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OIL FLOW PERFORMANCE OF ULTRASONIC METERS

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SUMMARY

Ultrasonic meters have significant potential for application in the oil industry due to their non-intrusive design, low maintenance requirements and diagnostic capabilities. For a number of reasons the industry's use of this technology for oil flow measurement is limited at present. Over the past year NEL have completed a DTI funded project to investigate the capabilities and limitations of current ultrasonic techniques for oil flow measurement. A series of tests were carried out in order to evaluate the performance of a selection of modern transit-time ultrasonic flowmeters. These meters included both wetted and clamp-on designs. Basic calibrations were performed using the NEL oil flow primary standard with kerosene, gas oil and 30 cSt oil. As offshore applications may not always be single-phase oil, the test programme was also designed to establish limitations with respect to the presence of gas and water components. The performance of the meters under evaluation is described in terms of repeatability and deviation from the reference flow rate.

1 INTRODUCTION

Ultrasonic flow measurement technology based on the transit-time principle offers a compact non-intrusive alternative for oil flow measurement. Combined with low maintenance requirements and stable long term operation, considerable cost savings may be achieved over turbine and prover loop systems. Potential uncertainties of ± 0.5 to 1 % of rate for calibrated systems and independence of changing fluid properties are generally claimed, indicating suitability for allocation metering duties. Such claims however are not well supported by independent evaluation data. Where such evaluation data exists it tends to be limited either in terms of the range of conditions to which the meters are subjected or in the number of meters which are evaluated under common conditions.

The report of a project co-ordinated by NEL and published in 1989 by Heritage [1] describes one of the most comprehensive ultrasonic flowmeter evaluations to date. Meters of nominal internal diameter of 100 mm from seven sources were calibrated in water over a flowrate range of approximately 8 - 80 l/s. Of eleven meters, three failed to complete the test programme, two performed within the manufacturers specification, five performed within specification only over part of the range, and one performed outside of the specification over the entire range. A summary of performance of nine meters which completed all or part of the first phase, 'ideal installation' tests, is given in Table 1 below. The conclusion drawn from these results was that the majority of 100 mm ultrasonic flowmeters were likely to be out of specification.

Maximum error (% rate)	Number of meters
error ≤ 2 %	2
2 % < error ≤ 5 %	3
5 % < error ≤ 10 %	2
error > 10 %	2

Table 1 A summary of past ultrasonic meter performance

The second phase of the project addressed the important issue of installation effects. However, as the 'ideal installation' tests were conducted only with water as the test fluid and no investigation into the effect of changes in fluid and temperature related properties was carried out, the results can not be considered exhaustive.

With the advent of new developments in design and a number of economic advantages to the oil industry, in 1995 NEL, under the DTI NMSPU Flow Programme, initiated a project to investigate the capabilities and limitations of ultrasonic meters for oil flow measurement. The remit of the project was to evaluate the oil flow performance of a range of ultrasonic meters in 'ideal' flow conditions and to determine limitations in terms of secondary flow components. Meters of 100 mm nominal diameter were specified in order that a velocity range of approximately 0.5 to 10 m/s could be covered using the primary flow loops of the oil flow National Standard and to give good comparison with the results of Heritage. Meters of clamp-on and wetted types were to be included due to oil industry interest in both types. In conjunction with this project, Amerada Hess Ltd commissioned some specific tests which have been included with the main project results.

At the time of writing this paper, basic oil calibrations and oil/gas tests have been concluded. The water-in-oil evaluations are underway and will be reported at a later date.

2 TEST FACILITIES AND METHOD

The tests reported in this paper were conducted in the main oil flow measurement standard facility of the NEL Oil and Multiphase Flow Laboratory. The facility comprises three separate flow circuits each with a 100 l/s flow rate capability using kerosene, gas oil and 30 cSt (velocite) oils respectively. Figure 1 shows a schematic diagram of one of these circuits. The oil for each circuit is stored in 30 m^3 tanks and is maintained to within ± 1°C of a pre-determined temperature within the range of 5 to 50 °C by a conditioning circuit linked to each tank. The test lines themselves can each accommodate 30m of horizontal straight lengths or other configurations as required. At the outlet of each test section a manifold directs the fluid either back to the storage tank or to one of the weigh tanks. Line temperature and pressure are monitored both upstream and downstream of the test section.

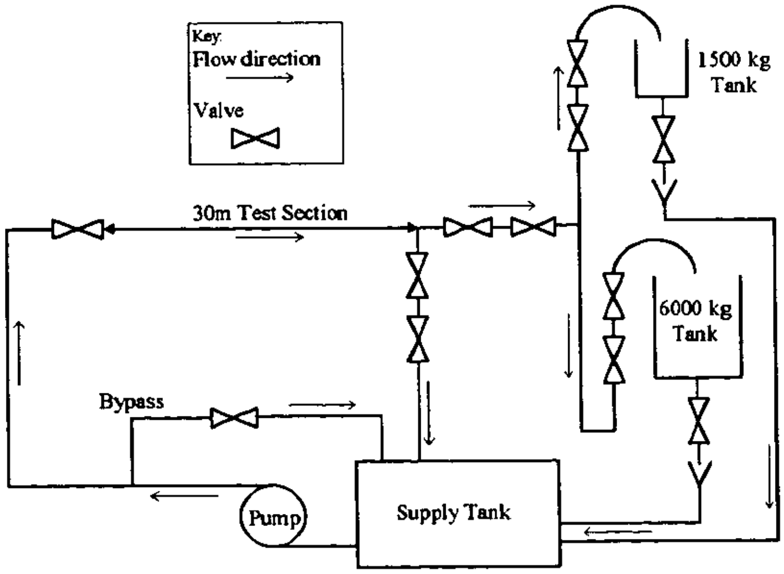

Figure 1 A Schematic Diagram of the Test Facility

The standard calibration method is a gravimetric standing-start-and-finish method by which the flow through the test section starts from zero at the opening of the inlet valve to the tank and returns to zero when the inlet is closed, during which time a quantity of fluid is collected in the weigh tank. For volumetric meters the calculated volume of liquid is then compared with the indicated volume passed through the meter, either in the form of a totalised pulse/frequency output or internal totaliser result. Alternatively calibration can be performed by a master-meter method using a sliding-vane positive displacement (PD) meter.

The facility is fully traceable to Primary National Standards and is accredited by the National Accreditation of Measurement and Sampling (NAMAS). The uncertainty in the measurement of the quantity of fluid passed through the meter is ±0.03% for the gravimetric method and ±0.08% for the master meter method, these uncertainties being estimated at a confidence level of not less than 95%.

For the two-phase oil/gas tests a skid comprising a manifold and ½, ¾ and 1 inch gas turbines was used to inject nitrogen from a pressurised supply into the test line on the downstream side of the reference PD meter prior to the meters under test. Measurement of line temperature and pressure were made at the gas meter skid and in the main test line to determine the volumetric gas fraction at the start of the 4-inch section and perspex sections were installed to enable viewing of the flow.

3 TEST CONDITIONS

The test programme was designed to determine meter performance in 'ideal' conditions and to quantify effects due to changes of temperature and fluid related parameters and the presence of second flow components. The key tests to which meters were subjected were calibrations in kerosene and velocite oil at a nominal temperatures of 16 and 20 °C and the second-phase tests. Where time has allowed, due to the prompt delivery of a meter, further tests have been conducted in gas oil and at additional temperatures.

An approximate specification for each of the oil calibrations reported is given in Table 2 below. A nominal pressure of 1.5 Bar gauge was maintained downstream of the test section throughout the tests.

Test identifier	ID1	ID2	ID3	ID4	ID5	ID6
Fluid name	Kerosene	Kerosene	Velocite	Velocite	Gas oil	Velocite
Calibration method	Gravimetric	Master meter	Gravimetric	Master meter	Gravimetric	Master meter
Test temperature (nominal)	16 °C	20 °C	20 °C	20 °C	47 °C	45 °C
Density @ test temperature	803 kg/m^3	800 kg/m^3	852 kg/m^3	852 kg/m^3	798 kg/m^3	836 kg/m^3
Viscosity @ test temperature	2.75 cSt	2.56 cSt	31.2 cSt	31.2 cSt	2.75 cSt	12.0 cSt
Velocity of sound @ test temp.	1340 m/s	1330 m/s	1420 m/s	1420 m/s	1250 m/s	1340 m/s
Reynolds number range	46,000 - 440,000	25,000 - 350,000	6,000 - 27,000	2,000 - 37,000	70,000 - 320,000	10,000 - 95,000

Table 2 An approximate specification of test conditions

The oil/gas tests were conducted in the velocite line of the oil flow primary standard at a nominal temperature of 20 °C. Preliminary trials were carried out prior to the specification of the tests. The following test matrix was constructed in light of the trial results.

