Main Index

NSFMW.97

North Sea FLOW Measurement Workshop

Paper 33: 6·4

FACTORS AFFECTING THE PERFORMANCE OF ULTRASONIC FLOWMETERS

Authors:
G.J. Brown, Flow Center, NEL, UK

Organiser:
Norwegian Society of Chartered Engineers
Norwegian Society for Oil and Gas Measurement
Co-organiser:
National Engineering Laboratory, UK

Reprints are prohibited unless permission from the authors and the organisers

FACTORS AFFECTING THE PERFORMANCE OF ULTRASONIC FLOWMETERS

Gregor J Brown
Flow Centre, NEL
UK

SUMMARY
A programme of work is currently underway at NEL to investigate and characterise the performance of liquid ultrasonic meters over a wide range of conditions. This paper presents the results of laboratory evaluations in addition to the initial results of combined flow and flowmeter modelling.

Two-phase, oil/gas performance tests were conducted on commercially available meters of 4-inch nominal bore. Specific results have been selected to illustrate performance variations related to factors in meter design and operation.

Two-phase, oil/water performance tests with water-cuts of up to 15 % were also conducted on the above meters. These results are presented in their entirety. The results show deviations from single-phase performance which vary for each meter design.

Baseline calibration results for four commercially available clamp-on meters are presented. The results were obtained in good installation conditions on stainless steel pipes of 4-inch and 8-inch nominal bore. The results show different levels of accuracy associated with each meter and a general conformation with predicted behaviour.

The final section of the paper presents results obtained by a systematic numerical method of determining the flow profile sensitivity of various meter configurations. The results provide quantitative confirmation of the reduced sensitivity of multipath designs to variations in the velocity profile.

1 BACKGROUND

The use of ultrasonic technology for flow measurement in offshore applications has increased in the last few years. This is due to advances in the metering technology in addition to the force of economic pressure on field development strategies. Transit time ultrasonic flowmeters are now employed in a diverse range of gas flow applications from flare stack monitoring to sales gas custody transfer.

Liquid meters have, until recently, been used mainly in areas peripheral to the main product transfer. Now they are being considered for many more critical applications. One notable use is in custody transfer of processed crude from floating production storage and offloading (FPSO) vessels to shuttle tankers. In such applications the accuracy demands are higher than traditional ultrasonic meter usage with the consequence that more consideration must be given to meter selection, configuration, calibration and installation in order to ensure best performance.

There is an increasing demand for continuous on-line flow measurement at intermediate stages in the production process stream. Many of these applications could be considered more demanding than custody transfer measurement, not in terms of accuracy, but in relation to installation and operating conditions. In these applications it may be necessary to trade accuracy against applicability. This will require a greater understanding of meter behaviour in 'non-standard' conditions.

2 INTRODUCTION

A programme of work is currently underway at NEL to investigate and characterise the performance of liquid ultrasonic meters over a wide range of conditions. The work was initiated in 1995 with the project *Ultrasonic Meters for Oil Flow Measurement*. The first stage results from the project were reported at last year's workshop [1]. The work has been continued in three further projects:

- Long-term evaluation of ultrasonic flowmeters
- Research into clamp-on ultrasonic meters
- Application of ultrasonic meters in non-standard flows

These projects have been specified to cover the following general application issues:

- Baseline performance in good installation and operating conditions
- Deviation from baseline performance due to meter installation downstream of flow disturbing pipe work configurations
- Behaviour in the presence of flow of more than one fluid component
- Performance and maintainability in the long-term

This paper details laboratory evaluation results from the second stage of the original project *Ultrasonic Meters for Oil Flow Measurement* and initial baseline results from the project *Research into Clamp-on Ultrasonic Meters*. In addition to the laboratory evaluation data, initial modelling results from the project *Application of Ultrasonic Meters in Non-Standard Flows* are presented.

3 THE METERS

Manufacturers of commercial transit time ultrasonic flowmeters have been invited to provide meters for inclusion in the laboratory evaluation tests of the programme. At present meters have been obtained from six different manufacturers covering a range of technological aspects both generic and proprietary.

Six meters were supplied in 1996 for the project *Ultrasonic Meters for Oil Flow Measurement*. Meter A was a single-beam clamp-on meter with 1 MHz transducers which were mounted in a horizontal diametric configuration on a 4 inch schedule 40 carbon steel spoolpiece provided by NEL. The design uses a digital correlation technique for the determination of the transit times and automatically corrects for profile effects on the basis of Reynolds number and bore roughness. Values of 20 cSt and of 0.21 mm were used for these parameters. The supplier of Meter A requested that manufacturer and model details be omitted as the results did not conform with expectations.

Meters B_C, B_W, C and D were supplied by Panametrics, Ultraflux and Danfoss respectively. Meters B_C and B_W were both model XMT868 dual channel flow transmitters supplied with a single 4-inch schedule 40 carbon steel spoolpiece comprising both wetted and clamp-on transducer configurations. The meter supplied by Ultraflux was a model UF322-2 with two pairs of 1 MHz clamp-on transducers which were installed on a 4-inch schedule 40 stainless steel spoolpiece provided by NEL. Meters B_C, B_W and C each employed dual single-reflection diametric paths in perpendicular planes. Meter D was a 4 inch nominal bore Danfoss Sonoflow with the standard path configuration of two parallel mid-radius chords. More detailed description of meters A to D are provided in reference 2 along with the complete set of open results for each meter. The sixth meter included in the project was a Krohne Altometer UFM Multichannel for which the open test results have been previously described [1].

Meters E to H have been supplied by four different manufacturers for inclusion in the project *Research into Clamp-on Ultrasonic Meters*. In this paper they are described only by these nominal identifiers and by their transducer configurations. Meters E and F are dual-path meters which employed single-reflection diametric paths in perpendicular planes. Meters G and H are single-path meters for which the default path configuration employed was a horizontal diametric path with a single reflection. Further details of meters E to H will be given at a later date once the manufacturers have been given sufficient time to comment on the test results.

4 UNCERTAINTIES AND PERFORMANCE CHARACTERISTICS

The performance of transit time meters can be characterised by quantifying uncertainties in the determination of the transit time intervals and geometrical parameters of the meter tube. Assuming that the transit time difference measurement, Δt, is independent of the measurement of the upstream and downstream transit times, and that the product of these transit times can be approximated by the square of their mean, $\bar{t}$, the flowrate can be given by

$$q_v = k_h \frac{\pi D^2}{4} \frac{L^2 \Delta t}{2x\bar{t}^2} \quad (1)$$

where D is the diameter of the meter tube, L is acoustic path length in the flowing fluid, x is the axial projection of the path and k_h is the hydraulic or velocity distribution factor given by

$$k_h = \frac{\bar{v}_{actual}}{\bar{v}_{measured}} \quad (2)$$

By differentiation of equation 1 the sensitivity coefficients given in the following table are obtained.

Table 1 The Sensitivity Coefficients of Equation 1

$\delta_{kh} = \frac{\partial q_v}{\partial k_h}\frac{k_h}{q_v}$	$\delta_D = \frac{\partial q_v}{\partial D}\frac{D}{q_v}$	$\delta_L = \frac{\partial q_v}{\partial L}\frac{L}{q_v}$	$\delta_{\Delta t} = \frac{\partial q_v}{\partial \Delta t}\frac{\Delta t}{q_v}$	$\delta_x = \frac{\partial q_v}{\partial x}\frac{x}{q_v}$	$\delta_{\bar{t}} = \frac{\partial q_v}{\partial \bar{t}}\frac{\bar{t}}{q_v}$
1	2	2	1	-1	-2

Using the above table the uncertainty in the flowrate measurement can be determined by assigning a percentage uncertainty, E, to each of the parameters in equation 1 and substituting these into the equation

$$E_{qv} = \sqrt{(\delta_{kh}E_{kh})^2 + (\delta_D E_D)^2 + (\delta_L E_L)^2 + (\delta_{\Delta t}E_{\Delta t})^2 + (\delta_x E_x)^2 + (\delta_{\bar{t}}E_{\bar{t}})^2} \qquad (3)$$

An example follows for illustrative purposes.

4.1 Illustrative analysis

The uncertainties in D, L and x will be dependent on the methods by which they are established. A reasonable estimate of the uncertainty in D is 0.1% for measurement in the factory. The same figure could also apply for measurement of L and x. However in some cases, for example the case of transducers recessed in a well, the end points of L and x have no true physical definition, so a greater figure should be applied, say 0.2%. For in-situ, clamp-on measurement an uncertainty of a few millimetres is a reasonable assumption for pipe diameters up about 1 meter. L and x for clamp-on installations are derived from the measurement of $\bar{t}$ and D in addition to characteristic data relating to the transducers. To assume that the uncertainty in L or x is equal to the uncertainty in D would appear reasonable.

The relative uncertainty in Δt is dependent on the flow velocity. A simple estimate can be obtained by considering the timing clock resolution. Assuming a clock frequency of 100 MHz and ten thousand averaged measurements of the transit time difference interval we can ascribe an uncertainty of 0.05 nanoseconds for the timing resolution plus a zero-flow offset differential delay of 0.05 ns, giving a total figure of 0.1 ns. For clamp-on installations the signal-to-noise ratio is likely to be lower and poor alignment or coupling to the pipe wall may introduce a more significant differential delay so a figure of 0.5 nanoseconds could be applied.

The uncertainty in measurement of the transit time $\bar{t}$ is dependent upon the elimination of delays in transducers, electronics and recesses. If these are determined with reasonable accuracy we could assume a figure of 100 ns for the uncertainty in $\bar{t}$.

Taking the above figures the following 'dummy' curves of characteristic uncertainty versus velocity have been constructed for 4, 8 and 16 inch pipe sizes assuming a fluid sonic velocity of 1500 m/s and interrogation angles of 45 and 30 degrees for 'wetted' and 'clamp-on' configurations respectively.

