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In-Service Performance of Ultrasonic Flowmeters

Application and Validation of CFD Modelling Methods

A Report for

National Measurement System Directorate
Department of Trade and Industry
151 Buckingham Palace Road, London SW1W 9SS

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Approved by: Mr D Boam ....

Date: 26 November 2002
for Michael Valente
Managing Director

SUMMARY

This report describes work in which the performance of different designs of ultrasonic flowmeter installed downstream of double and triple bends was measured in oil and water flow calibration loops and simulated using Computational Fluid Dynamics (CFD) methods.

An 8" dual mid-radius ultrasonic flowmeter was calibrated at different distances downstream of a twisted double bend in water flow. A similar 6" dual mid-radius meter and two dual diametric clamp on meters were calibrated in oil flow downstream of a twisted triple bend. The results of CFD simulations of these meters in identical installations were then compared against the test data to evaluate the applications and limits of CFD in the study of ultrasonic meters in field conditions. Further work compared CFD predictions with data from a fiscal gas metering system.

This report describes in detail the simulation work performed in this project. In a companion report laboratory data and field data are used to highlight and explain various issues associated with the performance of ultrasonic flowmeters in "in-service" conditions.

Based on this work the following conclusions have been drawn:

1. It is reasonable to use CFD methods to:

- identify problems and the causes of problems with ultrasonic flowmetering installations
- assess the magnitude of installation errors
- assess the effectiveness of different remedial measures
- extrapolate laboratory results for application to field problems
- assess the relative merits of alternative path configurations in flowmeters for a particular application
- assess how factors such as pipe wall roughness, manufacturing tolerances, contaminants and unusually operating conditions affect ultrasonic flowmeters

2. The CFD methods outlined in this report consistently reproduce the flow behaviour seen in the laboratory and in the field. In most cases a good quantitative match between predictions and measurements has been achieved. However, for some installations, although trends are well represented, there can be difference of a few percent between measured and calculated meter errors. This occurs with both dual diametric and dual mid-radius meters. It is therefore not possible to conclude that CFD techniques are better at modelling one design of meter compared to another design.

3. As CFD simulations can not always predict metering errors to within 1% their predictions should not be used to correct K-factors of fiscal metering stations without substantial test and field data to confirm the validity of the predictions.

CONTENTS

INTRODUCTION

Ultrasonics has been identified as one of the fastest growing flowmeter technologies, and it is anticipated that, that, within a few years, ultrasonic meters will be widely accepted for fiscal measurement in both liquid and gas applications. However there remain doubts in industry as to their performance when applied in real world applications and, although some of the potential problem areas, such as the effect of changes in fluid viscosity, have been investigated in previous Programmes, other areas remain to be studied.

This project has addressed an issue that is of major importance when considering in-service performance, namely the effect that piping installations have on downstream flow profile and the subsequent effect on ultrasonic meters. This "installation effect" has been investigated in extensive laboratory experiments using both clamp-on and wetted-transducer transit-time ultrasonic meters.

These experiments have been modelled using Computational Fluid Dynamics (CFD) flow simulations in order to evaluate the applications and limits of CFD in the study of ultrasonic meters in field conditions. Field data from fiscal oil and gas metering systems has also been analysed.

This report describes in detail the simulation work performed in this project. It addresses a range of issues identified in the 1996-1999 Flow Programme [1][1]. It compares the test and field data with CFD predictions and discusses the application of CFD techniques in estimating the error of ultrasonic flowmeters caused by upstream flow disturbances. The report describes the CFD analysis methods used, and the results of the CFD simulations are compared the experimental test data. The CFD simulation results are also compared with field data taken from a fiscal gas metering system. Finally the application and limits of CFD in the study of ultrasonic flowmeter installation effects are discussed.

In a companion report [2] laboratory data and field data are used to highlight and explain various issues associated with the performance of ultrasonic flowmeters in in-service conditions.

2 EXPERIMENTAL TEST METHOD

Two sets of laboratory tests were performed as part of this project. The first set took place in the water test laboratory and extended the range of data taken in earlier tests [1]; the second set took place in the oil laboratory. This section describes the methods used in these tests. Further details of the laboratory facilities and test meters is given in the companion report [2].

2.1 Double-Bend Water Flow Tests

In these tests a Danfoss Sonoflow 3000 8" ultrasonic flowmeter (identified as Meter 1 in the companion report [2]) was calibrated at various distances downstream of a twisted double bend in the 200 mm nominal bore test line of the NEL primary standard water flow facility. Figure 1 shows the path configuration of the meter calibrated in these tests.

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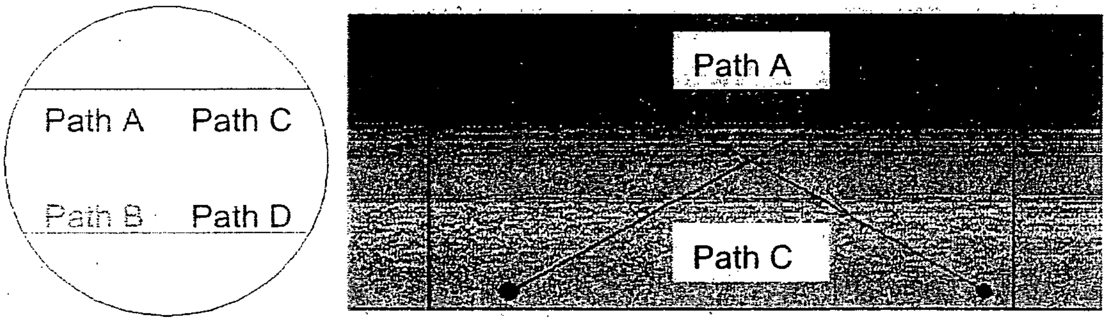
[1] Number in parentheses denote references given at the end of this report.



End View **Plan View**

Figure 1 Path configuration of the Danfoss Sonoflow 3000 8" Meter

The test loop consisted of a tube-bundle flow conditioner and about 30D of straight length upstream of a double bend. This double bend comprised two 1D radius bends as shown in Figure 2. The meter test section followed this and comprised a series of straight pipe spools, the flowmeter spool and a variable-length Vitolic coupling spool. The total length of the test section was approximately 30D. By varying the arrangement of spools in the test section and by adjusting the length of the Vitolic spool, the distance between the flowmeter and the double bend was varied. For these tests the flow range was varied between 7 and 158 l/s.

Figure 2 Water Laboratory

2.2 Triple-Bend Oil Flow Tests

In these tests a Danfoss Sonoflo 3100 wetted-transducer meter, an Endress and Hausser DMU 93 clamp-on meter and an Ultraflux UF322 clamp-on meter were calibrated at various distances downstream of a triple bend. The meters are identified as Meters 2, 3 and 4 respectively in the companion report [2]. Figure 3 shows the line set-up, oil flows from left to right along a 9-meter straight section (not in photo) before entering the triple bend and passing through the test meter section. All test-section pipework was 6" nominal bore sch 40 and all the pipe spools were flanged. During the manufacture of the spools all weld burs were removed from the internal pipe surface. The triple bend comprised three 90° long-radius bends each with weld-neck flanges. A set of pipe spools were fabricated to allow the location of the test meters to be adjusted by as little as one diameter (150mm) with respect to the triple bend.

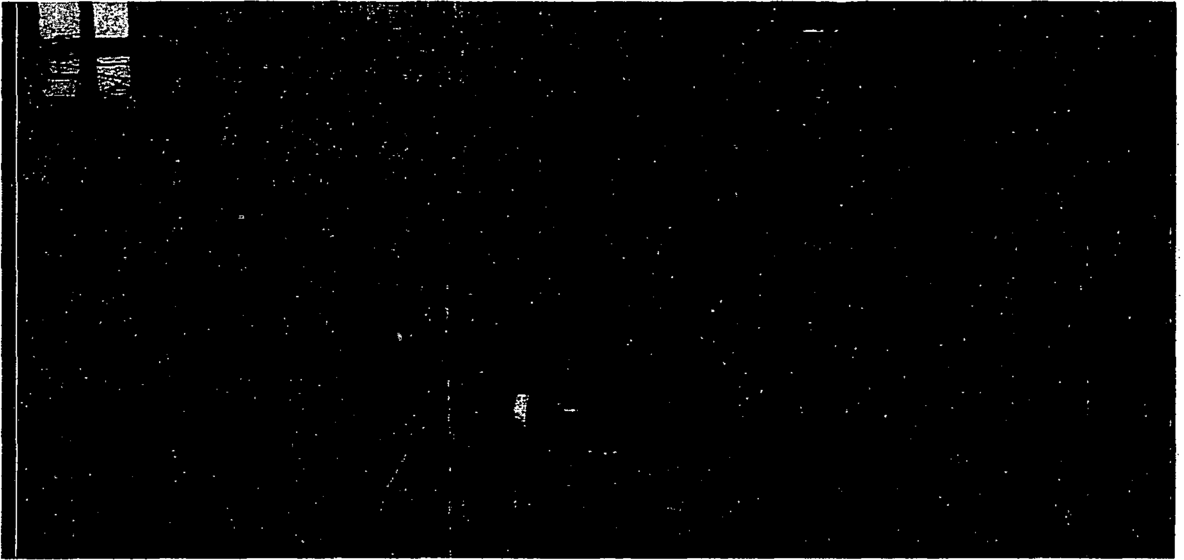


Figure 3 The triple bend and downstream straight section

Prior to performing the triple-bend tests, base-line tests were performed. These were standard calibrations carried out in the main test line with 9 m (58 diameters) of upstream straight length to ensure a fully developed flow profile at the test meters. The test conditions were identical to those of the triple-bend tests.

Figure 4 shows the orientation of the Danfoss Sonoflo 3100 (Meter 2) to the triple bend. Figure 5 shows the path orientations of the clamp-on meters.

In addition to the calibration runs on the meters at different distances downstream of the triple bend, the velocity and swirl profile downstream of the triple bend was measured by using a Pitot tube assembly. Profiles were measured across the pipe diameter at 45° intervals at 5 diameters and 20 diameters downstream of the bends. The measurement methods used were identical to those outlined in Reference 3.

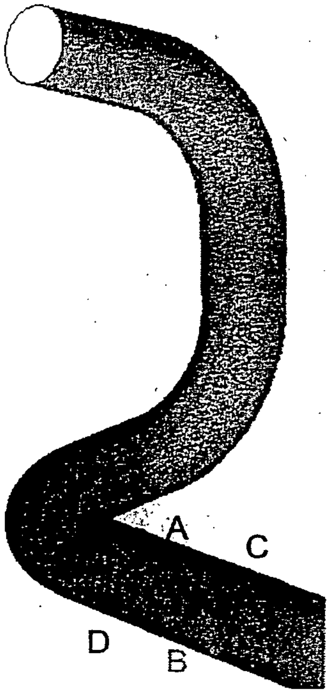
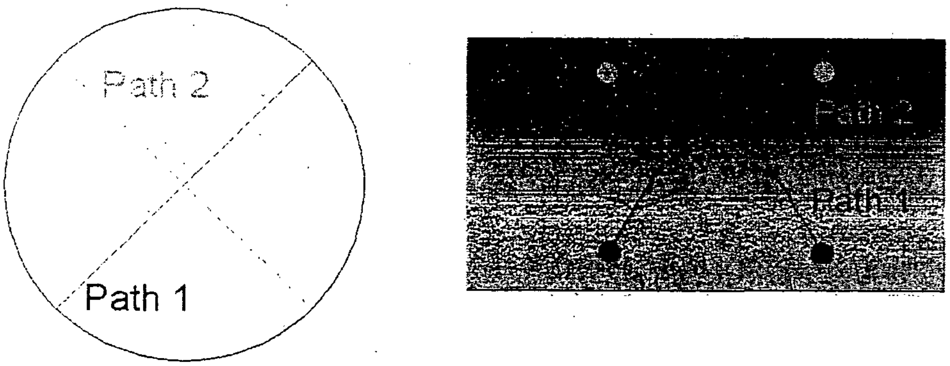


Figure 4 Orientation of the Danfoss Sonoflow 3100 meter to the triple bend



End View

Plan View

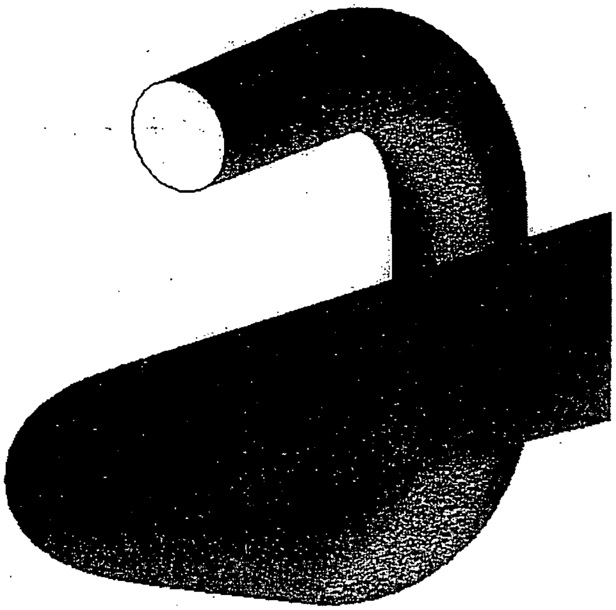


Figure 5 Path configuration and orientation of the E & H and Ultraflux clamp-on meters

3 CFD ANALYSIS METHOD

This section summarises the CFD method that was used to predict the performance of different types of ultrasonic meter downstream of a range of flow disturbances. The methods used in this project were essentially the same as those described in Reference 1.

The first stage of the calculation involved running a CFD simulation of flow through the upstream flow disturbance. Figure 6 shows a typical computational mesh used (in this case for the double bend).

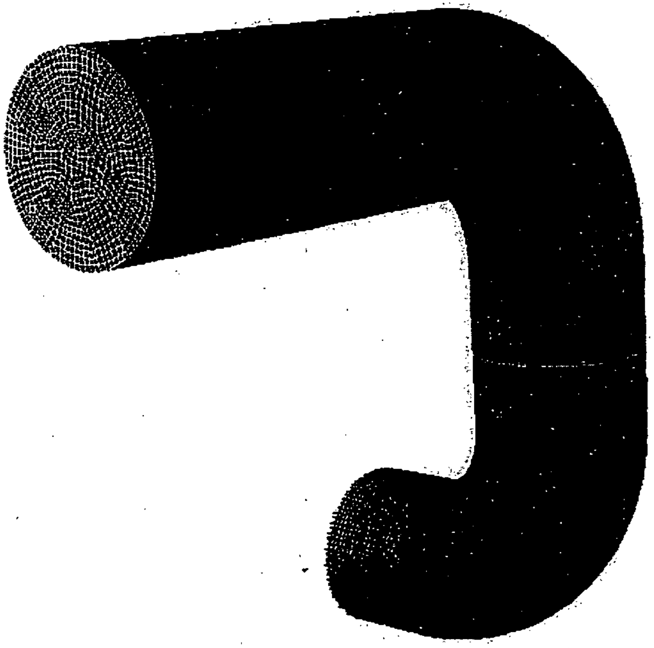


Figure 6 Computational mesh used to model the twisted double bend

Fully developed flow conditions were defined at the inlet to the disturbance and the walls were assumed to be smooth. The Reynolds Stress Turbulence model (RSM) and QUICK discretisation were used as the default solver settings. The disturbance simulation was converged until further iterations made insignificant changes in the residual values. The outlet flow conditions from the disturbance were then imposed on the inlet to a second CFD simulation representing the straight test section into which the flowmeter had been installed. Figure 7 shows the mesh used to model the test section. Again, smooth pipe walls were assumed.