Nominal flowrate	Nominal gas fractions by volume (GVF)		
10 l/s	5 %	10 %	20 %
30 l/s	1 %	2 %	5 %
50 l/s	0.5 %	1 %	2 %
70 l/s	-	0.5 %	1 %

Table 3 Nominal conditions for the oil/gas tests

4 DESCRIPTION OF TEST METERS

A number of companies were invited to provide meters for the duration of the project. These companies products were chosen to represent the state-of-the-art in ultrasonic flow measurement. Meters were supplied from five sources covering a range of technological aspects. In each case the meter supplied represented the manufacturers most recent product generation. The following sections are intended to provide a brief description of features relevant to the discussion of test results.

4.1 DANFOSS Sonoflow

The SONO3300 is a sensor tube with four wetted transducers forming two parallel tilted chordal sound paths. Each path is formed at a mid-radius position in the cross-section and is inclined at an angle of 39° to the tube axis. This configuration is represented schematically in Figure 2(a). The transducers are metal encapsulated piezoelectric crystals which are mounted in the cast body by means of a screw fitting. A memory chip which is pre-programmed with the primary physical parameters and factory calibration factor is provided with the meter tube. The meter provided by Danfoss for the project was taken from their normal production stream.

The excitation and detection of ultrasonic signals and subsequent processing and flow computation are performed by the SONO3000 signal converter. The transducers are excited by a sine wave of 8 cycles duration and a frequency of around 1 MHz. The received upstream and downstream signals are digitised and stored for processing. Automatic gain control (AGC) is utilised to optimise the analogue to digital conversion The flow computation is based on measurement of the overall transit-time and the upstream-downstream transit-time difference, which are both treated separately by a correlation technique. The transit-time difference is determined by cross-correlating the upstream and downstream signals whereas the overall transit-time is determined by cross-correlating one of the received signals with a stored reference signal. This stored reference signal is dynamically adapted to the operation conditions.

The mid-radius position of the measurement paths is chosen to minimise sensitivity due to Reynolds number dependent changes in flow profile [2]. The SONO3300/3000 therefore does not require user-input viscosity data.

4.2 ULTRAFLUX UF322-2

The Ultraflux UF322-2 is a dual path signal converter for use with clamp-on or wetted transducers. The meter was supplied with 1 MHz clamp-on transducers which were installed by a representative of Ultraflux on a 4-inch nominal bore stainless steel spoolpiece provided by NEL. The transducers were coupled to the outside of the spoolpiece using Polyken elastomer and secured in position with jubilee clips to form two tilted-diameter single-reflection sound paths in perpendicular planes, as illustrated schematically in Figure 2(b). The axial distance at which the transducers should be set apart is displayed by the converter following entry of transducer configuration, pipe dimensions and fluid velocity of sound parameters. Prior to the transducer installation, an approximately mid-range value for fluid sonic velocity and the tabulated dimensions for the Schedule 40 pipe had been entered into the converter.

The upstream and downstream transit time measurements are performed by detecting the first zero crossing in the received digitised pulse signals. The UF322-2 has an automatic flow profile compensation feature which was utilised to compensate for the difference between the measured diametrical velocity and the mean velocity in the cross-section. This feature requires fully developed symmetrical flow at the meter and that values for viscosity and for roughness of the pipe interior be input during set-up. For tests ID1, ID3 and ID5, performed by the standing-start and finish method, a constant value of 20 cSt was entered for the dynamic profile compensation. For tests ID4 and ID6, performed by the master meter method, viscosity values of 31.2 and 12.0 cSt respectively were entered. The roughness was entered as 0.1 mm.

4.3 PANAMETRICS XMT868

The Panametrics XMT868 is a dual channel flow transmitter for use with clamp-on or wetted transducers. Two XMT's were provided by Panametrics with a carbon steel spoolpiece comprising both wetted and clamp-on transducer configurations. The wetted transducers were 1 MHz 1 inch NPT 'extended-well' type transducers which are threaded into a welded boss such that the centre of the transducer face is aligned with the interior of the spoolpiece. The clamp-on transducers were 1 MHz shear wave transducers which were each mounted on the exterior of the spoolpiece by means of a welded yoke and coupled to the pipe wall using a silicon vacuum grease. Both wetted and clamp-on path configurations were dual tilted-diameter single-reflection sound paths in perpendicular planes as illustrated schematically in Figure 2(b). Each meter was flow calibrated prior to arrival at NEL.

The Panametrics XMT868 uses a coded excitation and correlation detection scheme to determine the transit time of the ultrasonic signals [3]. The excitation signal, rather than an impulse or sinusoid, is a phase-coded square-wave burst. AGC is utilised to optimise the signal level before digitisation and averaging of several successive signals. The digitised receive signals are then cross correlated with a stored version of the excitation signal to determine the upstream and downstream transit times.

As both clamp-on and wetted configurations employed diametrical paths, the flow profile compensation feature of the XMT868 was utilised in each case. This feature requires fully developed symmetrical flow at the meter and that a value of viscosity be entered in the meter during set-up. A value of 20 cSt was entered for both meters throughout the tests.

4.4 PEEK MEASUREMENT Polysonics DCT-6088

The Polysonics DCT-6088 is Peek's latest generation of transit-time ultrasonic flowmeter. It is a single-beam meter with 1 MHz clamp-on transducers which for the project were mounted on a 4 inch nominal bore carbon steel spoolpiece provided by NEL. The transducers were coupled to the outside of the spoolpiece using a mineral oil based couplant and secured in position with jubilee clips to form a tilted-diameter double-reflection sound path, as illustrated schematically in Figure 2(c). The axial distance at which the transducers should be set apart is displayed by the converter following entry of transducer configuration, pipe dimensions and fluid velocity of sound parameters. Prior to the transducer installation, an approximately mid-range value for fluid sonic velocity and the tabulated dimensions for the Schedule 40 pipe had been entered into the converter.

The DCT-6088 uses digital correlation to determine the transit-time of the ultrasonic signals. Several different signal types are used for excitation of the transducers including coded and modulated waveforms. Specific detail regarding the methods used was not available at the time of writing this paper.

The Polysonics meter has an automatic flow profile compensation feature which is utilised to compensate for the difference between the measured diametrical velocity and the mean velocity in the cross-section. A viscosity value of 20 cSt and bore roughness of 0.21 mm were utilised for this feature throughout the tests.

4.5 KROHNE ALTOMETER UFM Multi-channel

Krohne Altometer provided a 5-beam version development prototype of their UFM Multi-channel flowmeter. The sensor head of the 5-beam meter is constructed such that ten wetted transducers are paired to form measurement paths in two planes as illustrated schematically in Figure 2(d). Excitation and signal detection for each transducer pair is at present achieved by use of one of five UFC 500 signal converters, these being standard signal converters as employed in the single and dual beam ultrasonic flowmeter designs available from Krohne Altometer. Upstream and downstream transit-time measurements are performed by a threshold-armed zero-crossing detection technique. The five signal converters each produce a frequency output proportional to flow velocity which are input to a PC controlled data acquisition and transmission board. Computation of the volumetric flowrate from the five frequency inputs is performed in the software and the result output as a frequency at the PC controlled board.

The computation of volumetric flowrate is similar to multi-path meters based on Gaussian or Chebychev integration techniques [4] in that the individual path measurements are individually weighted and then summed. The meter also has the facility to reduce the non-linearity inherent in such techniques by identifying Reynolds number and applying a corresponding profile correction factor for fully developed flow. The Reynolds number/profile identification is performed by computing the difference in fluid velocity at two distinct radial positions in a manner similar to that described by Jackson et al [5]. It is also claimed that the meter should be able to compensate for asymmetric profiles and non-axial velocity components. However, such claims have not yet been tested by NEL.

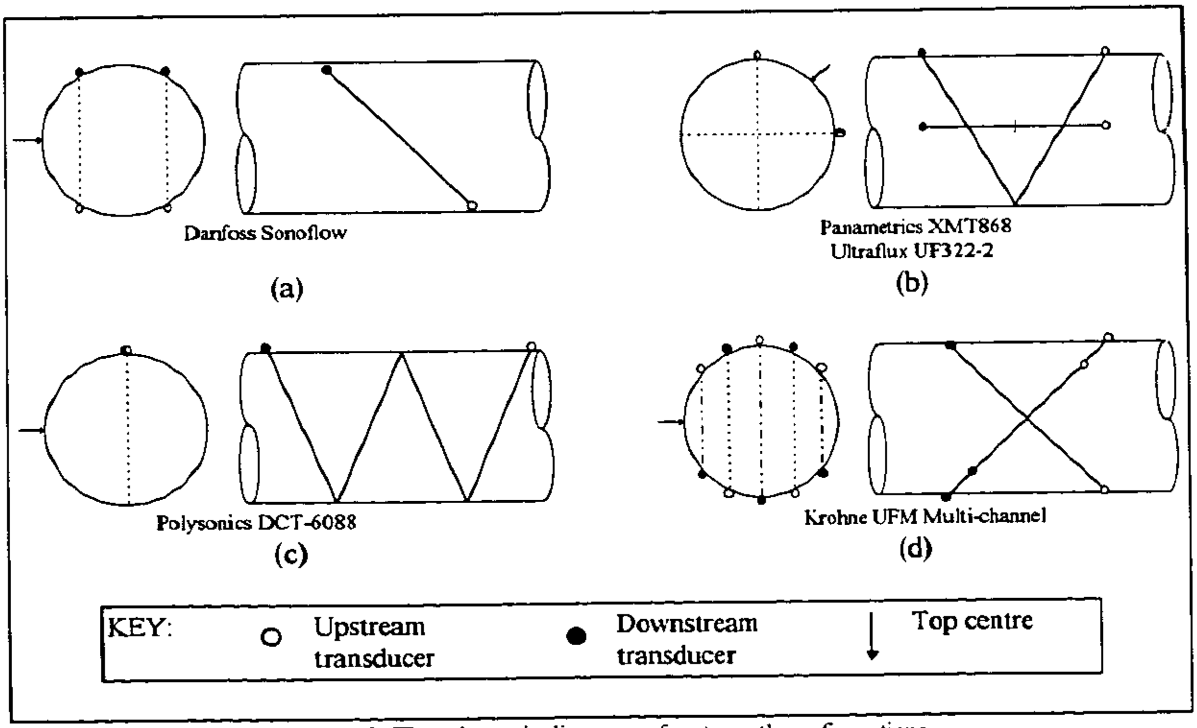

Figure 2 The schematic diagrams of meter path configurations

5 PRECURSIVE DISCUSSION

The following general points should be considered in relation to the results which follow.

