube are effectively constant this frequency is related to the density of the fluid in the flow tube. This measured density can be used to convert the directly measured mass flow to a volumetric flow.

A Coriolis flowmeter consists of a sensor and a flow transmitter. The sensor is essentially a flow tube with drivers to monitor and maintain the flow tube oscillation. The flow transmitter provides the flow tube control, calculates mass flow and density information, provides user interface for configuration and information, and gives analogue and digital outputs.

Three main geometries of flow tube exist: split tube (Figure 1A), continuous tube (Figure 1B) and straight tube (Figure 1C).




A B C

**Figure 1 Examples of Coriolis Flow Tube Configurations**

## 2.2 The Effects of Two-phase Flow on a Coriolis Meter

The main impediment to accurate measurement under two-phase flow conditions using a Coriolis meter is a dramatic rise in the flow tube damping. Mechanical energy is lost in the interactions between compressible bubbles, fluid and flow tube walls, and the drive energy required to maintain oscillation increases. Not only does the damping rise, but it varies rapidly due to the chaotic nature of the phase distribution. Similarly, the frequency and amplitude of oscillation exhibit much greater variation than for single-phase flow [1].

Traditional Coriolis metering systems were unable to supply high enough drive current (due to intrinsic safety requirements) and drive gain to maintain the tube oscillation under two-phase conditions. They were also unable to respond fast enough to rapid changes in the natural frequency of resonance thus the sensor stalled and the transmitter went into fault.

Another source of error is the flowmeter zero. The mass flow error in Coriolis meters is related to the meter zero by **±0.1% ± [(Zero Stability/Flow Rate) x 100] % of rate** [2].

An accurate zero can normally only be attained under process conditions (i.e. at operating pressure, temperature, and full of fluid) and at zero flow. It is not possible to obtain a field zero in a two-phase flow owing to the inherent unstable nature of two-phase flows.

Back in 1998 NEL carried out an investigation into the effect of two-phase flow on single-phase flow meters [3]. Part of the investigation included testing Coriolis meters in oil/gas flows. Figure 2 shows the performance of the split U-tube Coriolis flow meter evaluated during the 1998 test programme in the presence of oil/gas flow and Figure 3 shows the performance of the straight tube device under the same conditions. Straight tube designs are considered less suitable for two-phase operation as they generally operate at a higher frequency. This causes the gas bubbles in the liquid to move more relative to the tube wall than in a lower frequency bent tube design.

The 1998 tests were carried out in the NEL Oil Flow Facilities using test oil with a viscosity of 10 cSt, and nitrogen gas injected at gas volume fractions of 6% and 9%. The Coriolis meters were installed horizontally in the facility. It should be noted that this test programme used the Coriolis meters as volumetric flow meters rather than mass flow meters thus the "error in reading" shown in Figures 2 and 3 is the error in volumetric flow rate rather than error in mass flow rate.

