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Paper 8.2

Oil/Water Tests on a 4-Path Ultrasonic Meter at Low Flow Velocities

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1 INTRODUCTION

Multipath ultrasonic flowmeters are now capable of achieving the accuracies required in custody transfer applications. However, it must be recognised that all technologies have limitations and that optimum performance can not be achieved in every application. Previous papers presented at this workshop have shown that the performance of liquid ultrasonic meters can be adversely affected by the presence of water in oil [1 - 3]. It has also been shown that the behaviour of the meters is a complex function of the meter design, the flow regime, and the oil/water distribution [2, 3].

This paper describes the performance of a 4-path ultrasonic meter in oil/water flows at low velocities over a wide range of water-cut. These tests were performed as an acceptance test for the meter prior to deployment in the North Sea on an allocation duty, measuring oil from a first stage separator.

The tests were performed on a 4-inch Caldon LEFM 240C ultrasonic flow meter in the multiphase flow laboratory at NEL. The tests covered low flow velocities in the range of 0.15 to 2.5 m/s. Tests were performed at 3, 5, 7, 10, 15, 20, 50 and 75% water-cut. Prior to the tests Caldon estimated the measurement uncertainty based on experience from previous oil/water laboratory tests at Ohio University [3]. The meter performance was evaluated by comparison with the NEL reference meters, and ultrasonic meter diagnostics were logged at 5 second intervals during the tests.

This paper presents the performance data from the tests and compares these results with the uncertainties estimated by Caldon prior to the tests. Diagnostic data is also presented in order to show the interactions between the flow regime and the measurements on individual paths.

2 BACKGROUND

The AH001 is a converted drilling rig which started production from the Hess Ltd operated Ivanhoe, Robroy and Hamish fields (IVRRH) on the 7th of July 1989. On the 19th February 1999 a new development known as the R-Block was brought online over the AH001. The R-Block development, which comprised of two fields (namely the Renee and Rubie fields), was operated by Philips Petroleum and subsequently changed hands to Talisman Energy Ltd. Unitisation was not an option at the time of the development and it was decided to produce the R-Block via a dedicated separator and measure the oil, gas and water products from this separator to perform the field allocation. A schematic of the infrastructure associated with AH001 is shown in Figure 1 below.

Ivanhoe RobRoy and Hamish fields are owned by Hess and Talisman and are operated by Hess. The Renee and Rubie fields are owned Talisman, Hess and Marubeni and are operated by Talisman.

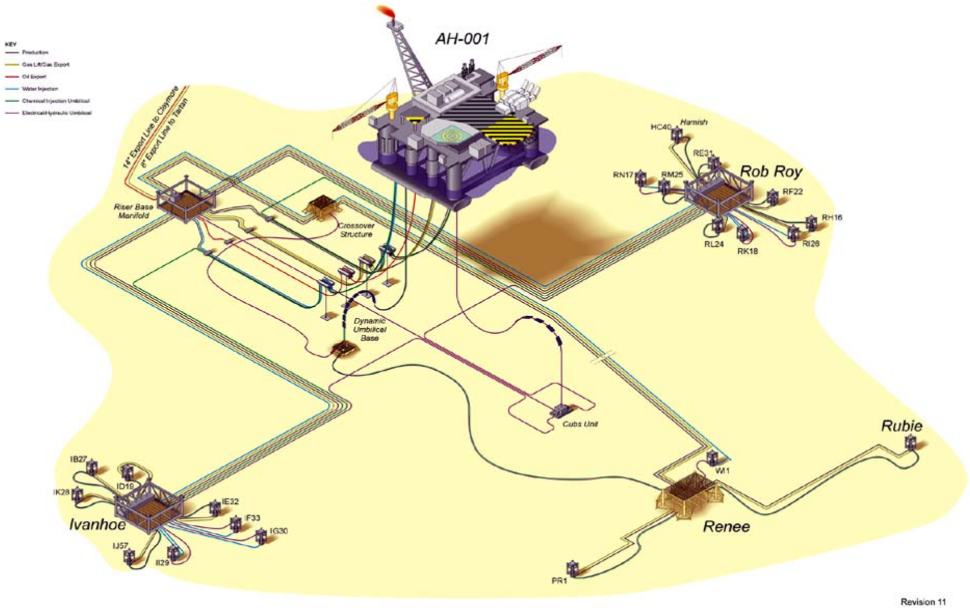

Figure 1 The AH001 platform and infrastructure

The principle adopted for the allocation was the 'by difference approach', where measurements from various process points through out the installation are used to calculate the allocation between the R-Block and IVRRH Fields. In conjunction with the field measurement a process model is used to apportion gas liquid products produced through the compression train. The block diagram schematic shown in Figure 2 below gives a general overview of the AH001 plant. This diagram shows that there is no separate production metering for the IVRRH fields, and therefore the allocation of the exported oil between R-Block and IVRRH is dependent on the Renee Rubie separator outflow measurements.

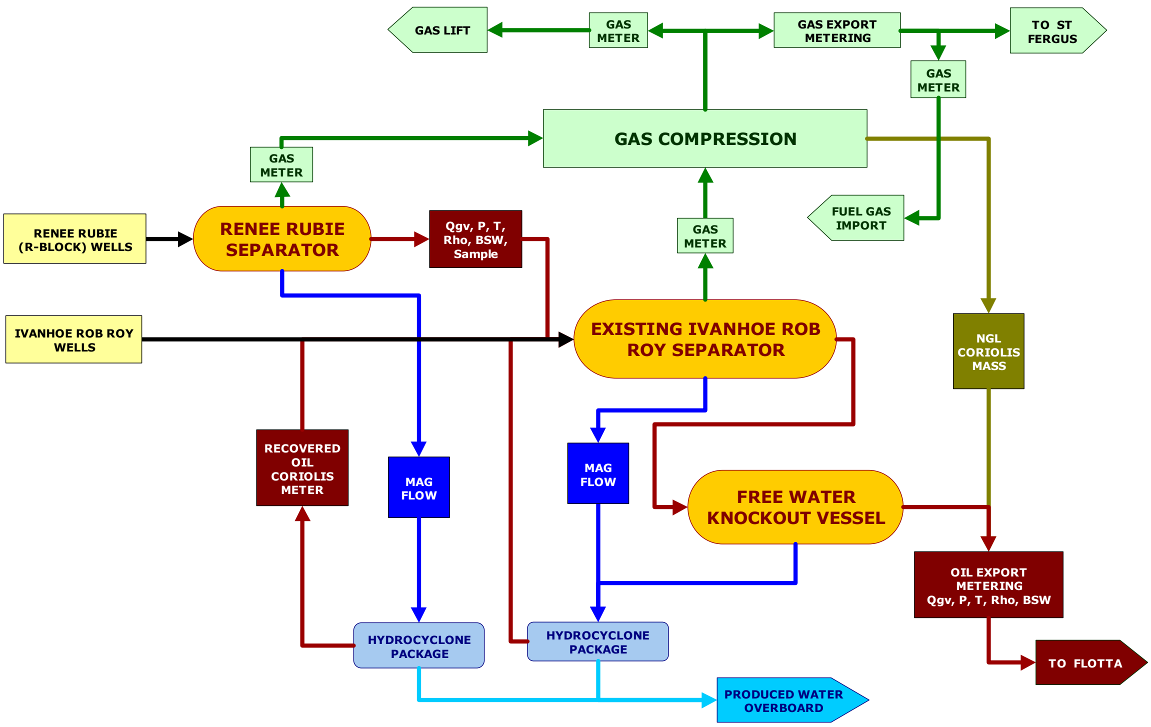

Figure 2 An overview of the AH001 plant

The original R-Block separator oil meter that was purchased at the time of the field development was an 8-inch 5-path ultrasonic, installed in a 10–inch flow line. Early production rates from R-block were around 140 m^3/hr of oil but by 2005 the production had dropped to around 20 m3/hr as illustrated in Figure 3 below. As a result the 8-inch meter was operating at about 2 % of its nominal maximum flow. This difficult operating condition was further exacerbated by the high water-cut in the oil outlet of the separator, which was assumed to be responsible for the intermittent loss of output from the 5-path meter. As the 8-inch meter was operating towards the bottom end of it measurement envelope a decision was made to change the meter out for a smaller device that would see out its duty to the end of R-Block's field life. A 4-inch Caldon ultrasonic meter was subsequently selected for the duty and installed for service on the 22nd of June 2006