5.1 The effect of meter size

Ultrasonic transit-time flowmeters generally utilise nominally identical primary elements (i.e. transducers and electronics) for all sizes of meter. However, a change in meter diameter can affect the performance in a number of ways. Such effects are not discussed in detail here but should be considered carefully when selecting an ultrasonic meter for a specific application. If similar velocities are maintained it is generally true to say that meter performance improves with increasing size.

5.2 The use of dynamic profile correction

Dynamic profile correction utilises an iterative process to compensate for difference between the measured diametrical velocity and the mean velocity in the cross-section.

$$\bar{v} = k_h v_{meas.} \tag{1}$$

where k_h is the profile correction factor. For the majority of results from meters employing only diametrical beams and dynamic profile correction, a nominal viscosity value of 20 cSt was entered into the meter software though out the tests. Therefore the results are in some cases artificially worse than they would have been had an appropriate viscosity value been entered for each test. To illustrate this two graphs have been constructed, Figure 3 showing theoretical curves of profile correction factor versus flowrate for viscosity values of 2.65, 20 and 31.2 cSt, and Figure 4 showing the approximate error introduced into kerosene and velocite calibrations for the diametrical meters. The analytical expression for the turbulent profile factor k_{turb} used here is derived from the power law for velocity distribution in a smooth pipe [6].

$$k_{turb}(R_{eD}) = \frac{1}{1.119 - 0.001 \times \log R_{eD}} \tag{2}$$

Where R_{eD} is the diametrical Reynolds number. In laminar flow conditions assuming a parabolic profile the factor is constant at $k_{lam} = 0.75$ [6]. In the transition between laminar and turbulent flow, the profile correction factor can not be defined without ambiguity. For illustrative purposes the switching function S of Pannell *et al* [4] has been adopted.

$$S(n, R_{eD}, R_c) = \frac{1}{1 + (R_{eD}/R_c)^n} \tag{3}$$

The function for the profile correction factor across all regimes can now be given as

$$k_h(R_{eD}) = [1 - S(n, R_{eD}, R_c)]k_{turb}(R_{eD}) + S(n, R_{eD}, R_c)k_{lam} \tag{4}$$

Here R_c, the critical Reynolds number at which transition occurs, was taken as 3200 and n which defines the width of the transition region was taken as 5 such that k_h is approximately 10 % k_{turb} at $R_{eD} = 2000$ and 10 % k_{lam} at $R_{eD} = 5000$.

It must be stressed that this k_h function is not strictly correct but is used only to illustrate the nature of error that can be incurred by inaccurate entry of the viscosity value for dynamic profile correction. Equally important is the fact that not only viscosity but other factors such as vibration, bore roughness and diameter will affect the flow profile and the point at which the flow regime transition occurs.

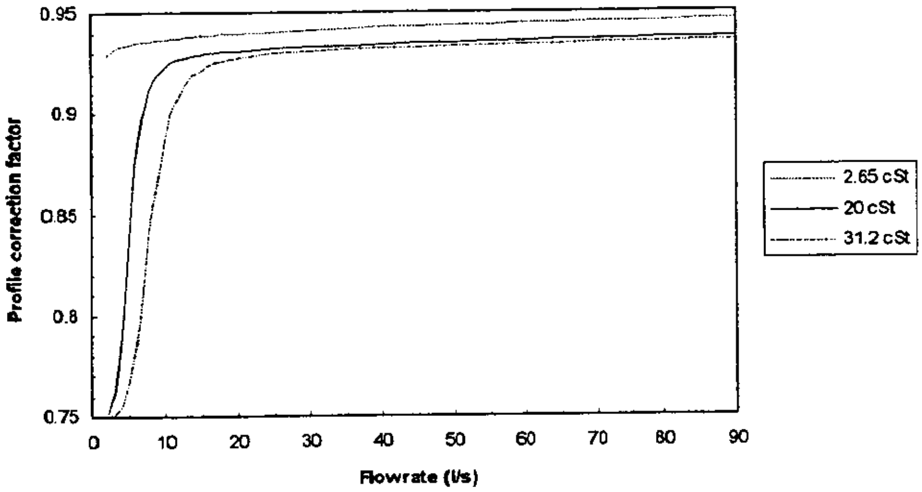

Figure 3 Viscosity dependence of profile correction for 100 mm bore diametrical meters

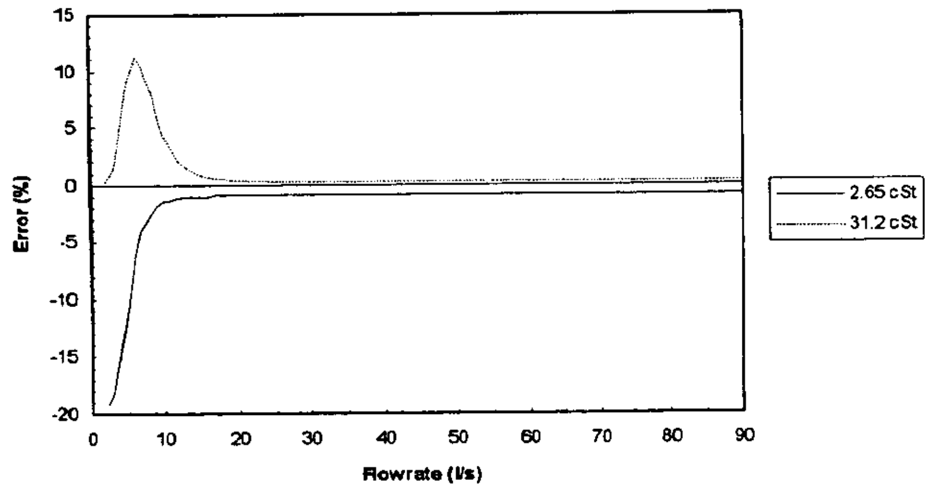

Figure 4 Error introduced by entry of the viscosity as 20 cSt

5.3 The effect of gas in liquid

The oil/gas testing was carried out to examine the potential of the meters to cope with gas content in an oil stream. The meters were not modified in any way between single-phase and two-phase tests and as such the results reflect indicative behaviour rather than the limitation of the technology if 'tuned' to specific application conditions.

The acoustic impedance (product of density and velocity of sound) of gases is significantly less than that of liquids (~ 3000:1). The consequence of this *acoustic impedance mismatch* is that extreme reflection/scattering occurs when ultrasound encounters gas in a liquid, this being the main mechanism of attenuating the received signals. Another point to note is that the low acoustic impedance of gases means that transducers designed for liquid use are not suitable for gas measurements. Therefore a transmitter-receiver pair will register signal loss when the fluid path between them is gaseous.

Johannessen [7] presented results which showed meter failure with as little as 0.4 % gas by volume at a flowrate of approximately 11 l/s. It was stated that the gas fraction could even have been less due to entrapment of gas in cavities in the closed-loop system. The meters tested were a Panametrics model 6468 and a Danfoss SONO 2000. Transit-time measurement in the wetted SONO 2000 was performed by threshold-armed zero-crossing detection. The Panametrics 6468 utilised digital correlation processing. It was not stated whether the 6468 was used with wetted or clamp-on transducers.

Different gas fractions were specified for each nominal flowrate during the oil/gas tests due to the effect of the flow velocity on the gas distribution and resultant behaviour of the meters. At the highest velocities the gas appeared to be fairly evenly distributed in the cross-section in the form of many sub-millimetre bubbles. As the velocity was decreased, the bubbles increased in size, decreased in number and were less evenly distributed with greatest concentrations in the upper area of the cross-section. At the lowest velocity the gas and liquid were clearly stratified with only a few bubbles present in the lower areas of the pipe. Throughout the tests no recirculation of gas was observed at a perspex viewing section upstream of the gas injection point.

