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Paper 7.3

Two Component Coriolis Measurement of Oil and Water at Low Velocities

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TWO COMPONENT CORIOLIS MEASUREMENT OF OIL AND WATER AT LOW VELOCITIES

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1 INTRODUCTION

In recent years, Coriolis flowmeters have gained widespread use for the metering of liquids and gases on offshore production installations. In general, experience has shown these instruments to be both reliable and accurate in terms of mass flow measurement. In addition, their ability to measure the density of the produced fluid is often utilised to calculate liquid water-cut in net oil computations.

However, some limitations of the current range of meters have been recognised, particularly in their application to two-phase flow. For example, attention has recently been drawn to the adverse effects that entrained gas can have upon liquid Coriolis meters [1] and manufacturers are making considerable efforts to alleviate this problem. Less information is available on their performance in multi-component liquid streams. It is generally accepted that in a well-dispersed oil-water mixture, for example, the metering performance is close to that for a single-phase fluid. However, at low liquid velocities, separation of the oil from the water has the potential to significantly influence the Coriolis meter response. Yeung *et al.* [2] recently tested a 2" Coriolis meter (horizontally orientated) in oil-water mixtures with water cuts ranging from 15 to 85%. At flowrates above 3 kg/s (~ 1.5 m/s) the mass flowrate and density reported by the Coriolis meter remained within ± 0.45% and ± 0.2% of the reference value and inside the experimental uncertainty of the flow rig. However, in similar tests at liquid velocities below 1.5 m/s, Skea and Hall [3] measured *volumetric* flowrate errors of up to - 6%. Above 1.5 m/s the errors remained within the expected tolerance of ± 0.5%. The large error at low velocities was attributed to separation of the oil and water phases, but in the absence of a direct density measurement it was unclear whether the error was due mainly to the mass flow or the density measurement.

A real-life example of such behaviour was recently encountered on the Harald platform operated by Mærsk Olie og Gas AS, a small production facility located in the Northern part of the Danish offshore sector. As part of an upgrade to the liquid metering set-up on a test separator, an existing pair of turbine meters, which operated in a master / slave arrangement, were changed-out for Coriolis meters. Following start-up of the new metering system, an anomaly became apparent between the Coriolis density measurements. The two Coriolis meters – installed in series, one in a vertically up orientation and the other in a vertically down – were found to report different fluid densities (by up to almost 1%) when monitoring the same oil-water mixtures at low velocity. As the meters were used for allocation purposes, the associated uncertainty in net oil production (of up to 5%) had significant financial implications. The whole metering set-up was reviewed and the integrity of the Coriolis meters checked, but no simple reason was found to explain the density measurement difference. From additional tests performed offshore, it was speculated that the problem might be due to velocity slip between the oil and water phases within the meter.

To properly quantify the problem and to allow correct production allocation amongst the various operating partners, a series of flow tests were commissioned at NEL. The primary aim of these tests was to reproduce the effects observed offshore under controlled conditions. However, since a change to the offshore metering set-up was also being considered, it was elected that a further set of investigative tests also be performed to identify the most suitable modification.

This paper reports on some of the practical experience gained from the offshore installation and on the subsequent flow tests conducted at NEL's multiphase flow facility. The tests comprised of a simulation of the offshore set-up, with the Coriolis meters installed in a vertical orientation, plus several alternative configurations, with the meters operated horizontally. The results from the different configurations are presented and recommendations offered on preferred installation and operational practice in similar situations.

2 BACKGROUND

2.1. Harald Test Separator Liquid Metering Set-up

The test separator on the Harald platform is of the vertical gas / liquid type. Gas is measured using an orifice meter and the liquid via two flow meters configured in a master / slave arrangement. The reason for this extensive metering set-up is that the test separator also serves as a proving system for a custody transfer multiphase meter. Originally turbine meters were used for the master / slave liquid metering application but, in connection with a downsizing of the system from 3" to 2" (to accommodate lower production rates), it was decided to replace these with 2-inch Micromotion CMF200 Coriolis meters.

The above selection of line and meter size was based on the following considerations:

- The liquid inside the separator is normally at its boiling point and to avoid flash gas in the liquid metering system it is essential to maintain a positive static head relative to the liquid level inside the separator, until the liquid has left the last meter. In other words it must be ensured that the height difference between the metering system and the separator liquid level is large enough to exceed the frictional losses suffered by the liquid as it travels down the metering line.
- To maximise the static head one would ideally like to install the meters on a lower deck than the test separator. However on Harald, like many other installations, the test separator is installed on the cellar deck, leaving no possibility for this option. Therefore only a few metres of height were available for creating the necessary static head. As a result the pressure drop through the system had to be kept to a minimum, whilst still allowing for the inclusion of bends etc. to create some mixing of the liquid.
- The meter line size was therefore selected such that the highest producing wells would not exceed the maximum allowed pressure drop whilst the lowest producing wells would still be above the minimum flow requirements.
- To avoid gas or settlement trap problems and to minimize the overall space requirement, it was also decided to install the meters in a vertical orientation. The actual metering arrangement is shown in Figure 1. After leaving the test separator the liquid travels upwards through the slave meter, then downwards past a manual sampling point, upwards again through the water-cut meter and finally downwards through the master meter (which would be blocked off in normal operation).

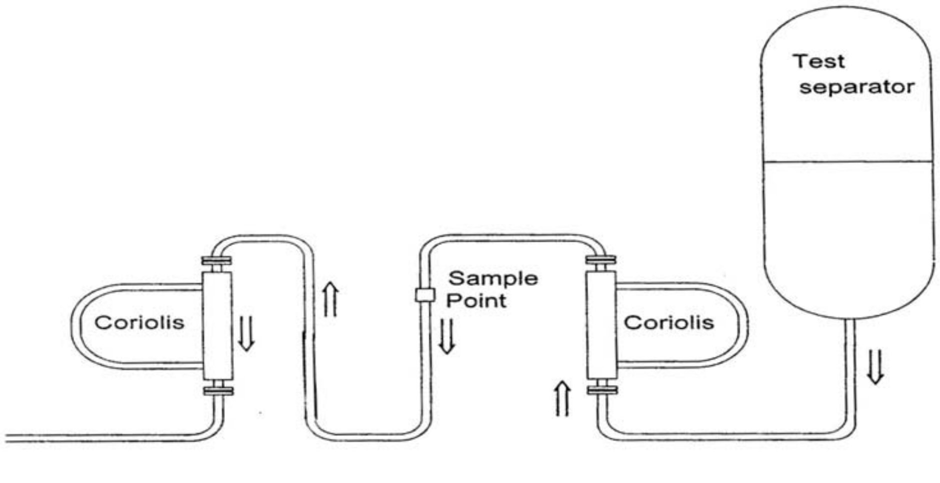

Fig. 1 – Layout of the metering system on the liquid leg of the Harald test separator.

2.2. Density Based Water Cut Determination

In the revised metering system, the mixture density measured by the Coriolis meters was used to determine the water cut (or BSW) of the liquid stream. In this case:

$$\mathrm{BSW_V} = \frac{(\rho_{MIX} - \rho_{OIL})}{(\rho_{WAT} - \rho_{OIL})}$$

ρ_{MIX} : Density of liquid mixture at process conditions [kg/m^3]

ρ_{OIL} : Density of oil at process conditions [kg/m^3]

ρ_{WAT} : Density of water at process conditions [kg/m^3]

From the above formula it can be seen that the uncertainty in the density-based water cut is a function of the density difference between the water and oil phases and of the measurement uncertainties in the three component densities. (In effect, the larger the difference between the oil and the water densities, then the greater the accuracy that can be obtained.)