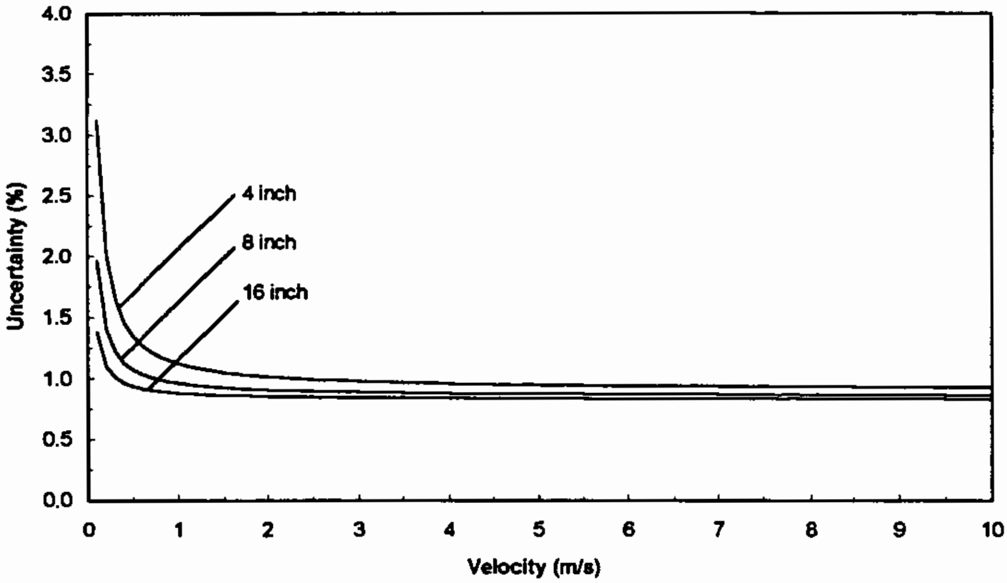


Figure 1 Illustrative performance curves (wetted assumptions)

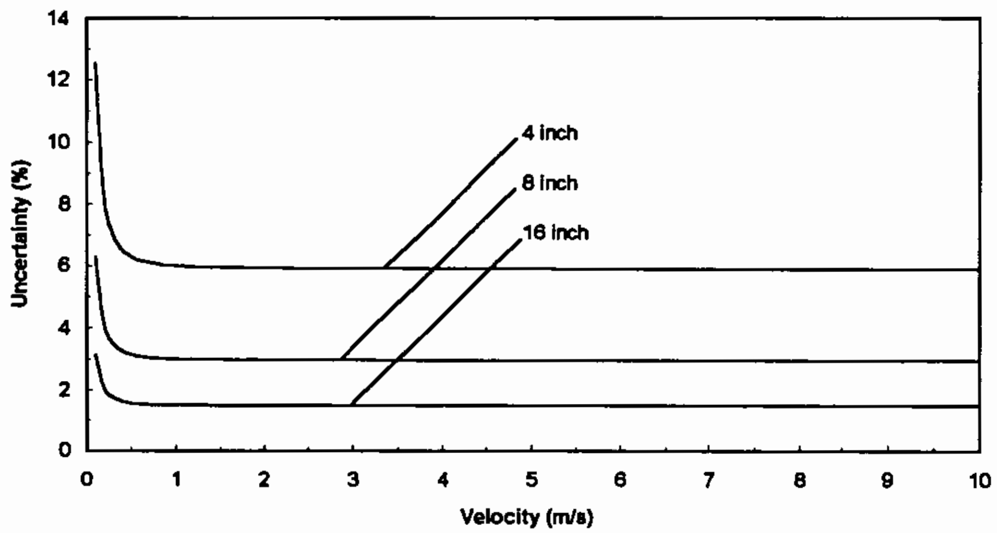


Figure 2 Illustrative performance curves (clamp-on assumptions)

Figures 1 & 2 illustrate two of the fundamental characteristics of the transit time measurement principle, i.e. increasing uncertainty as velocity is reduced and reducing uncertainty with increasing size. Not included in the above curves are the effects of the velocity distribution, attenuation, diffraction, noise etc.

4.2 Velocity Distribution Factors for Fully Developed Flow

In fully developed flows the velocity distribution factor, k_h, can be calculated as a function of Reynolds number and relative roughness, k/r. Figure 3 shows the turbulent flow k_h function derived by Fronek [3] for meters employing diametrical paths.

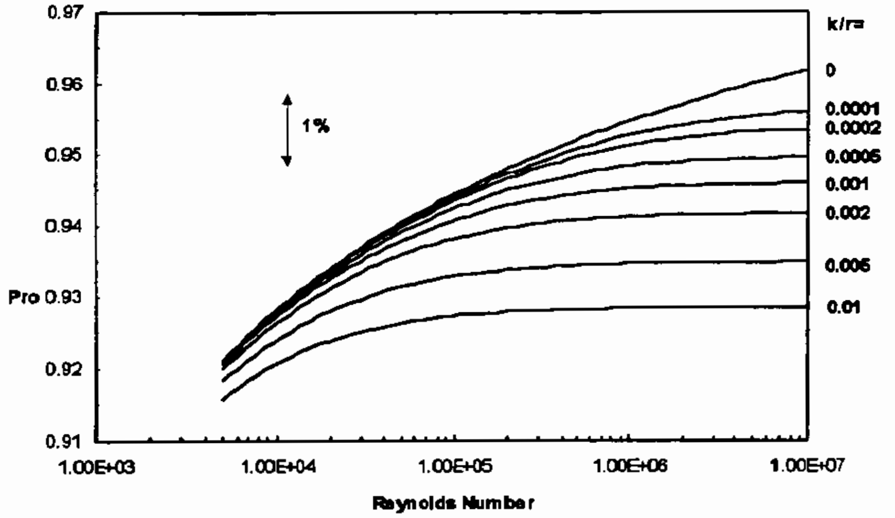


Figure 3 Diametric profile factor as a function of Reynolds number

In figure 4, the turbulent k_h factor is presented as a function of velocity for pipe diameters of 4, 6 and 16 inches, a constant roughness of 0.2 mm, and fluid viscosity of 1 and 5 cSt. From this figure we can see that non-linearity due to inaccuracy in k_h will be most significant at low velocities. The figure also illustrates that the linearity of the k_h function is relatively independent of the pipe size.

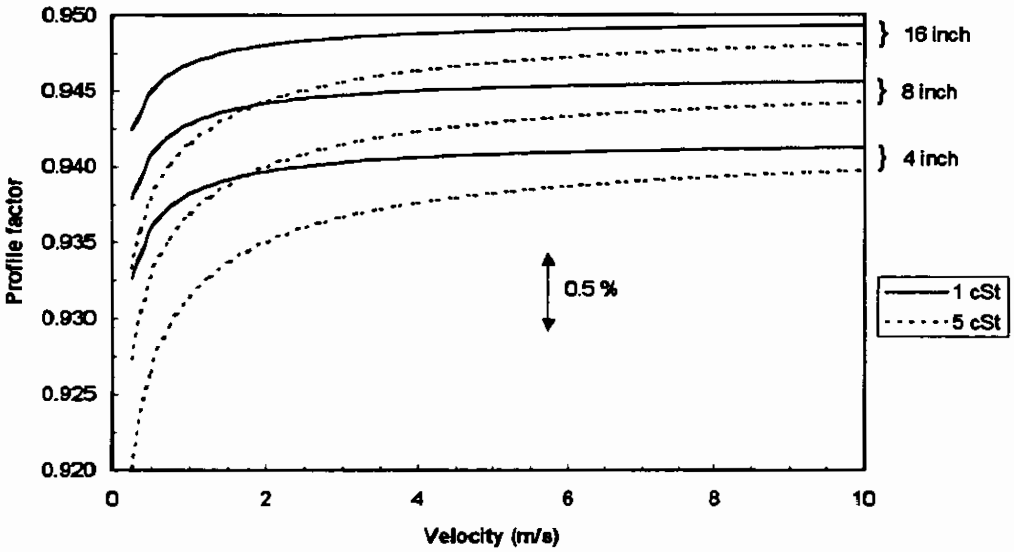


Figure 4 Diametric profile factor as a function of velocity

5 PERFORMANCE IN TWO-PHASE FLOW OF OIL AND GAS

The two-phase oil/gas tests reported here were conducted using a circuit of the main oil flow primary standard by introducing low flowrates of metered nitrogen into the test line on the downstream side of a reference positive displacement (PD) meter. The set-up is shown schematically in figure 5.

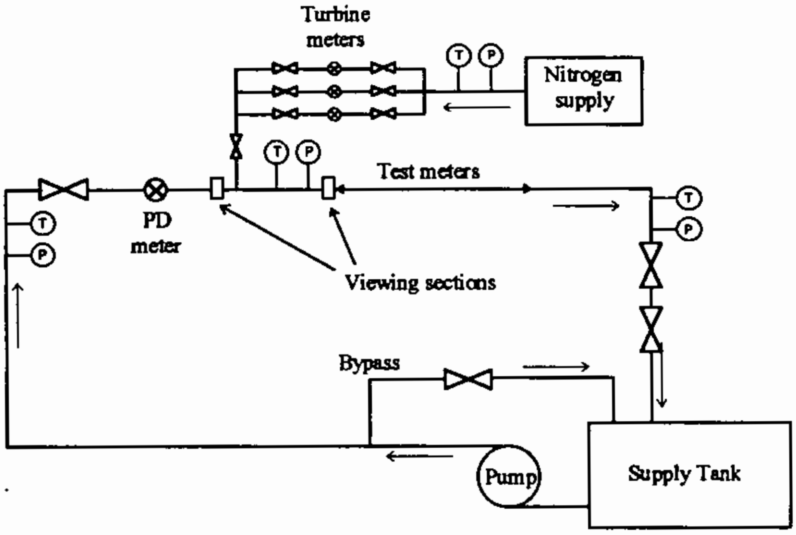


Figure 5 A schematic diagram of the oil/gas test facility

In general the performance of ultrasonic meters in flows of oil and gas is dependent on the gas distribution, the transducer locations and the signal detection and processing methods. The results of oil/gas tests have been presented previously in summary form [1]. Specific aspects of performance are studied here in greater detail.