6 PRESENTATION

Results are presented in graphical and tabular form and described in the following terms:

- *Error*: The difference between the total volume indicated by the meter under test and the recorded reference volume, expressed as a percentage and plotted against flowrate. In the oil/gas tests the reference volume is considered to include both liquid and gas components.

$$E = \left(\frac{V_{ind} - V_{std}}{V_{std}} \right) \times 100\% \tag{5}$$

- *Deviation:* The difference between the error at test and reference conditions.

$$D = \left(E_{test} - E_{ref} \right) \tag{6}$$

- *Repeatability:* A measure of the random uncertainty in measurement defined [8] as:

$$R = 2.83 s_E \text{, where } s_E = \sqrt{\frac{\sum \left(E - \bar{E} \right)^2}{n - 1}} \tag{7}$$

and n, the number of repeat measurements at a single test condition, is five.

7 RESULTS

7.1 DANFOSS Sonoflow

The Danfoss Sonoflow exhibited a well defined and repeatable dynamic response to the transient changes in flowrate inherent in the standing-start and finish method.

7.1.1 Baseline calibration

The results of calibration in kerosene at 20 °C are presented in Figure 4 which also shows by a dashed line the bounds of the manufacturers accuracy statement; *Accuracy better than ± 0.5 % of reading over a dynamic range with a turndown of 20:1*. The figure shows maximum and minimum errors of 1.2 and -0.5 % at flowrates of 14 and 51 l/s respectively. The results are within the bounds of the manufacturers accuracy statement for flowrates of 24 l/s and above.

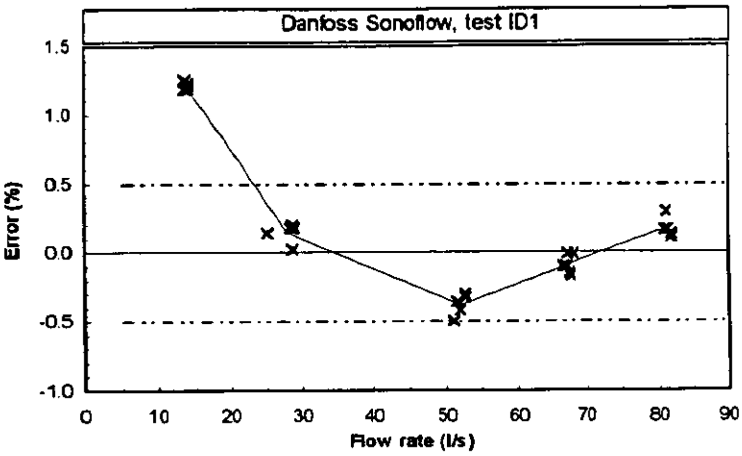

Figure 4 Kerosene calibration at 16 °C

7.1.2 Viscosity tests

The results of calibration in velocite oil at 20 °C are presented in Figure 5 which also shows by dashed lines the baseline calibration and manufacturers accuracy limits. The figure shows maximum and minimum errors of 4.8 and -0.68 % at flowrates of 9 and 51 l/s respectively. The results are within specification at flowrates of 70 l/s and above. The deviation from the baseline calibration is a maximum of approximately 1.5 % at 14 l/s and within ± 0.7 % at flowrates of 30 l/s and above.

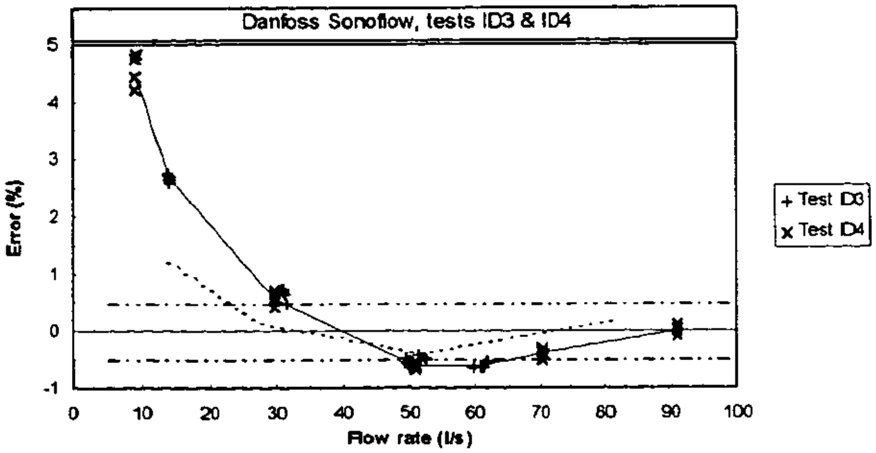

Figure 5 Velocite calibration at 20 °C

The results of calibration in velocite oil at 45 °C with are presented in Figure 6. The figure shows maximum and minimum errors of 2 and -0.65 % at flowrates of 10 and 50 l/s respectively. The results are within specification at 30 l/s and at 70 l/s and above. The deviation from the baseline calibration is within approximately ± 0.4 % across the range.

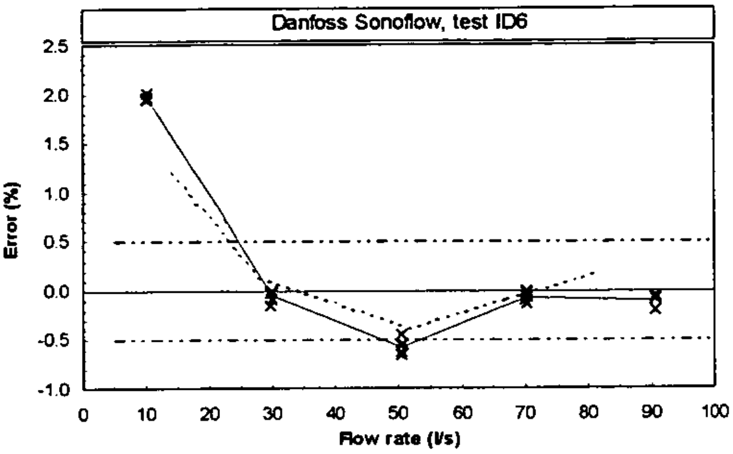

Figure 6 Velocite calibration at 45 °C

7.1.3 Temperature test

The gas oil test at 47 °C subjected the meter to a temperature change of 31 °C and a change in fluid sonic velocity of approximately 7 % whilst nominally maintaining viscosity with reference to the baseline calibration. The results of this test are presented in Figure 7 which also shows by a dashed line the baseline calibration. The figure shows maximum and minimum errors of 1.2 and -0.36 % at flowrates of 15 and 50 l/s respectively. The deviation from the baseline calibration is within ± 0.25 % across the majority of the range.

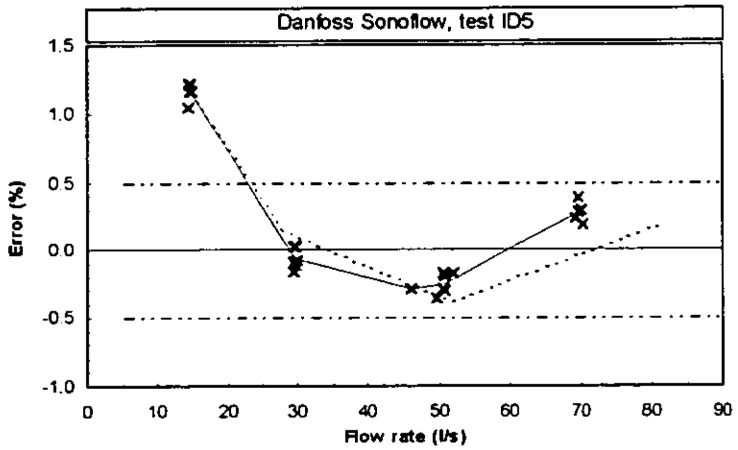

Figure 7 Gas oil calibration at 47 °C

7.1.4 Repeatability

Figure 8 shows the repeatability of the meter as determined during each of the oil calibrations. There is no clear relationship between flowrate and repeatability. The repeatability is better than 0.3 % for all but one point, which was calculated from results in the transition region of test ID4.