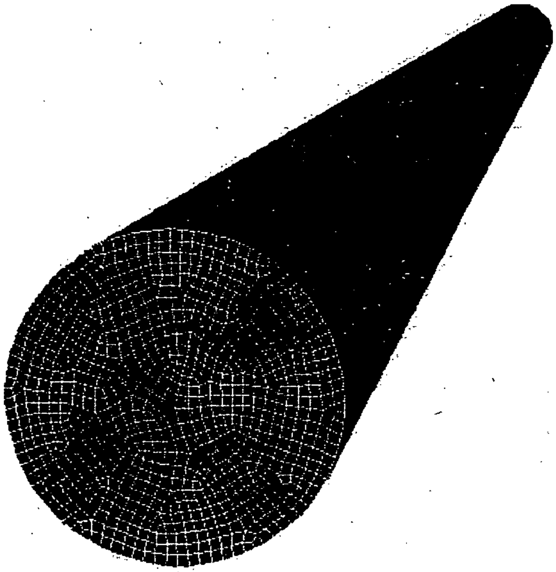


Figure 7 Computational mesh used to model the test section

After convergence had been achieved, lines were defined within the computational domain that represented the ultrasonic paths of the flow meter. By defining lines at different distances from the test section inlet the flow meter could be modelled as though installed at different distances from the disturbance.

The ultrasonic path velocity was calculated by extracting velocity data from the CFD simulation along each line. This data was integrated using a FORTRAN program to give the mean velocity (in the direction of the line) along each line.

These calculated path velocities could be compared directly with experimentally measured path velocities. Alternatively, the predicted path velocities could be combined, in a similar way to that in which the measured values are combined, to give a mean flow rate.

A range of tests was carried out to establish the sources of error in the CFD calculations, these tests were outlined in the interim report [4] and Report No 348/99 [1]. The main findings were:

- The errors associated with the data extraction and integration process are considerably smaller than the magnitude of predicted installation errors.
- Representing the ultrasonic paths as thin lines is a realistic approximation and does not significantly affect the predicted installation error characteristic.
- The primary cause of discrepancies between the CFD predictions and the experimental results is associated with limitations in the way in which the CFD represents the effects of turbulence on the flow.

4 COMPARISON OF TEST DATA AND CFD PREDICTIONS

4.1 Double Bend Water Flow Tests – Danfoss 8" Sonoflow

Figures 8, 9 and 10 compare CFD predictions and experimental measurements of flow made by the Danfoss 8" Sonoflow meter downstream of the double bend. The measured error characteristic of the meter remains roughly constant at about +1% (Figure 8). The CFD predictions oscillate about this value.

Examination of the individual paths (Figures 9 and 10) shows that the measured path velocities vary in a decaying sinusoidal manner. This sinusoidal behaviour is not apparent in the error characteristic as the oscillations of individual paths closely mirror each other, and fluctuations cancel out when the path measurements are combined to produce the volumetric flow measurement. For example, as the characteristic of paths A and B mirror each other, their average will not take a sinusoidal shape. As in Figure 8 the CFD predictions oscillate about the measured values.

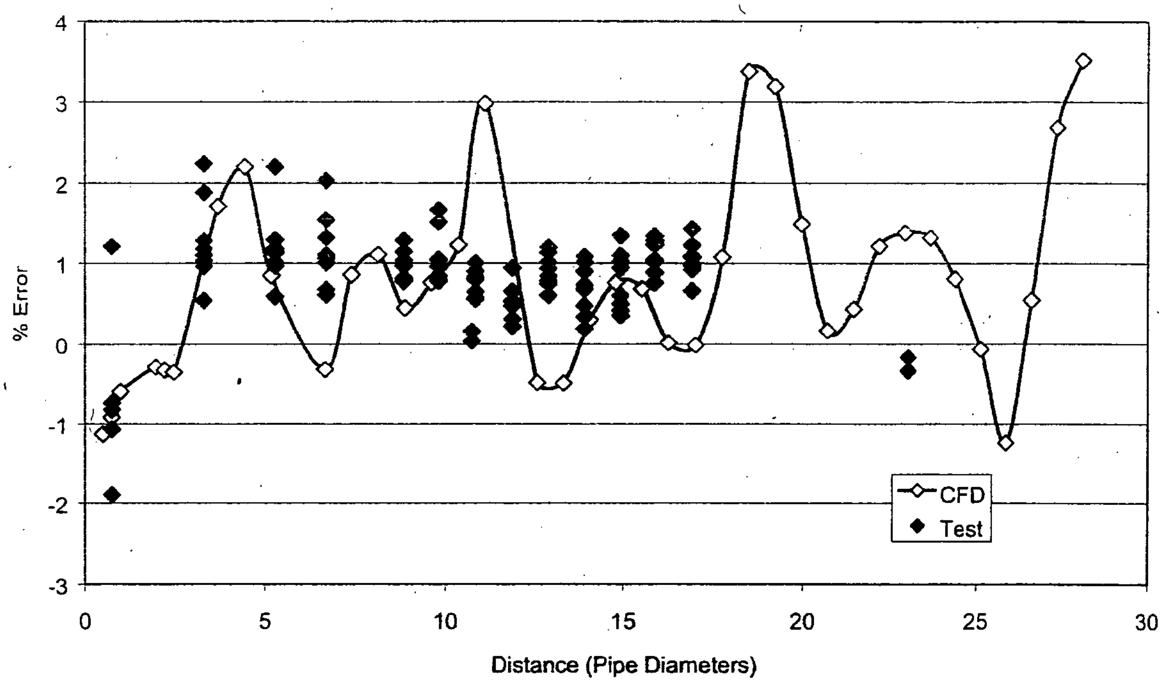


Figure 8 Measured and predicted error characteristic of the Danfoss 8" Sonoflow meter downstrean of a double bend in water flow

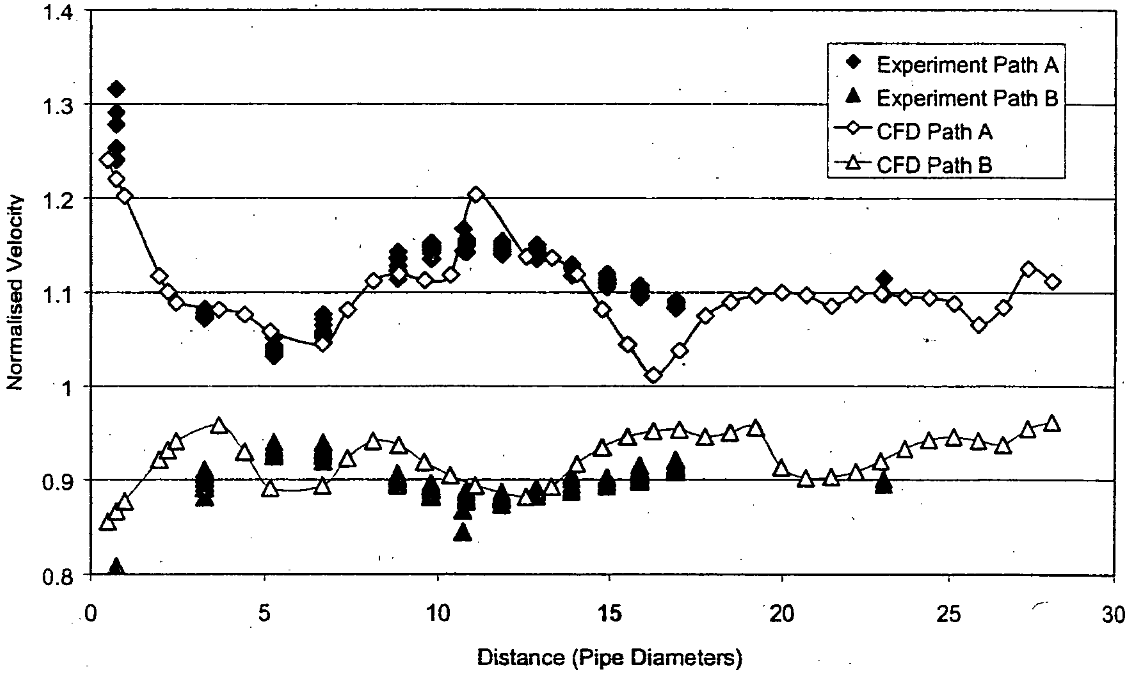


Figure 9 Measured and predicted normalised path velocities of the Danfoss 8" Sonoflow meter downstream of a double bend in water flow

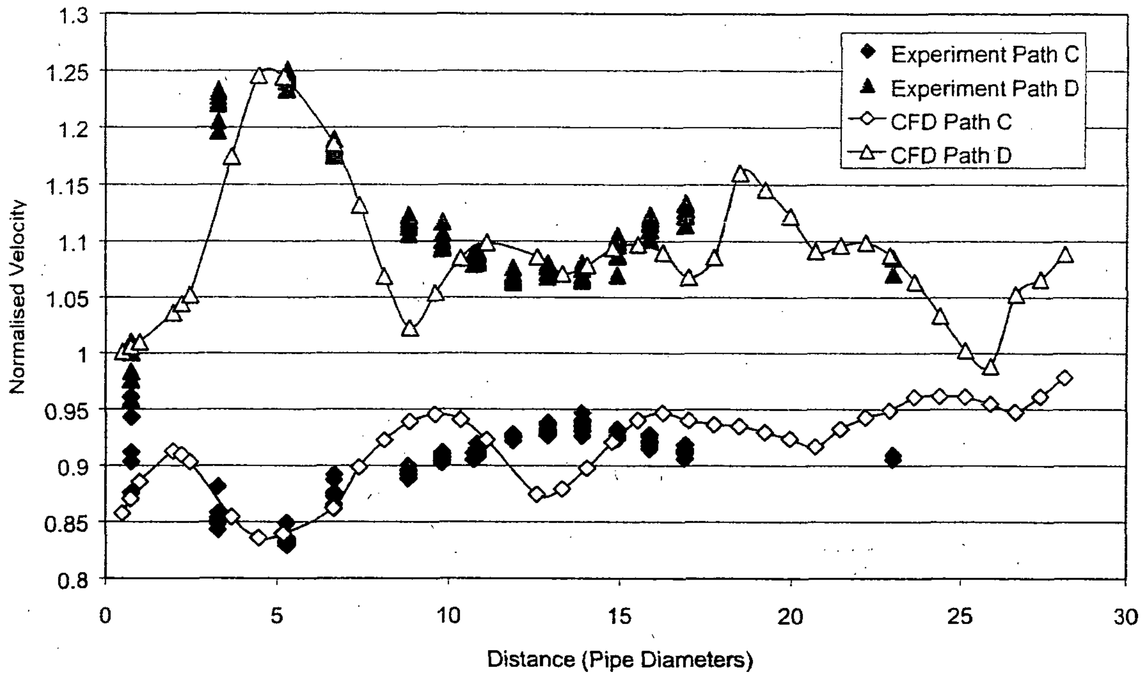


Figure 10 Measured and predicted normalised path velocities of the Danfoss 8" Sonoflow meter downstream of a double bend in water flow

To investigate the reason why the CFD predictions oscillated about the measured value, the path velocity data was decomposed into its individual components. Note that in this exercise the simulated flowmeter was orientated at 90° to the meter in the tests. However, the oscillatory behaviour is still apparent in these additional simulations.

Figure 11 shows the predicted transverse (swirl) velocity components along each path. The positive values for paths A and B are almost exactly equal in magnitude to the negative values for C and D and the swirl components cancel. The contribution of swirl to the error characteristic and the discrepancy between the measurements and the CFD predictions is therefore very small.