5.1 Detection and processing of signals and measured parameters

Signal detection methods employed to determine the transit time intervals tend to be based on zero-crossing or correlation methods. For any given meter a choice of signal detection methods is generally not available, so that the detection method is chosen at the stage of meter selection. The degree of access to meter signal limits and fault response options varies from manufacturer to manufacturer and constrains the extent to which the meter behaviour may be tailored. For example, meter A has a 'low signal' parameter which can be set by the user to generate a fault response when the signal falls below the cut-off. Meter D's 'signal limit' settings are not adjustable whereas meters B_C & B_W has more than ten variable signal and flow parameter limit settings.

Figures 6 and 7 illustrate a difference in meter behaviour influenced by signal limit settings. For these results the mixture velocity was approximately 9 m/s and the gas was evenly distributed throughout the cross-section in the form of many sub-millimetre sized bubbles. The results of figure 6 show a deviation of approximately 0.5 to 1 % in the reading of meter B_C at 0.4 % gas volume fraction (GVF) and errors corresponding to a continuous fault occurrence at 0.8 % GVF when the output was forced to zero.

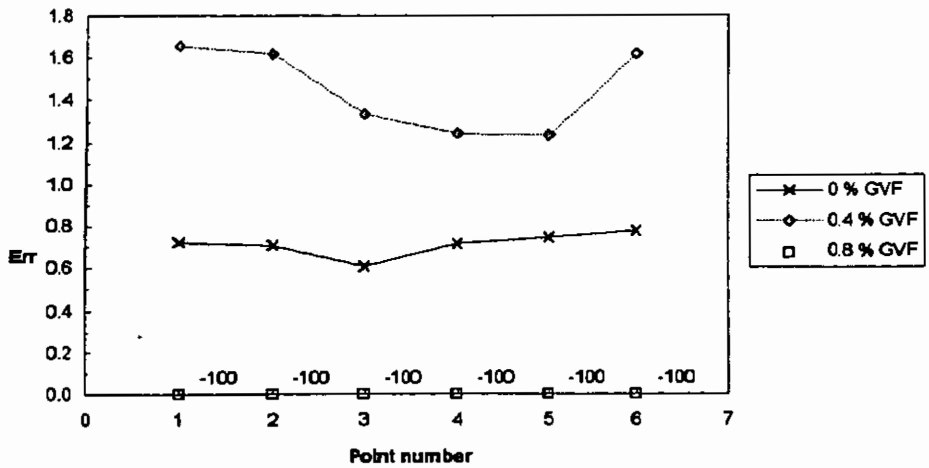


Figure 6 Oil/gas performance of meter B at a velocity of 9 m/s

Figure 7, however, shows a different response. At 0.4 % GVF the results lie within a few percent of the average 0 % gas result. At 0.8 % GVF the meter continued to output the flowrate although the magnitude of deviation from the 0 % gas results was increased to ±10 %.

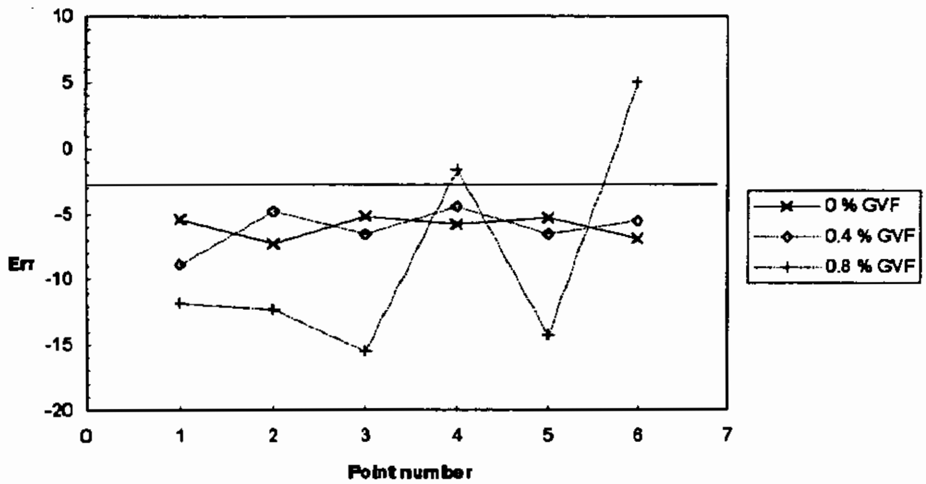


Figure 7 Oil/gas performance of meter A at a velocity of 9 m/s

Although meters A and B_C were supplied by different manufacturers and displayed some differences in basic characteristics (such as repeatability) they both employed correlation detection methods for the transit time measurement. The signal limit settings for meter B_C were set at default values (e.g. the signal low limit was set at 40 out of a possible range of -20 to 100) and the single limit setting of meter A was also set at its default, this taking the value 0 out of the possible range of 0 to 100. It can be considered then that by adjusting the signal parameters of Meter B_C its operating range may have been extended to include the 0.8 % GVF condition.

5.2 Void distribution and liquid velocity distribution

Figure 8 illustrates the influence of void distribution and liquid velocity distribution on meter D. The results shown here were obtained at a mixture velocity of approximately 4 m/s. At 0.75% GVF no fault indication was observed and the deviation was between approximately 3 and 5 %. At 1.5 % GVF intermittent faults and spurious high flowrate indications were observed which resulted in the high positive errors shown on the upper boundary of the graph shown in figure 8. At 4 % GVF signal fault conditions were indicated continuously but the magnitude of deviation was approximately the same as the 0.75 % GVF results.

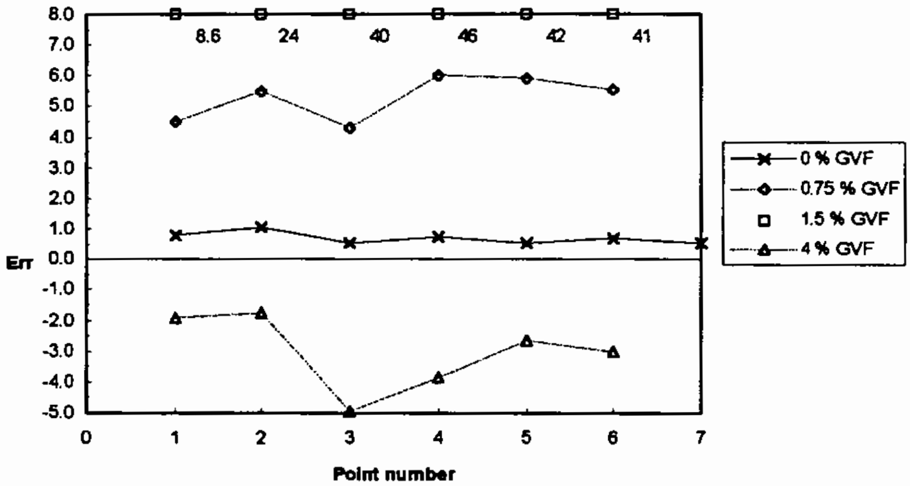


Figure 8 Oil/gas performance of meter D at a velocity of 4 m/s

This perhaps seemingly unusual behaviour can be explained qualitatively by considering the relation between the gas distribution and the position of the acoustic paths employed by the meter. As illustrated in figure 9 at the lowest gas fraction neither of the measurement paths are affected by the presence of the gas. At the second gas fraction the upper path is affected by the presence of the gas and spurious results are generated. At the highest gas fraction however, the amount of gas present in the upper chord has increased to such an extent that the measurement fails and the meter results are computed on the basis of the lower chord measurement only, which is free of gas.

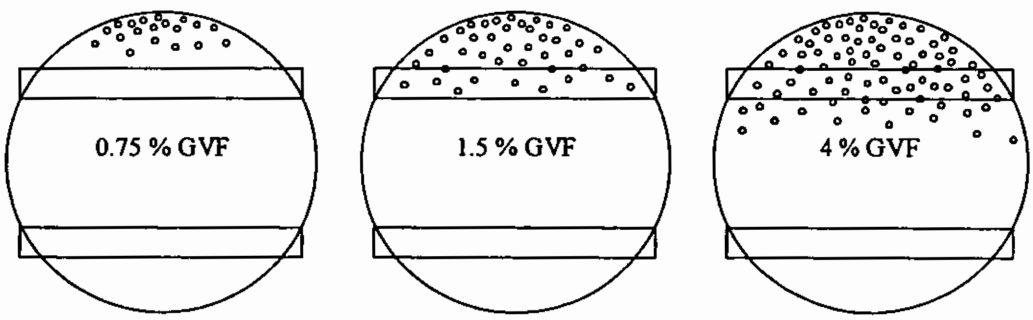


Figure 9 An illustration of the void distribution in meter D

The deviations at 0.75 and 4 % gas fractions show a bias due to the effect of the gas on the velocity distribution. Perhaps surprisingly, the deviations at 0.75 % GVF are, on average, greater in magnitude than those at 4 % GVF. It can be postulated therefore, that the performance of Meter D could be improved for two-phase, oil/gas horizontal flow by disabling the upper chord.

6 PERFORMANCE IN TWO-PHASE FLOW OF OIL AND WATER

The two-phase oil/water tests reported here were conducted in the multiphase calibration facility at NEL. A schematic diagram of the facility, as used for these tests, is shown in figure 10. The total reserve of oil and water is held in a vessel which acts as a combined storage tank and multiphase separator with water, oil and mixture compartments. The oil and water are drawn from each of the single-phase compartments and are delivered to the flow loop via calibrated reference meters. Also present in the system are sampling loops for the determination of background quantities of oil-in-water and water-in-oil. After the oil and water are allowed to co-mingle the fluids then flow to the test section along a 50m development length of straight pipe.