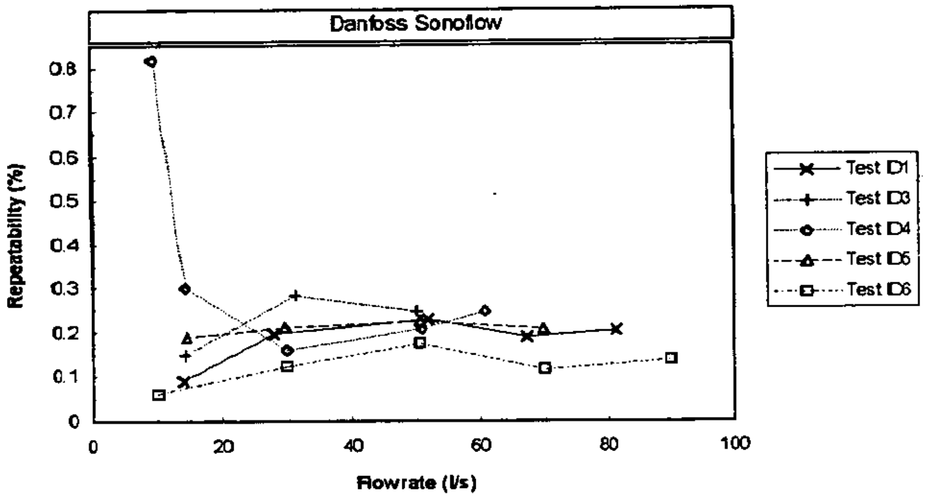

Figure 8 Repeatability versus flowrate

7.1.5 Oil/gas tests

During the oil/gas tests, the SONO3000 converter was observed at each test condition. The occurrence of fault conditions are recorded in Table 4 along with the range within which the maximum deviation from the 0 % GVF results occurred. The fault conditions observed corresponded to a *weak received signal* or an *unstable signal due to the presence of gas bubbles*.

Nominal flowrate	GVF	Converter fault indication	Max. deviation
10 l/s	2.5 %	no	±1 % < $d \leq$ ±5 %
	7.5 %	no	±1 % < $d \leq$ ±5 %
	22.5 %	yes	$d >$ ±10 %
30 l/s	0.75 %	no	±5 % < $d \leq$ ±10 %
	1.5 %	intermittent	$d >$ ±10 %
	4 %	yes	±5 % < $d \leq$ ±10 %
50 l/s	0.35 %	no	$d \leq$ ±1 %
	0.7 %	no	±1 % < $d \leq$ ±5 %
	1.5 %	yes	$d >$ ±10 %
70 l/s	0.4 %	no	±1 % < $d \leq$ ±5 %
	0.8 %	intermittent	$d >$ ±10 %

Table 4 Summary of oil/gas perfomance

From the table it can be seen that fault free operation with deviation within ±10 % is achieved at 10 l/s up to 7.5 % GVF, 30 l/s at 0.75 % GVF, 50 l/s up to 0.7 % GVF and 70 l/s at 0.4 % GVF.

7.2 ULTRAFLUX UF322-2

The Ultraflux UF322-2 exhibited a reasonably prompt and repeatable response to the transient changes in flowrate inherent in the standing-start and finish method.

7.2.1 Baseline calibration

The results of calibration in kerosene at 20 °C are presented in Figure 9 which also shows by a dashed line manufacturers accuracy limits. The figure shows maximum and minimum errors of -5.3 and -3.4 % at flowrates of 14 and 52 l/s respectively. The error is clearly greater than the manufacturers stated *Typical accuracy: 0.5 % at 10 to 100 % of the scale.* Also the magnitude of the error greater than the predicted deviation due to the entry of the viscosity as 20 cSt implying an error due to the uncertainties in pipe dimensions.

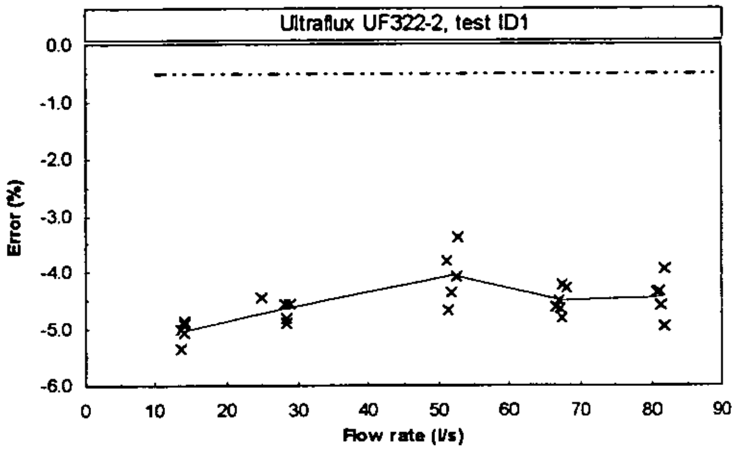

Figure 9 Kerosene calibration at 16 °C

7.2.2 Viscosity tests

The results of calibration in velocite oil at 20 °C are presented in Figure 10 which also shows by a dashed line the baseline calibration and manufacturers accuracy limits. The figure shows maximum and minimum errors of 1.5 and -1.8 % at flowrates of 14 and 60 l/s respectively. The deviation from the baseline calibration is reasonably constant at approximately 3.5 % for flowrates greater than 30 l/s. At 14 l/s the deviation has increased to approximately 6%.

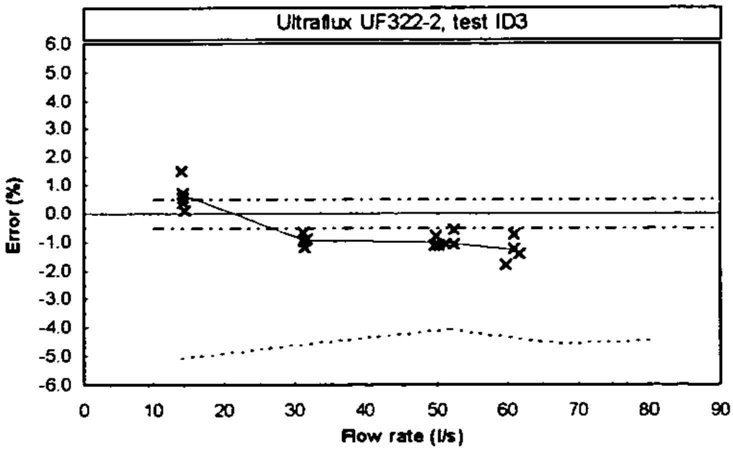

Figure 10 Velocite calibration at 20 °C

Two further tests were conducted by the master meter method in velocite at temperatures of 20 and 45 °C. For both of these tests the appropriate viscosity was entered so as to remove any 'artificial' error source. The results of these tests are presented in Figure 11. The figure shows average errors of -1.2 and -1.7 % at flowrates greater than 30 l/s for the 31.2 and 12 cSt calibrations respectively, supporting the hypothesis that a component of the error is due to dimensional uncertainties. The deviation between calibrations reaches a maximum of approximately 11 % at 10 l/s.

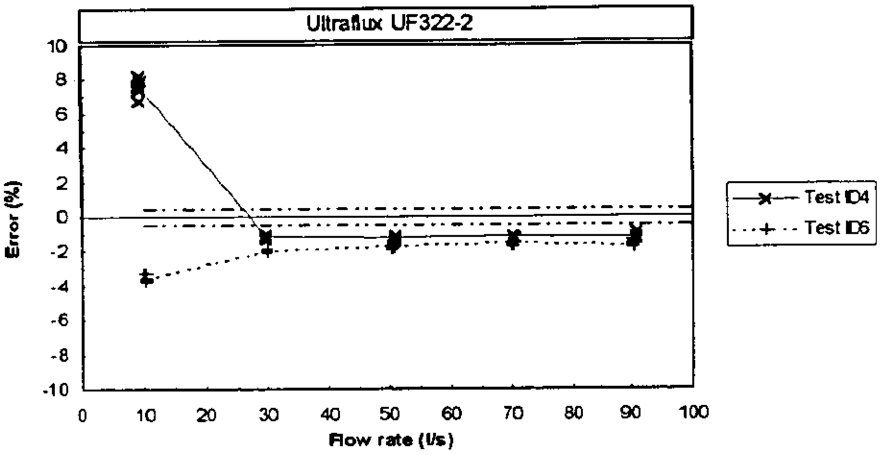

Figure 11 Velocite calibrations at 20 and 45 °C

7.2.3 Temperature test

The gas oil test at 47 °C subjected the meter to a temperature change of 31 °C and a change in fluid sonic velocity of approximately 7% whilst maintaining viscosity with reference to the baseline calibration. The results of this test are presented in Figure 12 which also shows by a dashed line the baseline calibration. The figure shows maximum and minimum errors of -2.2 and -4.0 % at flowrates of 51 and 30 l/s respectively. The deviation from the baseline calibration is reasonably constant at approximately 1 % for flowrates greater than 30 l/s. At 14 l/s the deviation has increased to approximately 2 %. The main source of this deviation is likely to be the manner in which the refracted angle of the ultrasonic beam in the fluid is calculated.

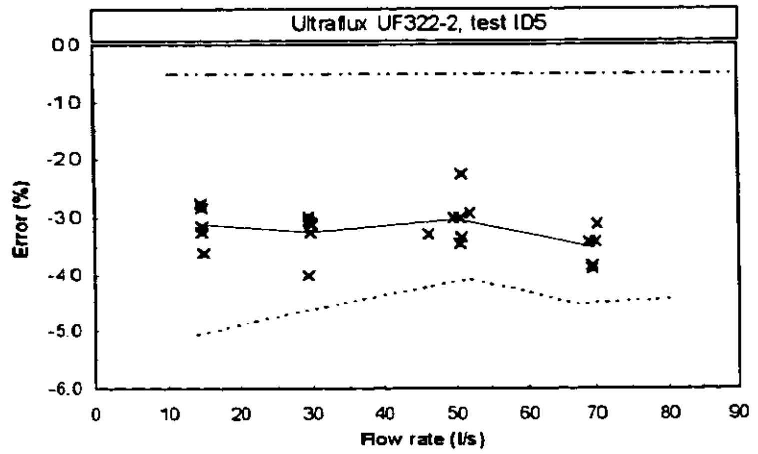

Figure 12 Gas oil calibration at 16 °C

7.2.4 Repeatability

Figure 13 shows the repeatability of the meter as determined during each of the oil calibrations. The expected trend of an improvement in repeatability with increased flowrate is seen for the master-meter tests, but is not apparent in the standing-start and finish tests. The significant difference in results between methods is due to the variation in test times in addition to the effects of the transients.