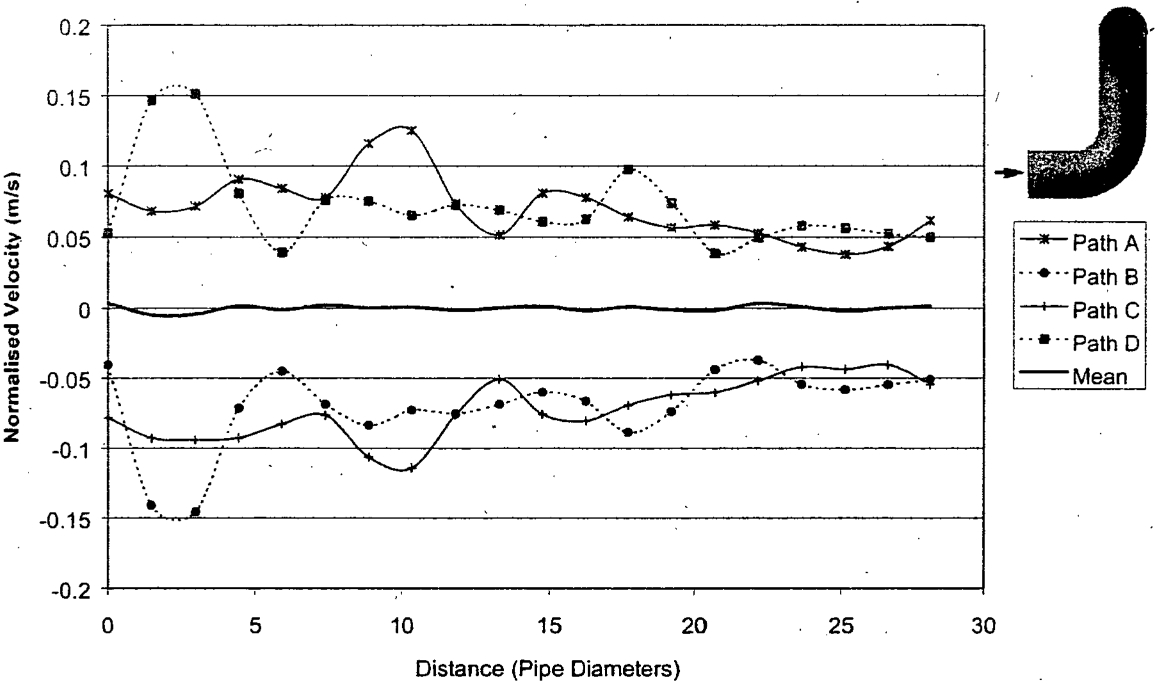


Figure 11 Predicted transverse (swirl) components

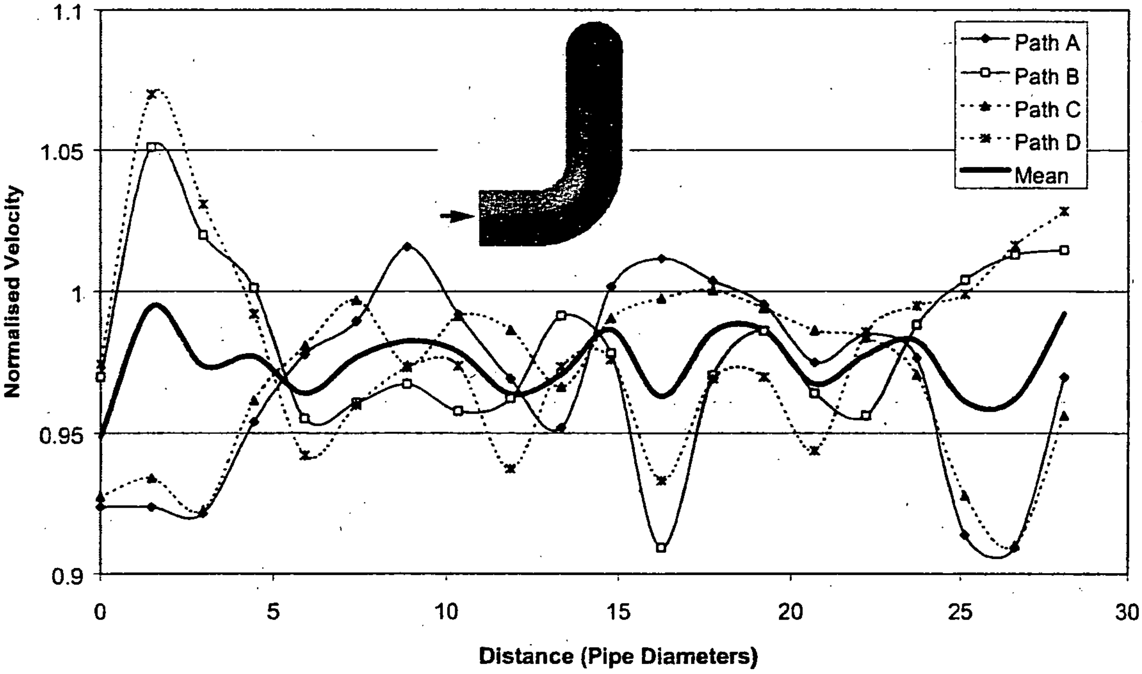


Figure 12 Predicted axial components

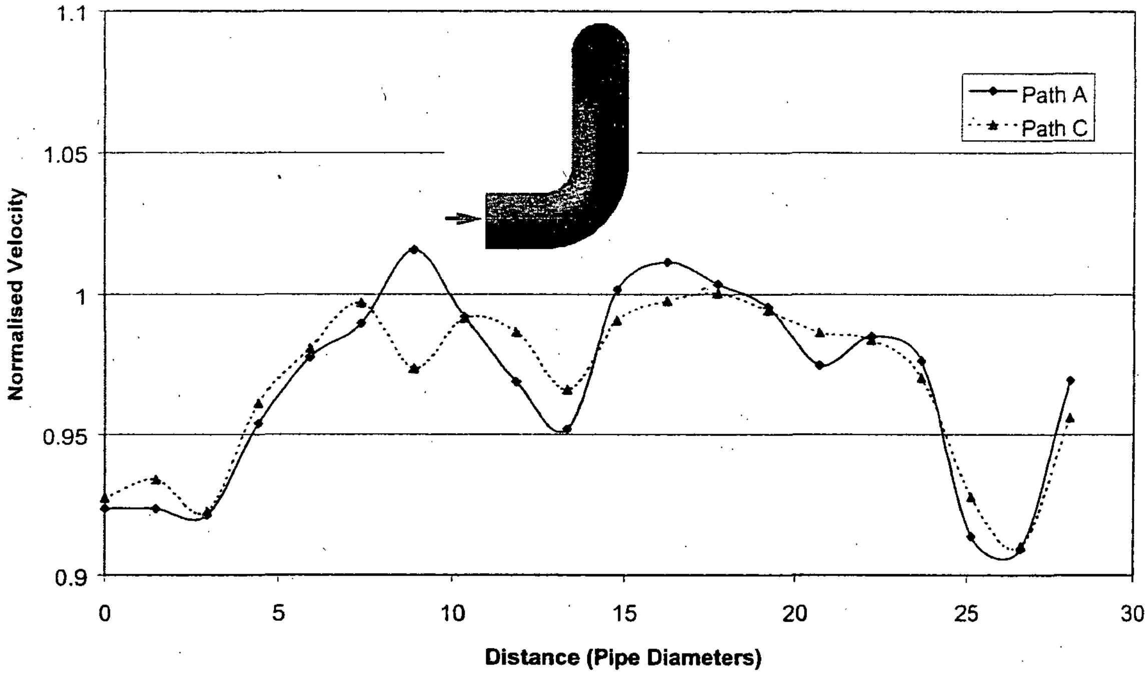


Figure 13 Predicted axial components for paths A and B

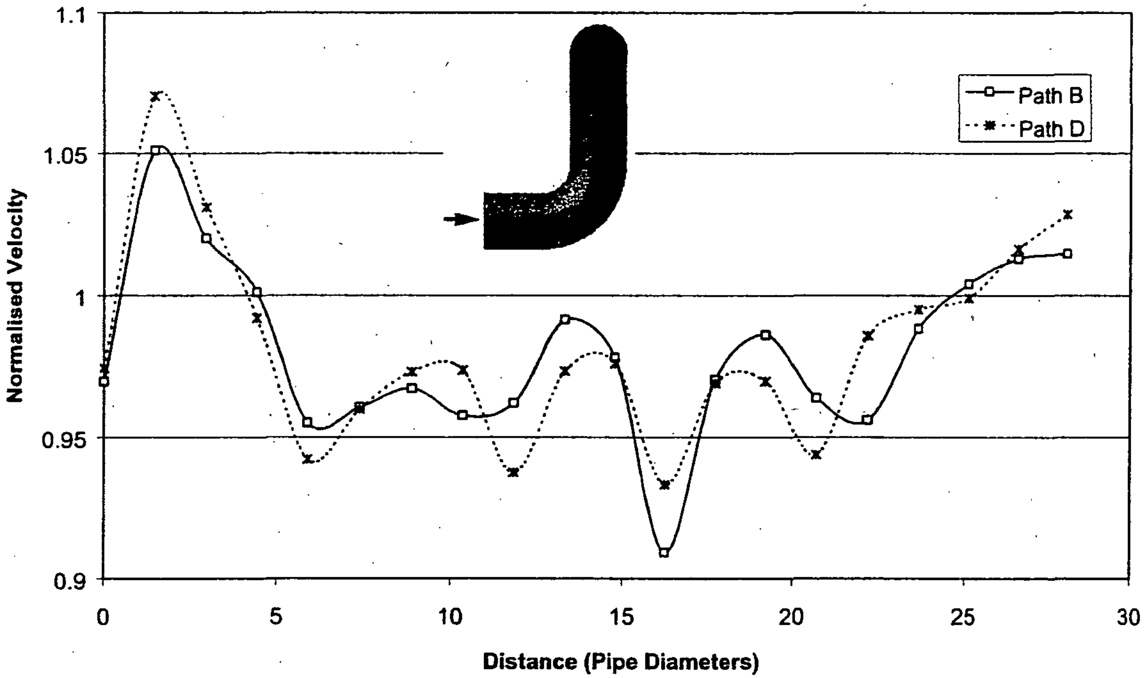


Figure 14 Predicted axial components for paths B and D

Figures 12, 13 and 14 show the predicted axial components. Figure 14 shows development of the axial velocity profile in more detail, with a large lobe and a small lobe that rotates clockwise as they move away from the bends.

Two phenomena contribute to the sinusoidal nature of the error characteristic: development of the axial velocity profile over the length of the meter and distortion of the axial velocity profile.

The development phenomenon is most clearly seen at 20.7D in Figure 14. At this point the small lobe just intersects paths B and C but does not intersect paths A and D. There is therefore a difference between the AC pair and the BD pair, as shown in Figures 12 and 13. However, the development of the axial velocity profile is not a major contributory factor in the sinusoidal behaviour, as can be seen when comparing the mean of all the paths and the mean of two paths on the same plane (Figure 15).

Between 14.8D and 19.2D the mean path characteristic shows a significant dip. The reason for this can be seen in Figure 14. Between 13.3D and 20.7D a slow rise is seen in the AC path pair as the large lobe passes through them. At the same time the small lobe is passing through the BD pair. At 16.3D the small lobe is to one side of the BD pair. As the BD pair no longer intersect the lobe there is a sudden drop in the BD measured velocities at a time when the AC pair are measuring a more or less constant value. Hence the mean of all the paths drops. This illustrates how a rotating lobed axial-velocity profile of this type generates a sinusoidal error characteristic. It is believed that the discrepancy between the CFD predictions and the measurements is caused by the fact that, in reality, only a single-lobed velocity profile occurs. This causes each path characteristic to take a smoother sinusoidal form, hence allowing individual paths to cancel out when they are combined to calculate the volumetric flow rate.

Axial Velocity Components

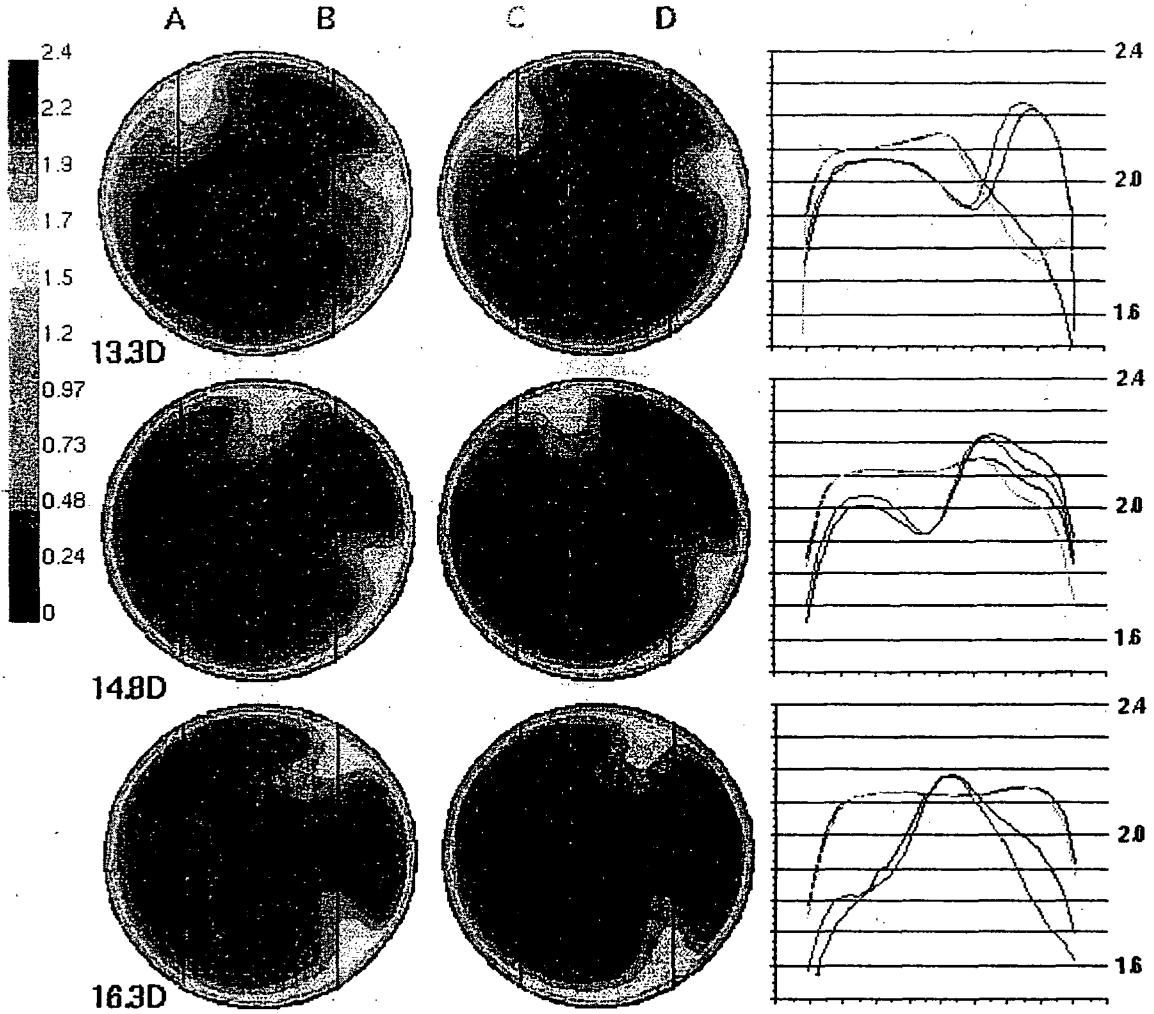


Figure 14A Axial velocity contours and profiles along the ultrasonic paths at a range of distances downstream of the double bend

Axial Velocity Components

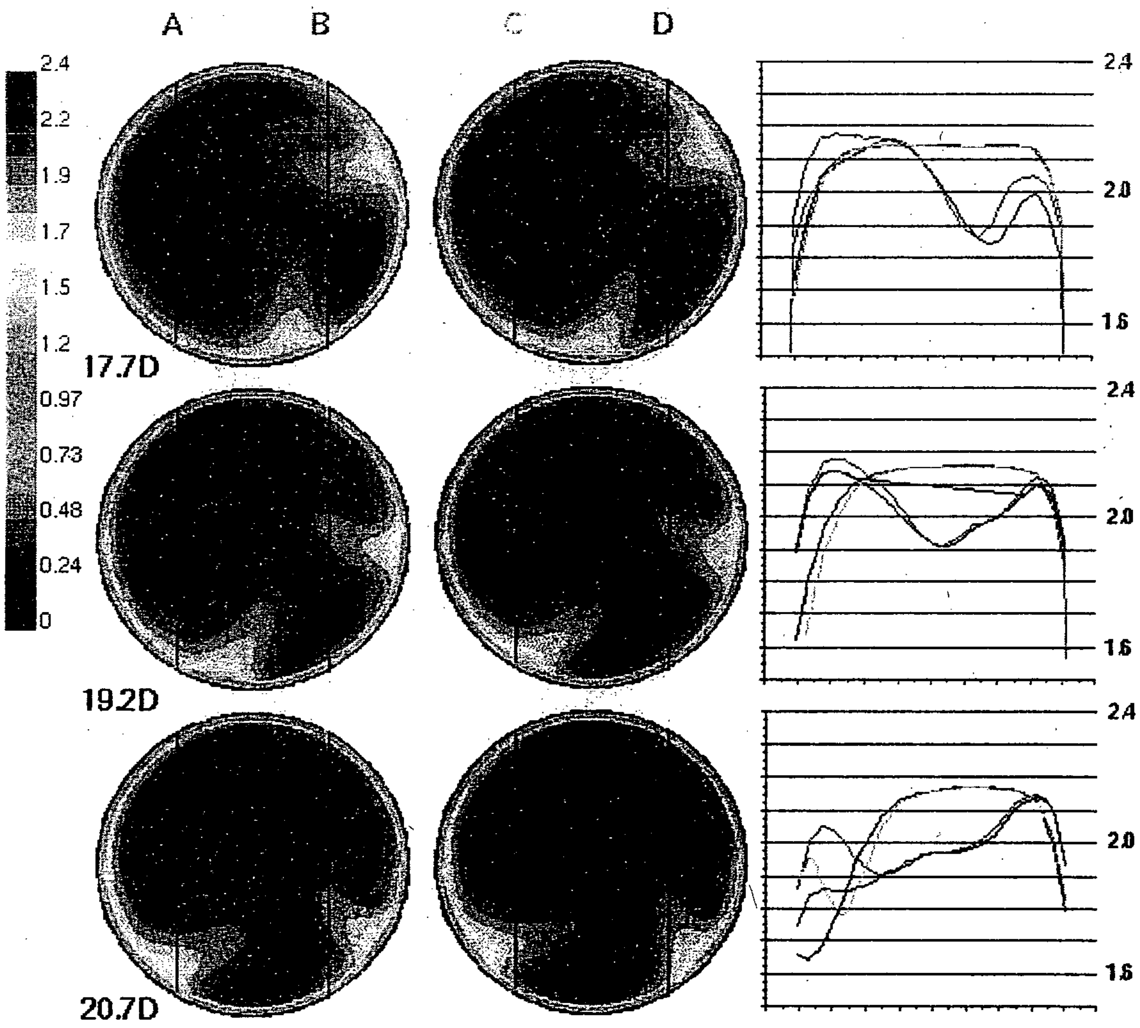


Figure 14B Axial velocity contours and profiles along the ultrasonic paths at a range of distances downstream of the double bend