Figure 3 R-Block averaged production rates

At the time when the meter was being selected the flowrate in the application was below 20 m^3/hr and was forecast to drop to approximately 8 m^3/hr in later field life. The resulting velocities of between approximately 0.3 and 0.7 m/s were below the normal expected operating range for a 4-inch meter, with the result that the measurement uncertainty would be higher than usual in this application, even under zero water-cut conditions[1].

The water-cut was estimated to be about 5 % on average. However, process data suggested instantaneous water-cut variations from around zero to in excess of 20 %. It was recognised that high water-cut combined with low velocities would result in additional measurement uncertainties. As a result Caldon specified the uncertainties expected for the conditions of operation and incorporated these into a factory acceptance test plan that would be carried out in the multiphase flow facility at NEL.

The meter Caldon provided for this application was the LEFM 240C 4-path custody transfer ultrasonic meter, which is illustrated in Figure 4 below[2]. The 4-path model was proposed as the multipath arrangement combined with the LEFM path substitution capabilities would enhance performance in oil/water applications where some individual path measurements may occasionally be rejected as a result of poor signal quality.

Some modifications were made to the standard design in order to improve the performance in oil/water flows. In particular the transducers on path 3 (the second from the bottom) were

[1] In single-phase oil the specified linearity of a 4-inch LEFM 240C 4-path meter over a 10:1 operating range is ± 0.15%, based on a maximum flow of 325 m3/hr. The corresponding minimum normal operating velocity is approximately 1 m/s.
[2] The path numbering convention for the Caldon meter is path 1 at the top and path 4 at the bottom of the pipe

intruded slightly into the flow in order to prevent accumulation of 'globs' of water at low velocities. The accumulation of water globs was noted in both bottom paths (paths 3 and 4) in the tests at Ohio University [3] but the transducers on path 4 were not intruded as this would have made the transit times on that path very short.

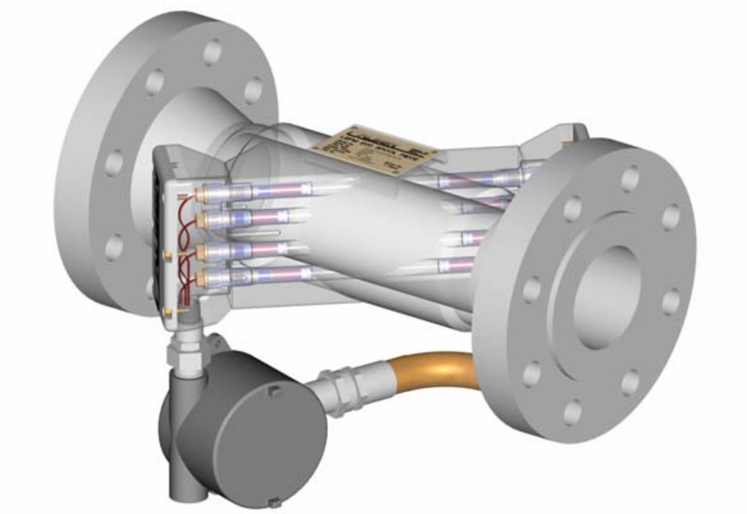

Figure 4 An Illustration of a 4-Path Caldon Ultrasonic Flowmeter (LEFM 240C)

Accounting for the effects of water-cut on measurement uncertainty is not trivial, as the effects on meter performance are a function of both velocity and water-cut (as well as other fluid properties such as density and viscosity). Caldon had previously performed oil/water testing at Ohio University [3], and although these tests had some limitations, the data provided sufficient information for Caldon to estimate the effects of water-cut.

A very conservative velocity dependent uncertainty estimate of ±0.01 m/s was applied to account for low velocity and Reynolds number effects over the full range of water-cut. In addition to this base uncertainty, an additional water-cut dependent uncertainty was estimated from information from the Ohio University oil/water data as follows:

For water-cut less than 7 %:

± 0.5 % for velocity > 1.5 m/s (44 m^3/hr)
± 5 % for velocity between 0.5 and 1.5 m/s (15 - 44 m^3/hr)
± 3 % for velocity < 0.5 m/s (15 m^3/hr)

For water-cut between 7 and 20 %:

± 5 %

These estimated uncertainties were combined along with the test system uncertainty of +/- 1% in order to define acceptance limits for the performance of the meter in the acceptance tests at NEL.

3 TEST CONDITIONS

The range of conditions that were planned for the NEL test are given in Table 1 below. The test conditions in bold correspond to the average flow rate conditions in the application, with a maximum water-cut of 20%. The additional points outside of this range were included in order to give Hess an indication of how the meter would perform outside of the normal application limits. In the actual tests the minimum water-cut that could be achieved was 3 %. The conditions highlighted in italics were not achievable as they were outside the calibration range of NEL's reference meters.

Table 1 NEL oil/water test conditions

Velocity m/s	Flow (m^3/hr)	Water-cut (nominal)							
		2%	5%	7%	10 %	15 %	20 %	50 %	75 %
		Oil rate (l/s)							
0.13	3.6	*1.0*	*1.0*	0.9	0.9	0.9	0.8	0.5	*0.3*
0.25	**7.2**	***2.0***	**1.9**	**1.9**	**1.8**	**1.7**	**1.6**	1.0	0.5
0.51	**14.4**	**3.9**	**3.8**	**3.7**	**3.6**	**3.4**	**3.2**	2.0	1.0
0.76	**21.6**	**5.9**	**5.7**	**5.6**	**5.4**	**5.1**	**4.8**	3.0	1.5
1.15	32.4	8.8	8.6	8.4	8.1	7.7	7.2	4.5	2.3
2.55	72	19.6	19.0	18.6	18.0	17.0	16.0	10.0	5.0

Taking the uncertainty estimates given earlier, the total uncertainty at each condition was evaluated, including the velocity measurement uncertainty, the water-cut effect uncertainty, and the NEL multiphase test facility uncertainty of +/- 1 % of liquid rate.

Table 2 below shows the uncertainty calculated at each condition (note that uncertainty was not evaluated for the 50 % and 70 % water-cut test points owing to a lack of knowledge of performance at these conditions).