On the Harald platform the actual densities of the oil and the water are around 800 kg/m^3 and 1100 kg/m^3 respectively. This relatively large difference of 300 kg/m^3 was considered as a good basis for a density-based water cut evaluation, with calculations estimating an overall uncertainty of the order of 2% (absolute BSW).

In practice, the water cut calculation is performed online by a flow computer. The density of oil is represented by a polynomial correlation with process temperature and pressure as inputs. The correlation is based on a PVT analysis of actual produced fluids. The water density is calculated using “properties of Reservoir Water” [5] with pressure, temperature and water base density as input.

2.3. Anomalies in Density Measurement

In order to obtain a water-cut accuracy within the 2% range mentioned above, it was required that the uncertainty of the density measurement remain within the meter manufacturer’s specifications. However, on start-up of the system a density discrepancy of the order of 0.8% was observed between the two meters. This was far above the value expected, and since an error in density of 0.8% corresponds to an error in net oil flow close to 5% (see Appendix A), it was not acceptable for an allocation metering application. The mass flow rates did, however, match reasonably well between the two meters and there was no abnormality apparent in their diagnostic information.

To exclude the possibility of malfunction or faulty calibration of the meters, they were swapped over, but without any change in performance. It was then considered that gas might be present in the downstream meter, as this was the one which measured the lowest density. Reductions in pressure can cause some of the lighter hydrocarbons in an oil stream to evaporate or “flash off” into the gas phase. If this was the problem then the density difference was expected to increase with flowrate, due to the higher pressure losses generated through the system. In facts, tests with different flow rates demonstrated that the opposite happened – the discrepancy increased as the flow rate went down.

From this result it became apparent that the error must in some way be related to poor mixing of the fluids inside the Coriolis meter. Since the main difference between the two meters was their orientation – one had flow upwards and the other flow down – it was speculated that the influence of gravity was inducing slip between the oil and water phases within the meter. The slip would mean that the velocity of the oil would be higher than the velocity of the water in the meter with flow upwards, and that the opposite would happen in the meter with flow down. The difference in velocities would then give different retention times of oil and water inside the meters and hence different effective densities. To get an indication of the correctness of this assumption, the downstream master meter was relocated to a nearby position where it also could be operated in vertically upwards flow. The two meters then measured the same density and flow rate, lending further weight to the phase-slip hypothesis.

Since the meters formed part of a custody transfer metering system it was mandatory to properly document the observed problem in order to make a basis for a re-allocation of the oil production. Furthermore, the plan was to rebuild the meter installation in such a way that the slip problem would be eliminated. However, before embarking on any modifications it was considered prudent to perform a series of evaluation tests in order to find the optimal orientation of the meters. NEL were commissioned to conduct these tests, which were performed in two stages as described in the following section.

3 FLOWLOOP TEST SET-UP

The flowloop tests were conducted at NEL's Multiphase Flow Facility in East Kilbride, Scotland, using two 2" Micromotion CMF200 Coriolis flow meters. These were of the same type as used in the offshore operation. Two separate installation geometries were investigated. Firstly the meters were installed in a vertical orientation – one with flow up and the other with flow down – in a set-up analogous to the original platform configuration. Secondly, the performance of the meters was investigated on a horizontal flowline, with their "U-shaped" flow tubes oriented in a variety of different planes around the pipe-axis.

3.1. Reference Metering

The standard reference metering consisted of a 1½" (water) turbine and a 1¼" (oil) turbine, each with a low-end flowrate of 0.5 litres / second (~ 0.47 kg/s). Above this value, the uncertainties in volumetric flowrate were less than ± 1% per phase. Rosemount pressure transmitters and PRT temperature probes (± 50 mK) were located upstream, downstream and adjacent to the test meter locations. The fluid temperature at the test section ranged between 35 and 40 ^{O}C, depending upon the liquid flowrate, but did not vary significantly within a given test point. The test fluids consisted of stabilised crude and $MgSO_4$ water solution (75 g/l), with densities of around 854 and 1030 kg/m^3 respectively. While this was lower than the density difference of the platform production, it was still sufficient to produce completely stratified flow at the horizontal inlet to the test section for all of the flowrates investigated.

3.2. Coriolis Test Meters

The 2" Micromotion CMF200 Coriolis meters had a mass flow range of approximately 0 – 12 kg/s with a mass flow uncertainty of ± 0.1% and nominal density uncertainty of ± 0.5 kg/m^3. It should be noted however that for much of the testing performed the Coriolis meters were operating at the lower end of their range (up to 60:1 turndown relative to full scale) where the intrinsic uncertainty can rise rapidly. Prior to commencement of the test programme, a new density calibration was performed on each meter, using single-phase (flowing) water at an accurately specified temperature. The original gas density calibration was retained. The meters were also tested using their original mass flow calibrations, i.e. as configured at the time of delivery. However, following each installation revision, the flowrate zero point was reset under no-flow conditions after raising the fluid to its nominal operating value of ~ 40 ^{O}C.

3.3. Vertical Installation

The physical layout for the vertical installation tests is shown in Figures 2 and 3. Reference fluids from the flow facility's bulk separator were delivered to the test section via a long horizontal pipe run, the latter part of which housed a Perspex viewing spool. The flow then passed vertically upwards through a non-intrusive jet-mixer (which could be switched off or on) to the first Coriolis meter (#1, flow up). The mixer was transparent and also served as a viewing section. The flow then followed a downward loop, simulating the offshore platform geometry, before passing through the second Coriolis meter (#2, flow down). All pipework in the test section was of 2" diameter.

The meters were firstly checked on both single-phase oil and single-phase water and the reported densities found to be within ± 0.5 kg/m^3 of the reference metering system. The agreement with each other was even closer and well within their specified tolerances. The two meters also agreed to within ± 0.2% of each other in terms of mass flow rate and to within 1% of the reference system, except at the very lowest end of its calibrated range (equivalent to about 0.5 kg/s). In general, the mass flow rates reported by the Coriolis meters (with their original mass flow calibrations) lay systematically higher than the NEL reference system by approximately 0.5% to 1.0%.

The main test matrix consisted of a series of points at a BSW of ~ 50%, ranging from 3.3 down to 1.1 litres/second, i.e. the nominal low end of the reference system under two-phase flow. A few additional tests were made at lower flow rates for comparative purposes only. Tests were made with the jet mixer both on and off to assess the relative effects of conditioned (i.e. homogenised) and unconditioned flow upon the response of the test meters.

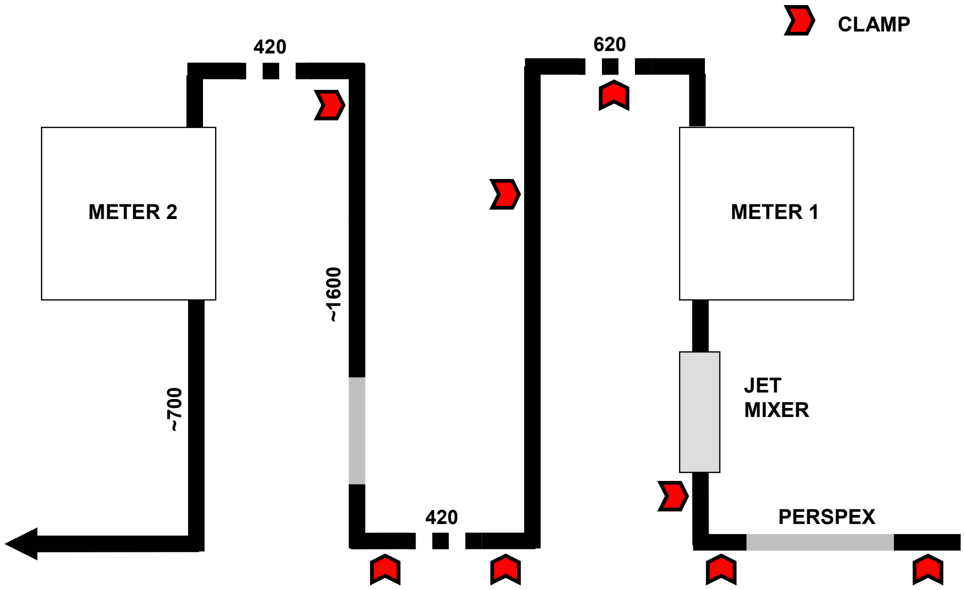

Fig. 2 – Schematic diagram of the Coriolis meters installed in a vertical orientation. The active mixer and viewing spools are also shown. Approximate dimensions are given in mm.