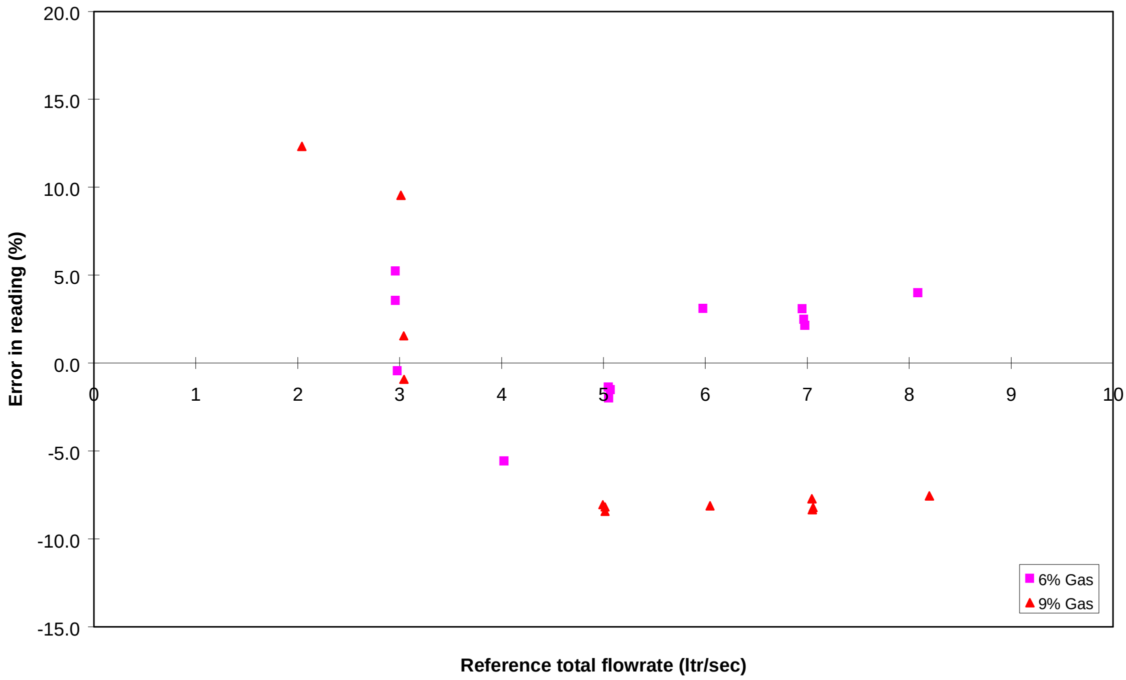



**Figure 2 2-Inch Split U-Tube Coriolis: Gas in Oil**

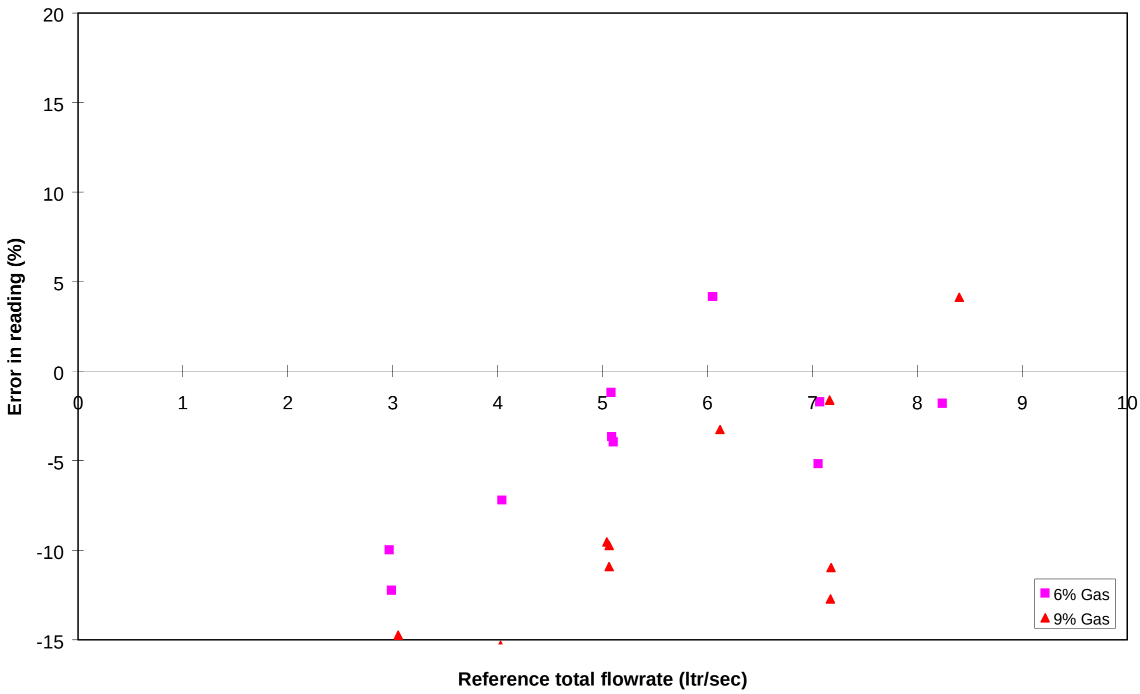



**Figure 3 1.5-Inch Straight-Tube Coriolis: Gas in Oil**

## 3 CURRENT STAGE OF DEVELOPMENT

Research is continuing into the operation of Coriolis flow meters under two-phase conditions and it is expected that these devices will continue to improve in terms of reliability and accuracy [4]. Owing to the inherent complexity of meter operation under two-phase conditions most major manufacturers are mainly concentrating their efforts on the area of entrained gas rather than the wider and more complex full range of two-phase flows. There is also a well defined existing market in entrained gas applications, likely to be less so in the wider area of two-phase flow. Figures 4 and 5 show flow pattern maps highlighting the area of two-phase flows where manufacturers claim current Coriolis technologies are likely to operate effectively.

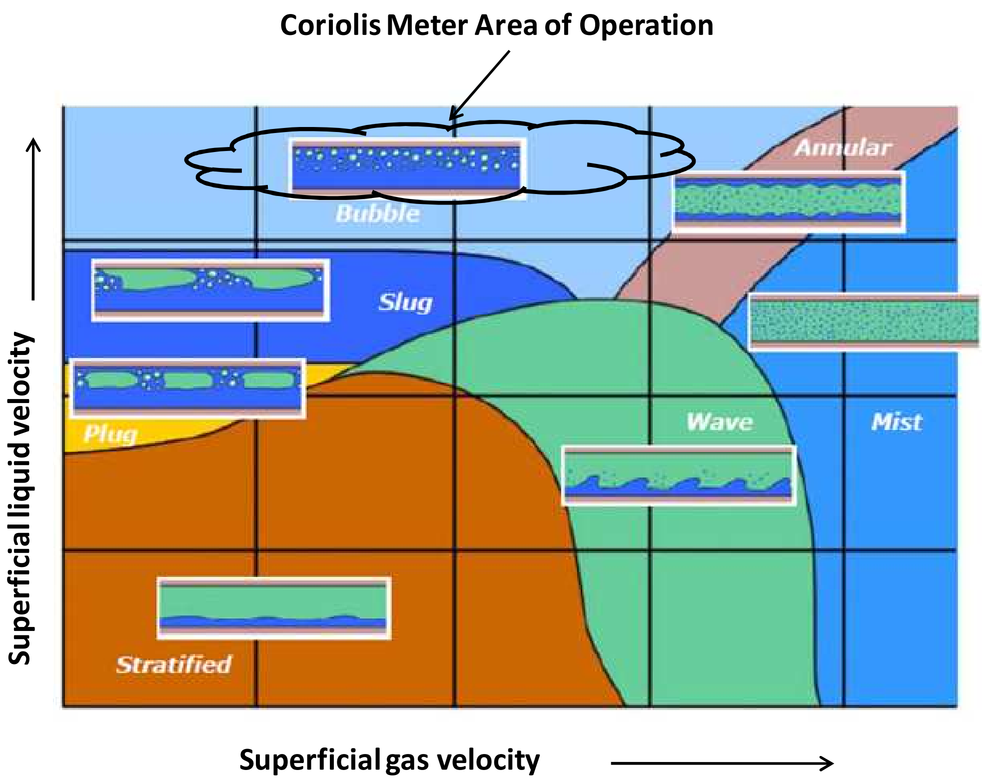



**Figure 4 Horizontal Flow Pattern Map**

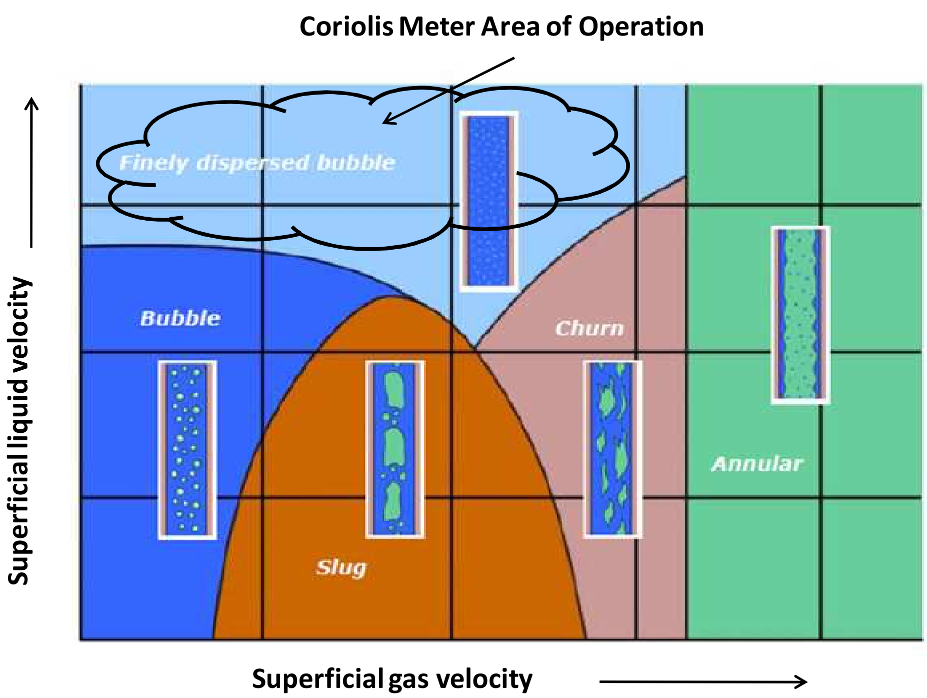
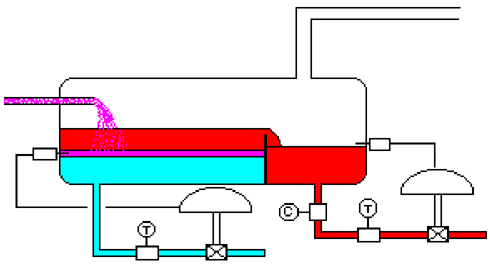



**Figure 5 Vertical Flow Pattern Map**

## 4 OIL & GAS APPLICATIONS

Whilst the oil & gas industry agree that the ability to measure mass flow directly is a benefit, there appears to be a lack of confidence regarding the performance of Coriolis meters in two-phase flow. Coriolis mass flow meters are widely used in the oil & gas industry to measure single-phase liquids. Even when a pipeline should only contain single-phase oil in reality the oil may contain entrained gas. Gas can become entrained during the loading and unloading of tankers, through changes in process conditions, or owing to poor separator efficiency.