Table 2 Estimated uncertainty for the NEL oil/water tests

Velocity (m/s)	Flow (m^3/hr)	Water-cut (nominal)							
		2%	5%	7%	10%	15%	20%	50%	75%
		Total uncertainty							
0.13	3.6	8.5%	8.5%	8.5%	9.4%	9.4%	9.4%	-	-
0.25	**7.2**	**5.0%**	**5.0%**	**5.0%**	**6.4%**	**6.4%**	**6.4%**	-	-
0.51	**14.4**	**5.5%**	**5.5%**	**5.5%**	**5.5%**	**5.5%**	**5.5%**	-	-
0.76	**21.6**	**5.3%**	**5.3%**	**5.3%**	**5.3%**	**5.3%**	**5.3%**	-	-
1.15	32.4	5.2%	5.2%	5.2%	5.2%	5.2%	5.2%	-	-
2.55	72	1.2%	1.2%	1.2%	5.1%	5.1%	5.1%	-	-

4 TEST FACILITY

The oil/water tests were conducted in the NEL multiphase flow secondary standard. A schematic diagram of this facility is shown in Figure 5 below. The working inventory of oil and water is held in a vessel that acts as a combined storage tank and multiphase separator. The oil and water are drawn from two compartments in the separator vessel and pumped into the test section via calibrated liquid turbine reference meters. The individual liquid streams are equipped with isokinetic density sampling loops in order to quantify background amounts of water-in-oil and oil-in-water. If required, nitrogen gas can also be added from an external supply via calibrated gas turbine reference meters.

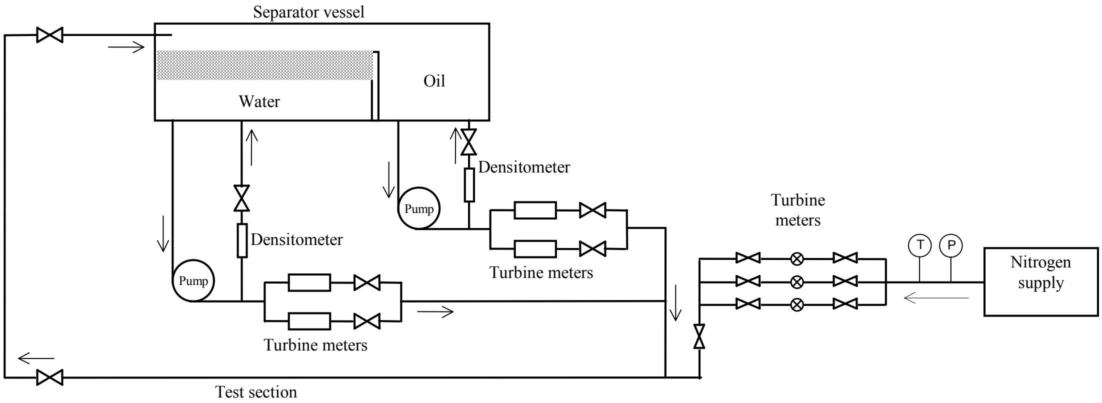

Figure 5 A schematic diagram of the NEL multiphase flow facility

The NEL multiphase test facility is normally operated at a temperature of between 30 and 40 °C to ensure adequate separation of the oil and water before they are metered individually. At these conditions the oil has a density of approximately 858 kg/m^3 and the water has a density of 1038 kg/m^3. Viscosity of the oil and water are approximately 14 and 0.9 cSt respectively. The oil is a mixture of Oseberg and Forties crudes with some added refined oils. The water is a 50 mg/litre solution of magnesium sulphate.

After each test condition was set, the NEL facility operator waited a short time for the line conditions to stabilise before data logging commenced on the NEL system. Diagnostic data from the meter was logged continuously throughout the test using a laptop with Caldon's LEFMLink software. Each test point ran for two minutes duration, and three of these points were acquired at each condition. The pulse output from the Caldon meter was totalised by NEL for each point and the flowrate results were then compared with the processed reference values from the NEL logging system.

5 PIPEWORK INSTALLATION

The meter was installed with the actual field upstream pipework. A photograph of the installation in the multiphase facility is shown in Figure 6 below. This pipework has a reduction from 10-inches in diameter to 4-inches in diameter. Eccentric reducers were used in an effort to minimise water hold-up upstream of the test section. Water hold-up upstream of a concentric reducer was expected to cause water slugging with flowrate variations in the application.

Flow conditioners were considered unnecessary in this application as it is believed that the oil/water effects would dominate the uncertainty and that the use of a flow conditioner would not provide any additional benefits.

Figure 6 A photograph of the meter installation

6 MEASUREMENT REJECTION AND PATH SUBSITUTION

Individual transit time measurements can be rejected when an oil/water interface or a 'coarse' mixture with large droplets of oil and/or water is present in the pipe at the height corresponding to a particular measurement path. Individual measurements are rejected when they fail to meet criteria based on reciprocity (or similarity), signal-to-noise ratio and transit time statistics. The Caldon LEFM240C performs one velocity measurement per path approximately every 20 milliseconds. If the percentage of measurements rejected on a given path exceeds a set threshold, then that path goes into fail mode and a substitute value of velocity is calculated for the path.

During earlier tests at Ohio University the reject threshold was set to 100%, i.e. all paths were considered operational even if 90% of the data was being rejected. This resulted in some large errors due to use of velocity information that would have normally been rejected [3]. For the results discussed here the reject threshold was set at 50%.

At low velocities a single distinct interface is present and only one path should fail. As the velocity is increased waves form at the interface and then large droplets of either fluid can detach, causing some measurement rejects and possible path failures, normally on one path only. As velocity is increased further this can lead to a more challenging flow regime where there is an oil layer at the top of the pipe, a water layer at the bottom of the pipe, and a coarse mixture of oil and water in between. Depending on the water-cut, this can cause failure of more than one path. At high velocities the droplets are reduced in size and the flow becomes well mixed. Caldon meters perform with zero signal rejects when the oil and water are well mixed.

When one or two paths fail the missing velocity values are substituted based on an assumed velocity profile and the actual measurements on the working paths. Each meter has a default velocity profile so that substitution can be performed even if the meter is started up in a situation where one or two paths fail. This default profile is derived from the baseline calibration data for the meter. When all four paths are working the profile information used for path substitution is replaced by the measured profile and is updated every ten seconds.

7 TEST RESULTS

The ultrasonic meter was first calibrated in the single-phase oil calibration facilities using kerosene at 20°C, with a viscosity of 2.3 cSt and a density of 797 Kg/m^3. Following the entry of the characteristic curve into the meter's software, the meter was calibrated again to provide traceability and to ensure that no errors had been made. The results of this calibration are shown in Figure 7 below. It can be observed that the calibration was carried out below the 10:1 turndown applicable for the +/- 0.15% linearity specification for the meter. As expected, the errors at these low flows are greater than +/- 0.15% but are well within the uncertainty limits stated for the field application.

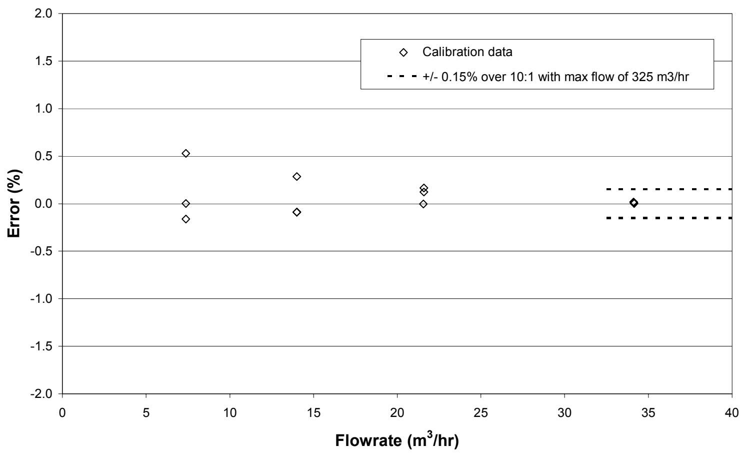

Figure 7 Single-phase oil calibration results

Multiphase test data was gathered over a period of three days, in a sequence chosen by the NEL facility operator in order to use the facility time efficiently. Results have been broken down into graphs ordered by water-cut for presentation below. All graphs show the points within the application flowrate range as filled circles and the points outside this range as open circles.