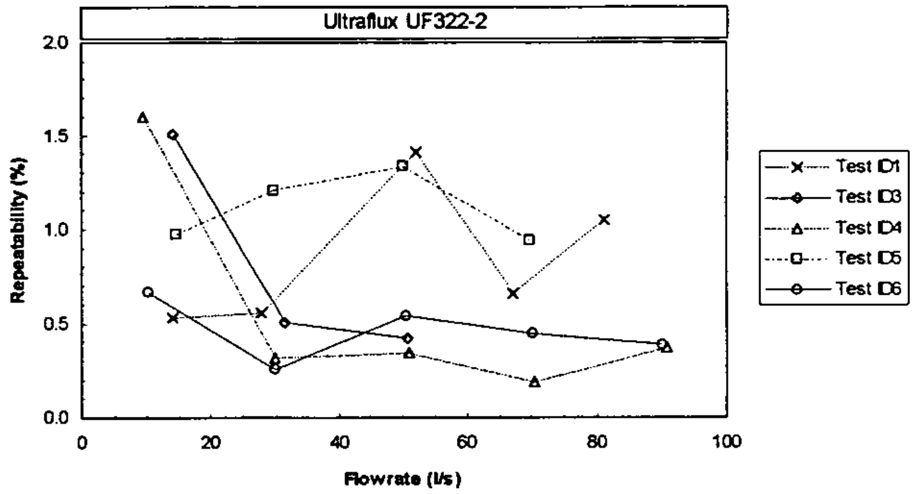

Figure 13 Repeatability versus flowrate

7.2.5 Oil/gas tests

During the oil/gas tests, the UF322-2 converter was observed at each test condition. The occurrence of 'echo loss' fault conditions are recorded in Table 5 along with the range within which the maximum deviation from the 0 % GVF results occurred. When echo loss faults occurred on both paths the flowrate indication was forced to zero.

Nominal flowrate	GVF	Converter fault indication	Max. deviation
10 l/s	2.5 %	none	$\pm 5\,\% < d \le \pm 10\,\%$
	7.5 %	frequent	$d > \pm 10\,\%$
	22.5 %	frequent	$d > \pm 10\,\%$
30 l/s	0.75 %	intermittent	$\pm 1\,\% < d \le \pm 5\,\%$
	1.5 %	frequent	$d > \pm 10\,\%$
	4 %	continuous	$d > \pm 10\,\%$
50 l/s	0.35 %	intermittent	$\pm 1\,\% < d \le \pm 5\,\%$
	0.7 %	continuous	$d > \pm 10\,\%$
	1.5 %	continuous	$d > \pm 10\,\%$
70 l/s	0.4 %	continuous	$d > \pm 10\,\%$
	0.8 %	continuous	$d > \pm 10\,\%$

Table 5 Summary of oil/gas performance

From the table it can be seen that operation with deviation less than ±10 % is achieved at 10 l/s with 2.5 % GVF, 30 l/s with 0.75 % GVF and 50 l/s with 0.35 % GVF.

7.3 PANAMETRICS XMT868

During initial standing-start and finish tests on the XMT868, it was noted that the repeatability of the meter was poorer than expected due to the transient changes in flowrate inherent in the method. In order that the meter was not subjected to these transients the calibrations were performed by the master-meter method.

7.3.1 Baseline calibration

7.3.1.1 Wetted transducers

The results of calibration in kerosene at 20 °C are presented in Figure 14 which also shows by a dashed line the lower bounds of the manufacturers accuracy statement; *pipe diameter ≤ 150 mm, velocity > 0.3 m/s, ± 2 % to 5 % of reading typical*. The figure shows maximum and minimum errors of -1 and -8.8 % at flowrates of 10 and 5 l/s respectively. At flowrates of 10 l/s and above, the calibration meets the manufacturers specification, even with the additional error predicted by entry of the viscosity as 20 cSt.

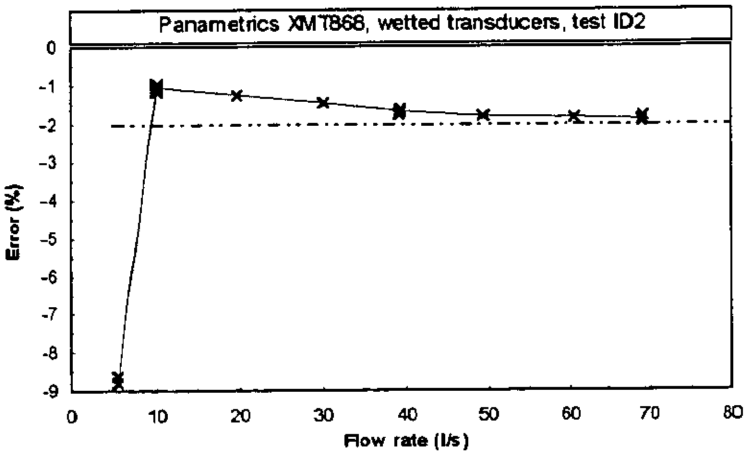

Figure 14 Kerosene calibration at 20 °C

7.3.1.2 Clamp-on transducers

The results of calibration in kerosene at 20 °C are presented in Figure 15 which also shows by a dashed line the lower bounds of the manufacturers accuracy statement. The figure shows maximum and minimum errors of -0.5 and -9.1 % at flowrates of 10 and 5 l/s respectively. Again the manufacturers specification is satisfied at flowrates of 10 l/s and above.

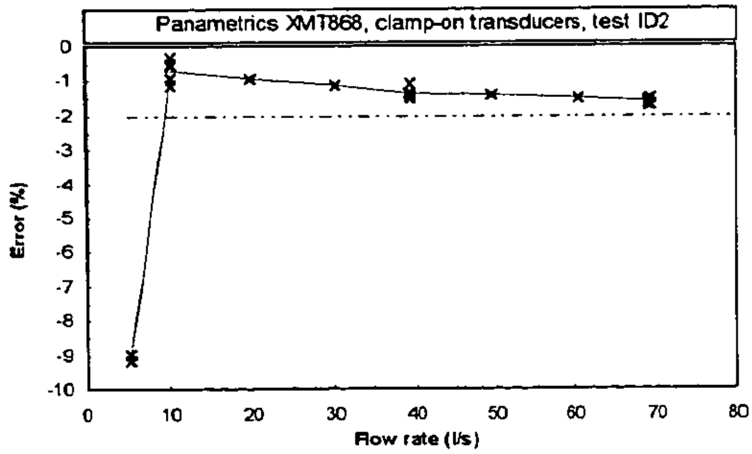

Figure 15 Kerosene calibration at 20 °C

The under-estimation at 5 l/s in both clamp-on and wetted meters is most probably due to the meters predicting the flow to be in transition between turbulent and laminar conditions, as a result of the entry of viscosity as 20 cSt, when indeed the flow was fully turbulent.

7.3.2 Viscosity test

7.3.2.1 Wetted transducers

The results of calibration in velocite oil at 20 °C are presented in Figure 16 which also shows by dashed lines the baseline calibration and the lower bounds of the manufacturers accuracy statement. The figure shows maximum and minimum errors of 10.1 and 0.7 % at flowrates of 5 and 69 l/s respectively. For flowrates of 20 l/s and above, the manufacturer's specification is satisfied and the deviation from the baseline calibration is reasonably constant at approximately 2.5 %.

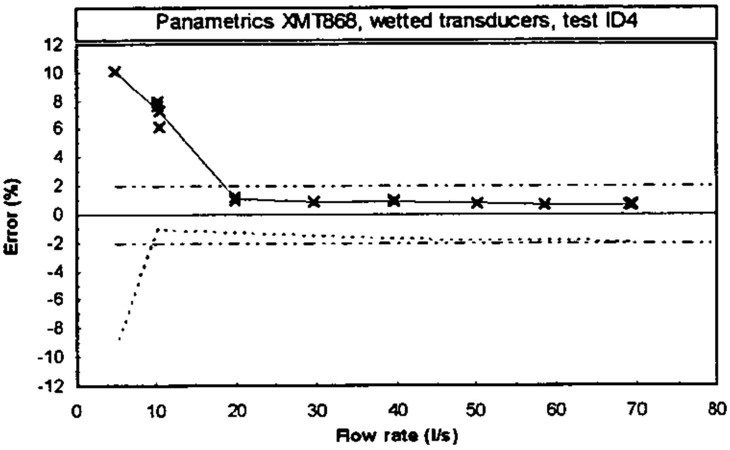

Figure 16 Velocite calibration at 20 °C

7.3.2.2 Clamp-on transducers

The results of calibration in velocite oil at 20 °C are presented in Figure 17 which also shows by dashed lines the baseline calibration and the lower bounds of the manufacturers accuracy statement. The figure shows maximum and minimum errors of 11 and 0.2 % at flowrates of 5 and 40 l/s respectively. The deviation from the baseline calibration is reasonably constant at approximately 1.8 % for flowrates of 20 l/s and above. Again, the manufacturer's specification is also satisfied at these flowrates.