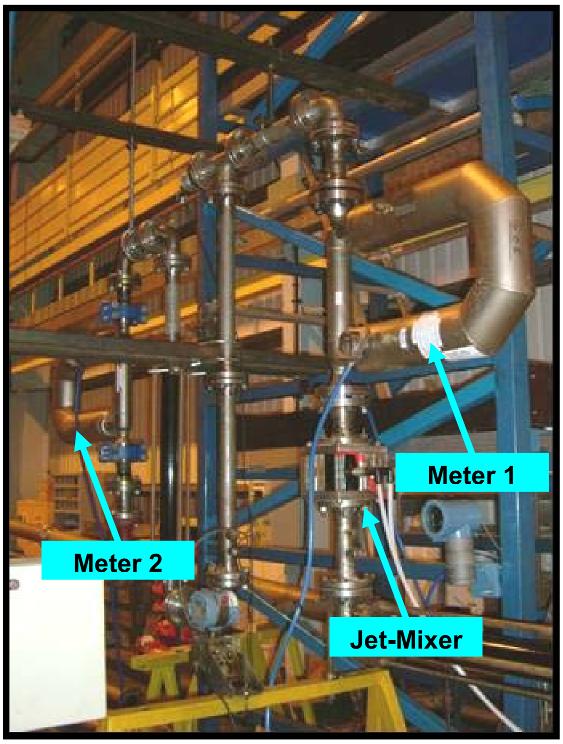

Fig. 3 – Location of the Coriolis meters and jet mixer for the vertical installation tests. Flow entered via the transparent pipe-section at the bottom right.

3.4. Horizontal Installation

In this series of tests the Coriolis meters were installed on a fixed horizontal pipeline. Three distinct orientations of the meter flow tubes were investigated. On this particular model of Coriolis meter the flow tube casing resembles a flag, which provides a useful means of describing the flow tube position in the three test configurations:

Set-up # 1: Flow tubes in a vertical plane pointing downwards ("flag down" position).
Set-up # 2: Flow tubes in a horizontal plane pointing to the side ("flag sideways").
Set-up # 3: Flow tubes in a vertical plane pointing upwards ("flag up" position).

The test set-up for the "flag up" position is shown in Figure 4.

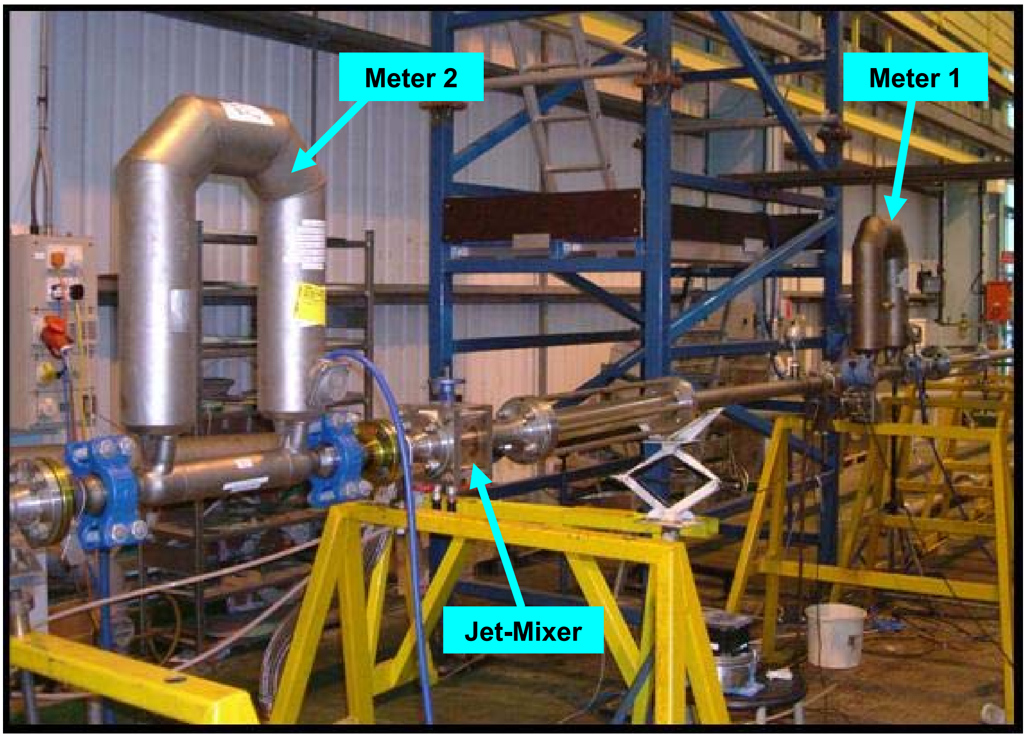

Fig. 4 – Horizontal installation of the Coriolis meters in NEL's multiphase flow facility. This set-up shows the "flags up" arrangement. Flow enters from the right.

Fluid entered the test section via a long horizontal pipe run, the latter part of which housed a Perspex viewing spool. The flow passed through the first Coriolis meter, followed by the jet-mixer and then the second Coriolis meter.

For this series of investigations, the 1½" and 1¼" turbines used for the vertical installation tests, were supplemented with the following smaller reference meters:

- ½" Turbine Meter (Water): 0.1 – 0.75 litres / second
- ½" Turbine Meter (Oil): 0.1 – 0.75 litres / second

Within these ranges the uncertainty in volumetric flowrate was less than ± 1% per phase.

The test matrix for each metering configuration consisted of a series of liquid flow rates ranging from 0.2 to 1.5 litres/second, at a water-cut of ~ 50%. Up to three repeat points were taken at each setting. Tests were made with the jet mixer both on and off, to assess the relative effects of conditioned (i.e. homogenised) and unconditioned flow upon the <u>second</u> test meter. The jet mixer lay downstream of first test meter so had no influence upon its response. Depending upon the flow velocity, the first meter itself introduced varying degrees of mixing upstream of the second test meter. The zero flow setting was reset after each physical installation change.

4 TEST RESULTS AND DISCUSSION

4.1. Vertical Installation Tests

The vertical installation tests were designed to simulate the Harald platform metering geometry, with the aim of recreating and quantifying the measurement anomalies observed offshore.