Figure 8 shows the results obtained at 3 % water-cut. It can be observed that all of the points are inside the estimated uncertainty limits for these conditions. There were no signal rejects on any path at 3 % water-cut.

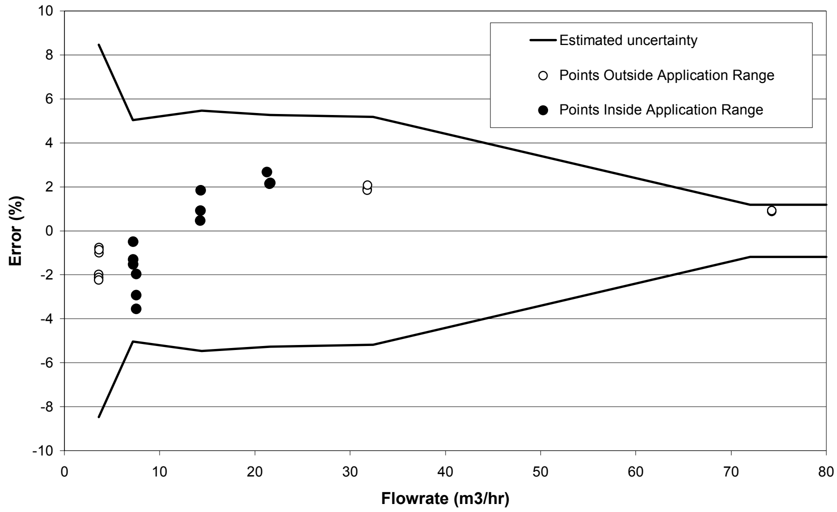

Figure 8 Test results at 3% water-cut

Figure 9 shows the results obtained at 5 % water-cut. It can be observed that all of the points are inside the estimated uncertainty limits for these conditions. At 22 and 32 m^3/hr there were low levels of signal rejects (less than 10%) on path 4 (the bottom path). At 7 and 14 m^3/hr there were intermittent occurrences of 100% rejects on path 4. Average percentage signal rejects at 5% water-cut are plotted as a function of flowrate in Figure 10 below.

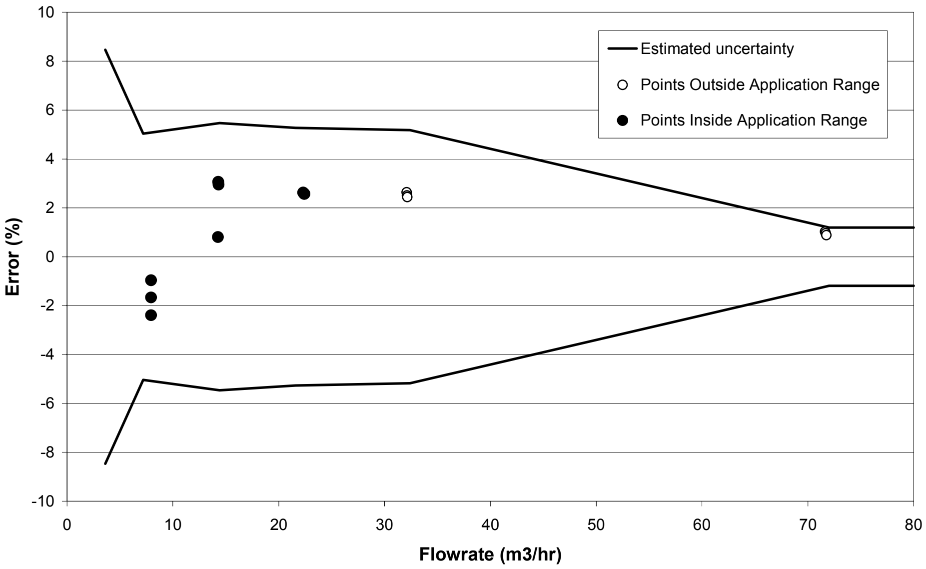

Figure 9 Test results at 5% water-cut

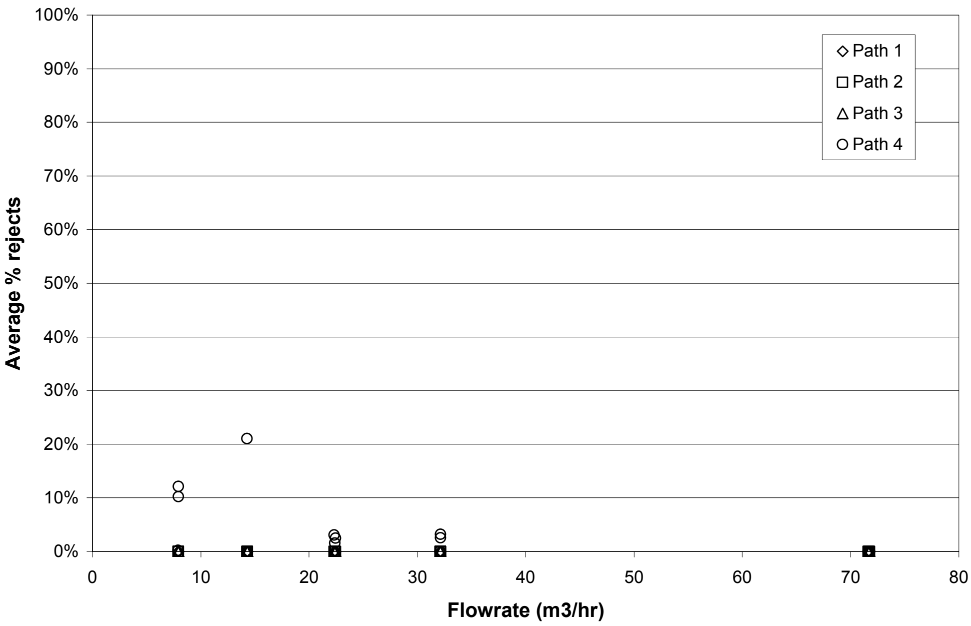

Figure 10 Signal rejects at 5% water-cut

Figure 11 shows the results obtained at 7 % water-cut. It can be observed that only the points at 22 m^3/hr are outside of the estimated uncertainty limits for these conditions, and that these are only marginally outside of the specification. At 22 m^3/hr path 4 was displaying 100 % signal rejection and was being substituted. At 32 m^3/hr the rejects on path 4 were above 70%. There were rejects of between 10 and 20 % on path 4 at 4 and 7 m^3/hr and no rejects at 14 and 72 m^3/hr. These variations can be related to the effects of velocity on the oil/water distribution, with the water at the bottom of the pipe going through the transition from a stratified layer to a well-mixed flow. Paths 1, 2 and 3 had no rejects at 7% water-cut. Average percentage signal rejects at 7% water-cut are plotted as a function of flowrate in Figure 12 below.