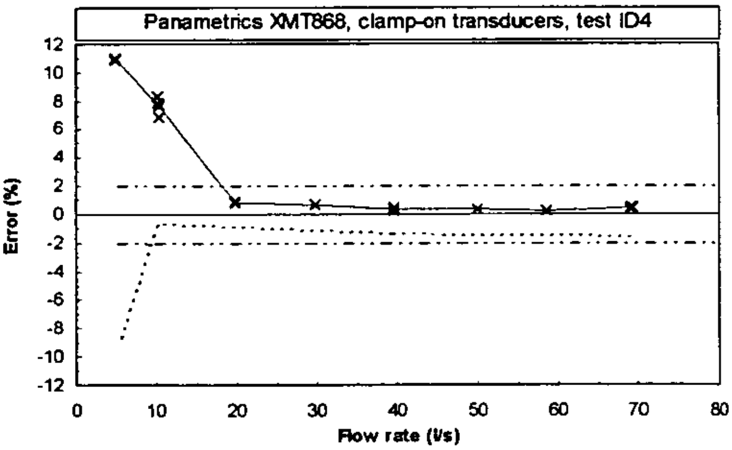

Figure 17 Velocite calibration at 20 °C

The over-estimation at 5 and 10 l/s in both clamp-on and wetted meters is most probably due to the meters predicting the flow to be nearer fully turbulent than laminar conditions, as a result of the entry of viscosity as 20 cSt.

7.3.3 Repeatability

7.3.3.1 Wetted transducers

Figure 18 shows the repeatability of the meter as determined at three flowrates across the range during both the kerosene and velocite calibrations and the bounds of the manufacturers repeatability statement; *Wetted transducers: ± 0.2 % of full scale* (12.2 m/s). The results are within the manufacturer's specification with the exception of the point from the velocite calibration at 10 l/s. This point lies practically on the boundary of the manufacturers limits and was determined when the flow was probably in laminar/turbulent transition.

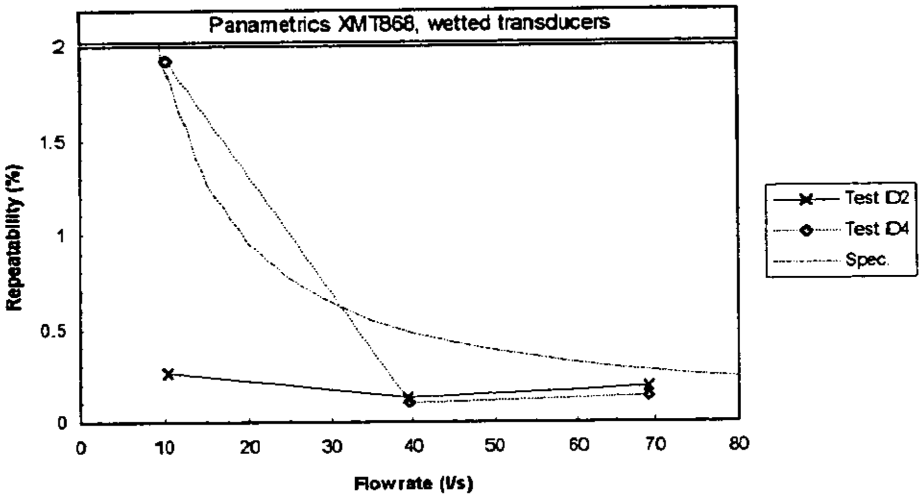

Figure 18 Repeatability versus flowrate

6.3.3.1 Clamp-on transducers

Figure 19 shows the repeatability of the meter as determined at three flowrates across the range during both the kerosene and velocite calibrations and the lower bounds of the manufacturers repeatability statement; *Clamp-on transducers: ± 0.2 % to 0.5 % of full scale* (12.2 m/s). The results are all within the manufacturer's specification and the display the expected trend of an improvement in repeatability with increasing flow velocity.

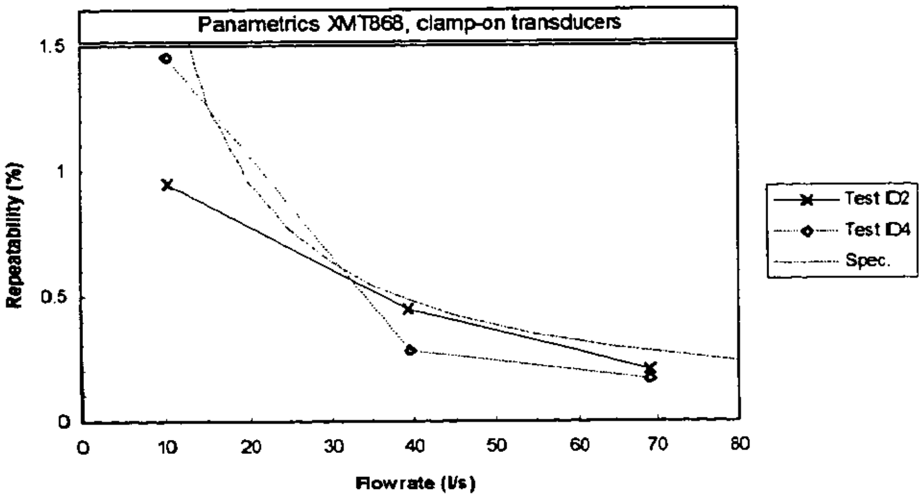

Figure 19 Repeatability versus flowrate

7.3.4 Oil/gas tests

During the oil/gas tests, the XMT868 converters were observed at each test condition. The occurrence of low signal fault conditions are recorded in Table 6 along with the range within which the maximum deviation from the 0 % GVF results occurred. During fault occurrence the flowrate indication of the XMT's were forced to zero.

Nominal flowrate	GVF	Wetted fault	Wetted max. deviation	Clamp-on fault	Clamp-on max. deviation
10 l/s	2.5 %	none	$\pm 1\,\% < d \leq \pm 5\,\%$	none	$\pm 1\,\% < d \leq \pm 5\,\%$
	7.5 %	intermittent	$d > \pm 10\,\%$	none	$\pm 5\,\% < d \leq \pm 10\,\%$
	22.5 %	frequent	$d > \pm 10\,\%$	frequent	$d > \pm 10\,\%$
30 l/s	0.75 %	intermittent	$d > \pm 10\,\%$	none	$d \leq \pm 1\,\%$
	1.5 %	continuous	$d > \pm 10\,\%$	none	$\pm 1\,\% < d \leq \pm 5\,\%$
	4 %	continuous	$d > \pm 10\,\%$	continuous	$d > \pm 10\,\%$
50 l/s	0.35 %	none	$d \leq \pm 1\,\%$	none	$d \leq \pm 1\,\%$
	0.7 %	continuous	$d > \pm 10\,\%$	none	$\pm 1\,\% < d \leq \pm 5\,\%$
	1.5 %	continuous	$d > \pm 10\,\%$	continuous	$d > \pm 10\,\%$
70 l/s	0.4 %	continuous	$d > \pm 10\,\%$	none	$d \leq \pm 1\,\%$
	0.8 %	continuous	$d > \pm 10\,\%$	continuous	$d > \pm 10\,\%$

Table 6 Summary of oil/gas performance

From Table 6 it can be seen that fault free operation of the wetted meter with deviation less than ±5 % is achieved only at 10 l/s with 2.5 % GVF and 50 l/s with 0.35 % GVF. The performance of the clamp-on meter is considerably better with fault free operation with deviation less than ±5 % being achieved only at 10 l/s with 2.5 % GVF, 30 l/s at up to 1.5 % GVF, 50 l/s at up to 0.7 % GVF and 70 l/s at 0.4 % GVF. The difference in performance between the clamp-on and wetted meters is most probably due to gas collecting in the small cavities at the faces of the wetted transducers.

7.4 PEEK MEASUREMENT Polysonics DCT-6088

The Polysonics DCT-6088 was included in the series of basic oil calibrations and oil/gas tests. These results have been withheld at the request of Peek Measurement Ltd until further consideration can be given to the findings. The results should be available for future publication.

7.5 KROHNE ALTOMETER UFM Multi-channel

The Krohne Altometer UFM Multi-channel was improperly set up during initial oil calibrations at NEL, and it has been agreed between Krohne Altometer and NEL to withhold these results as they are not truly representative of the meter's performance.