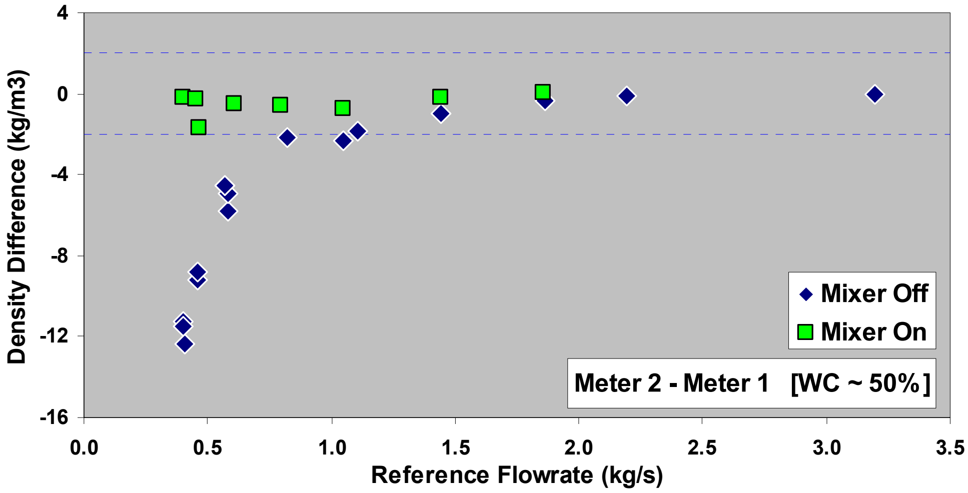

Fig. 5 – Difference in density reported by the two Coriolis meters when operated in vertical two-phase flow. The flow passed vertically upwards through Meter 1 then vertically down through Meter 2. Deviation bands of ± 2 kg/m^3 are plotted as a guide.

Figure 5 shows the difference in density reported by the two Coriolis meters as a function of liquid flowrate, when operated in two-phase oil / water flow at NEL. The water cut was approximately 50% and similar to that of the Harald production. For all of the flowrates investigated the liquid in the horizontal pipe section upstream of the test meters was observed to be completely stratified. With the jet mixer ON, the flow was homogenised immediately upstream of the first meter (Figure 2) and, from visual inspection, remained reasonably well mixed through the entire test section. Under these conditions, the densities reported by the two meters agreed to better than ± 2 kg/m^3 (approximately 0.2%) and within the expected tolerance.

However, in unconditioned flow (mixer OFF), Meter 2 (flow down) read significantly lower than Meter 1 (flow up) for flowrates below about 1.5 kg/s (~ 5 m^3/hr). This was analogous to the observations reported from the Harald platform.

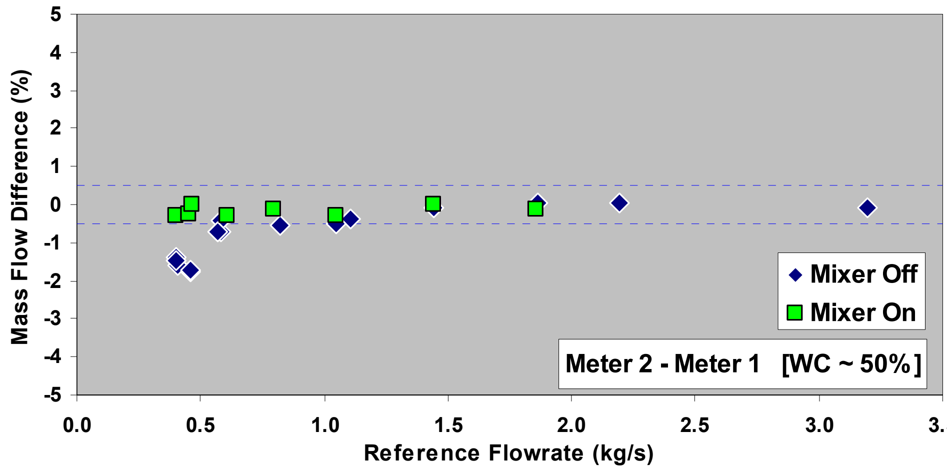

Fig. 6 – Difference in mass flowrate reported by the two Coriolis meters when operated in vertical two-phase flow. The flow passed vertically upwards through Meter 1 then vertically down through Meter 2. Deviation bands of ± 0.5% are plotted as a guide.

Figure 6 shows the difference in mass flow rate measured by the two meters in both conditioned and unconditioned flow. At the higher flowrates investigated, the difference is less than 0.5% and apparently insensitive to the nature of the flow regime. Only near the very lowest flowrates investigated (~ 0.5 kg/s) does a small deviation (< 2%) develop in unconditioned flow.

Overall, the results reported above appear to reflect the effects observed on the Harald production platform, but on a stand-alone basis can not confirm which meter is most affected by the flow regime. To determine this, the individual responses must be compared directly with the reference system values.

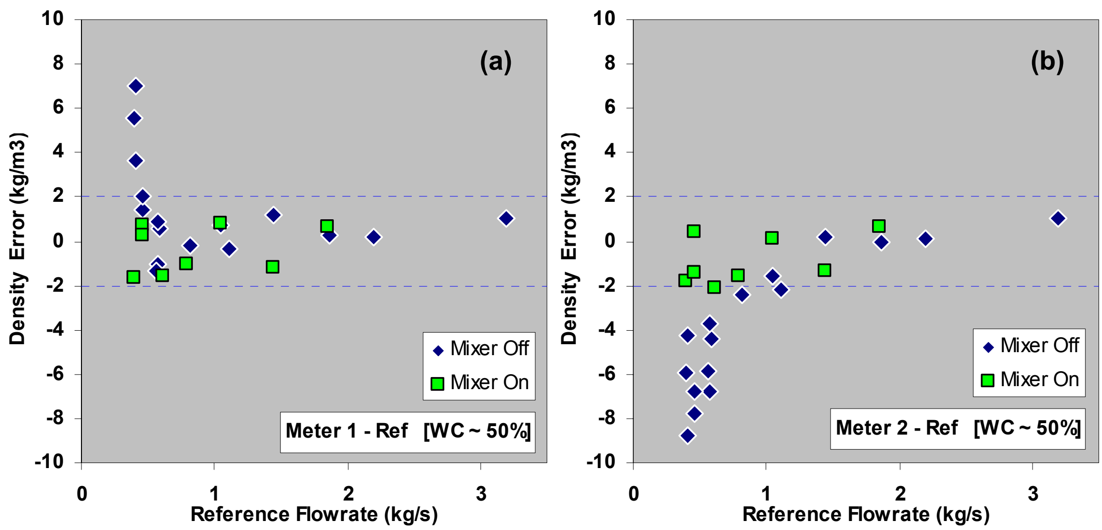

Fig. 7 – (a) Density difference between Meter 1 (flow up) and the reference system in vertical two-phase flow. (b) Corresponding data for Meter 2 (flow down). The active mixer was located upstream of both meters. Deviation bands of ± 2 kg/s are plotted as a guide.

Figures 7a shows the density difference measured between Meter 1 (flow upwards) and the reference metering system. With the mixer on (conditioned flow) the density error lies within 0.2% of reference for all of the flowrates investigated. With the mixer off (unconditioned flow), a similarly acceptable response is observed down to flowrates of about 0.45 kg/s. Below this value, Meter 1 begins to rapidly overestimate the reference mixture density. At these very low flowrates a form of “churn” flow was observed in the vertical viewing spool under Meter 1, with large water droplets appearing to fall back relative to the general up-flow of liquid. This, almost permanent, “hold-up” of water appears to be responsible for the sudden rise in density reported by the meter in upward flow at low velocities.

Figure 7b shows the equivalent comparison for Meter 2 (flow downwards). In this case an obvious underreading develops in the unconditioned regime from a much higher flowrate i.e. approximately 1.5 kg/s and below. The deviation is not observed in conditioned flow, where the density error remains within 0.2% of reference at all times. This suggests that phase separation effects may be more prevalent in the downwards direction, possibly due a less turbulent flow pattern in that orientation, which would better preserve any natural separation of the oil and water.