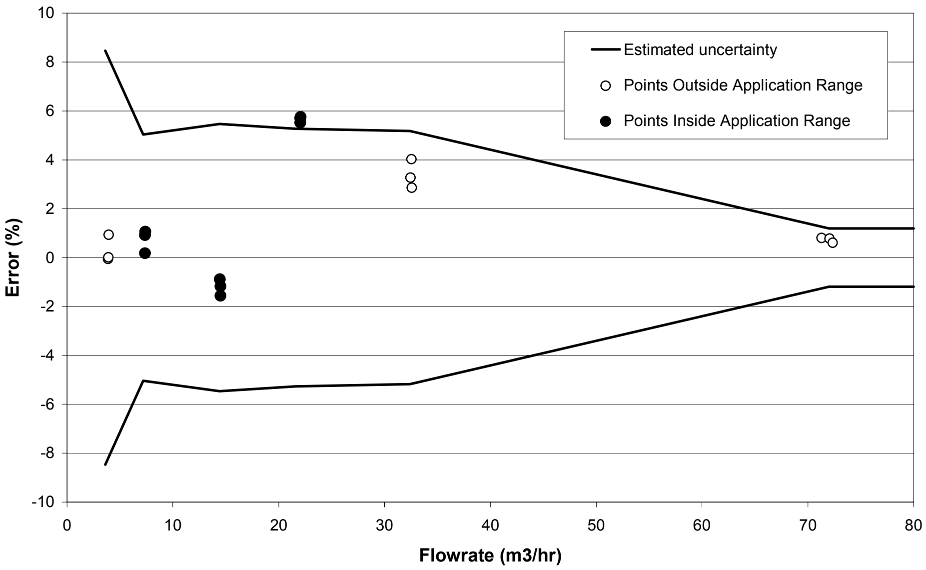

Figure 11 Test results at 7 % water-cut

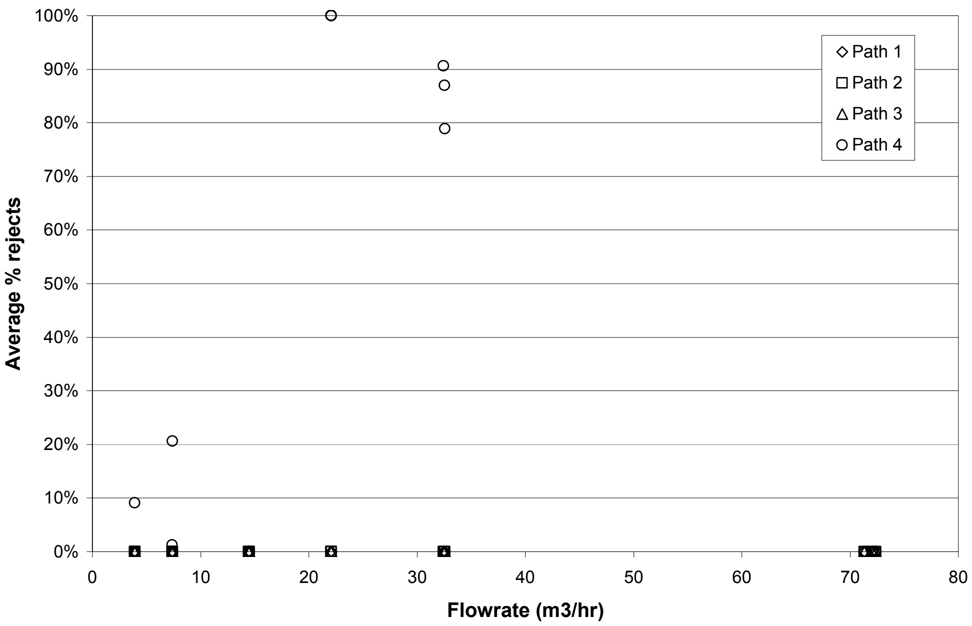

Figure 12 Signal rejects at 7 % water-cut

Figure 13 shows the results obtained at 10 % water-cut. It can be observed that all of the points are inside the estimated uncertainty limits for these conditions. Note that at 72 m3/hr the errors are within +/- 1%, which is the reference system uncertainty. At 22 and 32 m^3/hr path 4 was displaying 100 % signal rejection and was being substituted. Rejects were 10% at 7 m^3/hr and 0 % for all other flowrates. Paths 1, 2 and 3 had no rejects at 10 % water-cut. Average percentage signal rejects at 10% water-cut are plotted as a function of flowrate in Figure 14 below.

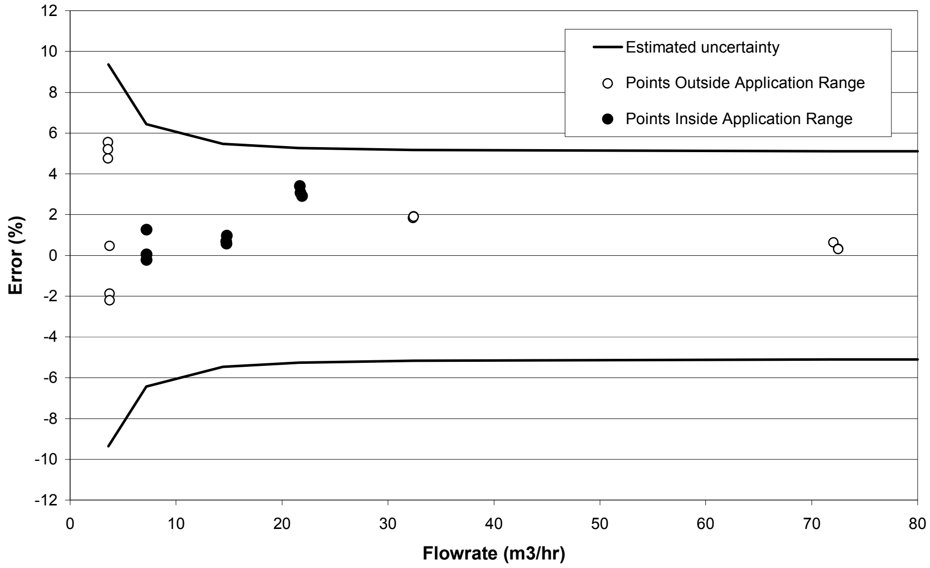

Figure 13 Test results at 10 % water-cut

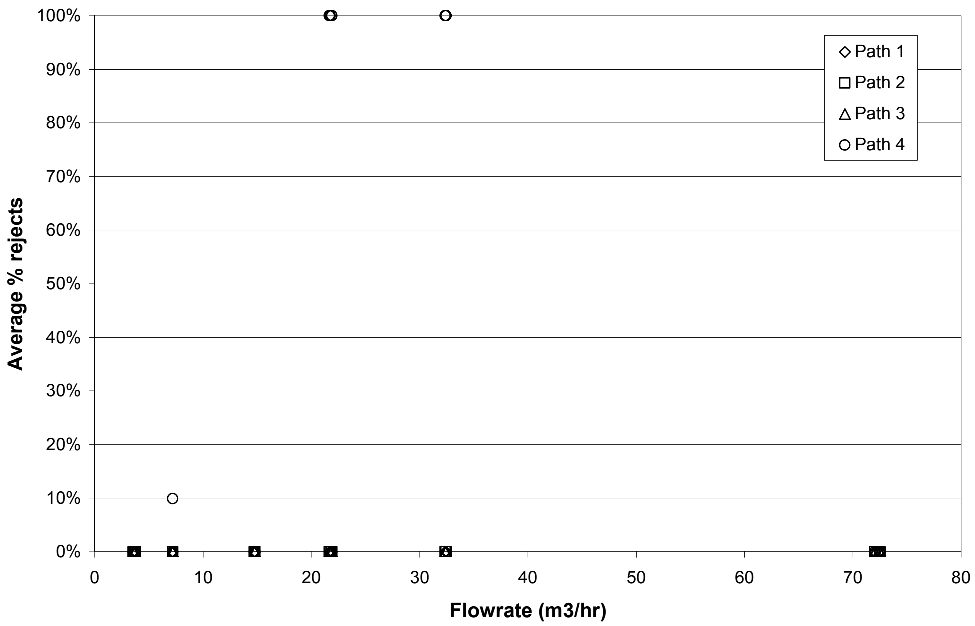

Figure 14 Signal rejects at 10 % water-cut

Figure 15 shows the results obtained at 15 % water-cut. It can be observed that all of the points are inside the estimated uncertainty limits for these conditions. Note that at 72 m3/hr the errors are within +/- 1%, which is the reference system uncertainty. At 22 and 32 m^3/hr path 4 was displaying 100 % signal rejection and was being substituted. Rejects were at 0 % for all other flowrates. Paths 1, 2 and 3 had no rejects at 15 % water-cut. Average percentage signal rejects at 15% water-cut are plotted as a function of flowrate in Figure 16 below.