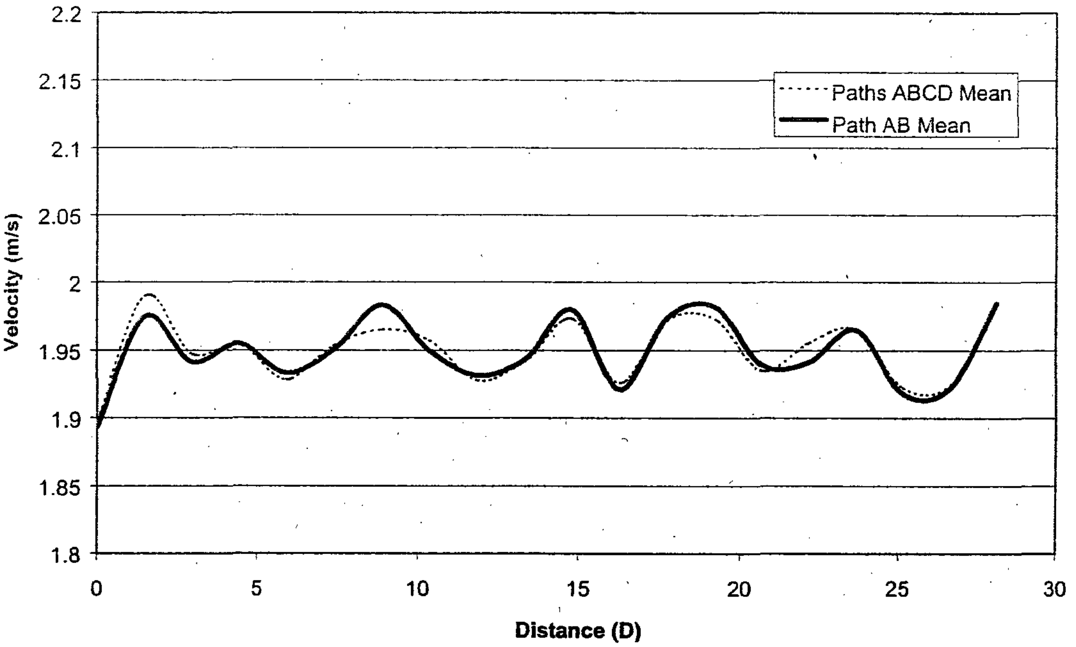


Figure 15 Comparison of mean velocity for all 4 paths with the mean for two paths

4.2 Triple-Bend Oil Flow Tests – Velocity Profiles

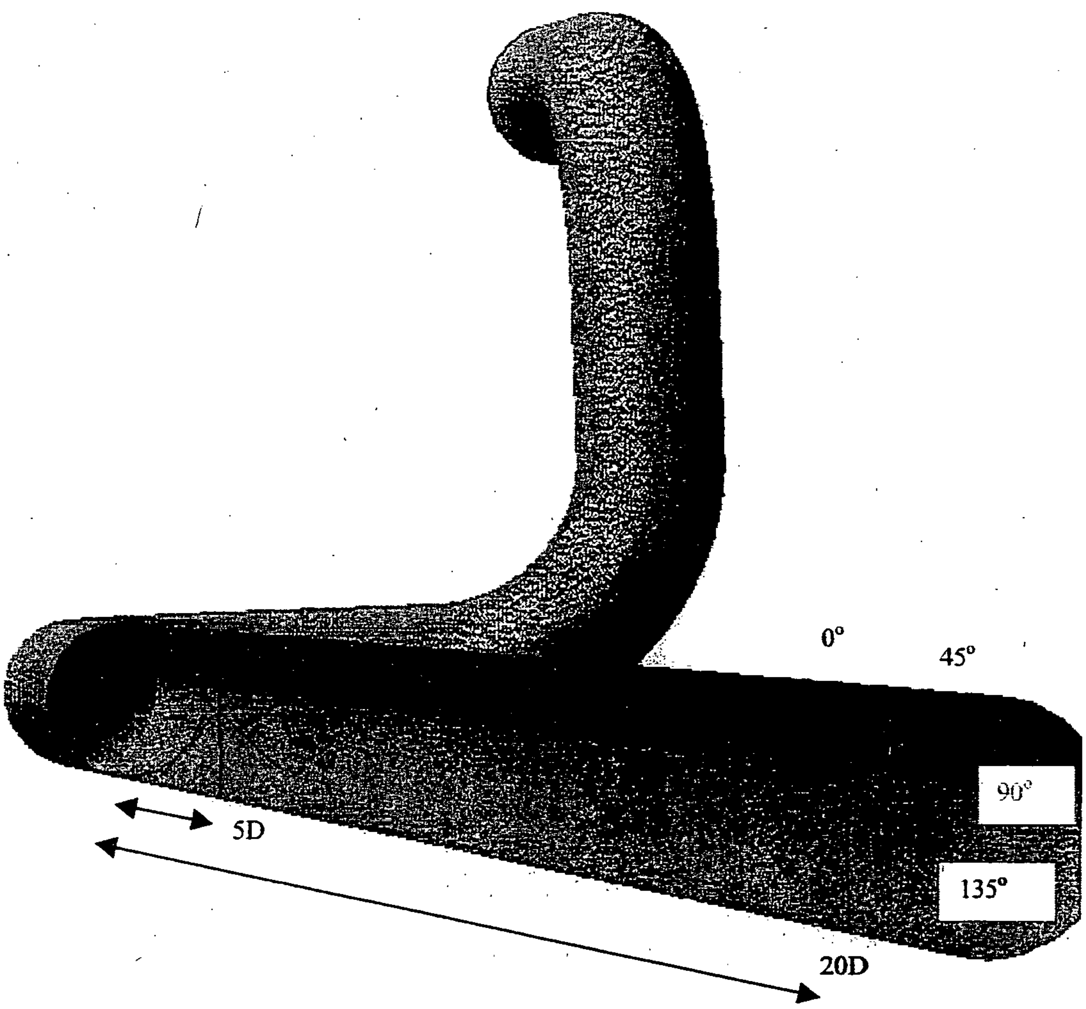


Figure 16 Positions of the velocity profile measurements

In addition to the flowmeter calibrations, a series of velocity profiles were measured downstream of the triple bend using a Pitot traverse. Figures 17 and 18 show the predicted axial-velocity profile and swirl-velocity vectors and Figures 19 and 20 compare the CFD predictions and the measurements. Figure 17 illustrates how a skewed velocity profile is generated immediately downstream of the bends and that swirl causes this profile to spiral down the pipe. This is similar to the flow pattern seen downstream of a double bend (see Figure 14). Figure 18 shows that the predicted velocity profile is in the shape of a crescent. This crescent shape manifests itself as a double-maximum-shaped velocity profile in the graphs in Figure 19. Comparison with the measured velocity profile shows that this double-maximum shape does not occur in reality. The measured velocity profile is skewed to one side, but that it is flatter than the predicted profile. The magnitude of maxima and minima in the velocity profile is also over-predicted (most apparent in Figures 19 c and f). Figure 20 shows that the swirl is skewed to one side of the pipe and that very little decay of the swirl occurs in 20 diameters. The CFD predictions give a good estimate of the swirl magnitude.