Turbine meters have traditionally been used to measure liquid flow rates from test separators. In more recent years, Coriolis meters have been adopted to measure liquid flow rates from separator outlets. If a three-phase separator is working efficiently then the flow meters on the separator outlet streams will be measuring single-phase liquid or single-phase gas as can be seen in Figure 6A. Figure 6B shows the reality where test separators are often under-sized and the fluids are not given enough residence time to separate. This can lead to liquid carry-over and gas carry-under. In the case of gas carry-under this means the flow meter on a liquid separator outlet stream will actually be measuring two-phase liquid and gas [5]. (Similarly in the case of liquid carry-over, the flow meter on the gas separator outlet stream will be measuring wet gas as opposed to the dry gas application it was originally specified for.) As the well test engineers are assuming the test separator is working correctly no allowance for the presence of gas in the liquid stream will be made. With little independent data available on the performance of Coriolis meters in gas/liquid flow it is difficult for the operators to quantify the error in flow rate. Entrained gas is also often a feature of high viscosity fluids such as heavy oil and bunkering fuels. Another test programme undertaken by NEL has looked specifically at the effects of high viscosity fluids with entrained gas on single-phase flow meters [6] and so high viscosity liquids were not included as part of this test programme.

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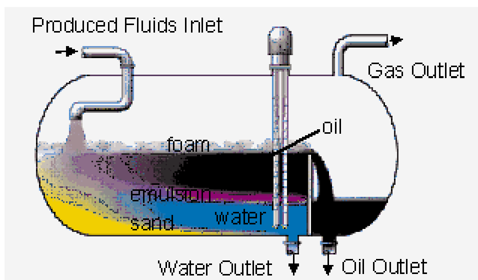


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**Figures 6A and 6B Examples of Good Separation and Reality Respectively**

# 5 EXPERIMENTAL PROGRAMME

## 5.1 NEL Oil Flow Facility

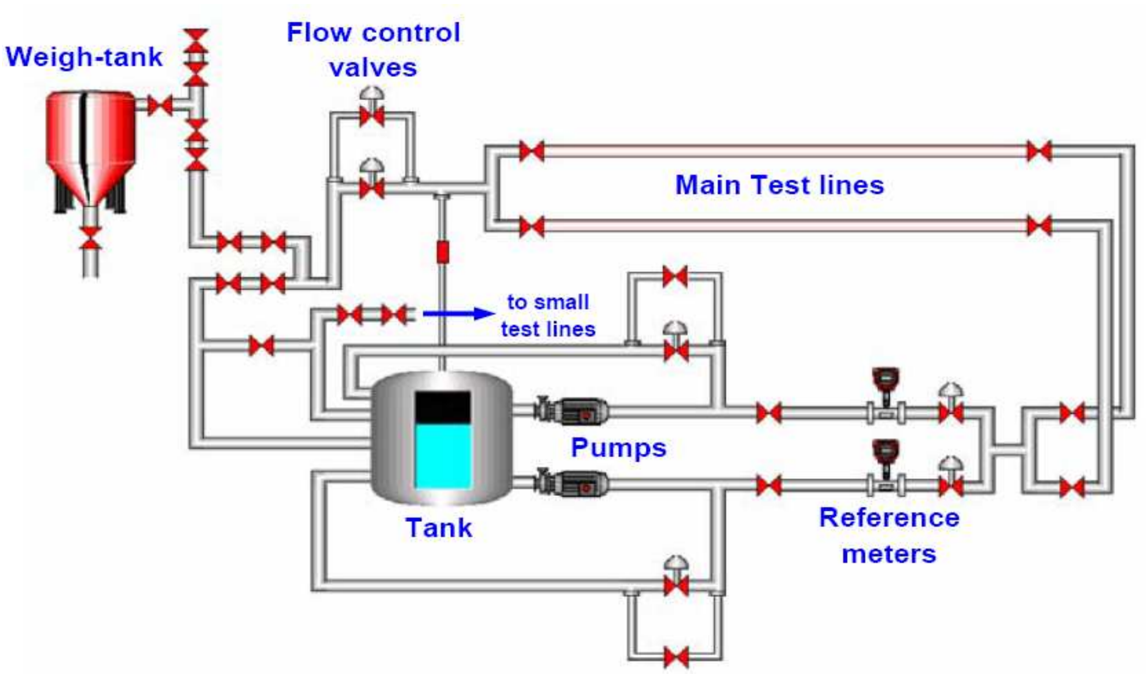


**Figure 7 Schematic Diagram of the UK National Standards Oil Flow Facility**

The UK National Standards Oil Flow Facility, located at NEL in East Kilbride, Scotland, 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 8”, and can operate at line pressures up to 10 bar. Test fluids can be delivered at flowrates up to 720 $m^3$/hr.

Figure 7 provides a schematic diagram of one of the flow circuits. The oil for each circuit is drawn from a 30 $m^3$ supply tank into the suction stream of the main pumps, from where it is discharged to the test lines. A conditioning circuit, linked to each tank, maintains the oil temperature to within ± 1 ºC of a pre-selected value (itself set in the range 5 – 45 ºC).

Each test line can accommodate up to 30 m of horizontal straight lengths or alternative configurations as required. At the outlet of each test section, a manifold directs the 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 weightanks 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).

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 weightank.

The gravimetric weightanks constitute the primary reference standard of the UK National Standards Oil Flow Facility. Using the above technique, the overall uncertainty in the reference flowrate, expressed at the 95% confidence level is approximately 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 meter used during this test programme had typical uncertainties of the order of 0.08 % (k = 2).

The storage tank that is used for the test work contains 25000 litres of the test fluid. It also has a ‘below the surface’ re-entry point and a baffle system to remove any bubbles. Moreover, the suction point for the pump is also at the opposite side of the tank from the re-entry point.

## 5.2 Test Fluids

There are several test fluids available for use at the UK National Standards Oil Flow Test Facility. The test fluids are all refined oils and cover a density range of 797 kg/m$^3$ for the lightest oil through to 867 kg/m$^3$ for the heaviest oil.

For these tests, lubricating oil was chosen as it is the test fluid with density and viscosity most similar to the “dead” crude oil used in the NEL Multiphase Flow Test Facility. The test oil had a density of 843 kg/m$^3$ and at test conditions its dynamic viscosity was 11 cP.

The gas injected into the UK National Standards Oil Flow Facility during the two-phase portion of this test programme was nitrogen gas.

## 5.3 Coriolis Meters

To allow comparison of the performance of each test meter on a like-for-like basis all the test meters were 3-inch nominal size. However, each test meter had its own, manufacturer-specific, flow tube(s) configuration. Each test meter was supplied with the latest electronics available from its manufacturer.

## 5.4 Reference System

During the two-phase portion of the test programme, the UK National Standards Oil Flow Facility was operated in “re-circulation” mode and the test meters compared with a secondary reference standard.

The reference meter used was a 3-inch turbine. Turbine meters give a pulsed output which is related to the number of revolutions the turbine makes which in turn is related to the flow rate of the fluid being measured. As turbine meters give a volumetric flow rate, this had to be converted to a mass flow rate using the live density of the lubricating oil.

Before the two-phase tests started, the reference 3-inch turbine was calibrated against the gravimetric primary standard. The uncertainty for the reference 3-inch turbine was 0.08% at a 95% confidence level.

The gas reference flowrate measurement was provided by three turbine flow meters and two variable-area meters all calibrated using NEL reference sonic nozzles. The uncertainty on the gas flowrate measurement was estimated to be 1.5% for the turbine flow meters and 3% for the variable-area meters.