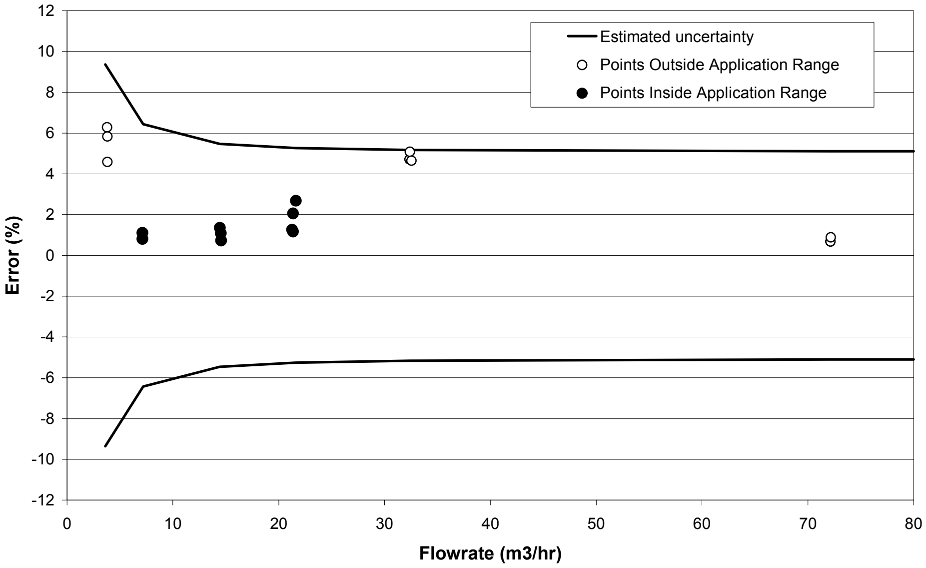

Figure 15 Test results at 15 % water-cut

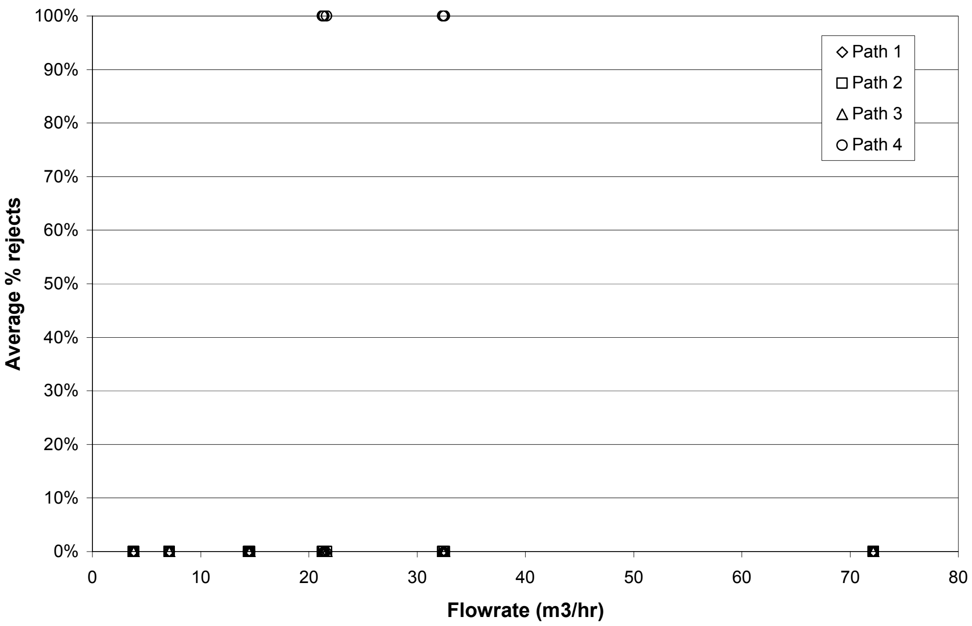

Figure 16 Signal rejects at 15 % water-cut

Figure 17 shows the results obtained at 20 % water-cut. It can be observed that there are points outside of the estimated uncertainty limits at 4 and 32 m^3/hr, but that the points inside the application range comply with the estimated uncertainty. Note that at 72 m3/hr the errors are within +/- 1%, which is the reference system uncertainty. At 22 m^3/hr the rejects values were zero on paths 1 and 2 and approximately 14% on path 3 and 95% on path 4. At 32 m^3/hr, the rejects were zero on paths 1, 2 and 3, and 100% on path 4. Rejects were at 0 % on all paths for all other flowrates. Average percentage signal rejects at 20% water-cut are plotted as a function of flowrate in Figure 18 below. Figure 19 overleaf the signal-to-noise ratio per path at 20% water-cut. The low signal-to-noise ratio on both paths 2 and 3 at 32 m^3/hr suggest that the larger errors at this condition arise as a result of both of the 'inside' paths being affected.