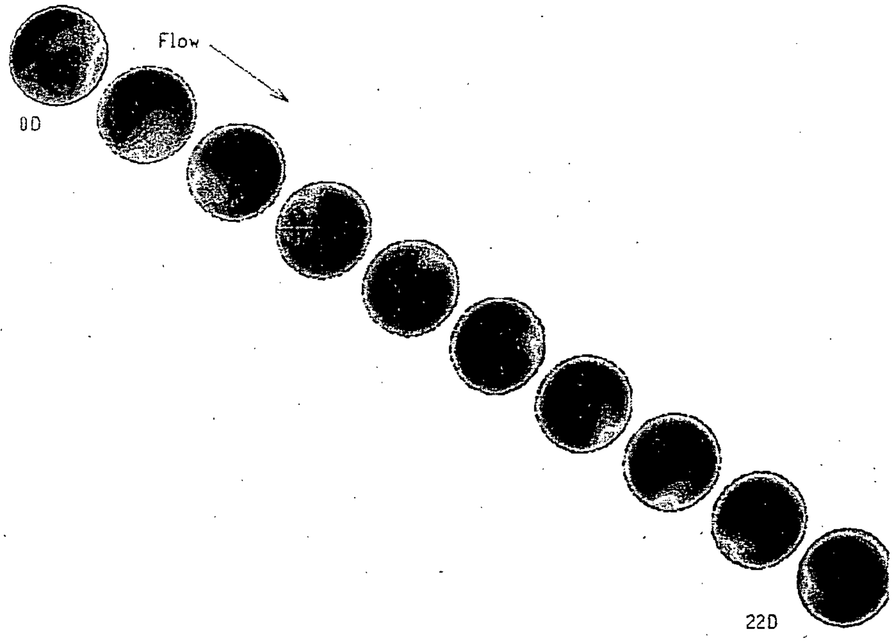


Figure 17 Predicted axial velocity contours downstream of a triple bend

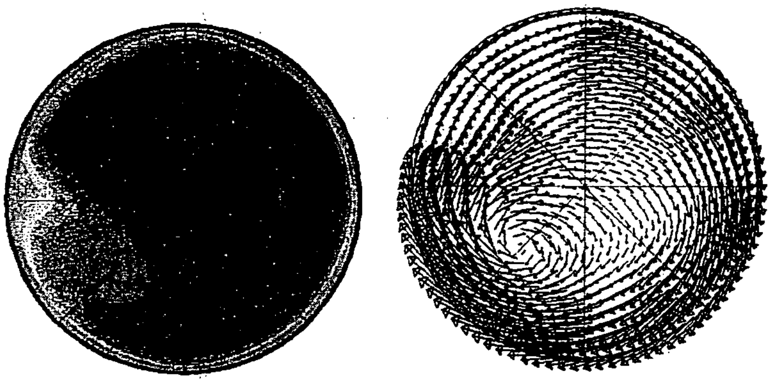


Figure 18 a) 5D

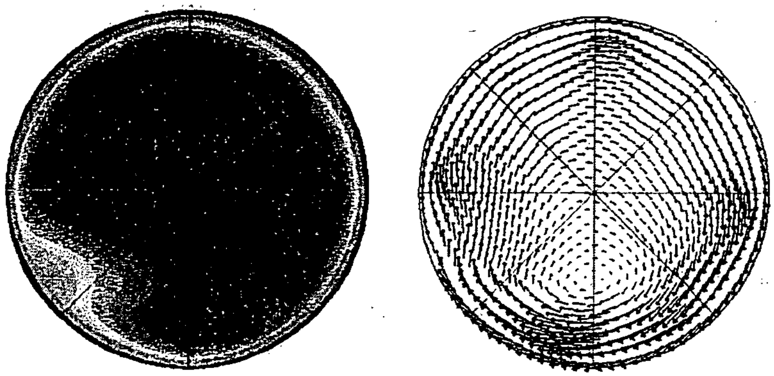


Figure 18 b) 20D

Figure 18 Predicted axial velocity contours and transverse velocity vectors

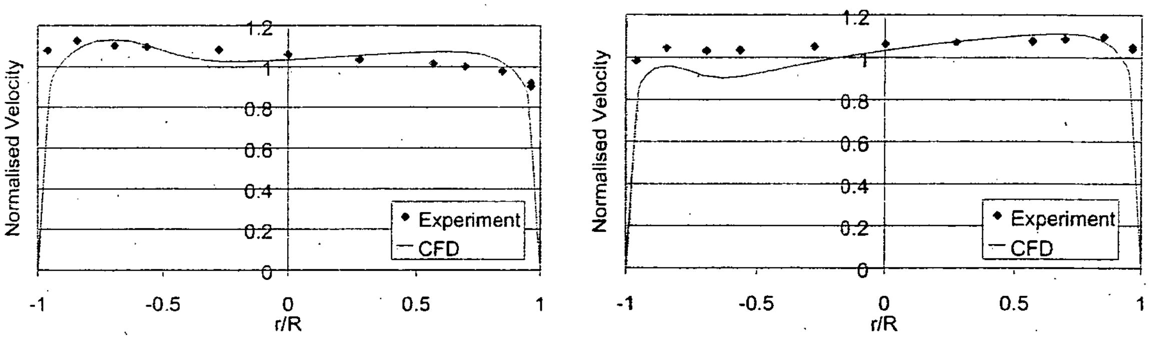


Figure 19 a) 5D 0°

Figure 19 b) 5D 45°

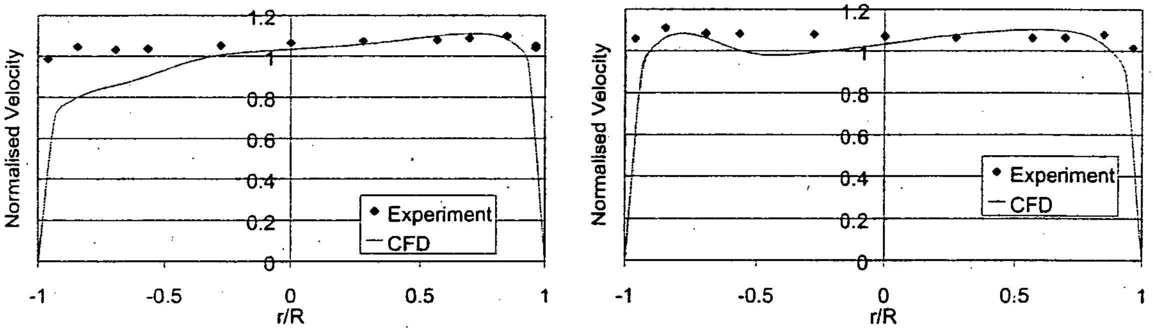


Figure 19 c) 5D 90°

Figure 19 d) 5D 135°

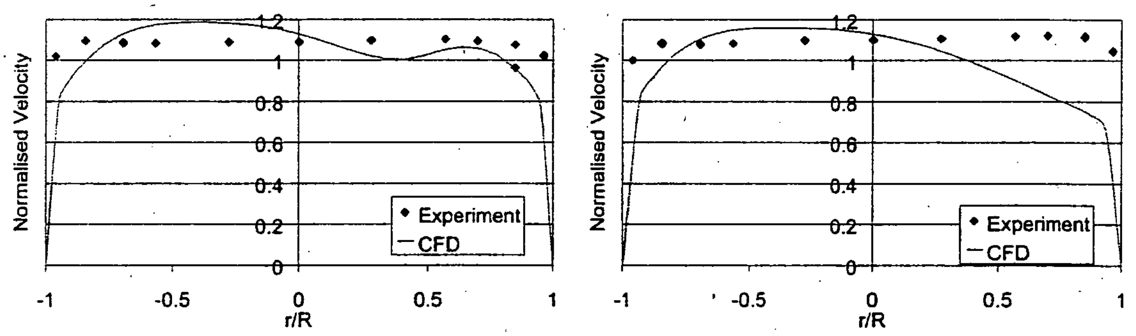


Figure 19 e) 20D 0°

Figure 19 f) 20D 45°

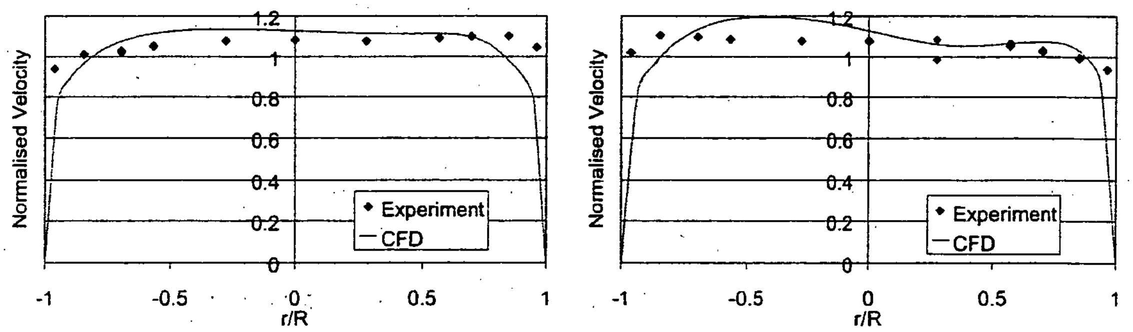


Figure 19 g) 20D 90°

Figure 19 h) 20D 135°

Figure 19 Comparison of predicted and measured axial velocity profiles

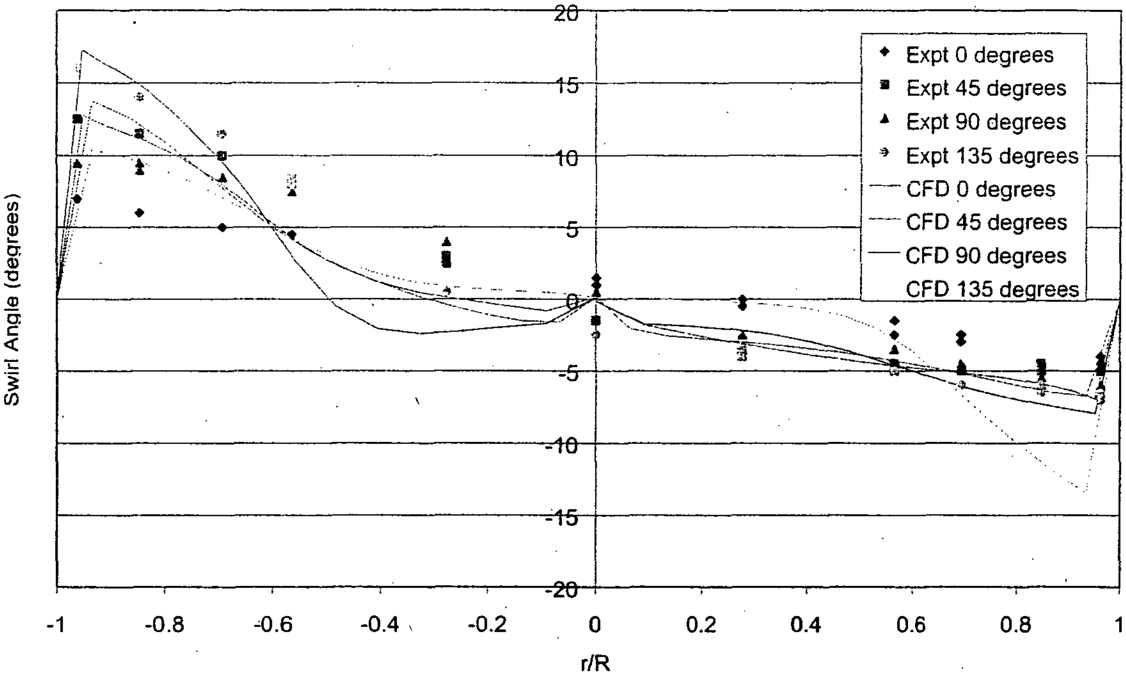


Figure 20a Swirl at 5D

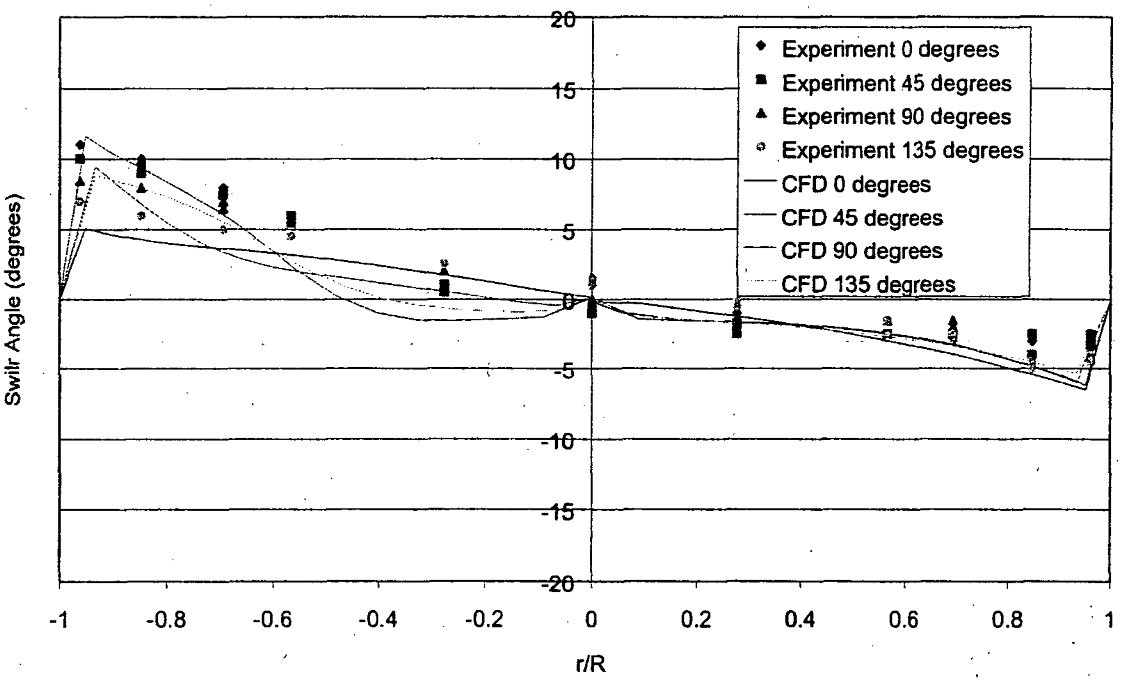


Figure 20b Swirl at 20D

Figure 20 Comparison of predicted and measured swirl profiles

4.3 Triple-Bend Oil-Flow Tests – Danfoss 6" Sonoflow

Figure 21 compares measured and predicted error characteristics of the Danfoss 6" Sonoflow meter downstream of a triple bend in oil flow. Figures 22 and 23 show the corresponding path velocities.

As in the double-bend case the path velocities take a roughly sinusoidal form, although in this case the error characteristic also takes a more obviously sinusoidal form. Both the double- and triple-bend cases show a small positive error for this type of meter; the measured error characteristic oscillates about a mean value of about +0.5% with an amplitude of about 0.5%.

The predicted error characteristic oscillates with a higher frequency and amplitude than the measured data about a mean value of about –1%. The close match between error characteristics at 3 m/s and 4 m/s is correctly predicted.

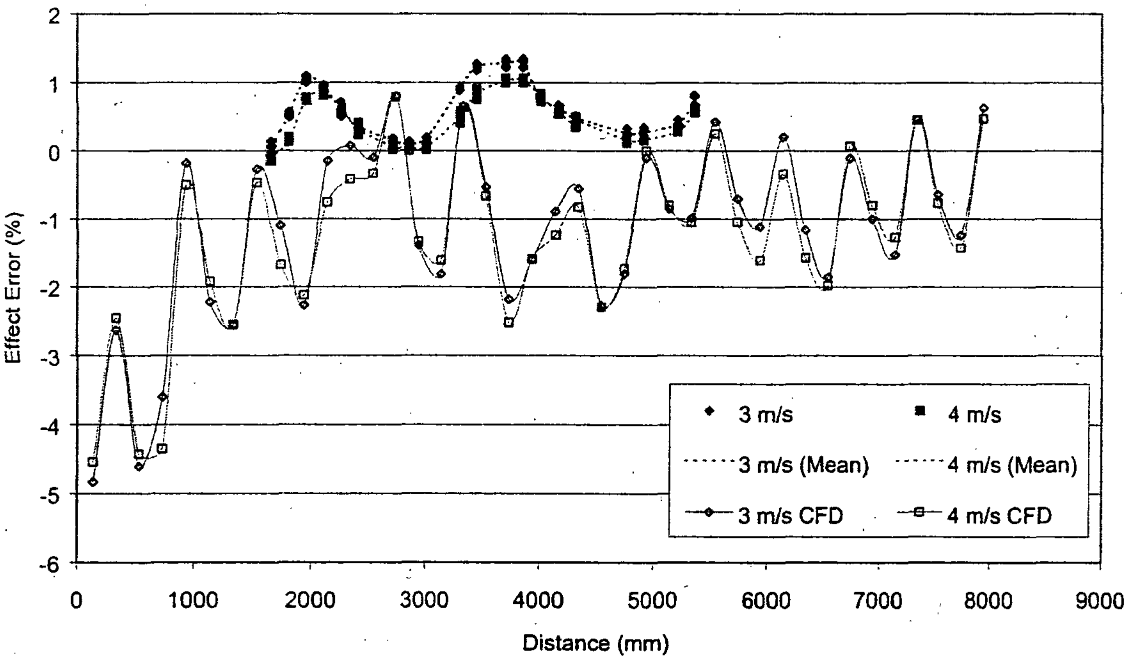


Figure 21 Measured and predicted error characteristic of the Danfoss 6" Sonoflow meter downstream of a triple bend in oil flow

The match between the measured and predicted path velocities is reasonable (Figures 22 and 23). The CFD path characteristics include a high frequency oscillation that is not seen in the experimental data, but the magnitude and location of the major peaks and troughs is about right (the CFD predicts a peak about 5D downstream of the peak seen in the measured paths). The double-maximum shape of the predicted profile (see Figure 19) causes a double peak in the path characteristic with each rotation of the axial velocity profile. This causes an increase in the frequency of the oscillation. Also, as the predicted axial profile is more rounded than the actual profile, the predicted mean path velocity (over the entire length of the straight section) is less than the actual mean path velocity. This causes the error characteristic to oscillate about –1% instead of +0.5%.

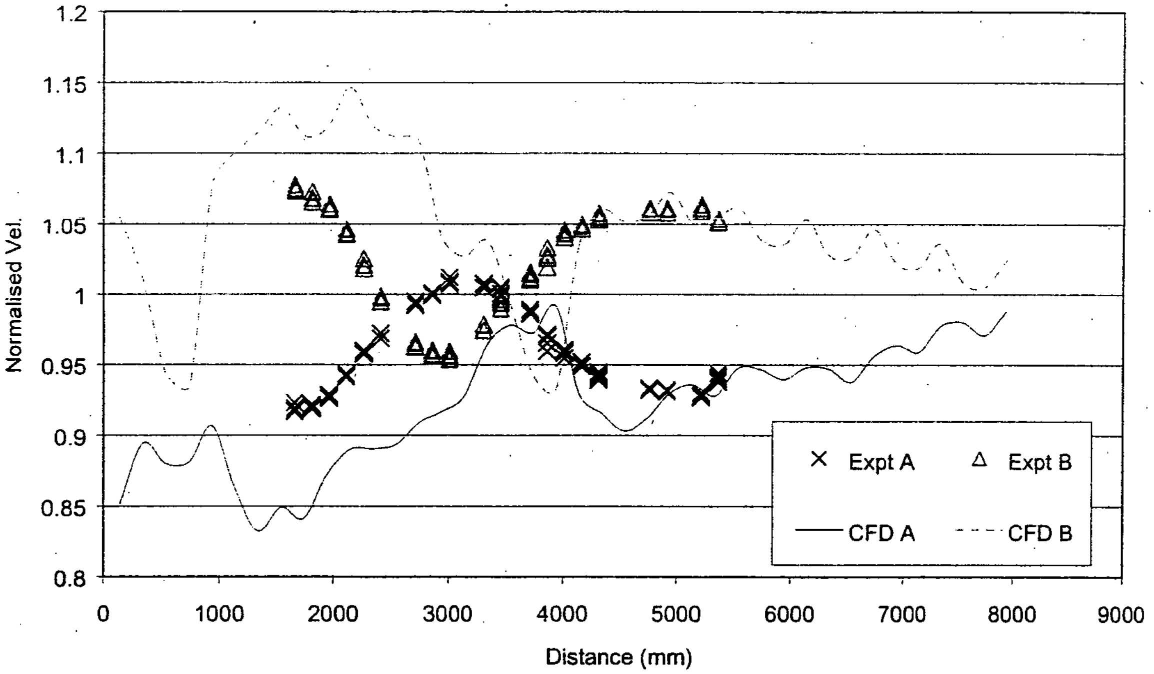


Figure 22 Measured and predicted normalised path velocities of the Danfoss 6" Sonoflow meter downstream of a triple bend in oil flow

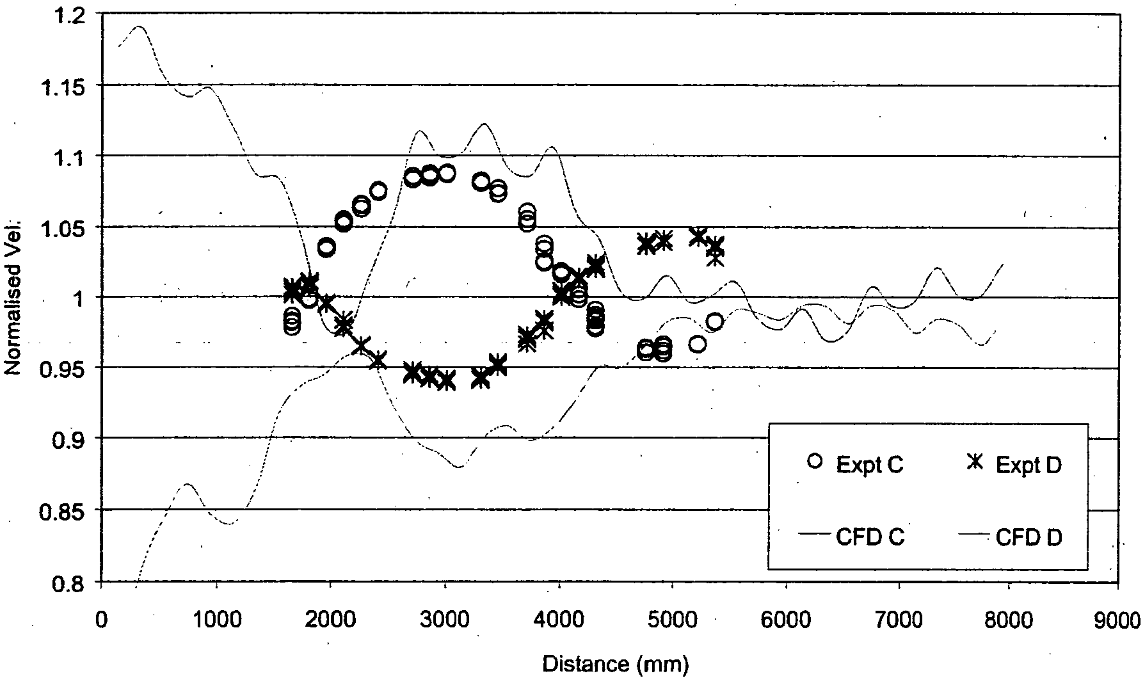


Figure 23 Measured and predicted normalised path velocities of the Danfoss 6" Sonoflow meter downstream of a triple bend in oil flow

4.4 Triple-Bend Oil-Flow Tests – Clamp-On Meters

Figure 24 shows the measured error characteristics of the E&H and Ultraflux flowmeters based on the normal dual-bounce-path operation and also on a single-bounce path. The behaviour of these meters is very similar. This is to be expected as the path configurations of these meters are identical. Both meters have a sinusoidally shaped error characteristic that approaches zero as the distance from the bends increases.

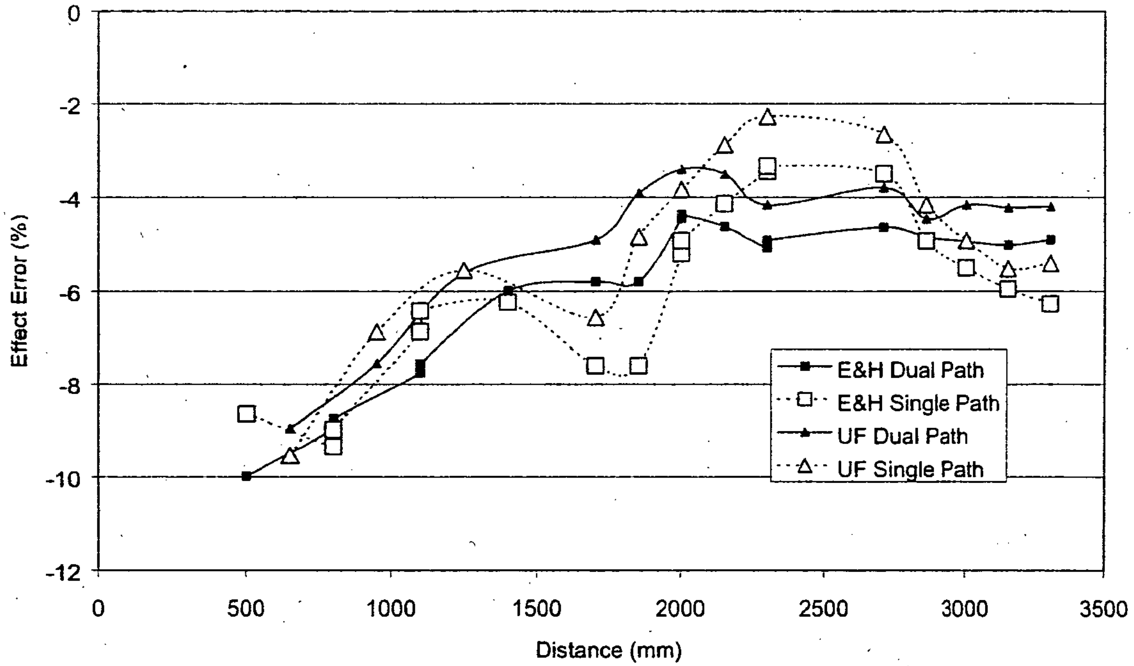


Figure 24 Measured error characteristic of the Ultraflux and E&H clamp-on meters downstream of a triple bend in oil flow

Figure 25 compares the experimental measurements with the predicted error characteristic (the Ultraflux results have been omitted for clarity). The trend in the predicted error characteristic is very close to the measured characteristic. The predictions correctly show that there is very little difference between the error characteristics at 3 m/s and 4 m/s. There are not enough test data points to compare the actual and predicted fluctuation amplitude and frequency. However, if measurements are made using only a single path, the fluctuation frequency is halved, making a clear comparison easier. Figure 26 shows that the CFD predicts the amplitude and frequency of the fluctuation of a single path quite well, implying that the prediction for the two-path meter is reasonable.