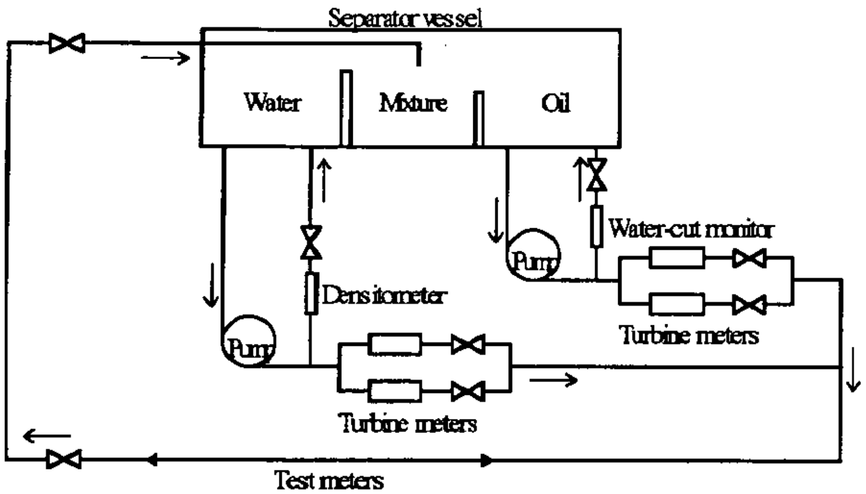


Figure 10 A schematic diagram of the multiphase facility as used for two-phase oil/water tests

The oil used in the facility was a crude-kerosene mix with approximate density and viscosity of 843 kg/m^3 and 7 cSt respectively at the test temperature of 35°C. The water used was a brine solution of density approximately 937 kg/m3 at the test temperature. The matrix of nominal test conditions is shown in Table 2.

Table 2 Nominal conditions for the oil/water tests

Nominal water-cut	Nominal flowrates (l/s)							
5 %	4	8	12	16	20	24	28	32
9 %	4	8	12	16	20	24	28	32
12 %	4	8	12	16	20	24	28	32
15 %	4	8	12	16	20	24	28	32

The results of the oil/water tests on meters A - D are shown in figures 11 to 16. Also shown for reference are the previously derived single-phase calibration results for oils of two viscosities. In general the results lie within a few percent of the oil calibrations at 3 and 30 cSt. Examining the characteristics in closer detail it can be seen that the deviations with respect to the single-phase calibrations are not consistent between the meters. These differences can be explained qualitatively by considering the influence of the physical aspects of the flow in relation to the measuring principle and the variations in meter design characteristics.

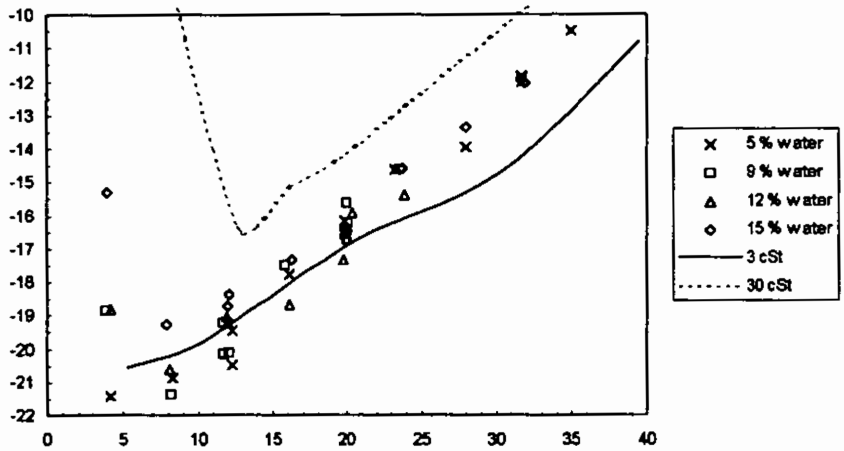


Figure 11 Oil/water performance of meter A

As the two fluids are immiscible the effect of gravity will produce a local fluid density profile which varies in the vertical direction. This will in turn influence the axial flow velocity profile and will also affect the ultrasonic propagation by means of refraction. The paths of meters A and D were orientated horizontally so it is expected that these results should show the influence of velocity profile but no strong influence of the density profile on the ultrasonic signal propagation. Both figure 11 and figure 12 show results which, considering the greater scatter shown, tend to lie within the envelope of the single-phase conditions. The greater scatter can be attributed to the scattering of the ultrasonic wave by water droplets which appear as local discontinuities in the acoustic impedance of the medium.

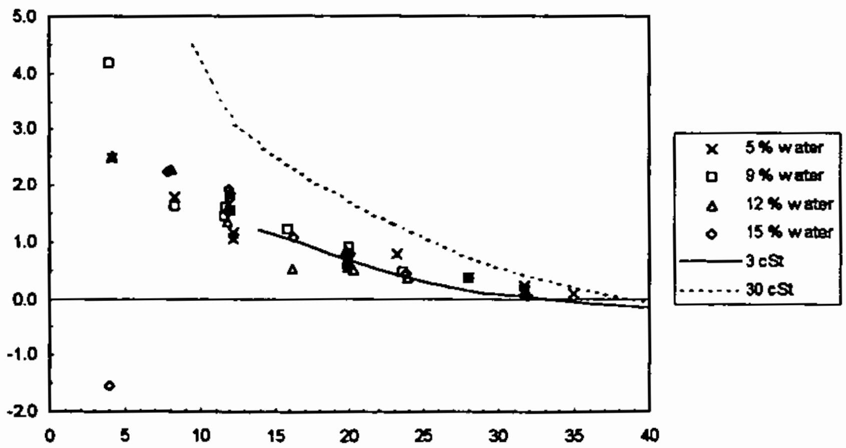


Figure 12 Oil/water performance of meter D

Note that the non-linearity displayed in figure 11 was considered to be the result of erroneous flow profile correction factors in the meter software for the Reynolds number range R_{eD} 6000 to R_{eD} 32,000.

The results for meters C, B_C & B_W presented in figures 13, 14 and 15 all show, in one form or another, behaviour which deviates from their single-phase performance.

The results of the oil/water tests conducted on meter C are shown in figure 13. The results at 9 and 12 % water-cut lie within the lines of the 3 and 30 cSt calibrations, however, the results at 5 % and 15 % water-cut show greater deviations. Especially remarkable are the 5 % results which show deviations of approximately -10 % from the 3 cSt calibration.

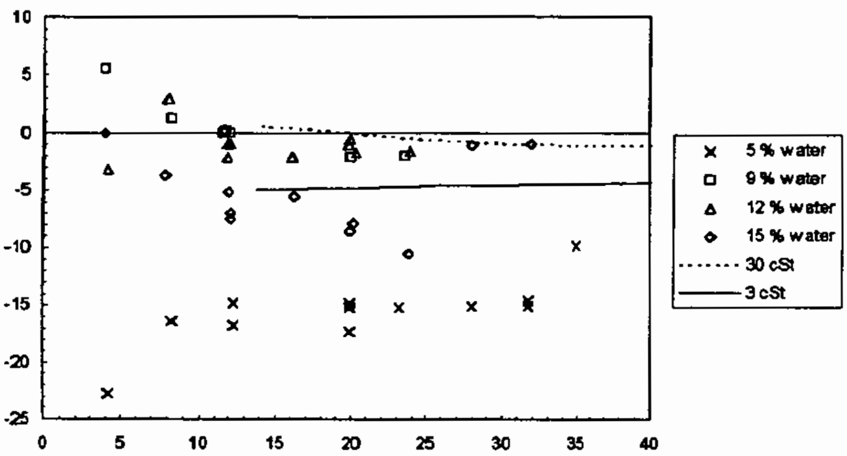


Figure 13 Oil/water performance of meter C

Figure 14 shows that the majority of results for meter B_W lie between the lines of the kerosene and velocite calibrations. When the spurious results shown of the lower limit of the graph were obtained, the meter was indicating a fault condition, but with no corresponding error message. It is interesting to note that the results produced during the fault condition correspond closely to 50 % of the actual flow, the implication being that the average flowrate is being computed from a valid measurement in one path and an indicated null in the other. The fault condition was eliminated by powering down the converter and occurred only once throughout the tests, so it would appear that the meter was subject to an internal error. However, it cannot be established conclusively that this fault was not caused by the two-phase conditions. Johannessen [4] also describes problematic results obtained in oil/water flow with a dual-path Panametrics meter, although the resulting deviations were of a lesser magnitude.

The results of the oil/gas tests on Meter B_C, the clamp-on configuration, show a similar trend to the wetted results. However all of the results above 20 l/s lie outside the envelope of the single-phase calibrations as shown in Figure 15.

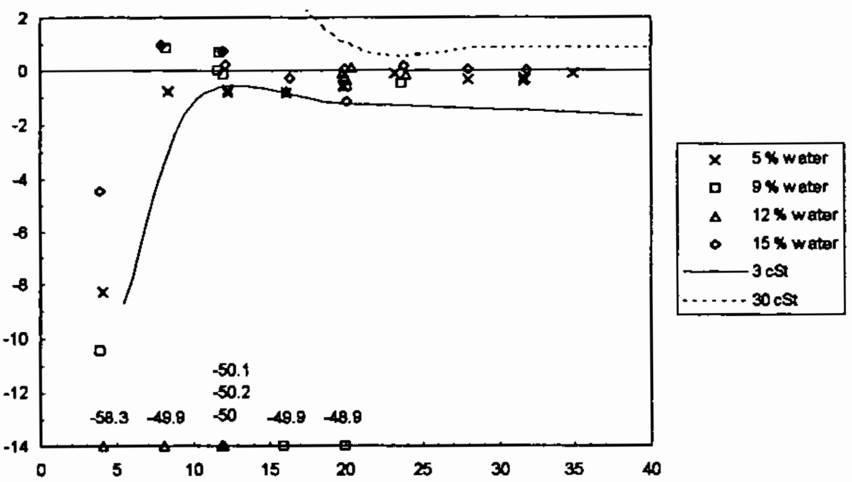


Figure 14 Oil/water performance of meter B_W

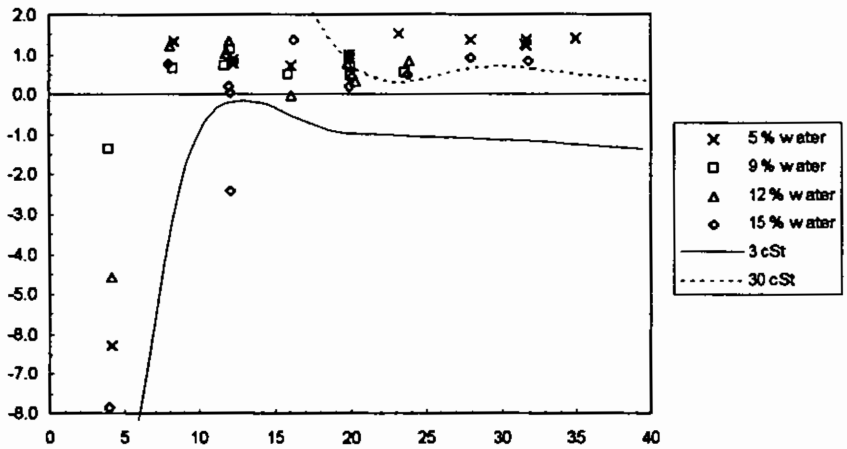


Figure 15 Oil/water performance of meter B_C

Meters B_W, B_C and C all employed dual diametric paths in perpendicular planes. As such each of the measurement paths has a component of length in the vertical direction. It can be considered that the performance of these meters was influenced by the density profile in the vertical direction in addition to the effects of the velocity profile and localised density variations.