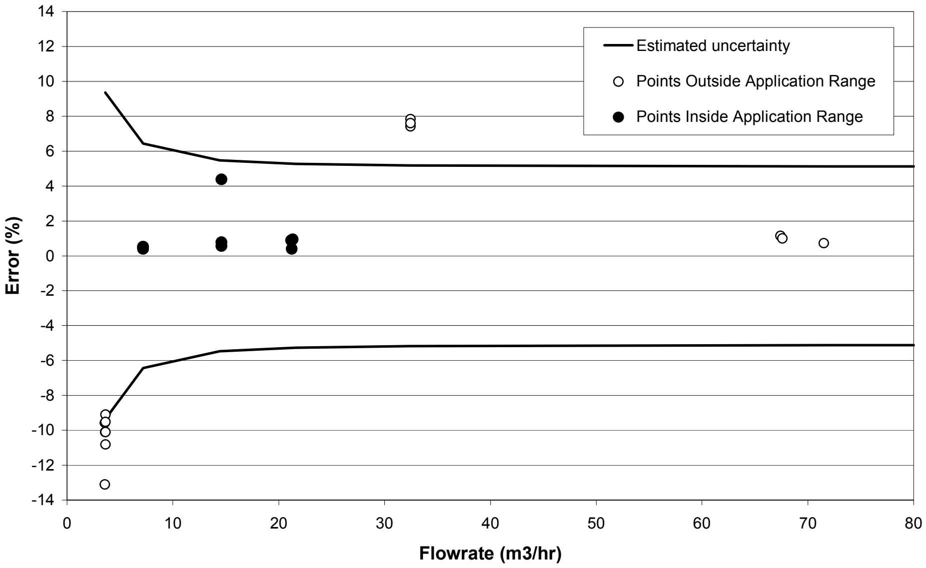

Figure 17 Test results at 20 % water-cut

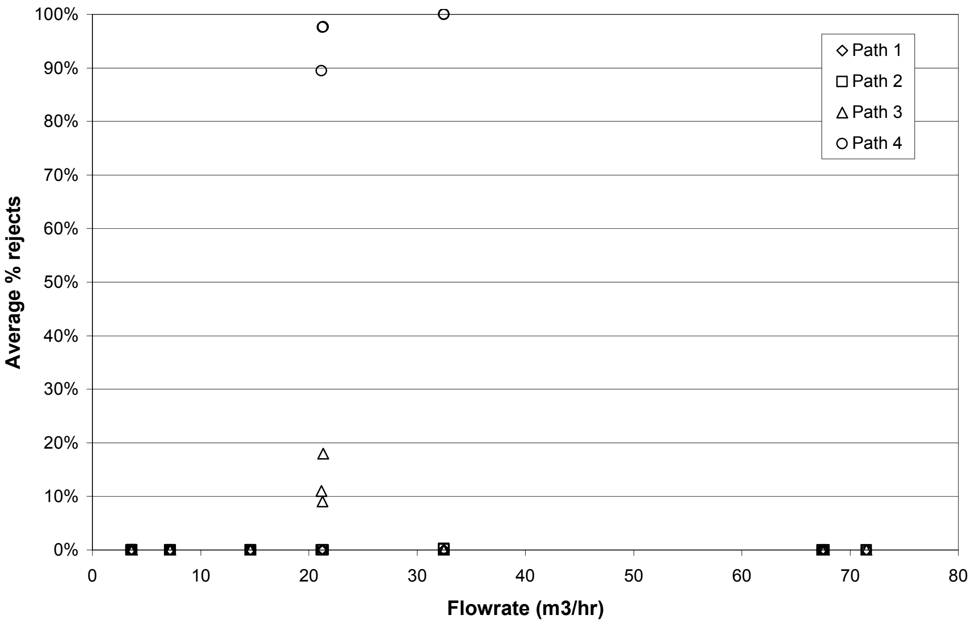

Figure 18 Signal rejects at 20 % water-cut

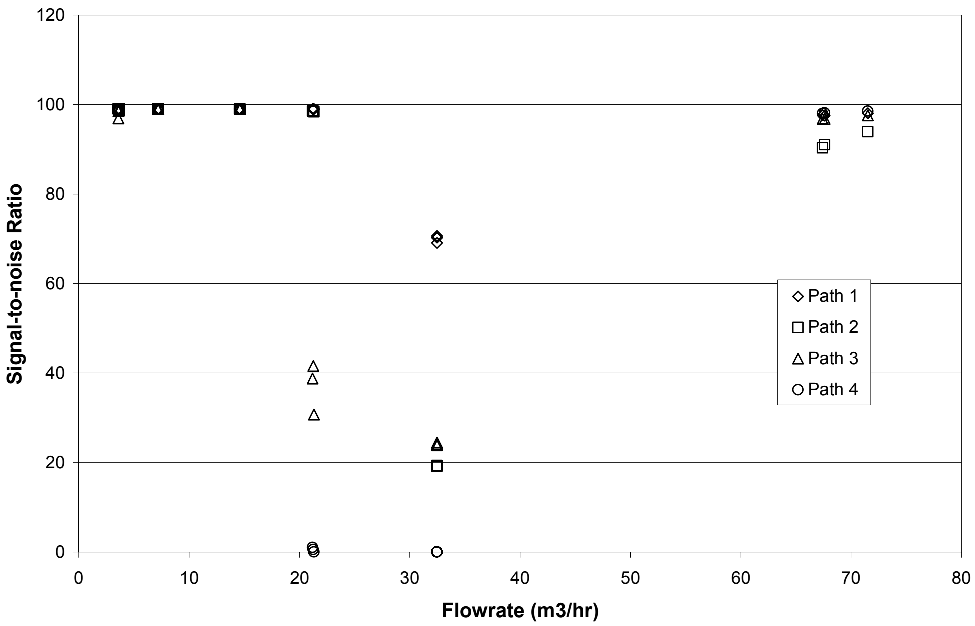

Figure 19 Signal-to-noise ratio at 20 % water-cut

Figure 20 shows the results obtained at 50 % water-cut. Most of the points are within the uncertainty limits that were estimated for 20 % water-cut. However, there were some large errors at 32 m/hr. At this condition both paths 2 and 3 were showing 100% rejects. However, it is reassuring that the point with the largest error was the first of 4 repeats at that condition, and that even with 100 % rejects on paths 2 and 3, the errors came within 5 % once the flow had had a few more minutes to stabilise. At 22 m^3/hr path 3 was showing 100% rejects, and the other paths were showing 0% rejects. At all other conditions all paths were operating with 0 % rejects. Average percentage signal rejects at 50% water-cut are plotted as a function of flowrate in Figure 21 below.