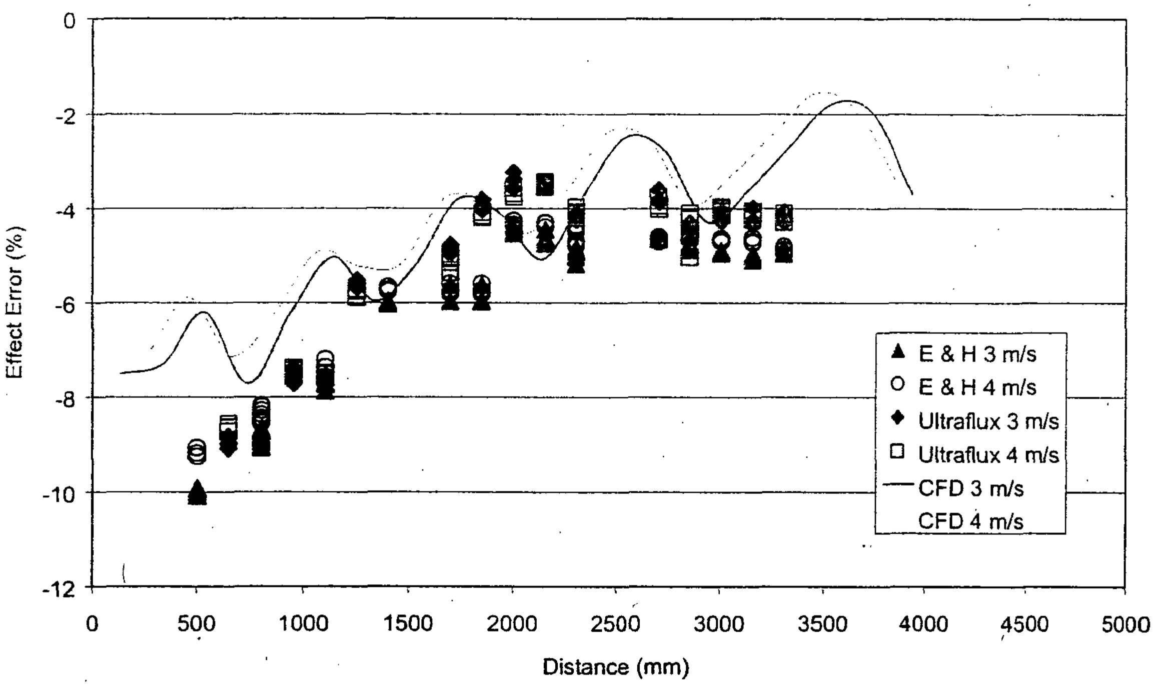


Figure 25 Measured and predicted error characteristic of the E&H and Ultraflux clamp-on meters downstream of a triple bend in oil flow

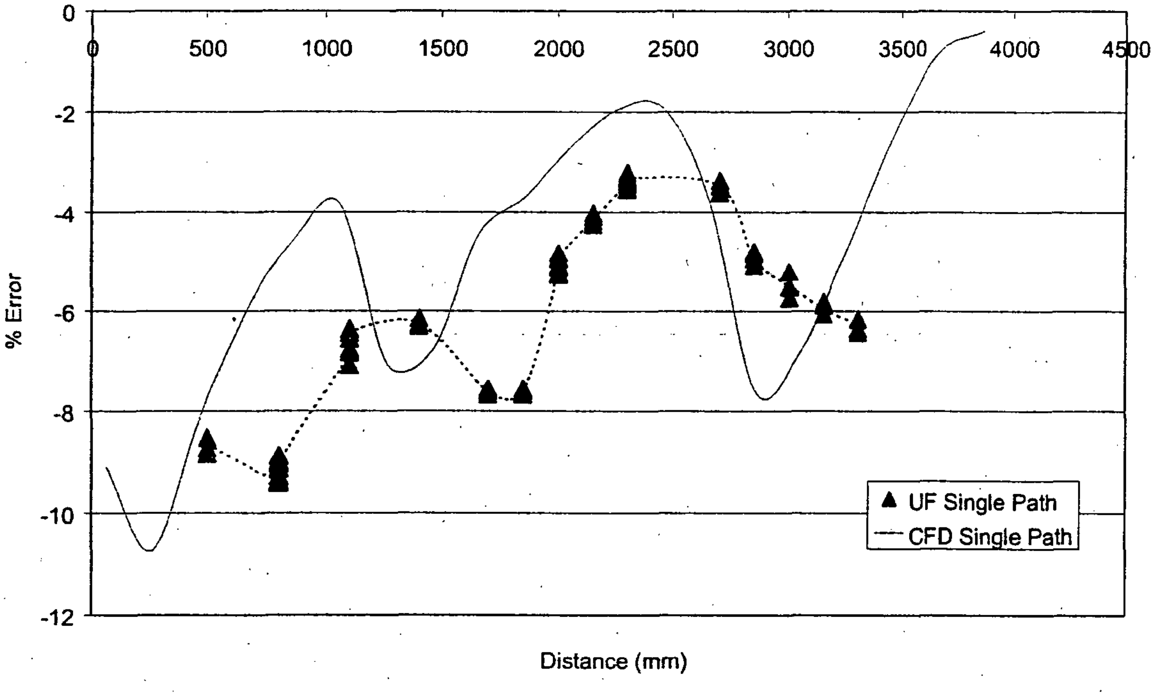


Figure 26 Measured and predicted error characteristic of the Ultraflux clamp-on meter downstream of a triple bend in oil flow based on one path only

5 COMPARISON BETWEEN CFD PREDICTIONS AND FIELD DATA

This section describes an exercise in which CFD predictions were compared with measurements taken with ultrasonic flowmeters in a three-stream fiscal gas-metering system. Each stream had included an ultrasonic meter with a Gaussian four-path configuration (as illustrated in Figure 27) with the paths in a horizontal orientation. During normal operation the gas flowed through two streams, the third being closed off by a valving system. For the purposes of this work two tests were run, one in which Stream 1 was on line, the other in which Stream 2 was on line.

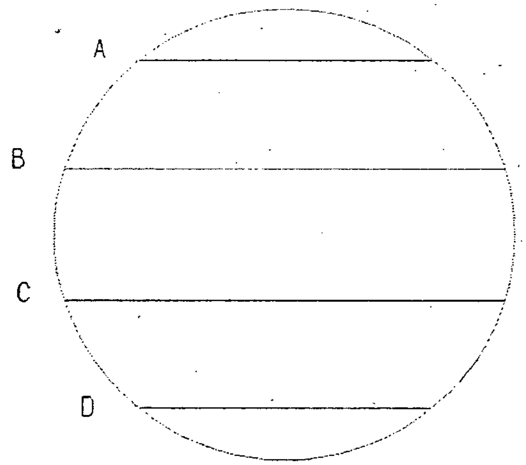


Figure 27 a) Looking downstream

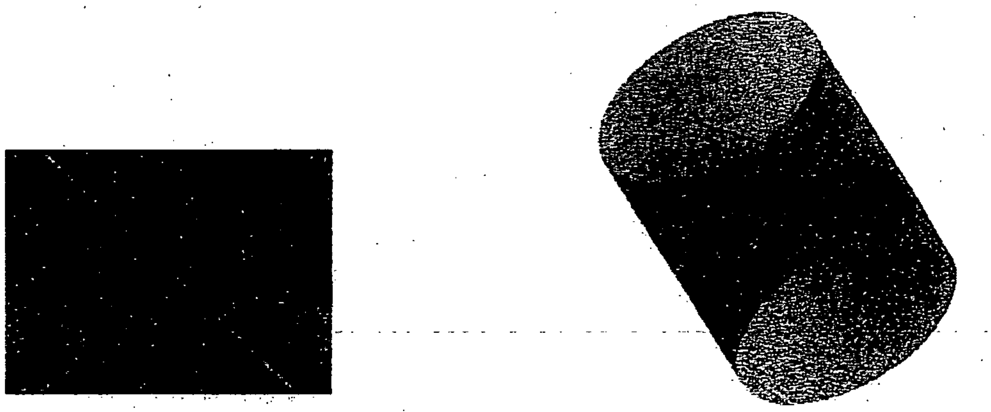


Figure 27 b) Plan View Figure 27 c) Isometric view

Figure 27 Path Configuration of the Gaussian Four-Path Meter

5.1 Test One – Stream 1

During the first test, gas was flowed through Stream 1 at a constant nominal flow rate of about 0.55 m^3/s with Streams 2 and 3 off line. At this flow rate the mean flow velocity was approximately 2 m/s. Figure 28 shows the measured path velocities from this test. The velocities measured by the inner paths are greater than those of the outer paths, indicating that the axial flow velocity is higher in the centre of the pipe (as would be expected). The path velocities also oscillate, the outer paths (A & D) showing a larger oscillation than the inner paths. This oscillation is likely to be partially caused by turbulence, although the ±5% seen in paths A and D is higher than would be expected. When the CFD simulations were run it was found that the flow pattern downstream of the header also varied with time. The separation zones at the junctions between the header and the streams were found to oscillate, as illustrated in Figure 29. This caused the axial velocity profile entering the flowmeter to oscillate (Figure 30) and hence the individual path velocities also varied with time.

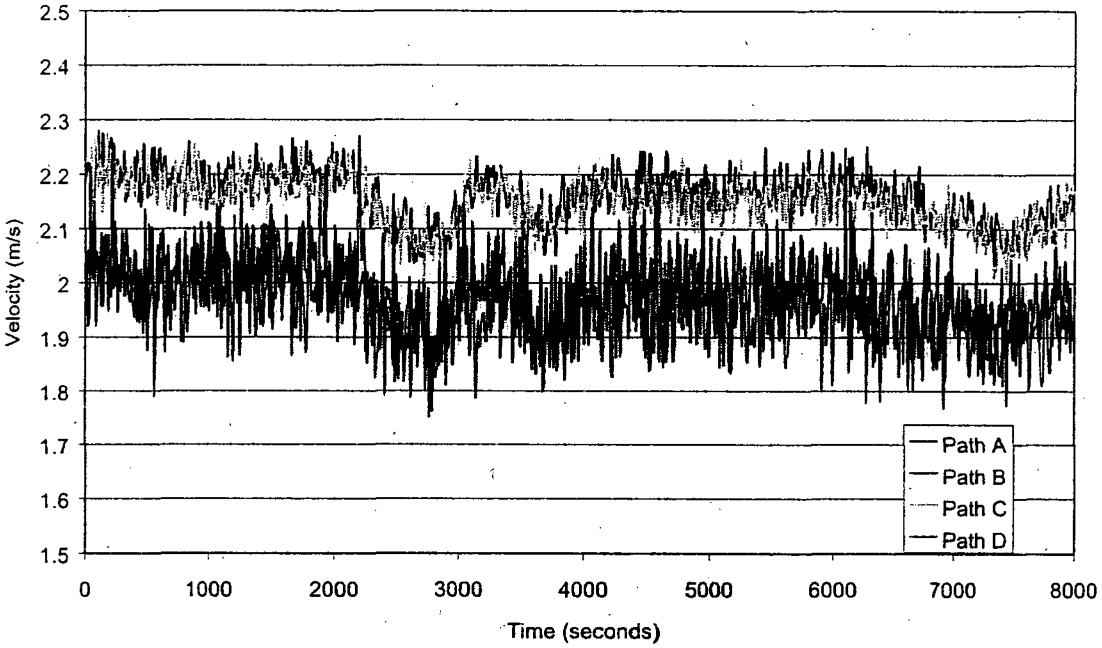
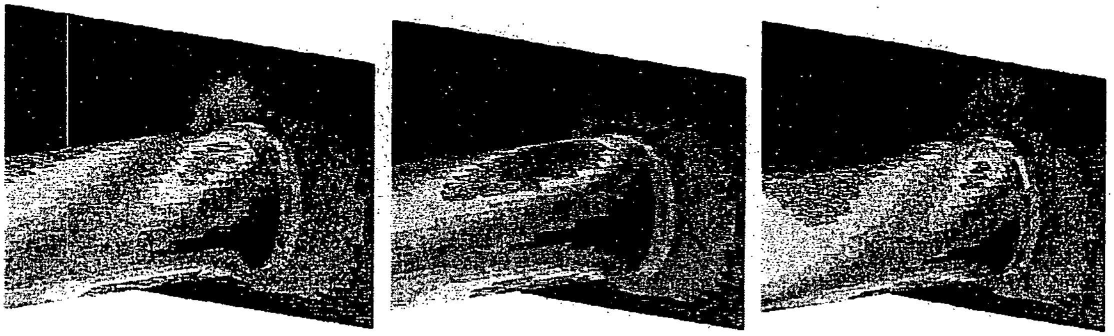


Figure 28 Measured path velocities during Test 1



(a) 36 seconds (b) 100 seconds (c) 379 seconds

Figure 29 Contours of velocity magnitude at the junction between Stream 1 and the header at 36 seconds, 100 seconds and 379 seconds

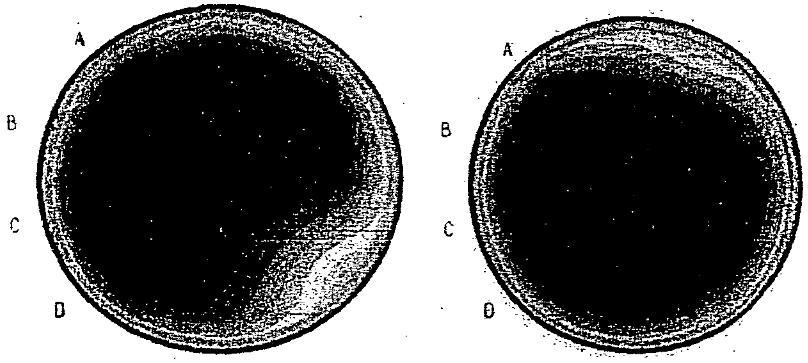


Figure 30 Contours of axial velocity at the Stream 1 flowmeter at 100 seconds and 379 seconds

Figure 31 compares the predicted and measured path velocities. The mean path velocities for the inner paths (paths B and C) are well predicted. The mean path velocities for the outer paths (A and D) are slightly lower than the measured value. In Figure 31 the CFD appears to over-predict the amplitude of the oscillations. However, the experimental data represents instantaneous measurements taken at ten-second intervals. Hence oscillation maxima and minima are not well captured. When the CFD predictions are plotted on a similar basis (see Figure 32), the magnitudes of the measured and predicted oscillations of path B (and also C, which is not shown) are very similar. The CFD slightly over-predicts the magnitude of the oscillation in the path velocity. However, in general, the match between the predictions and measurements shown in Figure 32 is very good.

It should be noted that the filtering and data processing methods used in this meter are such that this oscillatory behaviour is unlikely to compromise the accuracy of the volumetric flow measurement made by the flow meter.