If we assume that the large deviations exhibited by meter B_W are the result of an internal error (this is supported to some degree by the fact that 9 and 12% water results prior to and following the fault condition lie within the single-phase envelope) then the greatest deviations due to two-phase oil/water flow conditions were those of meter C. This performance can be related to the signal detection method employed by meter C, a zero-crossing detection method. It is generally accepted that zero-crossing detection methods are less robust than correlation detection methods when the ultrasonic waveform is subject to distortion or a reduction in signal-to-noise ratio.

7 BASELINE TESTS ON CLAMP-ON METERS

In this section preliminary results showing the performance of clamp-on meters in good installation conditions are presented. The results were obtained by gravimetric calibration in the water flow primary standard at NEL. The meters were installed on straight lengths of 4 and 8 inch nominal bore stainless steel pipework and were calibrated over a common velocity range. Upstream lengths of straight pipe were 65D and 45D for the 4-inch and 8-inch tests respectively.

For each of the meters common values were used for the pipe dimensions and default fluid property and pipe roughness parameters were input for dynamic profile correction. Automatic zero-setting procedures were followed according to the manufacturers instructions.

The behaviour of the meters generally conforms with the characteristics discussed in section 4. It should be noted that a relatively low velocity range was chosen for these tests in order to highlight variation in performance, and that, in most cases, the maximum velocity tested was around 50 % of the meter's range. Based on previous experience it is considered that observed performance can be extrapolated to higher velocities within the range of the meter. The results presented here have had a calibration factor applied and are discussed in terms of linearity and repeatability, not absolute error.

The 4-inch calibration results for meter E show a variation in meter factor of approximately 8 % over the range tested. For velocities of approximately 0.5 m/s and above the variation is less than 1%. The repeatability of the meter is better than 1 % for velocities lower than 1 m/s and better than 0.5 % for velocities above this limit.

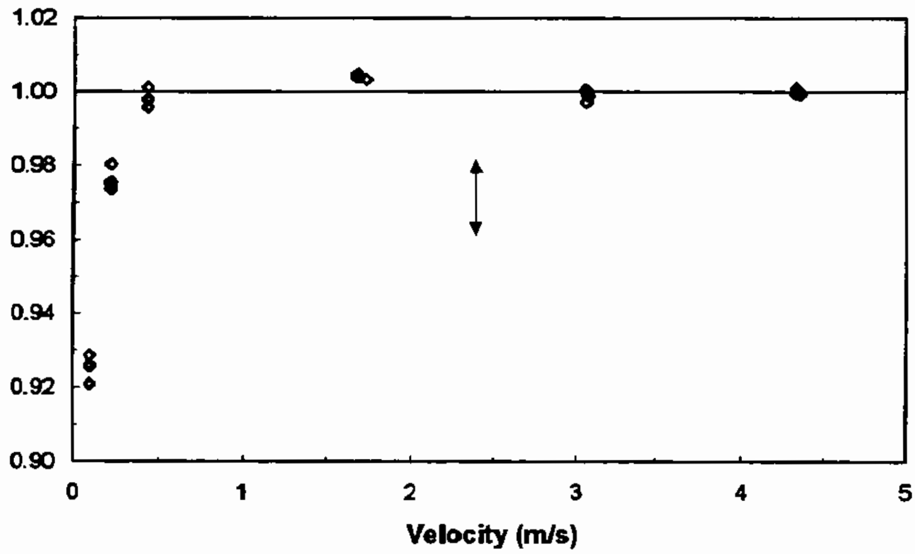


Figure 16 4-inch water calibration results for clamp-on meter E

The 8-inch calibration results for meter E show a variation in meter factor of approximately 6 % over the range tested. For velocities of approximately 0.5 m/s and above the variation is less than 1%. The repeatability of the meter is better than 0.8 % for velocities lower than 1 m/s and better than 0.4 % for velocities above this limit.

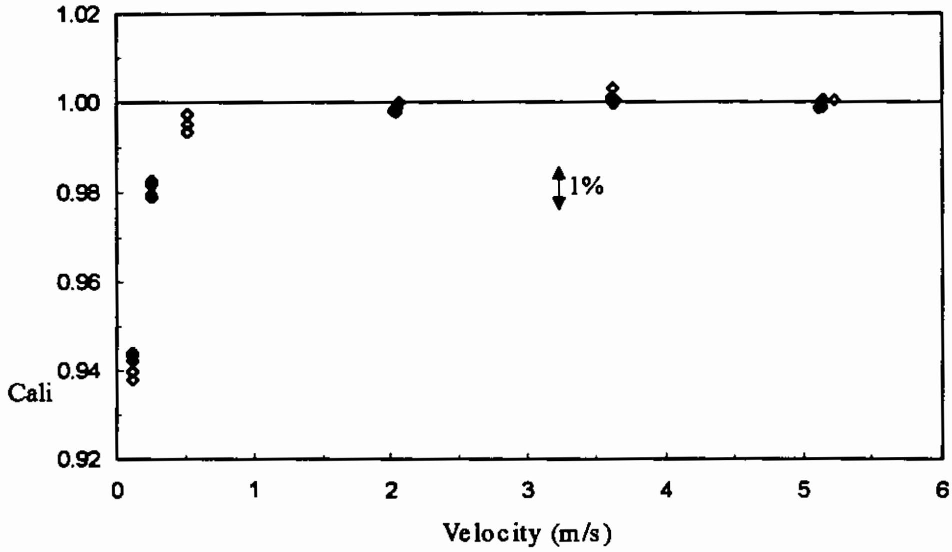


Figure 17 8-inch water calibration results for clamp-on meter E

The 4-inch calibration results for meter F show a variation in meter factor of approximately 10 % over the range tested. For velocities above 1 m/s the variation is less than 1 %. The repeatability of the meter is between approximately 1 and 2 % for velocities lower than 1 m/s and better than 1 % for velocities above this limit.

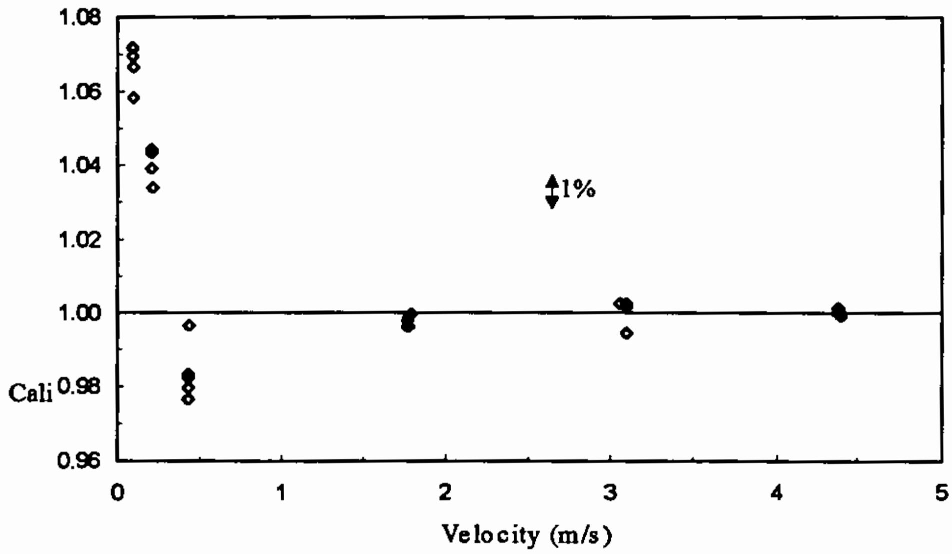


Figure 18 4-inch water calibration results for clamp-on meter F

The 8-inch calibration results for meter F show a variation in meter factor of approximately 2.5 % over the range tested. For velocities above 1 m/s the variation is less than 0.6 %. The repeatability of the meter is between approximately 1 and 3 % for velocities lower than 1 m/s and better than 0.7 % for velocities above this limit.