## 5.5 Test Matrix

The test programme was designed first to calibrate the Coriolis meters in single-phase liquid flow to categorise base-line performance. Then two-phase tests were carried out using increasing gas volume fractions (GVF) through a range of liquid flow rates. The nominal test matrix used for the two-phase tests is given in Table 1.

**TABLE 1**

**NOMINAL TEST MATRIX**

| Liquid | Gas Volume Fraction % | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Flow m³/hr | 1 | 3 | 5 | 7 | 9 | 12 | 15 | 18 | 25 |
| 10 | x | x | x | x | x | x | x | x | x |
| 20 | x | x | x | x | x | x | x | x | x |
| 40 | x | x | x | x | x | x | x | x | x |
| 80 | x | x | x | x | x | x | x | x | x |
| 110 | x | x | x | x | x | x | x | x | - |
| 150 | x | x | x | x | x | x | x | - | - |

## 5.6 Test Procedures

### 5.6.1 Single-Phase Flow Tests

In order to establish a base line performance for the Coriolis meters, each meter was calibrated in single-phase liquid against the UK National Standards Oil Flow Facility's primary and secondary references.

Each Coriolis meter under test was zeroed at operating pressure and temperature with zero flow prior to the test programme starting.

The test fluid was circulated until a stable line temperature was achieved to achieve a viscosity of 11 cP. The reference turbine flowmeter and the Coriolis test meter were then calibrated in series against the primary system using the standing start-and-finish method. The performance of the Coriolis test meter was then checked with the facility operating in "recirculation" mode using the turbine as the reference. Outputs from the test meter, the reference 3-inch turbine meter, line pressures, and line temperatures were recorded using the NEL Oil DAQ system. The meter manufacturer also logged various parameters such as drive gain and tube frequency using their own meter diagnostic software.

The reference system and test Coriolis meter results were then collated and compared offline following collection of the raw data. As the reference flow meters measure a volumetric flow rate, this had to be converted to a mass flow rate using the density of the lubricating oil.

The Coriolis meter errors were then assessed as functions of reference liquid mass flow rate and reference gas volume fraction.

### 5.6.2 Two-Phase Flow Tests

Once the single-phase base-line performance had been recorded for the test meter, the effect of the presence of gas was then investigated. Figure 8 below shows the test set-up used to evaluate the performance of the Coriolis meters in two-phase flow. Nitrogen gas was injected, at a controlled and monitored rate, upstream of the test meter. The 3-inch reference turbine was installed upstream of the gas injection point to ensure it only measured the liquid flow rate with no gas present. Downstream of the gas injection point was a blinded tee to try and distribute the gas evenly through the liquid phase.

The gas injection system consisted of a pressurised gas inlet stream and a series of reference flow meters – one small and one large variable area meter and three gas turbine meters (1/2-inch, ¾-inch and 1-inch) – together with pressure and temperature sensors. All instruments were pre-calibrated at NEL.

Pressure measurements were taken immediately upstream of the test meter to allow offline calculation of the local gas volume fraction.

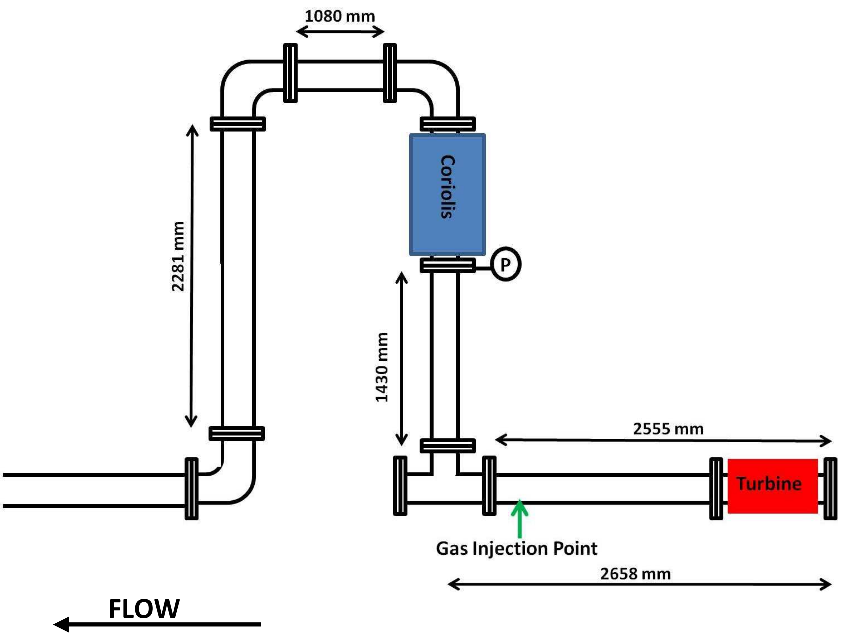


**Figure 8 Test Meter Installation**

## 6 SINGLE-PHASE RESULTS

The mass flow errors for Meters A, B and C are given in Figures 9 to 11 below. The mass flow errors are shown as a function of reference liquid mass flow rate.

Figure 9 shows the calibration curve for Meter A. It shows that Meter A always under-read mass flow with the worst performance at low mass flow rates. Figure 10 shows that Meter B under-read mass flow at low mass flow rates, and that Meter B gave the best performance of the three meters in single-phase oil. Figure 11 shows that Meter C also under-read mass flow at low mass flow rates.

The root mean square averages for each of the meters' mass flow errors are given in Table 2 below.