7.5.1 Baseline calibration

Subsequent to ensuring proper grounding and electronic set-up of the meter, a test was performed in velocite oil at 20 °C to determine accurate values for Reynolds number compensation. Parameters of the Reynolds number compensation curve were then entered into the meter software and a calibration in velocite oil at 20 °C performed. The results of the calibration are presented in Figure 23 which also shows the manufacturers uncertainty specification of ±0.15 % of rate. The figure shows maximum and minimum errors of 0.11 and -0.04 % at flowrates of 5 and 31 l/s respectively. The meter showed good dynamic response to the transient changes in flowrate inherent in the standing-start and finish method and the repeatability was determined as 0.033 % at 58 l/s.

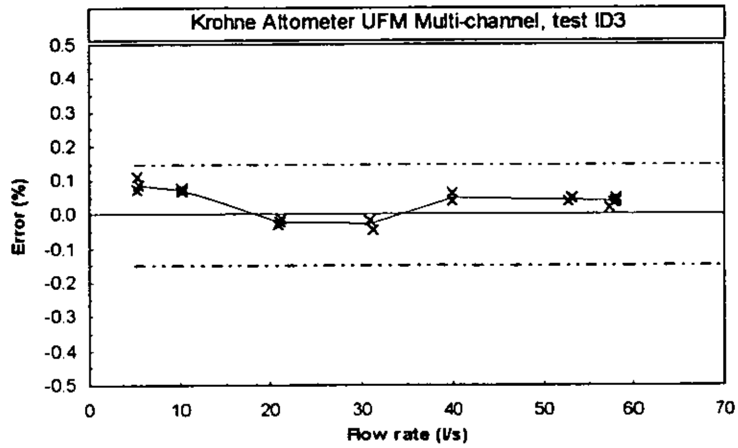

Figure 23 Velocite calibration at 20 °C

7.5.2 Viscosity

This meter determines Reynolds number and the corresponding profile correction without the necessity of user-input values of viscosity and bore roughness, and in principle deviations due to changes in fluid viscosity should be minimal. However, further laboratory evaluation is required and therefore results presented here should be considered only as an indication of the performance that may be achieved.

7.5.3 Oil/gas tests

The UFM Multi-channel ultrasonic flowmeter was included in the series of oil/gas tests. The results from these tests have been withheld at the request of Krohne Altometer until further evaluation can be carried out.

8 DISCUSSION & CONCLUSIONS

8.1 Baseline calibration

From the results reported, one meter performed within specification across the range, three performed within specification across the majority of the range and one performed outside its specification across almost the entire range.

8.2 Viscosity

The viscosity of the fluid influences the velocity profile. Meters employing only diameter paths are most sensitive to these profile changes. Modern meters employ dynamic profile compensation and utilise user-input values of diameter, viscosity and roughness and measured velocity to determine a profile correction factor. Results in the turbulent regime show deviations of the order of a few percent when the viscosity was varied from approximately 2.65 cSt to 31.2 cSt and the input viscosity was constant. Both clamp-on and wetted meters performed very similarly in this respect. If the viscosity input is adapted to application conditions the influence in the turbulent regime should be minimal. From equation 3 it can be shown that a ±10 % uncertainty in viscosity will give rise to an uncertainty of less than ±0.05 % in the correction factor.

It has been illustrated that inaccuracy of the profile compensation in transition from turbulent to laminar flow can result in uncertainties of up to approximately ±20 %. It is important to stress that the velocity profile, particularly in transition, is dependent not only on Reynolds number but on bore roughness and vibration [6].

Mid-radius positioning of the measurement paths is chosen to minimise the effect of viscosity dependent changes in velocity profile. The results from the mid-radius pathed meter show that in the turbulent regime the deviation was within ±0.7 % when the viscosity was varied from 2.75 cSt to 31.2 cSt and within ±0.4 % when the viscosity was varied from 2.75 cSt to 12.0 cSt. At Reynolds numbers close to accepted values for the transition region, the deviation was increased to approximately 1.5 %.

The five-beam meter exhibited excellent linearity when calibrated with velocite oil. As the methodology applied is to identify the profile and compensate on the basis of measured variables, viscosity effects should be minimal. However, until this has been thoroughly evaluated, the magnitude of possible effect cannot be quantified.

8.3 Temperature

Two of the meters, one clamp-on, one wetted, were subjected to a calibration in gas oil at 47 °C in an attempt to quantify temperature effects independent of viscosity. The deviation of the clamp-on meter was between 1 and 2 %. The deviation of the wetted meter was within approximately ±0.25 %. The major difference in design, aside from the path configuration, is that the ultrasonic beam in the clamp-on design undergoes refraction at each interface between the transducer crystals and flowing fluid. As a result, the angle of the beam in the flow changes and must be dynamically calculated, and this introduces a further source of uncertainty into the measurement.

8.4 Repeatability

The repeatability of the meters varied from design to design. Best performance was achieved by the 5-beam meter although this was assessed only at one high flowrate. The repeatability of the mid-radius pathed meter was better than the diametrical meters. Among the diametrical meters, the repeatability of the wetted meter showed slight improvement over the clamp-on designs. Repeatability points calculated in the transition region were significantly poorer.

Repeatability is dependent on environmental factors, and temperature affects the flow profile, thus linking repeatability and path configuration. Also, as the 5-beam meter employs a converter for each path, rather than multiplexing, the number of transit-time measurements in a given period is increased, thus improving repeatability.

8.5 Oil/gas Performance

The performance in the presence of free gas is varied but generally poor and is critically dependent on the distribution of the gas in addition to the volume fraction. The reason for this is twofold, firstly, the gas has to actually be in the path between transducers to affect measurement of the transit time, and secondly, how the fluid velocity profile departs from gas-free conditions is dependent on the gas distribution. However, erroneous readings can be identified by fault indications. The signal limits for fault indication can generally be adjusted to tailor the uncertainty limits to specific applications. The performance, although poor, appears to have improved in some cases since the work of Johannessen [7] was carried out. This is almost undoubtedly due to the adoption of techniques based on digital correlation. This is supported by comparison of the results of the two clamp-on meters as one employs correlation detection and the other utilises zero-crossing detection.

Also of interest is to compare the results of the otherwise nominally identical wetted and clamp-on meters. The wetted meter, contrary to the expectation of maintaining a greater signal-to-noise ratio and hence performing better, actually performs worse. This is most likely due to inexpedient positioning of the transducer wells in the upper quadrant of the pipe, and may have been prevented simply by rotating the spoolpiece through 180°.

8.6 Clamp-on versus Wetted Transducers

The discussion of clamp-on versus wetted transducers covers many aspects of performance as well as ease of installation and maintenance. In considering high accuracy applications the following points are probably the most important of those which should be considered.

By comparison of results from the XMT868 with wetted and with clamp-on transducers it is clear that if care is taken in setting up the clamp-on meter similar performance can be achieved. However, what is not obvious is that the limitations of current ultrasonic technology constrains the use of clamp-on transducers to diametrical paths. This means that for the foreseeable future, the problems of dynamic profile compensation must be tolerated. On-line determination of viscosity, either by a viscometer or inferentially by measurement of temperature and/or velocity of sound in the fluid, is one way of improving the situation. However, the effectiveness of either of these solutions must be evaluated.

Perhaps more important is the issue of dimensional uncertainties. Considering that a 1 % uncertainty in the determination of the inner diameter gives rise to a 2 % uncertainty in the cross-sectional area, it is easy to see the importance of the dimensional uncertainties. This is supported by the results shown in Figure 11. Obviously the electronics and spoolpiece with transducers in place can be calibrated in a laboratory, however, when the meter is installed in the field the validity of the calibration must be called into question, especially if the transducers have been removed from the calibrated spoolpiece.

The following conclusions can be drawn form this work:

- Manufacturers specifications in many cases should be more detailed, specifically in relation to pipe dimensions, transducer configurations, calibrated and uncalibrated uncertainties.
- The number and positioning of paths in addition to the manner of processing the individual velocities considerably effects the performance of ultrasonic meters.

- Mid-radius paths are less sensitive than diametrical paths to viscosity dependent changes in velocity profile.
- When specifying either a mid-radius or diametrical beam ultrasonic meter the diameter should be chosen so as to avoid the transition region.
- Clamp-on meters are susceptible to additional sources of uncertainty over wetted meters.
- Transit-time meters should not be utilised if it is expected that free gas could be entrained in the liquid. The velocity as well as the volume fraction should be considered. A useful rule of thumb is that the gas component should be less than 0.5 % by volume.

Ultrasonic flowmeters have been subject to progressive development. Advances in transducer technology, signal processing and high speed electronics have all assisted in the process. It is important that progress continues and this will require a structured programme of development and evaluation both by the manufacturers and on behalf of the end-users. Equally important is that the standards organisations and independent bodies are apprised of developments. Issues such as reliability and installation effects must be addressed and new developments tested. The performance of currently available meters is sufficiently encouraging to suggest that ultrasonic technology will be widely adopted for allocation and eventually fiscal metering duties.

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