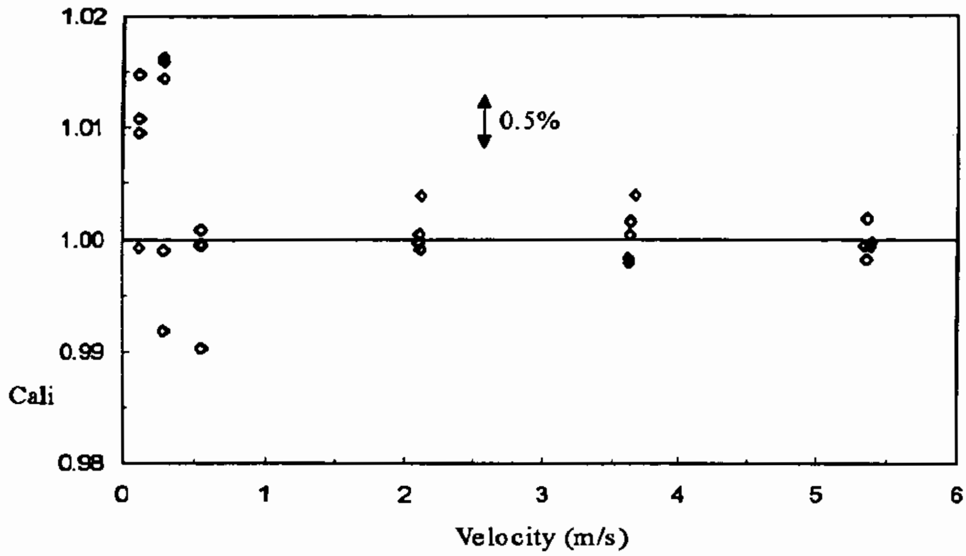


Figure 19 8-inch water calibration results for clamp-on meter F

The 4-inch calibration results for meter G show a variation in meter factor of approximately 65 % over the range tested. For velocities above 1 m/s the variation is approximately 8 %. The repeatability of the meter is between approximately 1.4 and 3.4 % for velocities above 1 m/s.

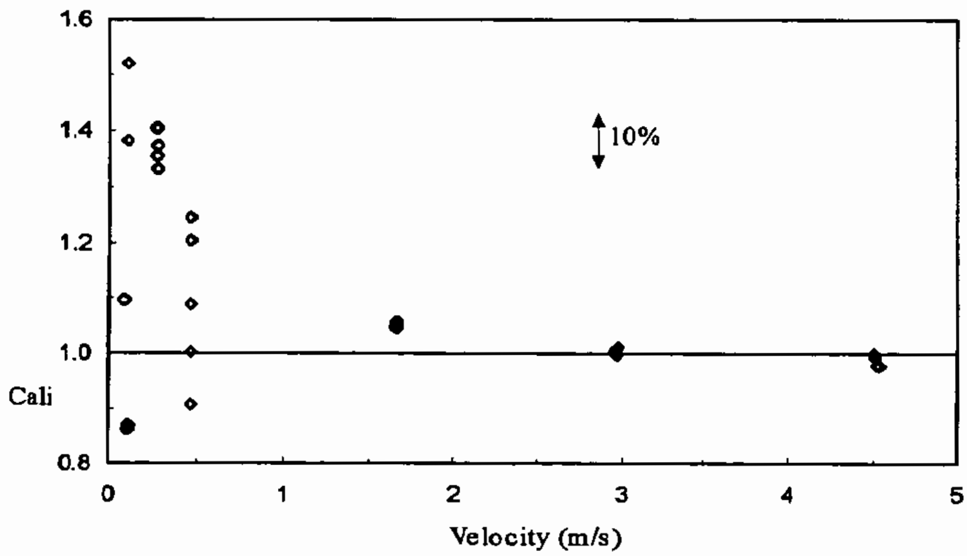


Figure 20 4-inch water calibration results for clamp-on meter G

The 8-inch calibration results for meter G show a variation in meter factor of approximately 21 % over the range tested. For velocities above 1 m/s the variation is approximately 1.2 %. The repeatability of the meter is better than 0.8 % for velocities above 1 m/s.

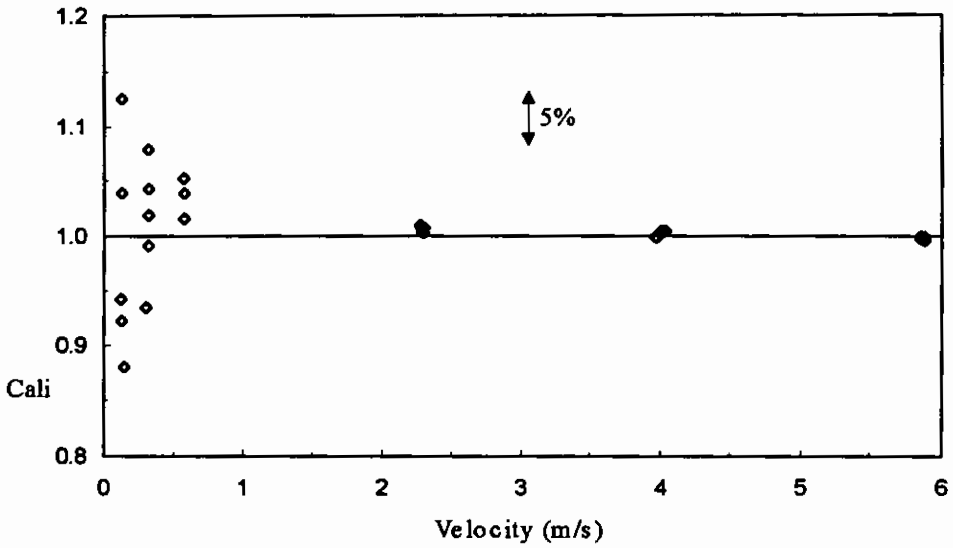


Figure 21 8-inch water calibration results for clamp-on meter G

The 4-inch calibration results for meter H show a variation in meter factor of approximately 30 % over the range tested. For velocities above 1 m/s the variation is approximately 5.5 %. The repeatability of the meter is between 1 and 2.5 % for velocities of approximately 0.5 m/s and above and is better than 7 % for velocities below this range.

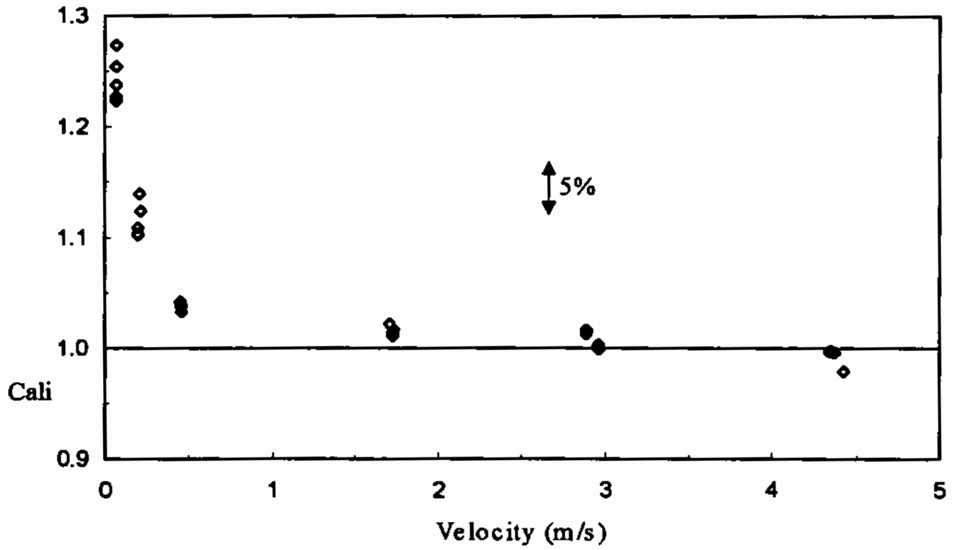


Figure 22 4-inch water calibration results for clamp-on meter H

The 8-inch calibration results for meter H show a variation in meter factor of approximately 24 % over the range tested. For velocities above 1 m/s the variation is less than 1.5 %. The repeatability of the meter is between 0.5 and 2 % for velocities above 0.25 m/s and is approximately 2.6 % for the tests at 0.15 m/s.