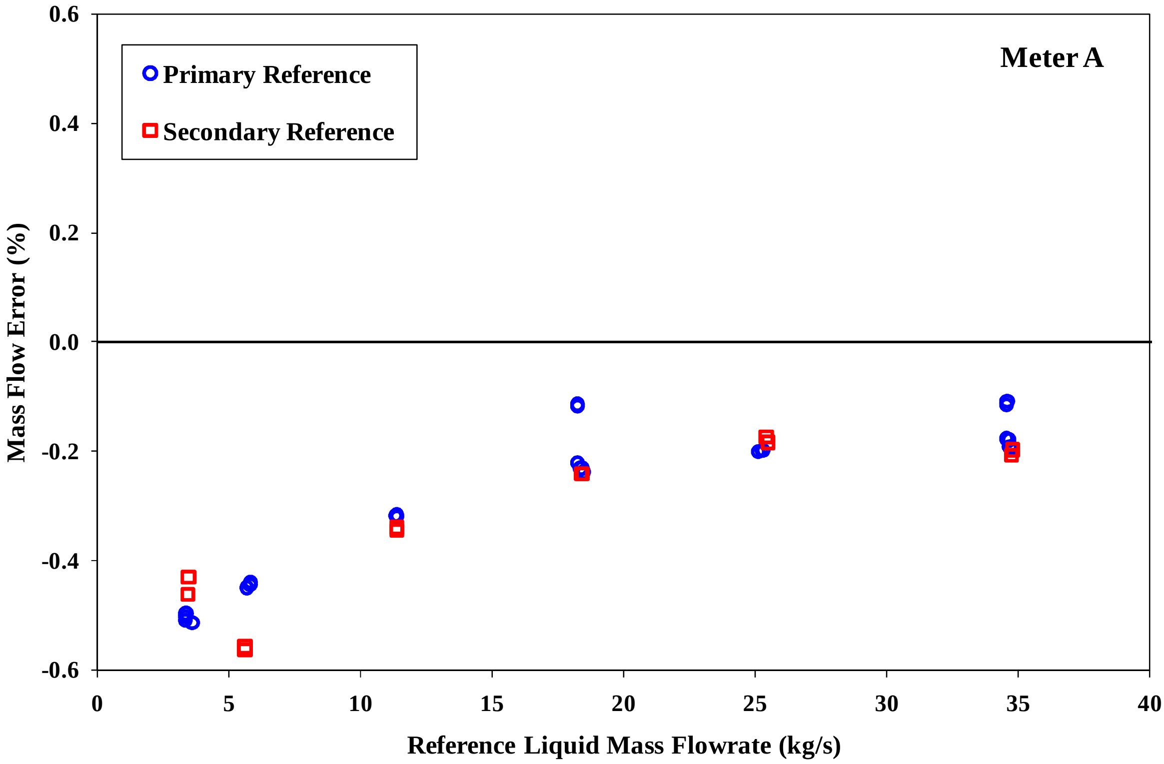


**Figure 9 Calibration of Meter A in UK National Oil Flow Standard**

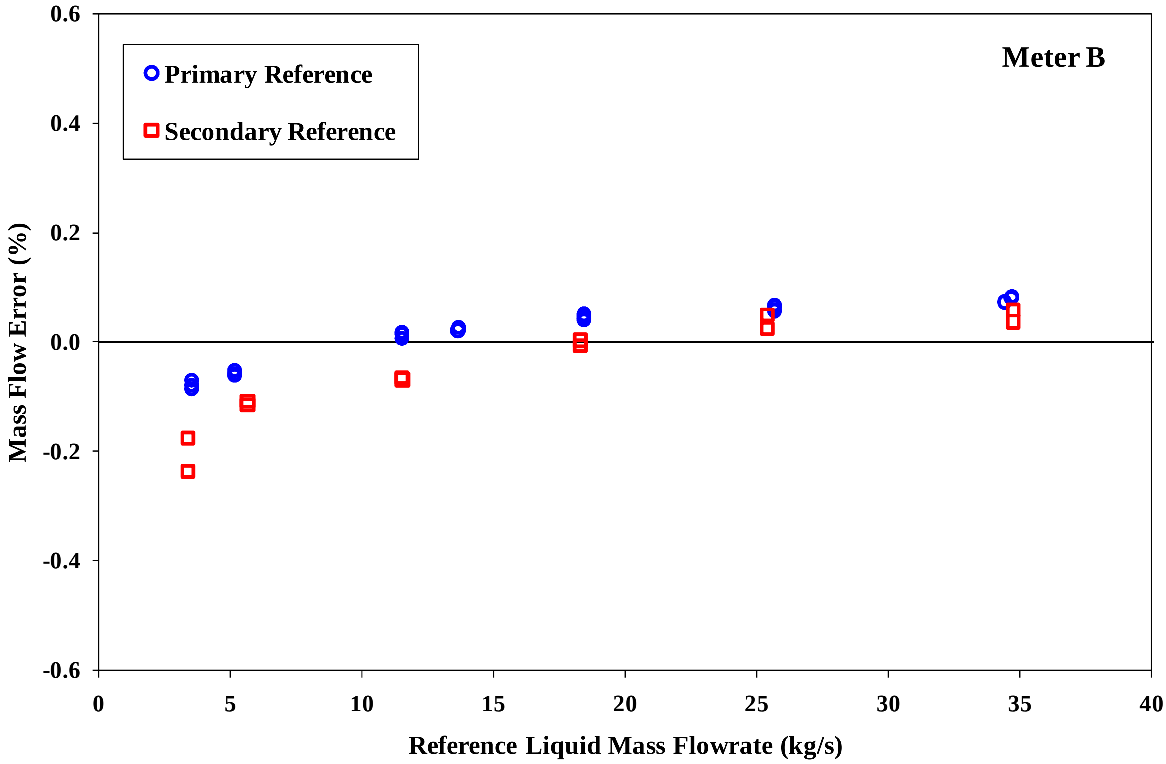


**Figure 10 Calibration of Meter B in UK National Oil Flow Standard**

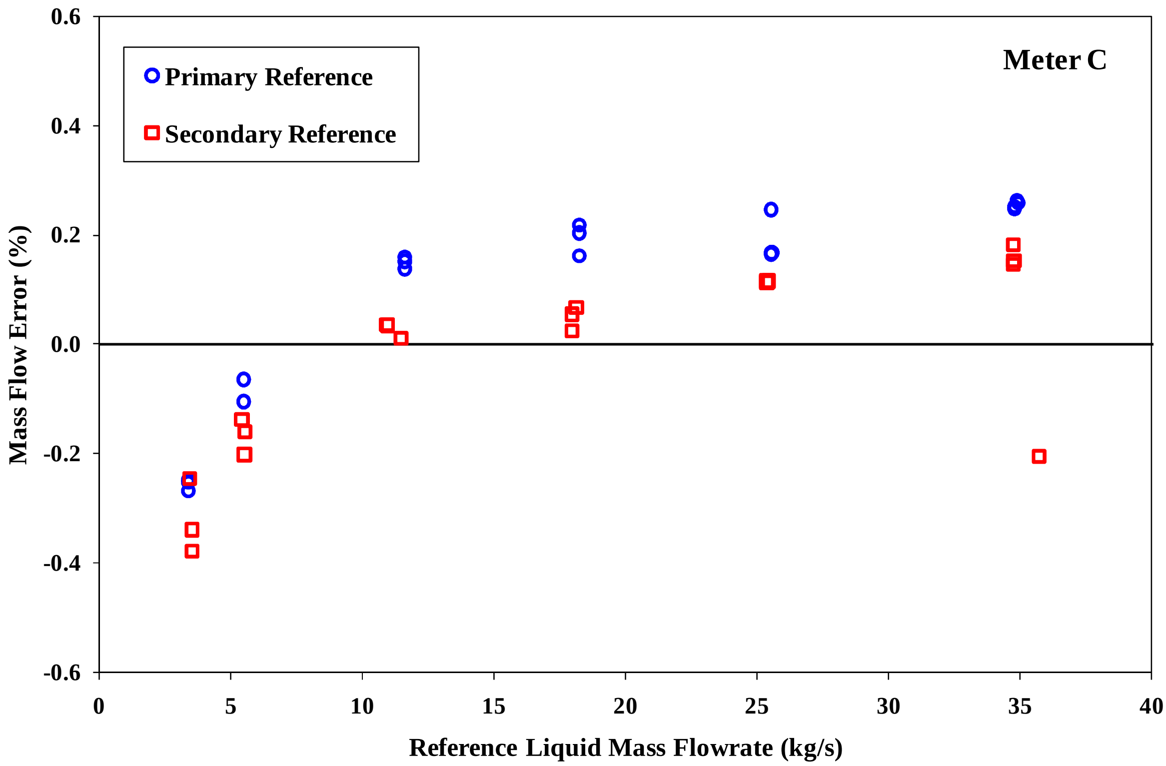


**Figure 11 Calibration of Meter C in UK National Oil Flow Standard**

**TABLE 2**

**SINGLE-PHASE TEST RESULTS**

| | **Meter A** | | **Meter B** | | **Meter C** | |
|---|---|---|---|---|---|---|
| | Primary Reference | Secondary Reference | Primary Reference | Secondary Reference | Primary Reference | Secondary Reference |
| **Root Mean Square (%)** | 0.312 | 0.357 | 0.057 | 0.104 | 0.202 | 0.174 |

## 7 TWO-PHASE RESULTS

The two-phase test results have been plotted in terms of mass flow rate error as a function of reference mass flow rate and as a function of gas volume fraction. Arbitrary ± 10% error bands have been added to the graphs. In addition to this, density errors have been plotted as a function of gas volume fraction. The root mean square averages of the meters' mass flow rate errors and density errors are shown in Tables 3 and 4 respectively.