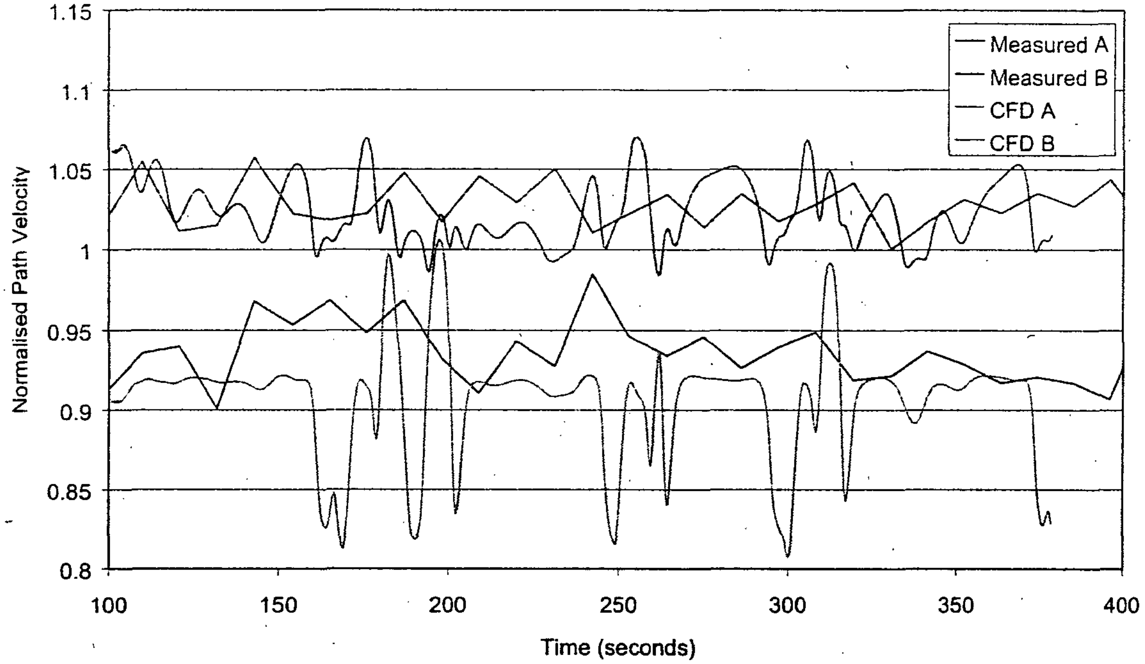


Figure 31 a) Paths A and B

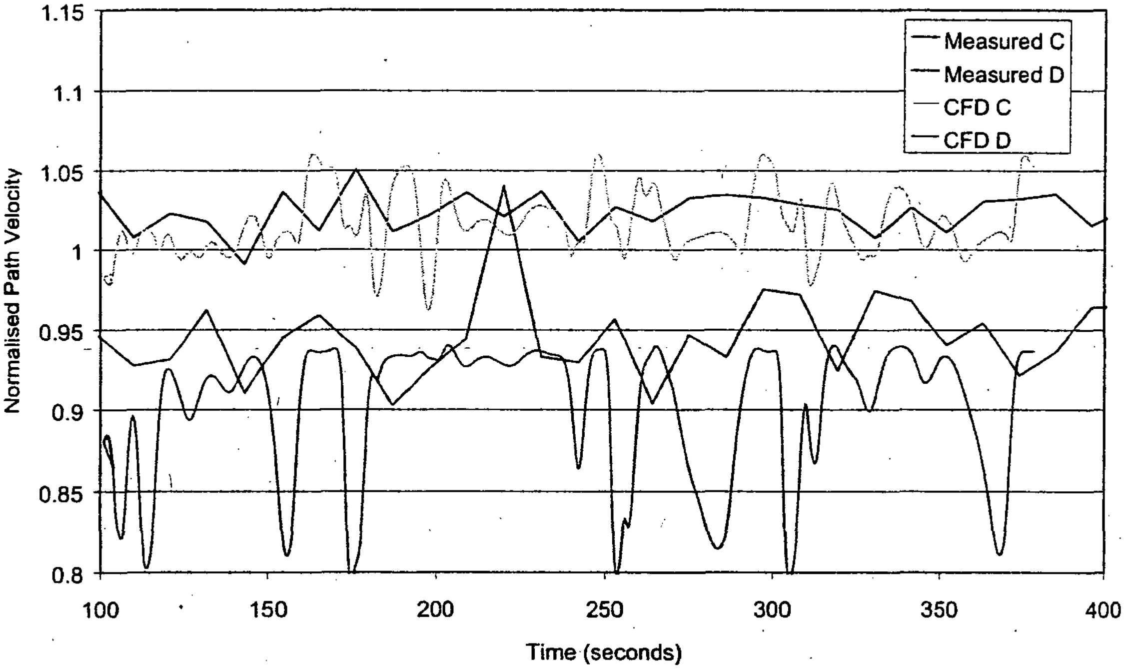


Figure 31b) Paths C and D

Figure 31 Comparison of the measured and predicted path velocities (normalised against the mean of all four paths)

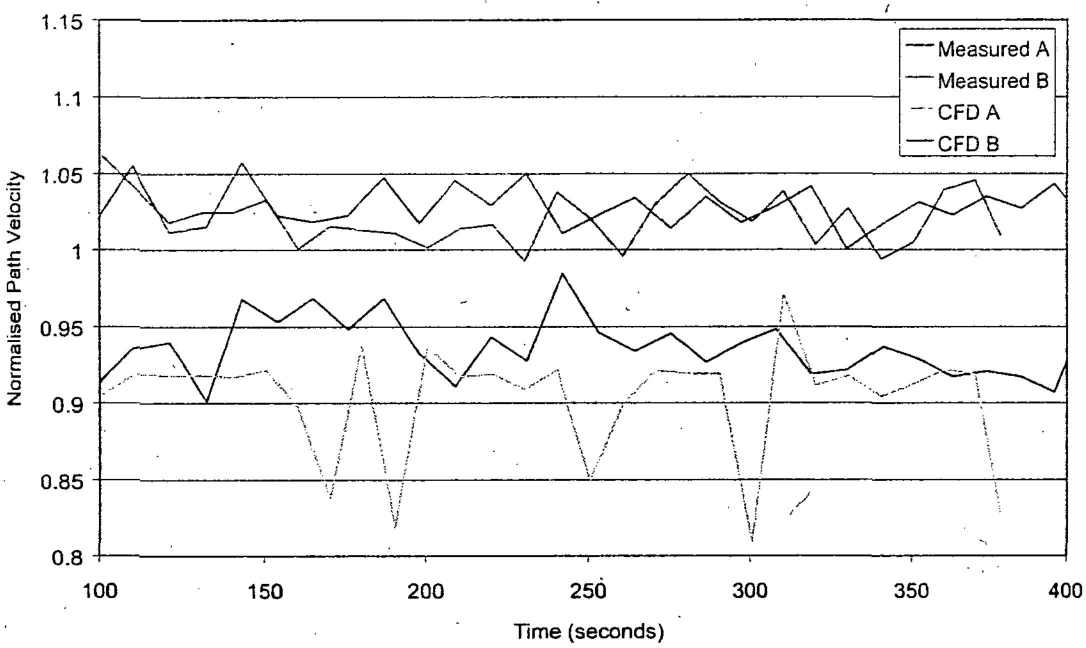


Figure 32 Comparison of the measured and predicted path velocities (CFD data replotted at 10-second intervals)

5.2 Test Two – Stream 2

In the second test, only Stream 2 was on line and the flow velocity was stepped up from 1 m/s to 6 m/s and then to 13 m/s, as shown in Figure 33.

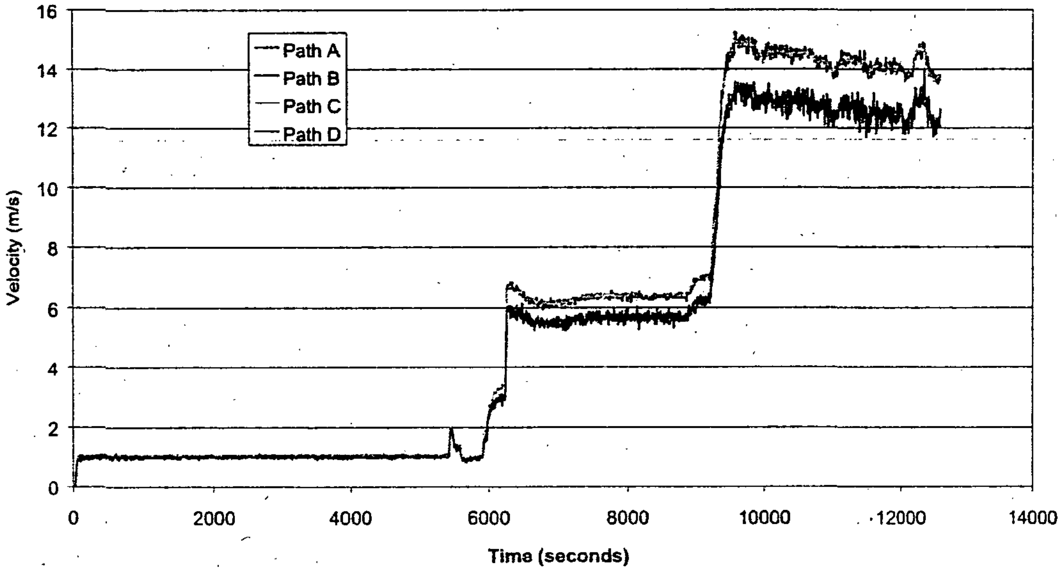


Figure 33 Measured path velocities during Test 2

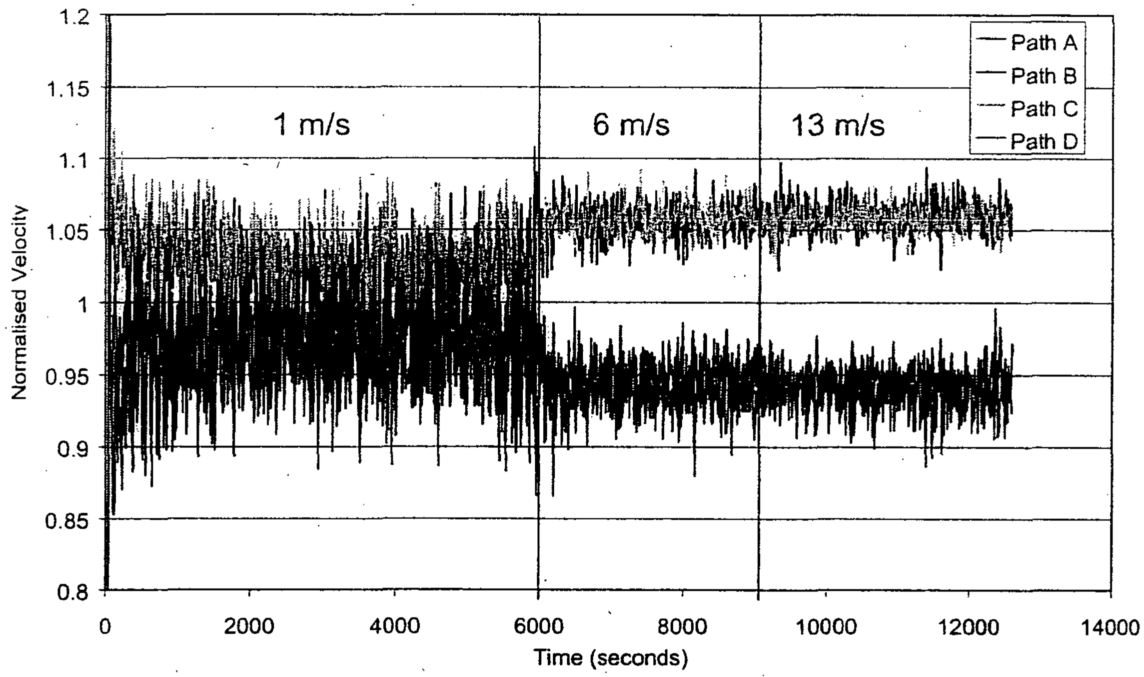


Figure 34 Measured path velocities (normalised against the mean of all four paths)

In Figure 34 the measured path velocities have been normalised against the mean of all four paths. There is an apparent change in flow behaviour when the flow velocity is increased from 1 m/s to 6 m/s with the relative magnitude of the oscillations reducing and a distinct shift in the velocity measured by the BC- and AD- path pairs.

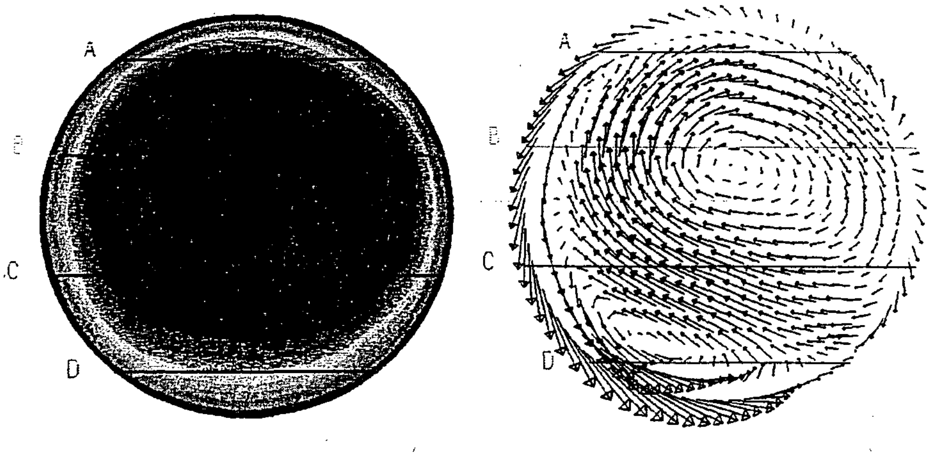


Figure 35 a) 17 seconds

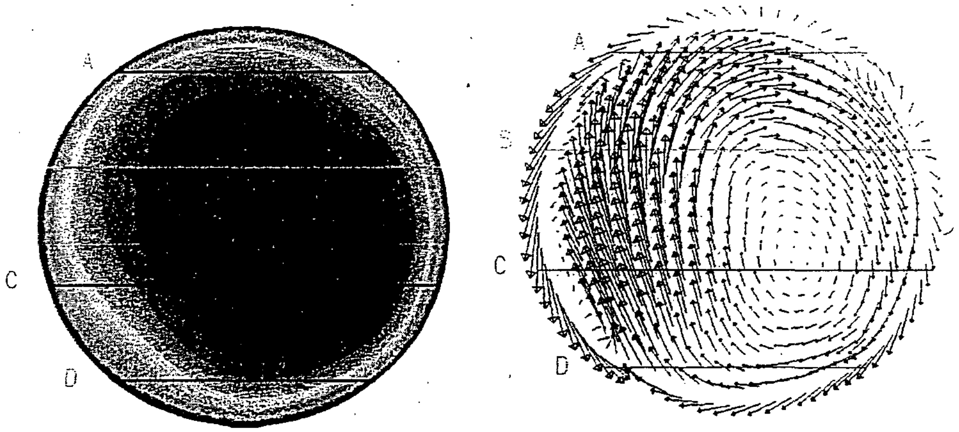


Figure 35 b) 33 seconds

Figure 35 Axial velocity contours and swirl vectors at the flowmeter, Stream 2 at 1 m/s