There are several mechanisms by which phase separation might affect the Coriolis meter response. For example:

- Depending upon the density difference between the two phases, the nature of the flow pattern (dispersed, annular etc.), degree of phase separation (e.g. droplet size) and the direction of flow, gravity will act to a greater or lesser extent in changing their relative velocities. Under such “slip” conditions the slower moving phase occupies a relatively larger cross-sectional area of the meter tube, as the total volumetric flowrates in and out are fixed. This has the effect of changing the “resident” mass within the meter (equivalent to a different “effective” density) whilst maintaining the same overall mass flow rate.
- In addition, if the more viscous phase (oil in this case) is in substantial contact with the pipe walls, then the increased drag can have the effect of reducing its velocity relative to the lower viscosity (water) phase. (Such an effect is observed in the main horizontal pipe sections of the NEL flowloop under stratified conditions).

- Conversely however (and depending upon the level of phase separation, pipe material, pre-wetting etc.) there can be a tendency for the *lower* viscosity fluid to migrate to the region of highest shear [4], resulting in oil flow in the core of the pipe with water around the perimeter.

- In Coriolis meters with curved tubes (i.e. of the present type), the denser phase of a separated fluid will tend to flow at a higher velocity around the outer radius of the flowtube bends, again giving rise to a reduction in the average cross-sectional area occupied.

- In Coriolis meters with twin tubes (i.e. of the present type), where the fluid is significantly separated before reaching the Coriolis meter, there is the possibility that the phases will be unevenly split between the two internal flowtubes. The fluid density is derived from the principle that the Coriolis flow tubes vibrate against each other, at a natural frequency proportional to the contained mass, and any bias in the mass split between the two tubes will have the effect of increasing this resonant frequency. The effect of the bias does not average out but always leads to an underreading in the apparent density. The problem is analogous to two masses connected by a spring, which oscillate at a natural frequency of vibration proportional to $(m_1 + m_2) / m_1m_2$. Any division of the total mass away from an even distribution (i.e. $m_1 = m_2$) serves only to increase this frequency.

In terms of mass flow measurement, Figure 8 shows the response of the two Coriolis meters with respect to the reference system. At flow rates within the calibration range of the reference system (i.e. above 1 kg/s for two-phase flow) the mass flow responses lie within 1% of the reference values, although systematically high by a similar amount. (The uncertainty on the reference flowrates was ~ 1% by volume per phase). At lower flow-rates, a noticeable overreading occurs, but this is in a region where the measurement uncertainties of both the reference system and the Coriolis meters are expected to increase. A similar behaviour was noted in single phase flow, suggesting a small error in the test meter calibrations. (The Coriolis meters were operated with their original calibrations and no re-tuning against the reference system was made prior to testing). The mixer appears to have no significant effect in the data of Figure 8, and it is only in the “difference” data of Figure 6, at very low flowrates, that some small effects of flow regime are recognisable.

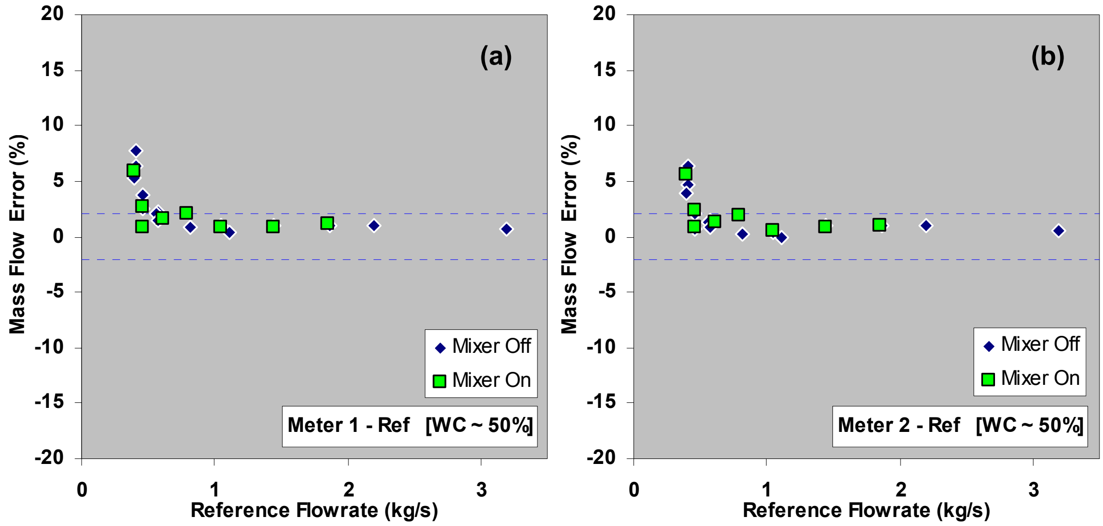

Fig. 8 – (a) Mass flowrate difference between Meter 1 (flow up) and the reference system in vertical two-phase flow. (b) Corresponding data for Meter 2 (flow down). The active mixer was located upstream of both meters. Deviation bands of ± 2 % are plotted as a guide.

4.2 Horizontal Installation Tests

The following sections describe the density and mass flowrate responses of the two Coriolis meters when installed in a horizontal Flowline. Three different orientations of the flow tubes are considered. The jet mixer was installed downstream of Meter 1 but immediately upstream of Meter 2. Meter 1 was therefore subjected to unconditioned flow in **all** cases. Invariably the oil and water were in a stratified flow regime on entry to the test section. With the jet-mixer on, Meter 2 meter was, in principle, subjected to fully homogenised flow. With the jet mixer off, Meter 2 received partially conditioned flow, the level of mixing being dependent upon the velocity through, and orientation of, the upstream test meter (Meter 1).

4.2.1. “Flags Down” Orientation

The density response of the two meters in the “flags down” position is shown in Figure 9.

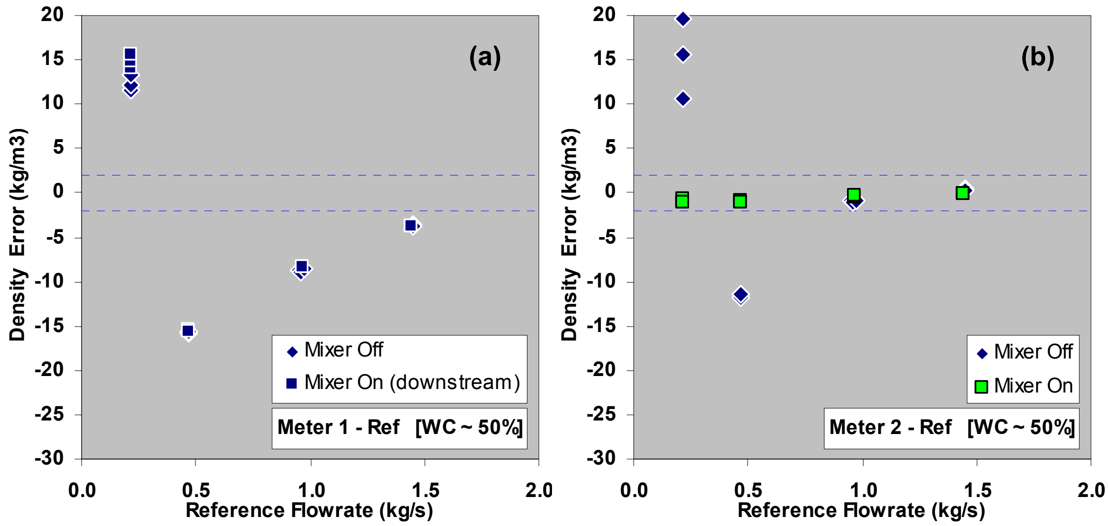

Fig. 9 – (a) Density difference between Meter 1 (“flag down”) and the reference system in horizontal two-phase flow. (b) Corresponding data for Meter 2 (“flag down”).