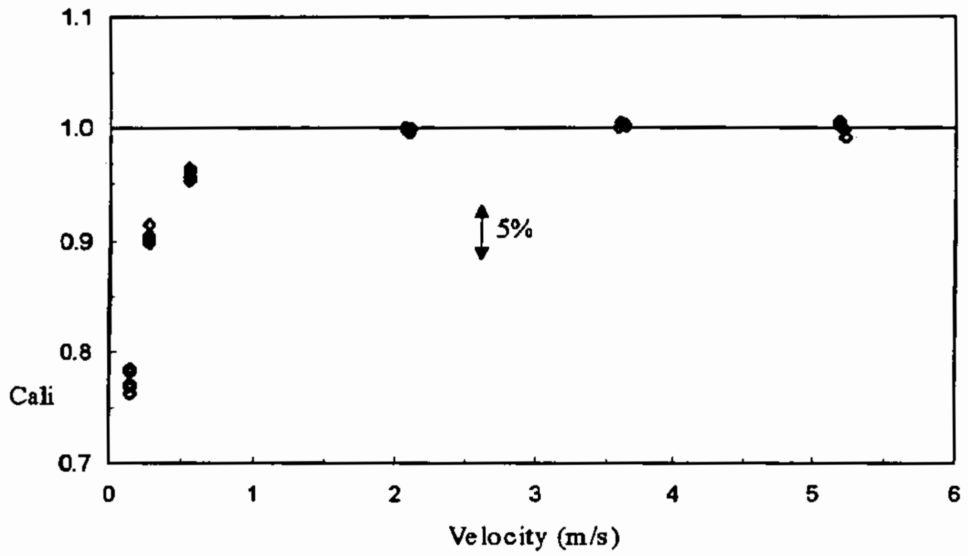


Figure 23 8-inch water calibration results for clamp-on meter H

8 THE INFLUENCE OF A DISTORTED VELOCITY PROFILE

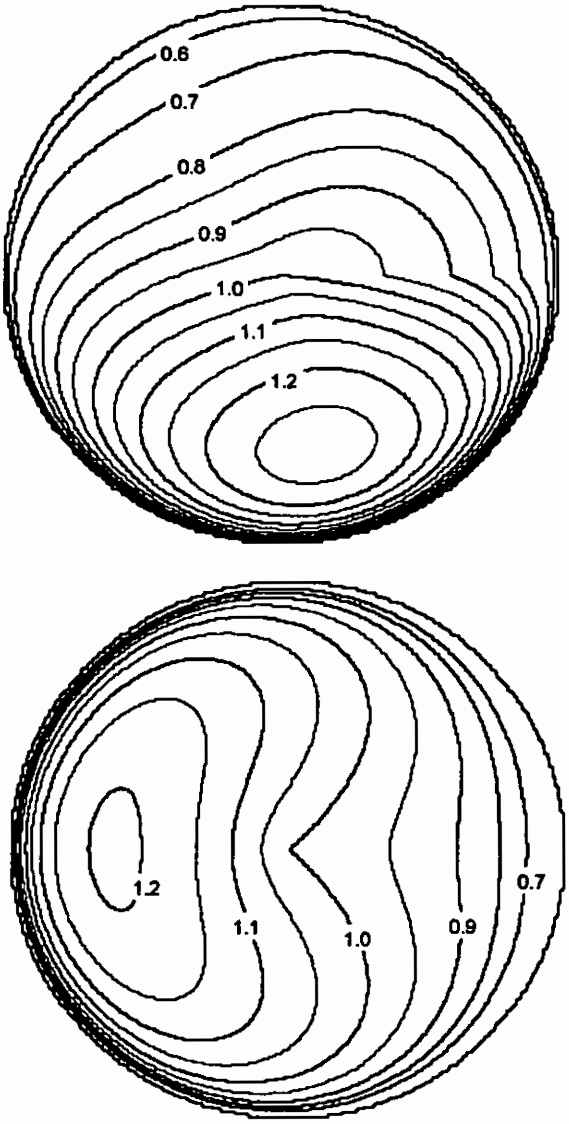
The performance of ultrasonic meters in non-ideal installation conditions will be the cumulative effect of a number a number of factors. Two important factors are transverse velocity components (cross-flow and swirl) and distortions of the axial velocity profile. Other factors such as high turbulence intensity or acoustic noise at frequencies within the transducer bandwidth will also affect performance.

The influence of velocity profile distortion and swirl produced by upstream pipework is a major concern in offshore applications. Space and weight constraints are often prohibitive to the provision of long lengths of straight pipe. Flow conditioners or in-situ proving may be used but these methods are in conflict with two of the major incentives for using ultrasonic meters, i.e. reducing flow restriction and lowering operational costs.

The determination of installation effects by laboratory simulation of actual conditions is favoured as producing the most realistic results. A problem with this approach is that the resulting data is not easily applicable to differing pipework or meter configurations. Flow and flowmeter modelling has already proven to be useful in improving the understanding of measurement interaction mechanisms. It is also potentially useful for deriving quantitative information which could be used when installing a flowmeter.

The current work at NEL involves parallel model-based and experimental investigation of installation effects on transit time ultrasonic meters. The primary aim is to determine the potential of combining computational fluid dynamics (CFD) with a simple model of the flowmeter to determine the hydraulic calibration factor, k_h. To enable this the simulated results will be compared with experimentally derived data for a range of configurations.

As a precursor to the CFD work numerical modelling has been carried out using mathematical velocity profiles formulated to depict real profiles encountered in practice. This approach is especially useful in the study of velocity profile effects as numerical calculations can be performed rapidly for various meter configurations. As the profiles can be integrated analytically, an exact reference can be determined against which the results can be compared. Results are given here for two velocity profiles and four meter configurations.



P6

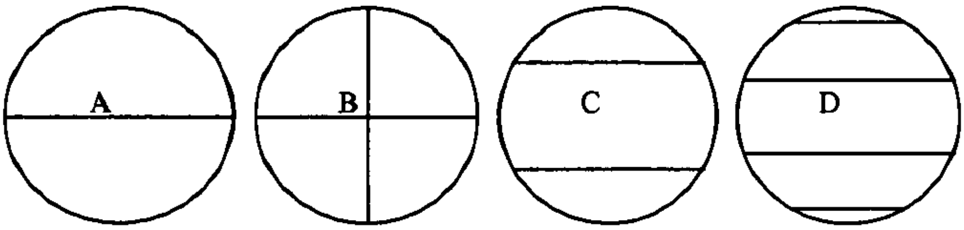
$$u=(1-r)^{1/9}-\frac{r}{2\pi}(1-r)^{1/4}\theta\sin\theta$$

P9

$$u=(1-r)^{1/9}+\frac{2r}{\pi^5}(1-r)^{1/4}\theta^2(2\pi-\theta)^2$$

Figure 24 Contour plot representation of velocity profiles P6 & P9

The contour plots of figure 24 depict the profile functions P6 and P9 formulated by Salami [5] describing the ratio of local to central velocity, u, as a function of radial and angular location (r, θ). Using these functions k_h factors have been determined by numerical integration of the velocities along the measurement paths for each of the configurations given in Figure 25. For single diametric, orthogonal dual diametric and parallel dual mid-radius configurations the velocity determined by the meter is simply the average of the mean velocities determined on each path. For the 4-path arrangement the velocity determined by the meter is proportional to the sum of velocities which have been integrated and weighted according the rules of Gaussian quadrature [6].



$\bar{v} = v_1$ $\qquad \bar{v} = \frac{v_1 + v_2}{2}$ $\qquad \bar{v} = \frac{v_1 + v_2}{2}$ $\qquad \bar{v} = \frac{\sum w_i V_i}{\pi r^2}$

Figure 25 Meter configurations used in the numerical analysis

Figure 26 shows the k_h factor plotted against path orientation for the single diametric case. Also shown for reference are the k_h factors obtained using the power law profile with exponents of 1/6 and 1/10.

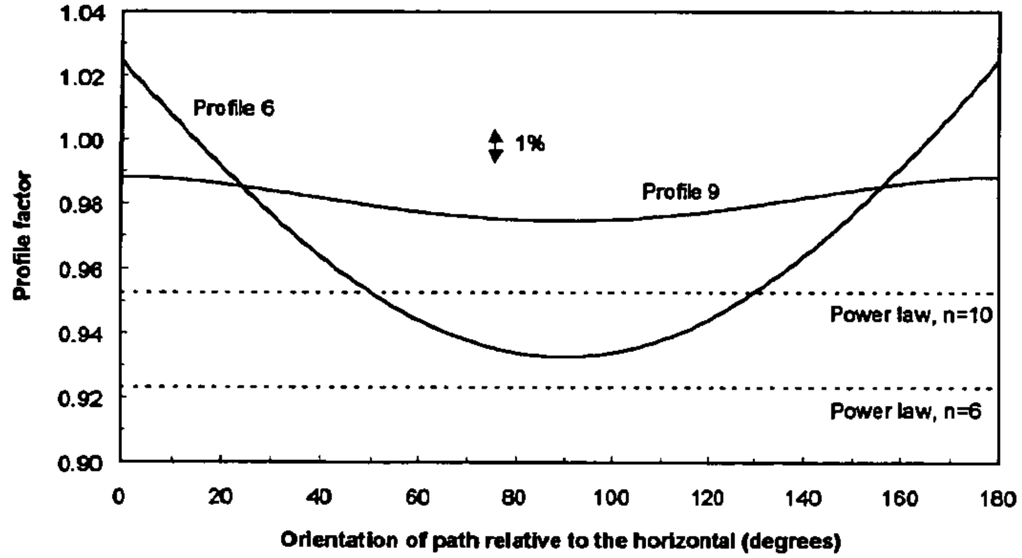


Figure 26 Profile factors for the single diameter path configuration

As can be seen from the figure the k_h factor for profile P6 varies significantly with orientation with a maximum installation effect of 7 - 10 % at an angle of 0°. For profile P9 the k_h factor varies less with orientation but is consistently about 2 to 6 % higher than for the powerlaw profiles.

Figure 27 shows the k_h factor plotted against beam orientation for the orthogonal dual diametric case. Again the k_h factors obtained using the power law profile are shown for reference. For both profiles the variation in k_h with orientation is reduced. For profile P9 the benefit of adding the second path is small. For profile P6 however the maxima have been reduced by about 4 % thus limiting the possible installation effect. However, there is now no orientation at which the k_h factor crosses into the powerlaw profile region.

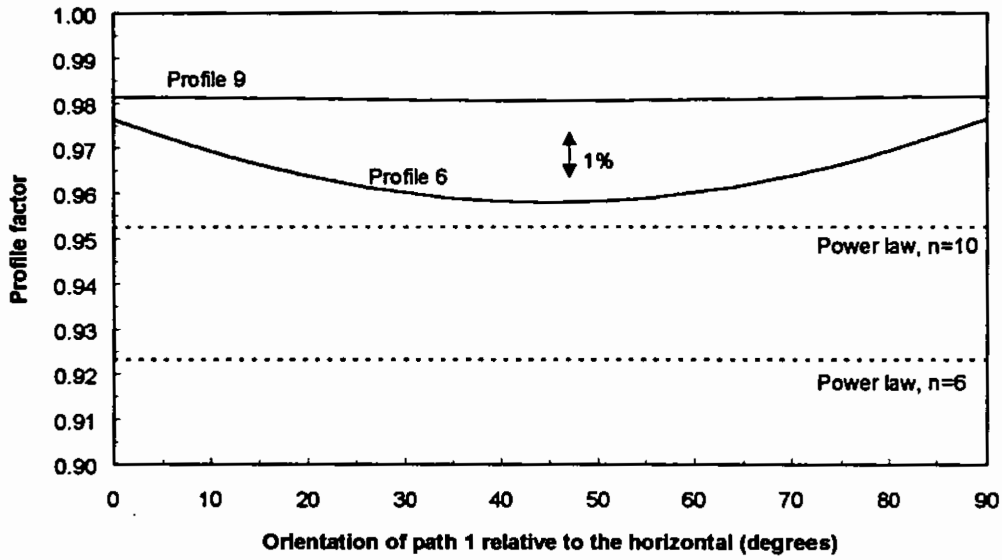


Figure 27 Profile factors for the dual diameter path configuration

Figure 28 shows the k_h factor plotted against path orientation for the parallel dual mid-radius configuration. Again the k_h factors obtained using the power law profile are shown for reference. In this case the deviation from the ideal k_h factor is within about 2 % for all orientations and for profile 6 the deviation is less than 0.5 % for over half of the angular range.