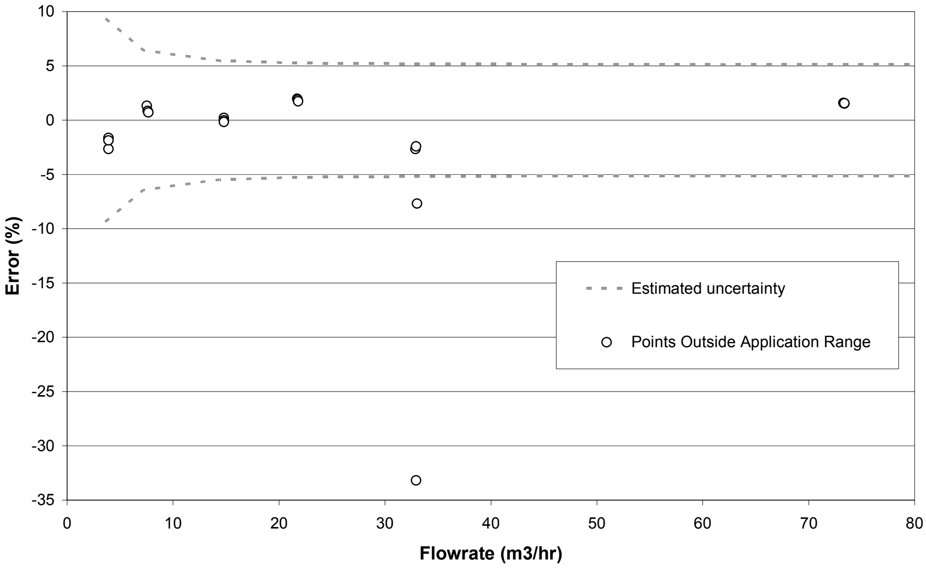

Figure 20 Test results at 50 % water-cut

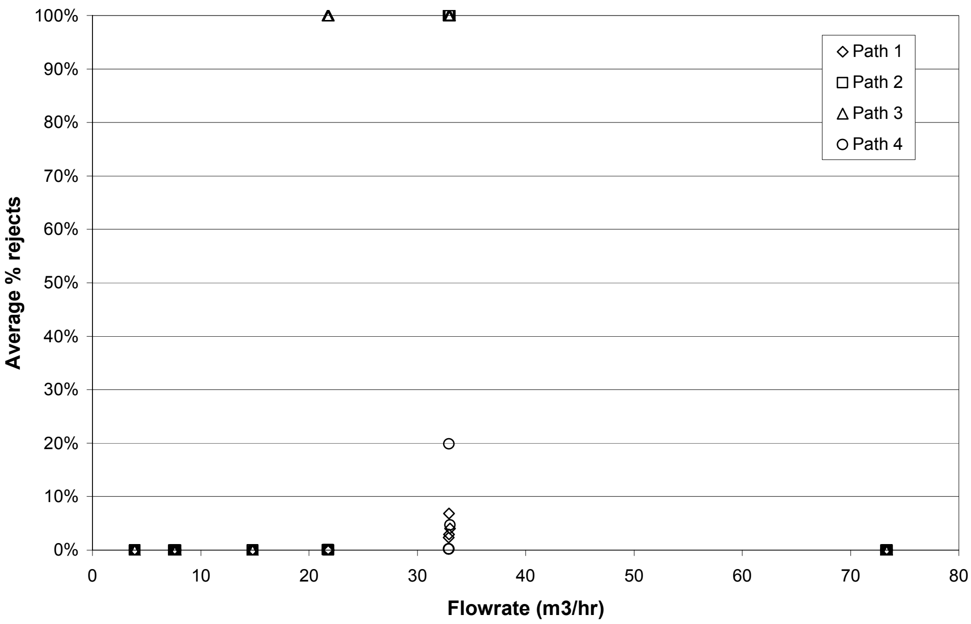

Figure 21 Signal rejects at 50 % water-cut

Figure 22 shows the results obtained at 75 % water-cut. Most of the points are within the uncertainty limits that were estimated for 20 % water-cut. However, there were some large errors at 72 m/hr. At this condition the percentage rejects were 9%, 100%, 47% and 0% for paths 1 to 4 respectively. The signal-to-noise ratio on path 3 was poor at this condition (as the % rejects were only marginally below the failure threshold), suggesting that it was velocity measurement errors on this path that were responsible for the larger errors at this condition. Average percentage signal rejects at 75% water-cut are plotted as a function of flowrate in Figure 23 below.

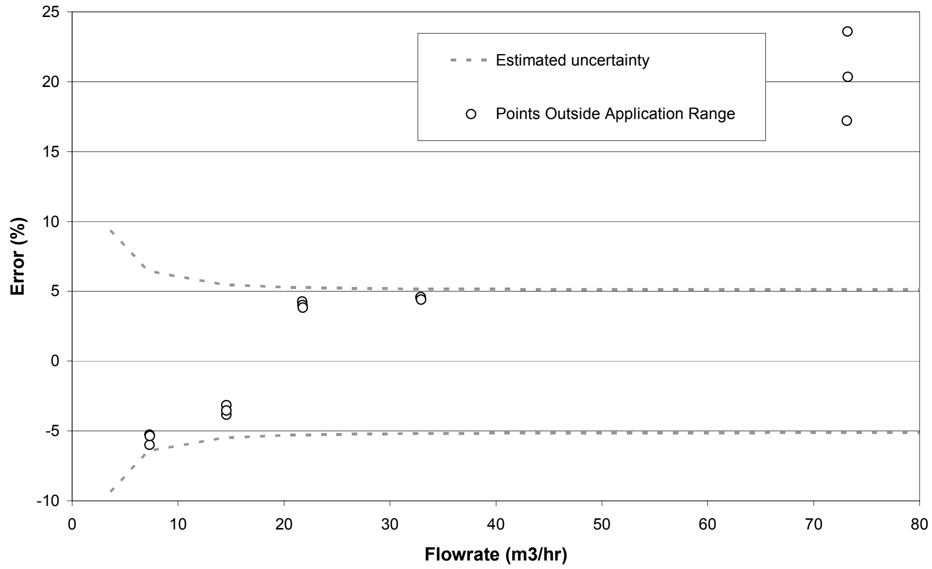

Figure 22 Test results at 75 % water-cut

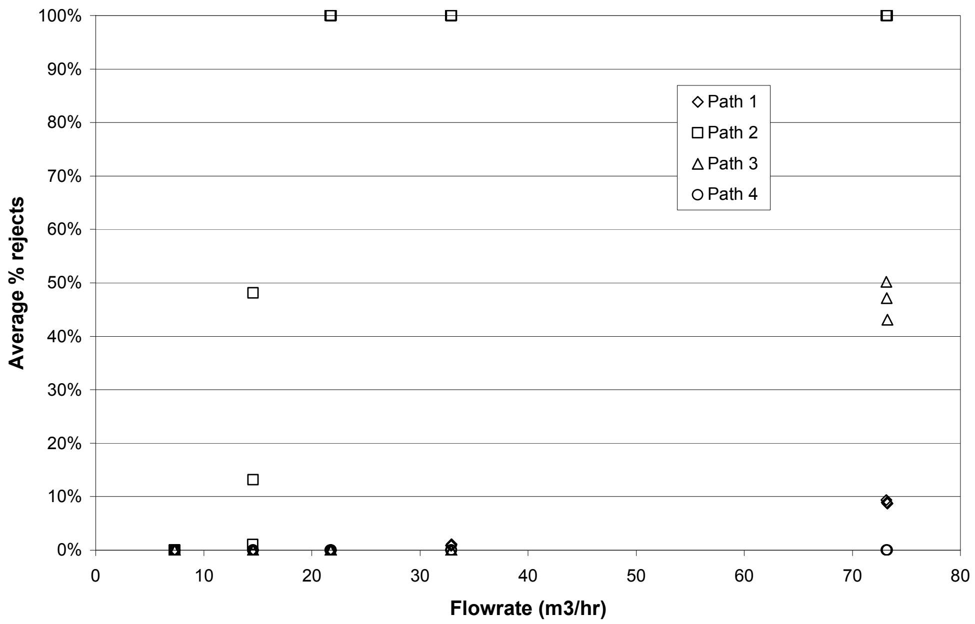

Figure 23 Signal rejects at 75 % water-cut

8 DISCUSSION AND CONCLUSIONS

Within the application range of 7 to 22 m^3/hr and water-cut less than 20 % the 4-inch Caldon LEFM240C tested satisfied the estimated uncertainty at all but one condition and generally agreed with the NEL reference to within +/- 3%. At 22 m^3/hr and 7 % water-cut the errors were within +/- 5.7 % compared with an estimated uncertainty of +/- 5.4% at that condition.

Larger errors were encountered outside of the application range, in particular at 50 and 75 % water-cut and flowrates above 22 m^3/hr.

At the highest flowrate tested (corresponding to a velocity of ~2.5 m/s), the errors were within the NEL reference system uncertainty of 1% for water-cuts of up to 20%. It is expected that the additional uncertainty in the ultrasonic meter is very low under these conditions. However, a more accurate reference measurement system is required to verify this.

Analysis of the percentage of measurements rejected on each path gives a clear indication of the oil/water distribution in the pipe and its varying effects on the measurement performance. Additional diagnostic information not presented here, such as signal gain and velocity of sound, provide further information that can also be used in order to understand the flow conditions in the pipe.

Below 20 % water-cut the only path to fail was path 4, and there was only one occurrence where any other path was rejecting data (path 3 at 20% water-cut and 22 m^3/hr, with rejects of less than 20%). Even at 50 and 75 % water-cut, no more than 2 paths failed at any one time. From analysis of a continuous log of diagnostic data this was true even for the transients during the test where the flow conditions were being changed by the facility operator.

Diagnostic information has also been obtained from the meter in service. Samples taken over a four hour period show that the meter is currently operating with all four paths operational for 57% of the time and three paths for the remaining 43% of the time. At no time were there two concurrent path failures.

The information obtained during the tests at NEL and with the meter in service show that the Caldon LEFM240C 4-path meter can make robust measurements in difficult oil/water application conditions and that the measurement uncertainty in these applications can be predicted with a fair degree of confidence.

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