### 7.1 Mass Flow Measurements

In 1998, NEL conducted an investigation into the effects of two-phase flow on single-phase flow meters [3]. As part of that project a 3-inch Coriolis meter was tested but, it was not possible to obtain a stable measurement at the gas volume fractions (GVF) used.

Each of the Coriolis meters used in this experimental programme responded differently to the presence of gas. At this time it was not possible to determine whether the differences in response are due to tube configuration/design and/or meter electronics.

Figure 12 shows that the mass flow errors of Meter A were ±10% for gas volume fractions of up to 10%. This graph also shows that for gas volume fractions between 15% and 25% the errors were ±20%.

Meter A over-read mass flow rate at low mass flow rate/low GVF combinations, and under-read at low mass flow rate/high GVF combinations.

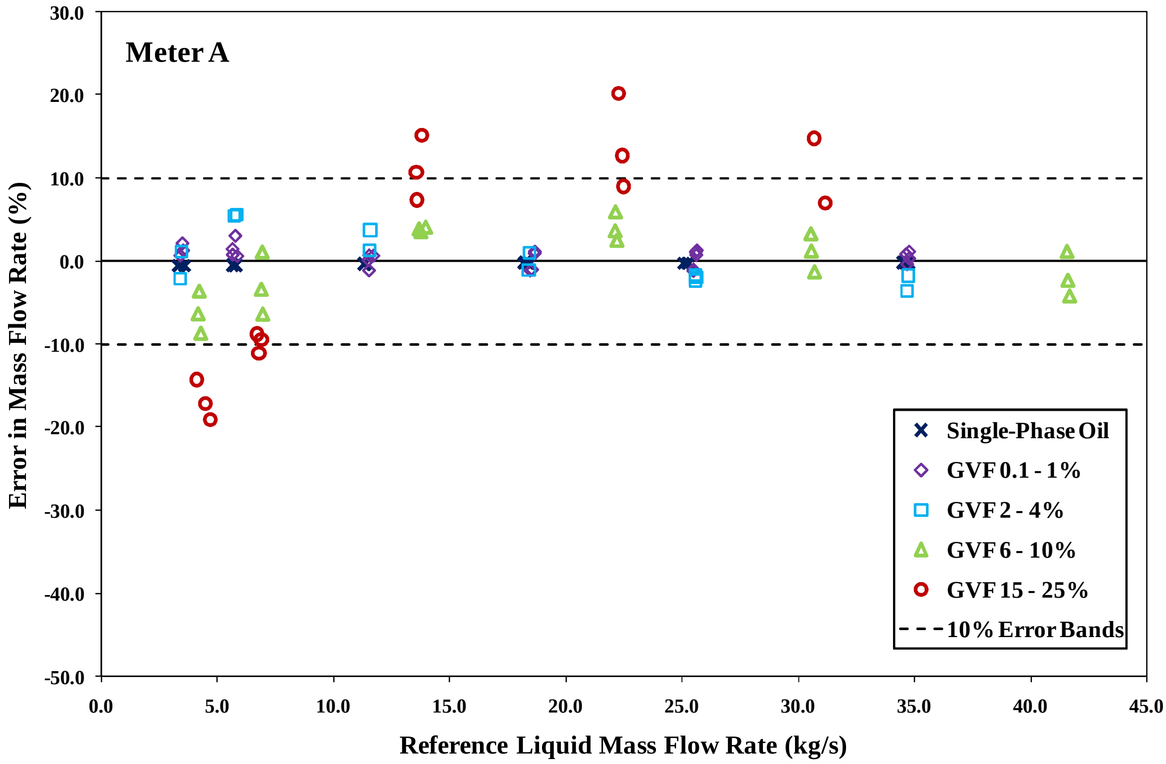


**Figure 12 Mass Flow Rate Error for Meter A Versus Reference liquid Mass Flow Rate**

Figure 13 shows that Meter B under-read mass flow rate when the GVF was 6% or above. However, it can be seen that Meter B performed slightly better than Meter A at medium and high mass flow rate/low GVF combinations.

Figure 14 shows that Meter C under-read at low mass flow rate conditions but then switched to over-reading the mass flow rate between 15 kg/s and 20 kg/s. When the gas volume fraction was 15% or greater Meter C always under-read the mass flow rate.