The data are labelled according to whether the mixer was off or on during the test, but it should be noted that for Meter 1, which lay upstream of the mixer, **all** test points correspond to unconditioned flow. The effect of reducing the fluid velocity is firstly to cause an underreading in the density measured by Meter 1, characteristic of phase slip and/or an uneven mass distribution between the flow tubes inside the meter. As the flowrate approaches zero, this changes to a sudden overreading, as water appears to become "permanently" trapped within the downward hanging bend of the flow tubes.

The response of Meter 2, with the mixer off, is similar to that of Meter 1, although the latter was observed to partially mix the flow upstream of Meter 2. In fact, at flowrates greater than ~ 1 kg/s, the flow appears to be sufficiently turbulent from its travel through Meter 1 that Meter 2 performs with reasonable accuracy. At lower flowrates, the liquid emerging from the upstream meter was observed to re-stratify before reaching Meter 2, under which conditions its response follows that of Meter 1. With the mixer on, Meter 2 reads close to the reference at all flowrates.

Figure 10 shows the mass flow error for the two meters in the "flag down" orientation. At the higher flow rates investigated (> 0.5 kg/s) both meters read systematically high by about 2%, which is larger than expected given the nominal uncertainties of the test meters and the reference system. However, the same behaviour was observed in single phase flow and, given that the mixer has no obvious effect upon the response of Meter 2 (Figure 10b), the bias does not appear to be flow regime related. It is more likely to be due to an offset in the Coriolis meter calibration or an effect of the installation conditions or zero-setting. The key point is that flow conditioning appears to have little effect upon the mass flow response of the test meters (Figure 10b), except at the very lowest flowrates investigated (< 0.5 kg/s).

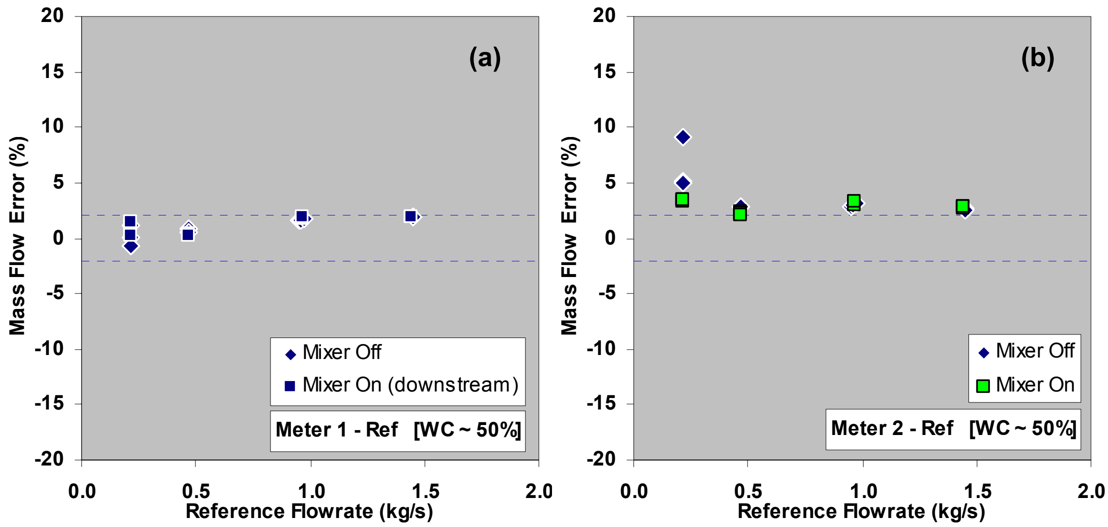

Fig. 10 – (a) Mass flowrate difference between Meter 1 ("flag down") and the reference system in horizontal two-phase flow. (b) Corresponding data for Meter 2 ("flag down").

4.2.2. "Flags Sideways" Orientation

The density response of Meter 1 with its flag sideways (Figure 11a) shows a substantial underreading in unconditioned flow (i.e. all test points), which increases as the flow velocity is reduced. However, unlike the "flag down" arrangement, the effect of "permanent" water hold-up is not observed.

With the mixer off, the flow was seen to remain largely stratified on its passage through both meters, resulting in similar density errors. However, at the higher flowrates investigated, the response of Meter 2 is not quite as poor as Meter 1, presumably due to the partial mixing generated by the latter. Because of the horizontal oil / water stratification, this orientation is likely to be most susceptible to the effects of uneven mass distribution between the meters' internal flow tubes.

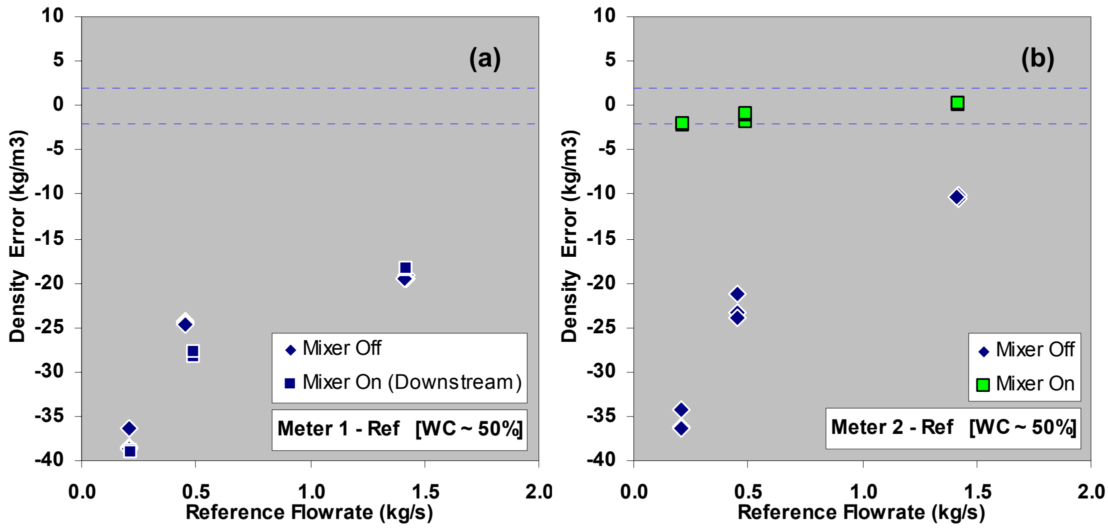

Fig. 11 – (a) Density difference between Meter 1 ("flag sideways") and the reference system in horizontal two-phase flow. (b) Corresponding data for Meter 2 ("flag sideways").

With the mixer on, Meter 2 reports close to the reference density, and only at the very lowest flowrates tested is a slight deviation discernible. Here the liquid emerging from the mixer had time to separate slightly before entering Meter 2, as was observed visually.