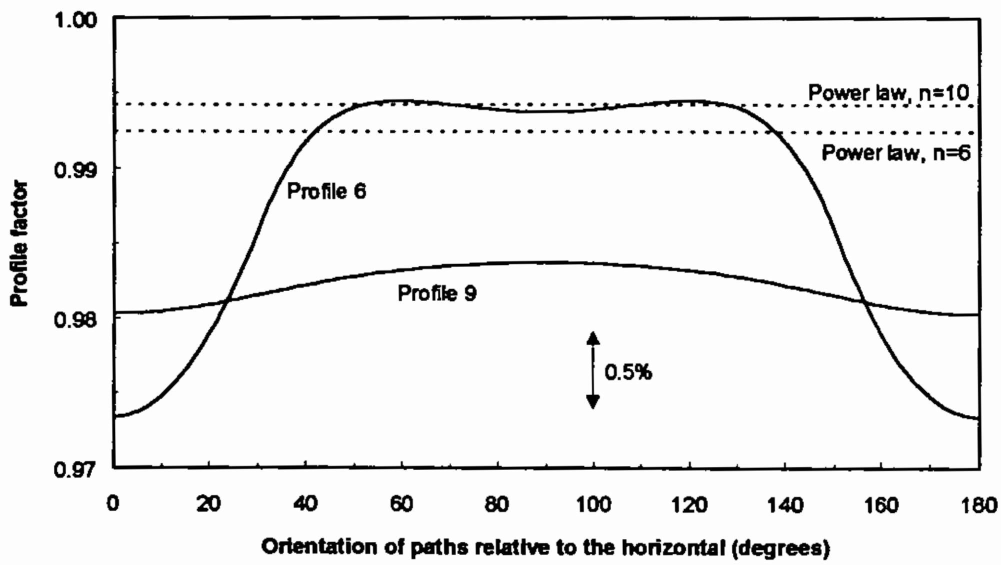


Figure 28 Profile factors for the dual mid radius path configuration

Figure 29 shows the k_h factor plotted against path orientation for the four-path Gaussian configuration. In this case the deviations from the powerlaw k_h factors are within 0.5 % for all but the extremes of profile 6.

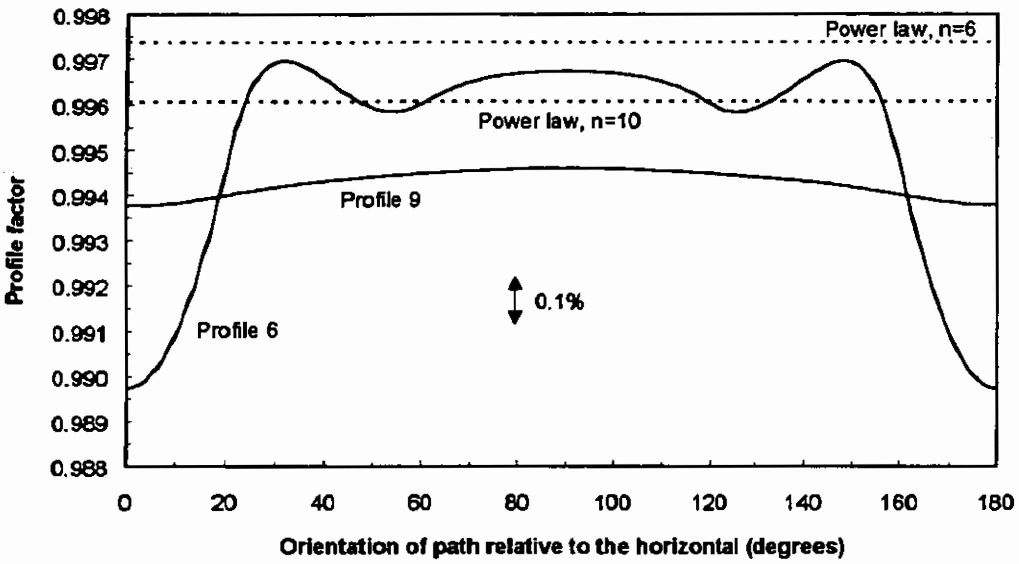


Figure 29 Profile factors for the Gaussian configuration

Summarising the above results in bar chart format (Figure 30) the reduction in sensitivity to distortions of the axial velocity profile realised by increasing the number of paths is clearly demonstrated. Indeed the Gaussian configuration (D) reduces the possible installation effect by more than a factor of 10. Figures 26 to 30 also illustrate that it is not only the number of paths which is important but also their location and orientation with respect to the velocity profile. For example orientating a single diameter path at 90° with respect to profile P6 produces a k_h factor which is in the range of values expected for fully developed flow.

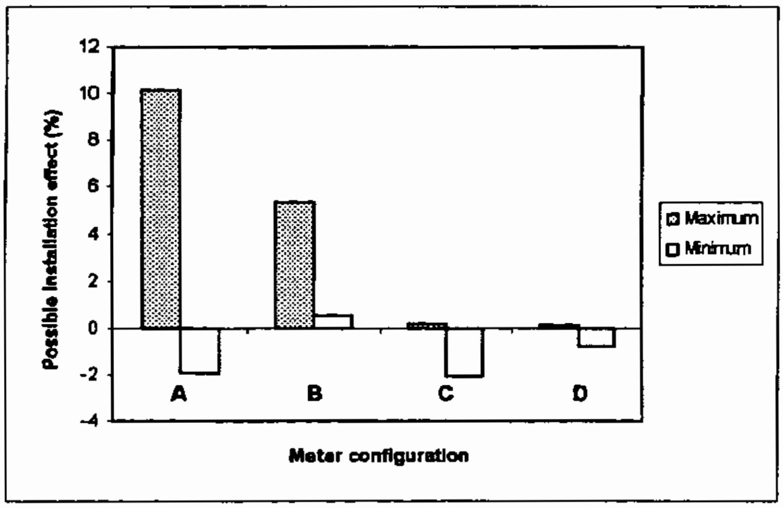


Figure 30 A bar chart summary of the results presented in Figures 26-29

Additional results have been obtained by this method for a wide range of profiles and meter configurations [7]. Further work will include the analysis of individual path velocities with respect to diagnosing distortions of the velocity profile.

9 DISCUSSION, CONCLUSIONS AND FURTHER WORK

The performance of transit time meters is adversely affected in the presence of two-phase flow. The effect on performance is dependent on the quantity, size, distribution and physical properties of the secondary component. As the acoustic impedance mismatch between oil and gas is much greater than that between oil and water, the effect of scattering and attenuation is significantly higher in oil/gas flow and thus this condition represents the greater problem.

Performance in oil/gas flow may be improved by adjusting signal parameters to accommodate a wider range of gas fractions. However, as the limiting gas fraction is approached the performance will suffer in terms of accuracy. Another way in which oil/gas performance may be improved is by operating the meter in a manner more suited to the flow pattern. For example in horizontal oil/gas flow disabling measurement chords which are in the upper half of the cross-section is likely to improve accuracy, especially at moderate velocities where gravitational separation of the phases is more distinct.

During the oil/water tests, meter signal quality was never reduced to such an extent that the ability of the meters to make transit time measurements was interrupted. However, large deviations were observed in two cases. In the first case, the deviations were thought to be related to errors in signal detection. This is related to the zero-crossing detection method employed by the meter, which is generally considered to be less robust than correlation detection methods. In the second case the occurrence of an internal error was suspected.

The clamp-on meter baseline calibration results show behaviour generally conforming with expected characteristics, i.e. repeatability and linearity improving with increasing velocity and pipe size. The results show that the zero-bias may be positive or negative and may change sign from one installation to another. Significant variations in the performance of the meters have been demonstrated. These results are currently under review by the meter manufacturers.

The numerical simulation of velocity profile effects demonstrates the relative sensitivity of various configurations encountered in practice. The results clearly show, in quantitative terms, the limitations of single and dual path configurations in relation to distortions of the axial velocity profile.

Ongoing and further work at NEL on ultrasonic flowmetering includes the following topics:

- Analysis of diagnostic capabilities of transit time meters in relation to two-phase and disturbed single-phase flows.

- Laboratory determination of installation effects on single and multipath ultrasonic liquid flowmeters

- CFD modelling of installation effects and comparison with experimental results

- Evaluation of transit time and reflective (e.g. Doppler) meters over a common range of two-phase flow conditions.

- Evaluation of clamp-on meter performance on a variety of pipe materials and in various flow conditions

- Long-term performance and maintainability tests on a selection of liquid ultrasonic meters

Completion of the current programme of work will result in a substantial database of ultrasonic flowmeter perfomance data and guidelines on use which, along with the cumulative result of other programmes, will assist in the development and successful deployment of ultrasonic flow measurement technology.

ACKNOWLEDGEMENTS
The work described in this paper was carried out as part of the Flow Programme, under the sponsorship of the DTI's National Measurement System Policy Unit. The author would also like to thank all those who have contributed to the projects in their many different ways.

REFERENCES

[1] BROWN, G. J., *Oil flow performance of ultrasonic meters* Proceedings of the North Sea Flow Measurement Workshop, Peebles, Scotland, 28-31 October 1996.

[2] BROWN, G. J., *Ultrasonic meters for oil flow measurement* NEL Report No: 169/96, April 1997.

[3] FRONEK, V., *Ultrasonic measurements of oil flow in a laminar flow-turbulent flow transition region* Flow Measurement of Fluids, Ed. Dijstelbergen, H. H., and Spencer, E.A., North-Holland Publ. Co., pp. 141-146, 1978

[4] JOHANNESSEN, A. A., *Evaluation of ultrasonic liquid flowmeters* Proceedings of the North Sea Flow Measurement Workshop, Bergen, Norway, 26 -28 October 1993.

[5] SALAMI, L. A., *Application of a computer to asymmetric flow measurement in circular pipes* Trans. Inst. M C 6(4), pp. 197-206, 1984.

[6] PANNELL, C. N., EVANS, W. A. B., and JACKSON, D. A. *A new integration technique for flowmeters with chordal paths* Flow Meas. Instrum., 1(4), pp. 216-224, 1990.

[7] BROWN, G. J., *The influence of asymmetric velocity profiles on ultrasonic transit time flow measurements* Manuscript in preparation.