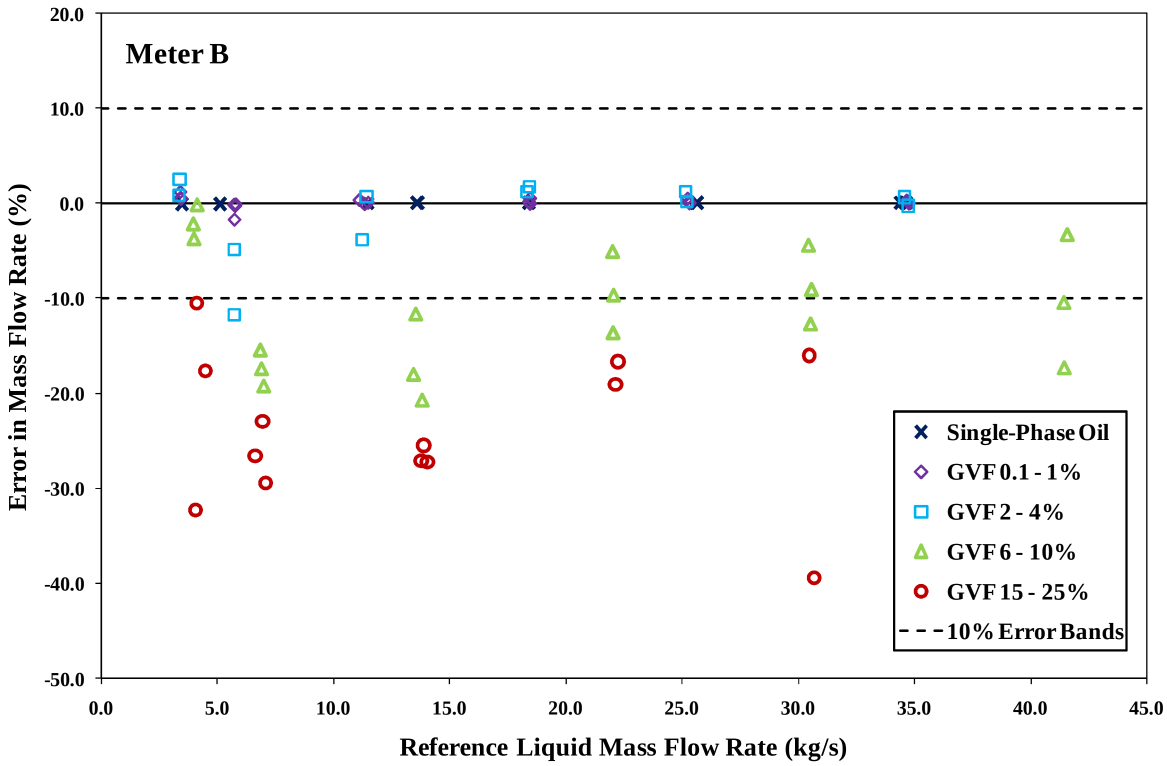


**Figure 13 Mass Flow Rate Error for Meter B Versus Reference liquid Mass Flow Rate**

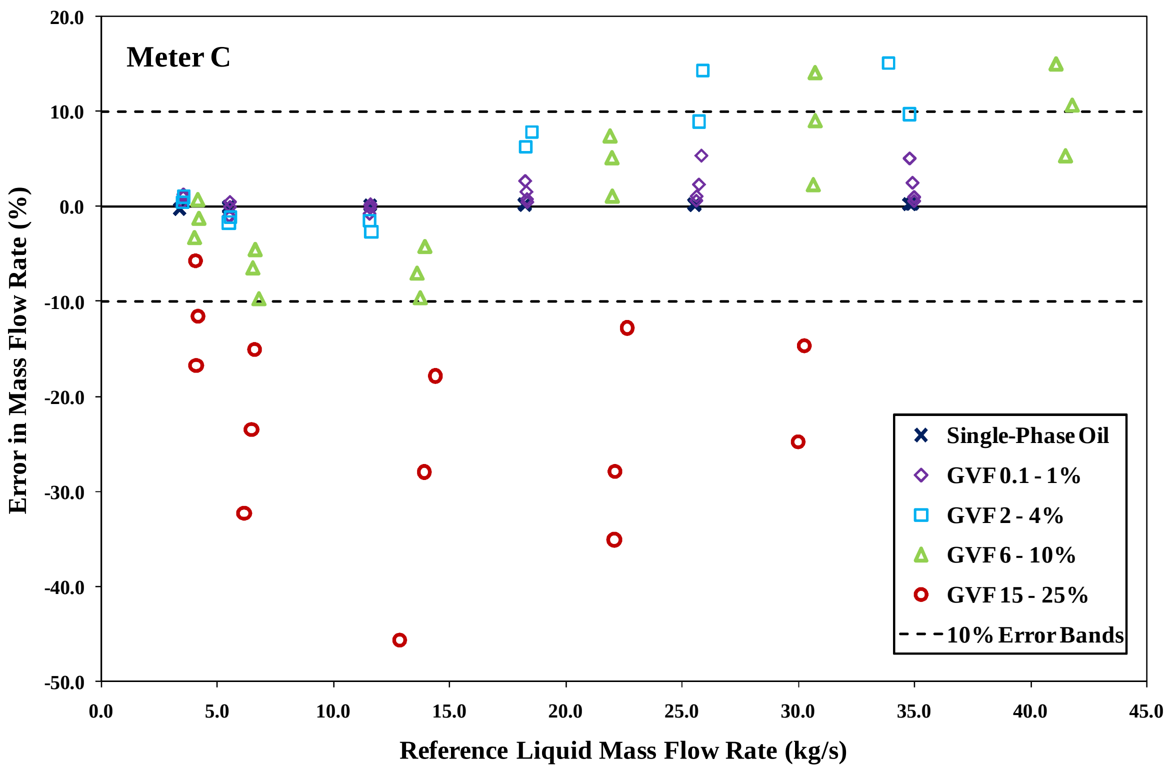


**Figure 14 Mass Flow Rate Error for Meter C Versus Reference liquid Mass Flow Rate**

Figure 15 shows that for all three Coriolis meters, the error in mass flow rate increased with increasing gas volume fraction. Of the three meters tested, Meter A gave the best performance in mass flow rate. That said, the errors in mass flow measurement are large for all three meters. The quoted uncertainty of a Coriolis meter is usually in the region of 0.15% at a 95% confidence level and these test results show that in the presence of gas the errors are an order of magnitude larger, in some cases two orders of magnitude larger than the manufacturers' uncertainty.

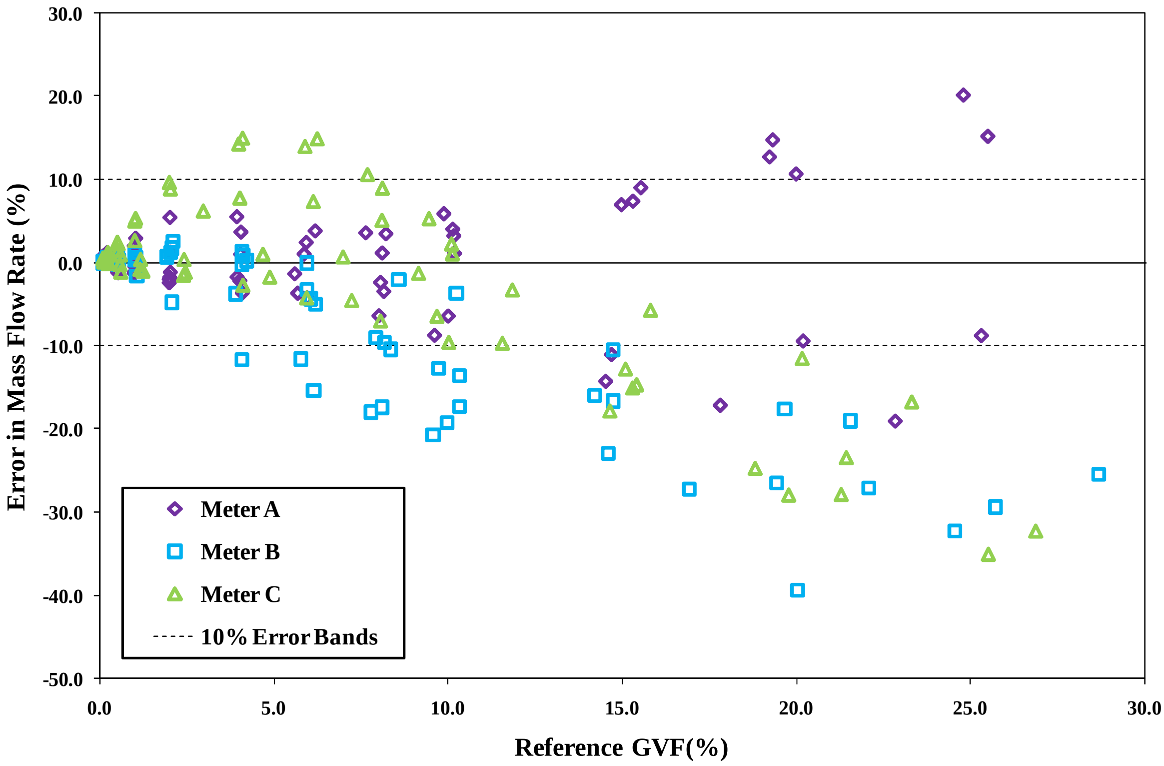


**Figure 15 Mass Flow Rate Errors for All Three Test Meters Versus Reference GVF**

The results from this test programme were similar to the findings of the report by James R. Reizner [7] from 2004.

As each of the meters responded differently to the presence of gas, NEL has not been able to pick out any specific trends to create a correction factor at this time. Further testing of Coriolis meters in two-phase flow may give the confidence required to develop correction factors.