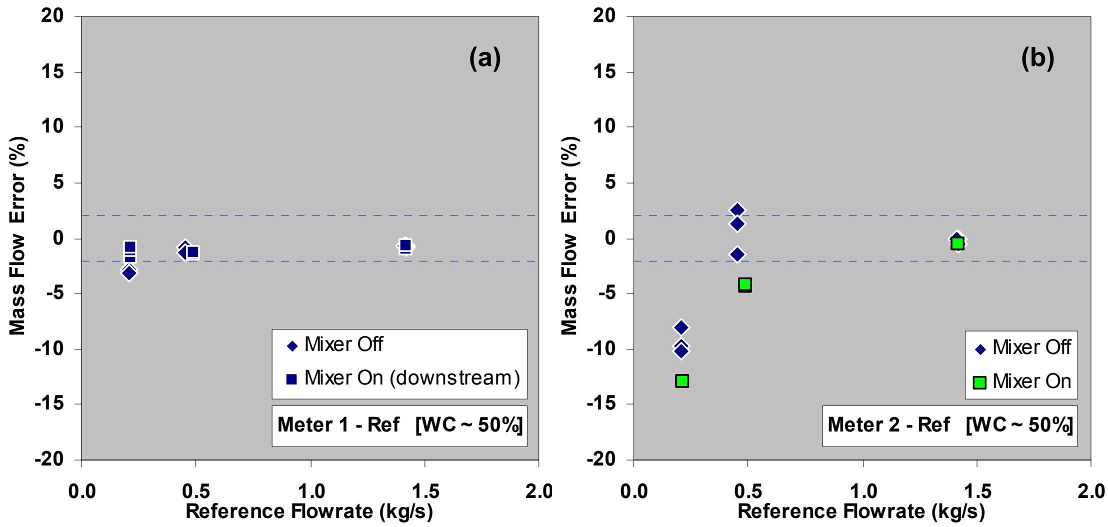

Fig. 12 – (a) Mass flowrate difference between Meter 1 ("flag sideways") and the reference system in horizontal two-phase flow. (b) Corresponding data for Meter 2 ("flag sideways").

Figure 12a shows the mass flow error for Meter 1. The agreement with reference is within ± 2%, except at the very lowest flowrates tested, but unlike the "flag down" orientation the meter slightly underreads the mass flow. For Meter 2 (Figure 12b) the agreement with reference is satisfactory at high flowrate, but extremely poor at low flowrates (< 0.5 kg/s), even with the mixer on and even in single phase flow. It may be that Meter 2 was particularly susceptible to installation effects in the "flag sideways" orientation (e.g. the large stresses acting upon the cantilevered flowtubes), which is generally discouraged by meter manufacturers, even for single phase flow. However, there is evidence (Figure 12b – mixer "on" vs. "mixer off") that, at low flowrates, the flow regime also plays some part in the mass flow response in this set-up.

4.2.3 “Flags Up” Orientation

Figure 13a shows the density response of Meter 1 in unconditioned flow in the “flag up” orientation. An underreading is observed that worsens as the flowrate falls from 1.5 to 0.5 kg/s. Again this is most likely due to phase slip between the oil and the water and/or an uneven mass distribution between the internal meter flow tubes. Below 0.5 kg/s the underreading diminishes again, presumably as a result of increasing water hold-up (due to gravity) in vertical sections of the flow tubes. The upturn is less severe than in the “flag down” position (Figure 9), which would be expected if only the rising leg was significantly affected.

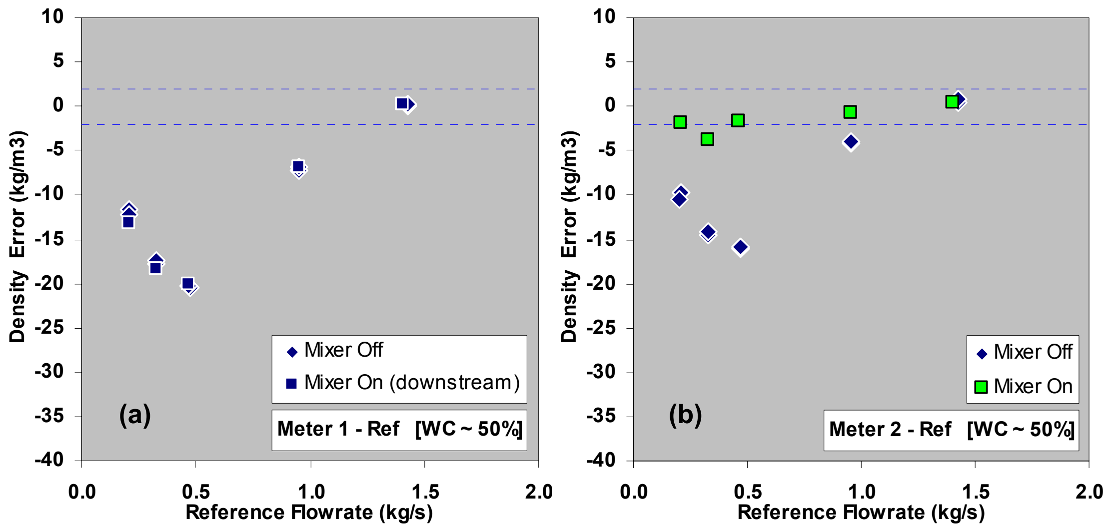

Fig. 13 – (a) Density difference between Meter 1 (“flag up”) and the reference system in horizontal two-phase flow. (b) Corresponding data for Meter 2 (“flag up”).

Figure 13b shows the density behaviour of Meter 2. With the mixer on, the meter reads close to the reference density. With the mixer off, the behaviour is similar to that of the upstream meter, although the absolute value of the underreading is slightly less. Again, this is most likely due to the small degree of mixing generated by the upstream meter.

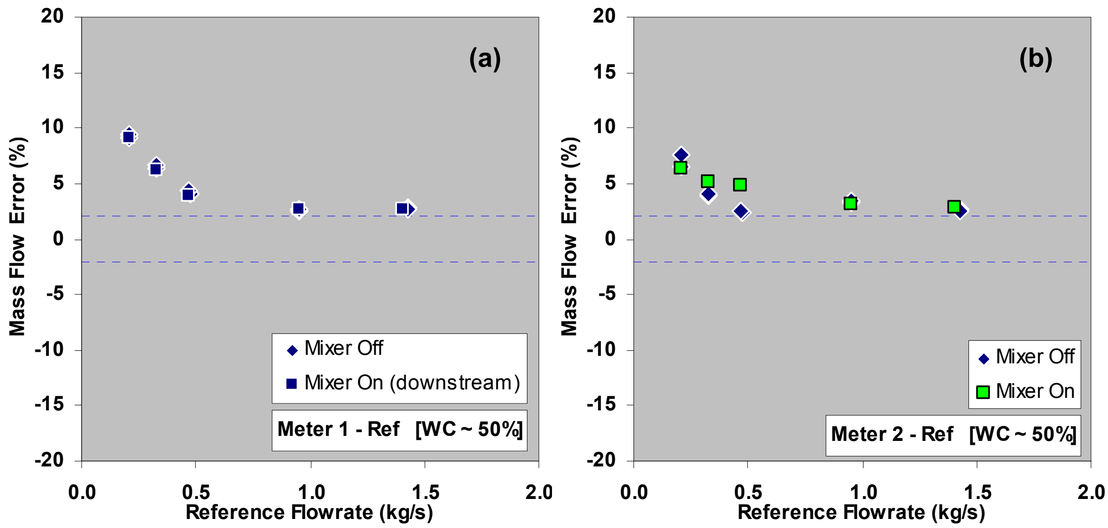

Fig. 14 – (a) Mass flowrate difference between Meter 1 (“flag up”) and the reference system in horizontal two-phase flow. (b) Corresponding data for Meter 2 (“flag up”).