**TABLE 3**

**TWO-PHASE MASS FLOW RATE TEST RESULTS**

| | Mass Flow Rate | | |
|---|---|---|---|
| | **Meter A** | **Meter B** | **Meter C** |
| **Root Mean Square (%)** | 6.52 | 12.99 | 12.40 |

## 7.2 Density Measurement

As well as a mass flow rate output, Coriolis meters give a density output. This is because the mass of the fluid has already been measured and the tubes are of a known volume, and therefore the fluid density can be determined.

Figure 16 shows the density errors of the three meters plotted as a function of GVF. The graph shows that Meter A under-read density but of the three meters tested its performance in terms of density measurement was significantly better than that of Meters B and C.

Meters B and C gave very similar responses in density in the presence of gas. The magnitude of the errors in both meters' measurements increased up to approximately 20% and then started to reduce again.

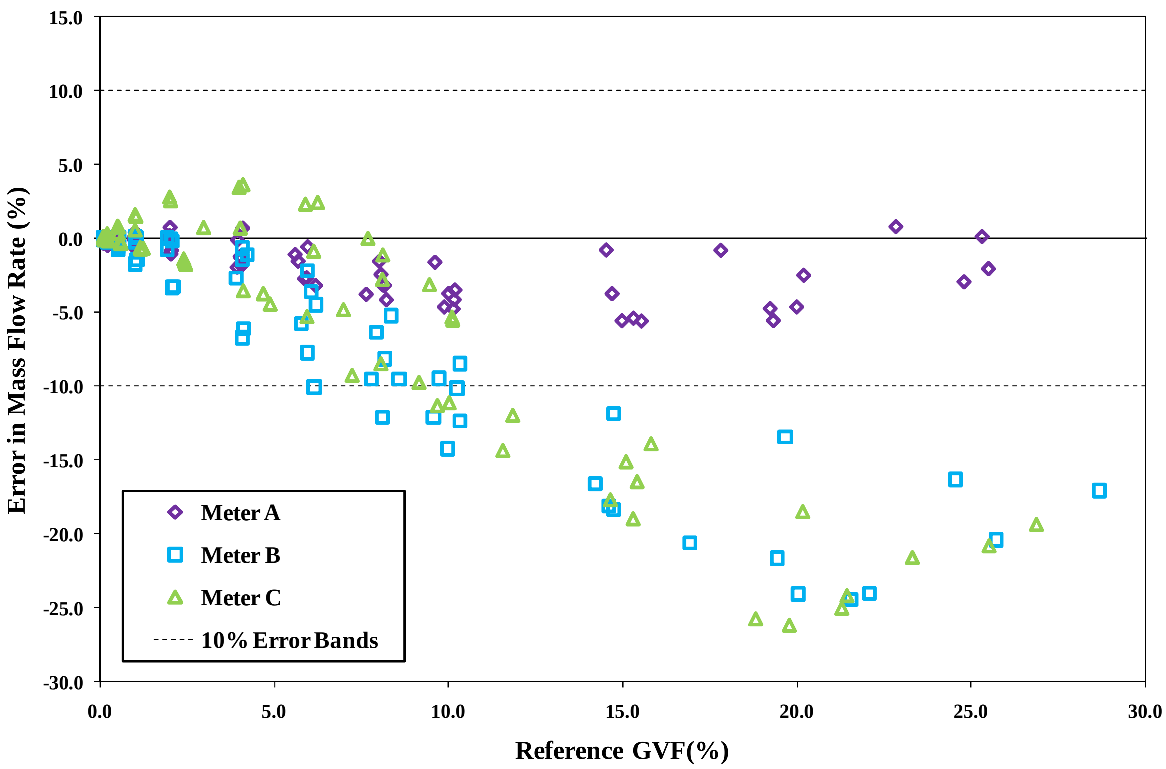


**Figure 16 Density Errors for All Three Test Meters Versus Reference GVF**

**TABLE 4**

**TWO-PHASE DENSITY TEST RESULTS**

| | Density | | |
|---|---|---|---|
| | **Meter A** | **Meter B** | **Meter C** |
| **Root Mean Square (%)** | 2.40 | 9.89 | 10.10 |

### 7.3. Meter Diagnostics

In addition to the mass flow rate and density outputs, several other parameters measured by the test Coriolis meters were also recorded using the manufacturers' meter diagnostic software. The additional measurements included parameters such as drive gain and tube frequency.

The results from the diagnostic data collected show that drive gain is a good indicator of gas presence. The more gas there is the more power (drive gain) has to go into oscillating the Coriolis tubes. Eventually there comes a point when there is so much gas present that the drive gain becomes saturated.

At this time, however, there is no correction which can be applied when the end-user knows gas is present in the liquid stream.

## 8 SUMMARY AND CONCLUSIONS

Compared with the test programme carried out at NEL in 1998 [3] there have been significant advances made in Coriolis electronics. The 3-inch Coriolis meter tested then was unable to give any reading in the presence of gas. However, during this test programme all three 3-inch Coriolis meters were able to give measurements at every gas volume fraction tested over a range of liquid flow rates.

Each of the Coriolis meters tested responded differently when gas was present. It is unclear from these tests whether these differences are due to the tube configuration or the electronics, or both. As each of the meters responded differently to the presence of gas, NEL has not been able to pick out any specific trends to create a correction factor at this time. Further testing of Coriolis meters in two-phase flow may give the confidence required to develop correction factors.

Although the Coriolis meters tested during this project do give mass flow rates in the presence of gas, the magnitude of the error when gas is present is a concern. If the end-user is expecting an uncertainty of 0.15% at a confidence level of 95% but is actually experiencing errors of ± 10% then this could have a significant impact on production decisions.

The advent of Coriolis meter diagnostic data and software could help the end-user identify when gas is present in the liquid stream. This information could potentially help the end-user apply a correction factor to the mass flow rate given by the Coriolis meter or, more importantly, help the end-user identify production upsets such as a gas/liquid separator not functioning correctly.

## 9 FUTURE WORK

This test programme focussed on Coriolis meters installed vertically with gas volume fractions of up to 30%. Under these conditions it was likely that the flow pattern observed was bubble flow which is reasonably homogeneous in terms of two-phase flow.

As the Coriolis meters were tested in a vertical configuration during these performance trials, the follow-on project is investigating the performance of Coriolis meters installed horizontally. Testing in a different piping configuration would allow end-users to build a picture of Coriolis meter performance, not only on the presence of gas and to know which installation configuration is most appropriate when gas is present.

This project concentrated on Coriolis meters in liquid/gas flow. In addition to developing Coriolis meter electronics to cope with the presence of gas, some Coriolis meter manufactures have developed software for using Coriolis meters to meter two liquid phases simultaneously. This software claims to give not only the total mass flow rate of the two liquid phases but also the phase fractions of each liquid. However, there is little independent data available to industry on the accuracy of Coriolis meters in such applications.

If possible, NEL would like to extend the test programme to include more than the three meters evaluated as part of Phase 1.

## 10 ACKNOWLEDGEMENTS

The work described in this paper was undertaken by NEL as part of a National Measurement System project entitled ‘Industry guidance on the use of Coriolis meters for multiphase flows’, under the National Measurement Office’s Engineering & Flow Programme.

This project was not intended to be an evaluation of any particular manufacturer but rather as a generic evaluation of the effect of the presence of gas on liquid Coriolis mass flow meters. The vendors who provided test equipment for this purpose did so in good faith and on this understanding, and their confidentiality and valued cooperation are gratefully acknowledged.

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