Figure 14a shows the mass flow error for Meter 1 (unconditioned flow – all test points). At high flowrates, the agreement with reference is only slightly outwith 2% and, like the “flag down” orientation, systematically high. However, below 0.5 kg/s a significant overreading occurs. Again this may be an effect of the installation or zero setting.

The mass flow behaviour of Meter 2, in unconditioned flow, is similar to that of Meter 1. At high flowrates the mixer makes no difference to the mass flow response. At low flowrates (< 0.5 kg/s) there is perhaps some evidence of flow regime dependence, but with the limited data available the effect of the flow mixing is difficult to quantify.

5 SUMMARY AND CONCLUSIONS

Two Coriolis mass flowmeters (2" Micromotion CMF200) have been tested at NEL's multiphase flow facility to determine the extent to which their mass flow and density measurements are influenced by their installation orientation in two-phase liquid-liquid flows. The tests were conducted in two stages on oil-water mixtures of around 50% water cut.

The first set of tests was designed to simulate the metering set-up of a real-life production platform (Harald), where density differences of up to 0.8% had been observed between two vertically installed allocation meters (one with flow up and the other with flow down), when monitoring the same oil-water mixtures at low velocity. In the equivalent NEL tests, a similar density *difference* was observed between the two meters when operated in unconditioned flow at flow rates below about 1.5 kg/s. In this region, the oil and water phases have a tendency to separate, which appears to have a detrimental effect upon the Coriolis density measurement. Several mechanisms by which this might occur (velocity slip between the phases, uneven mass distributions between the internal flowtubes etc.) have been suggested.

The Coriolis meter with flow directed upwards was least affected by the oil / water phase separation, remaining within 0.2% of the reference density over the majority of the flow range investigated. Measurement taken under homogenised (jet mixer activated) and unconditioned flow were also within 0.2% of each other. Only at exceptionally low flowrates (< 0.45 kg/s) did a sudden overreading in density develop. At these flowrates, a form of churn flow was evident in the rising vertical test section, leading to increased (and effectively "permanent") water hold-up within the metering line and consequently an increased local density. The Coriolis meter with flow directed downwards displayed an underreading in density, which was still in evidence up to flowrates as high as 1.5 kg/s. This suggests that the natural separation of the oil and water is better preserved in the downwards direction, presumably due to a less turbulent flow regime. This in turn increases the potential for velocity slip and/or uneven mass distributions. On the whole, the mass flow measurements were less affected by phase separation, with the influence of flow regime becoming apparent only at the very lowest flowrates investigated (< 0.5 kg/s).

A second set of tests was also conducted on a horizontal flowline, with the meter flow tubes ("flags") arranged in three separate orientations around the flow axis (i.e. up, down and sideways). The aim of these tests was to determine whether such a configuration would improve or worsen the Coriolis meter performance. In fact, none of the horizontal installations offered an acceptable metering alternative for unconditioned flow at low velocities, with all three orientations demonstrating a significant underreading in density measurement when the oil and water phases became significantly separated (in this case at flowrates below ~ 1.5 kg/s). The "flag sideways" installation showed the largest density errors (up to 4%), while the "flag up" and "flag down" orientations were susceptible to the additional effect of "permanent" water hold-up in their vertical sections as the flowrate approached zero. The latter effect was greatest in the "flag down" position, presumably because the whole hanging "U-tube" had the potential to fill with water. The effect was diminished in the "flag-up" position as only the rising leg was prone to becoming water dominated. No effect whatsoever was evident in the "flag sideways" configuration.

For each of the meter set-ups investigated, conditioning of the flow immediately upstream of the metering station, using an active mixing element, almost completely eradicated all measurement deviations.

From an operational point of view, the experience gathered on Harald and the subsequent tests conducted at NEL demonstrate that low flow rates of oil / water mixtures can cause significant problems for Coriolis meters, with a high risk that the reported measurement will be wrong. If only a single meter is in use, then the abnormality may not be apparent as the meter diagnostics will continue to appear okay. The same holds for master / slave configurations if both meters are installed in the same orientation (i.e. the normal set-up). Here the same error will be generated in both meters and, since they appear to remain in agreement, no fault condition will be flagged.

The NEL tests also show that, for a single meter installation, the optimum orientation is vertical with flow directed upwards; if the available static head allows it preferably with a blind-T or some other turbulence generator near the inlet. For a master / slave arrangement, the actual installation on Harald (i.e. with the meters installed vertically but with opposite flow directions) is the optimum configuration for the detection and avoidance of measurement errors. In all cases the inclusion of a jet mixer element is an efficient way of eliminating all phase separation problems.

Furthermore, when designing a new meter installation for Coriolis metering of live liquids it should be ensured that the static head between the separator level and the position of the flow meters is so large that it allows for high velocities in all situations. It should also be noted that, when there is a large difference between the oil and water densities, the risk of an error will be greater as both the phase separation and gravity-induced slip will increase. The phenomena is particularly problematic if the density measurement is used for water cut evaluation, since even a small error in the density can lead to a significant error in the water cut and net oil.

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6 NOTATION

BSW_V	:	Liquid water cut by volume at process conditions.
ρ_{MIX}	:	Density of liquid mixture at process conditions [kg/m^3]
ρ_{OIL}	:	Density of oil at process conditions [kg/m^3]
ρ_{WAT}	:	Density of water at process conditions [kg/m^3]

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APPENDIX A

UNCERTAINTIES IN WATER-CUT AND NET OIL

The large uncertainty associated with the Coriolis density measurement has a significant impact on both the derived water cut and net oil evaluation.

The following definitions are noted, together with typical values for this application:

w	Water cut of liquid	0.40
ρ_O	Density of oil [kg/m^3]	800
ρ_W	Density of water [kg/m^3]	1100
$\rho = w.\rho_W + (1-w).\rho_O$	Density of liquid [kg/m^3]	920
$\left(\frac{\Delta\rho}{\rho}\right)$	Uncertainty in liquid density	0.008
Q	Volume flow rate of liquid [m^3/hr]	5
Q_O	Volume flow rate of oil [m^3/hr]	3
q	Mass flow rate of liquid [kg/hr]	4600

The effect of the density uncertainty at these process conditions is outlined below. Zero error is assumed on the mass flow rate measurement.

A.1 EQUIVALENT ERROR IN WATER CUT

The effect of the density uncertainty on water cut evaluation is as follows:

$$w = \frac{\rho - \rho_O}{\rho_W - \rho_O} \qquad \Rightarrow \qquad \left(\frac{\partial w}{\partial \rho}\right) = \frac{1}{\rho_W - \rho_O}$$

$$\Delta w = \left(\frac{\partial w}{\partial \rho}\right)\Delta\rho \qquad \approx \qquad \frac{0.008\,\rho}{\rho_W - \rho_O} \qquad \approx \qquad 2.45\ \% \quad [\text{abs}]$$

A.2 EQUIVALENT ERROR IN NET OIL

The effect of the density uncertainty on net oil evaluation is as follows:

$$Q_O = \frac{(1-w)q}{\rho} = \frac{(\rho_W - \rho)q}{(\rho_W - \rho_O)\rho} \qquad \Rightarrow \qquad \left(\frac{\partial Q_O}{\partial \rho}\right) = \frac{-\rho_W\ q}{(\rho_W - \rho_O)\rho^2}$$

$$\Delta Q_O = \left(\frac{\partial Q_O}{\partial \rho}\right)\Delta\rho \quad \approx \quad 0.147\ \text{m}^3/\text{hr} \qquad \Rightarrow \qquad \frac{\Delta Q_O}{Q_O} \quad \approx \quad \frac{0.147}{3.00} \quad \approx \quad 4.9\ \% \quad [\text{rel}]$$