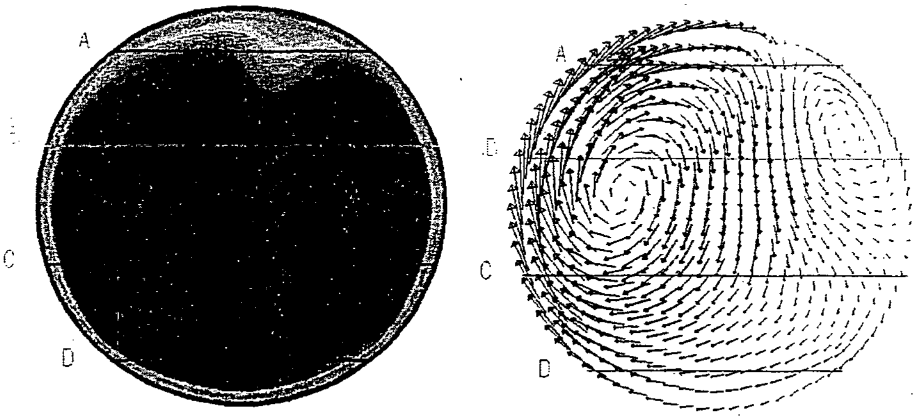


Figure 36 a) 10 seconds

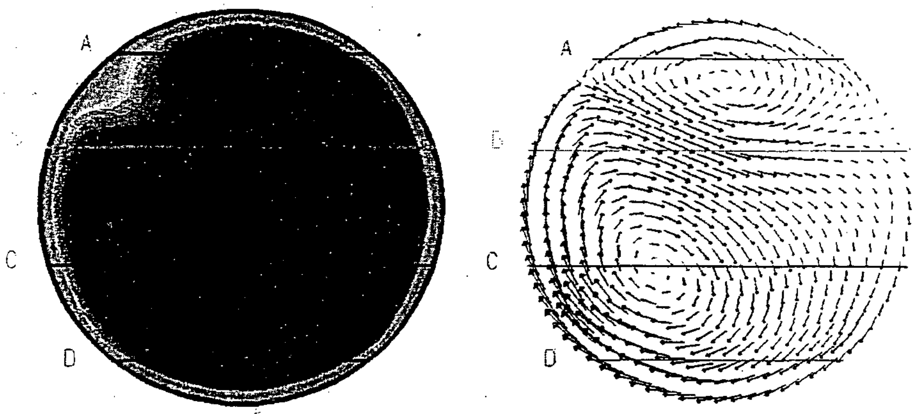


Figure 36 b) 20 seconds

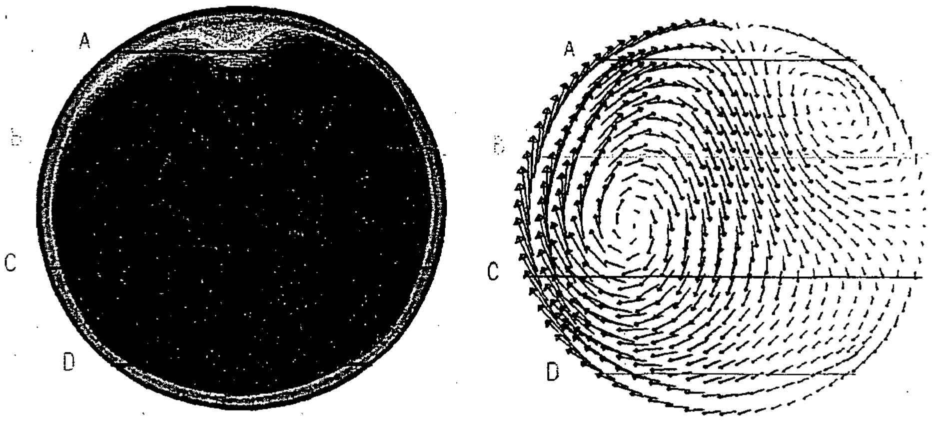


Figure 36 c) 33 seconds

Figure 36 Axial velocity contours and swirl vectors at the flowmeter, Stream 2 at 6 m/s

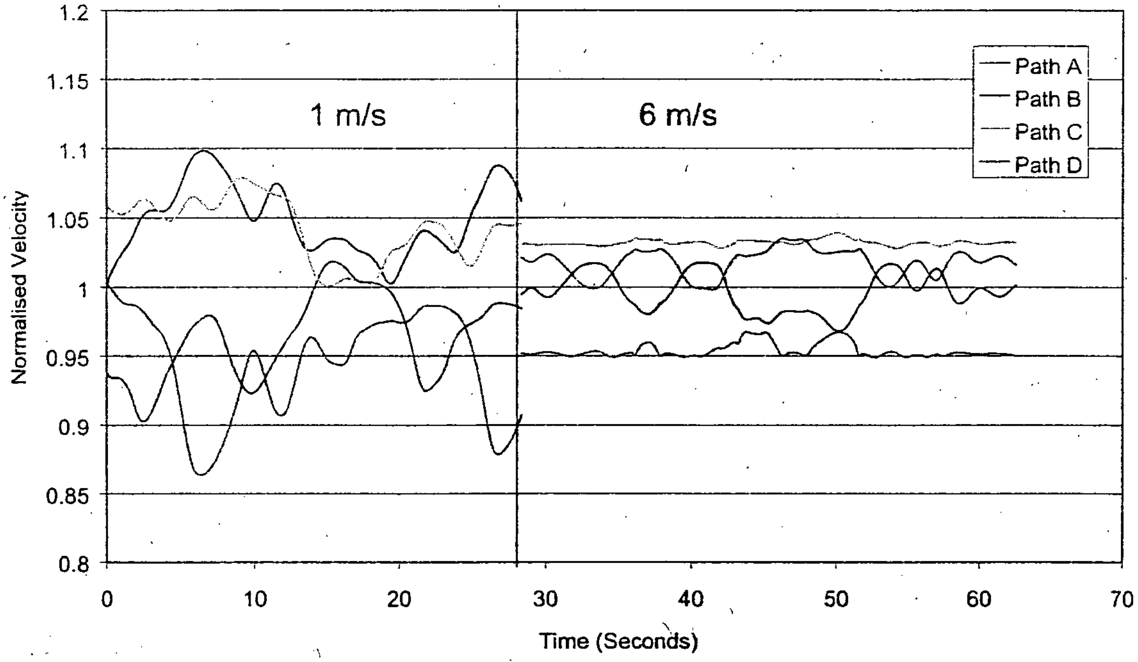


Figure 37 Predicted path velocities (normalised against the mean of all four paths)

Figures 35 and 36 show the predicted flow behaviour at the meter at 1 m/s and 6 m/s and Figure 37 shows the resultant time-varying path velocity graph. Comparing Figures 37 and 34 shows that the CFD produces a reasonable prediction of the mean value and oscillation amplitude of all four paths (note the differing time scales used in these figures). The CFD also correctly predicts a change in the oscillation amplitude when the mean velocity increases from 1 m/s to 6 m/s.

At 6 m/s the CFD predicts a skewed axial-velocity profile with a low velocity region at the top of the pipe (Figure 36a). This low velocity region intersects path A, causing it to measure a low velocity at all times and periodically intersects path B, causing it to oscillate. Paths C and D remain high, as the highest velocities occur at the bottom of the pipe. However, this does not match the behaviour seen in the measured data, in which paths B and C are high and paths A and D are low.

A simplifying analysis has shown that this shift could be caused by a solid-body single-vortex swirl of approximately 3°. Alternatively, if the axial velocity profile is more rounded at 6 m/s than at 1 m/s this would also account for this effect. It should also be borne in mind that the decrease in oscillation amplitude may be associated with a decrease in signal-to-noise ratio when changing the flow rate from 1 m/s to 6 m/s.

6 CONCLUSIONS: APPLICATION OF CFD TO ULTRASONIC FLOWMETERING PROBLEMS

This section summarises the results of this work and other relevant Flow Programme projects and draws conclusions on the use of CFD techniques to model installation effects in ultrasonic flowmeters.

6.1 Comparison of CFD Predictions and Measured Data: Summary

Downstream of Expansions

Figure 38 compares predicted and measured error characteristics of two different ultrasonic meters downstream of an expansion [1]. The CFD models correctly predict the relative difference in the meters' performance and the trend of the error characteristics. The predictions for the dual diametric meter are particularly close to the measured data. There is a discrepancy of about 4% between the simulation and the measurements for the dual-diametric meter immediately downstream of the expansion.

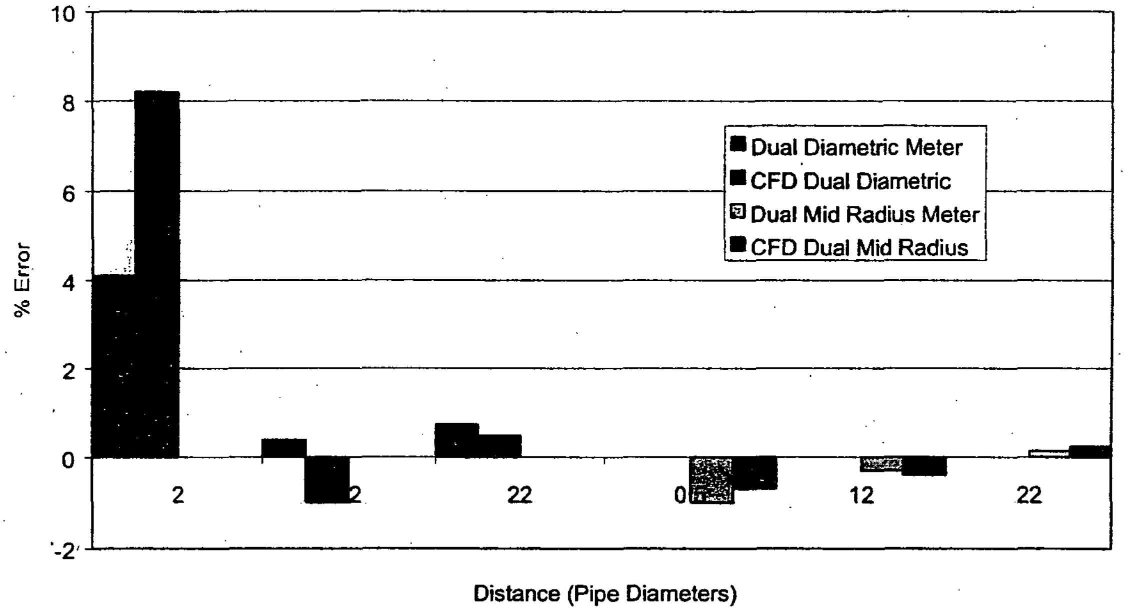


Figure 38 Comparison of predicted and measured error characteristics of a dual mid-radius meter and dual diametric ultrasonic meters (average of two similar meters) downstream of an expansion

Downstream of Contractions

Figure 39 compares predicted and measured error characteristics of ultrasonic meters downstream of a contraction[1]. In this case, both the dual mid-radius and dual-diametric meter characteristics are predicted to within 0.5%.

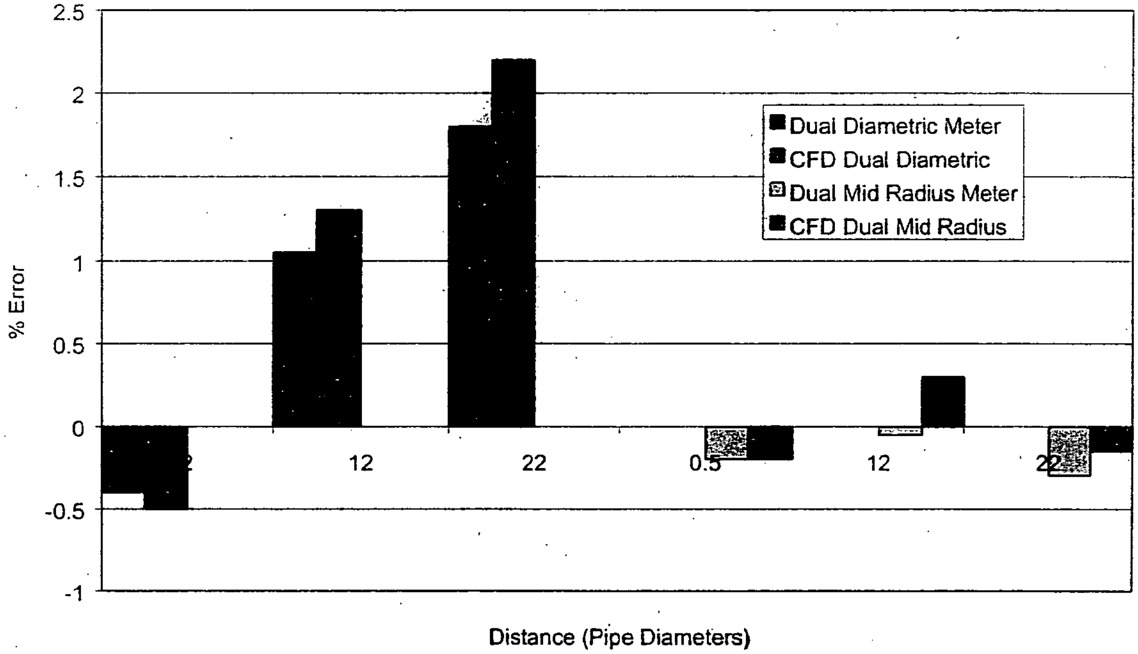


Figure 39 Comparison of predicted and measured error characteristics of a dual mid-radius meter and dual diametric ultrasonic meters (average of two similar meters) downstream of a contraction.

Downstream of Single Bends

Figure 40 compares CFD predictions and measured errors for ultrasonic meters downstream of a single bend [1]. In both meters, the trend of the error characteristic is correctly predicted and, in the case of the dual-diametric meter, there is a good quantitative match with test data. The error characteristic of the dual-mid-radius meter is exaggerated with errors over-predicted particularly near the bend.

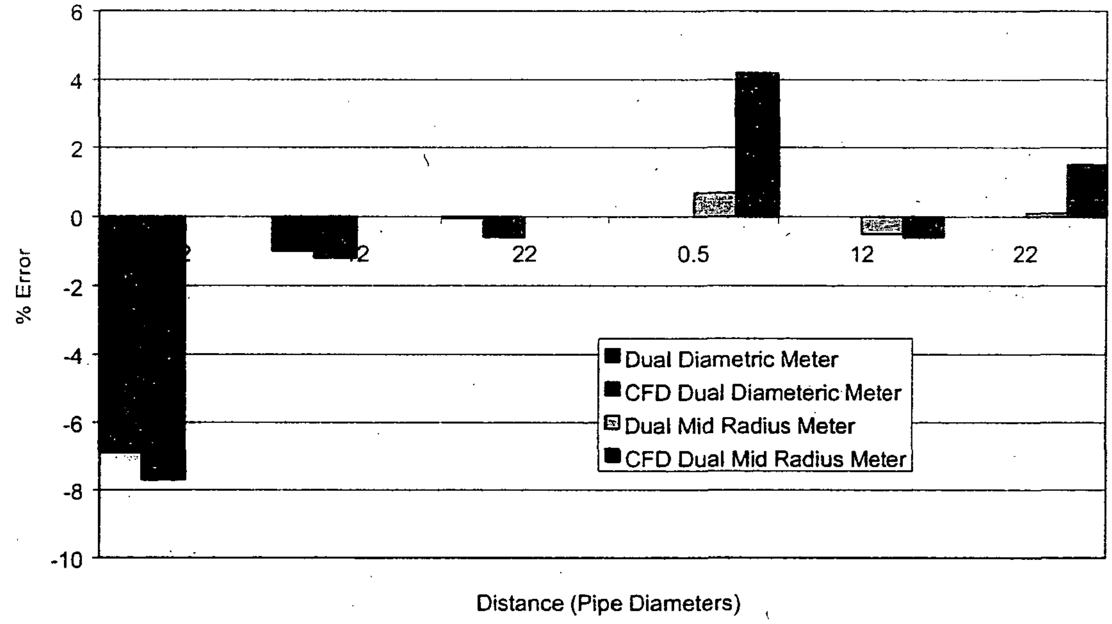


Figure 40 Comparison of predicted and measured error characteristics of a dual mid- radius meter and dual diametric ultrasonic meters (average of two similar meters) downstream of a 1D bend

Downstream of Twisted Double and Triple Bends

Section 4 gave a detailed comparison of predicted and measured error characteristics of dual-diametric meters and dual-mid-radius meters downstream of twisted double and triple bends. Figure 41 shows additional data for dual-diametric meters [1].

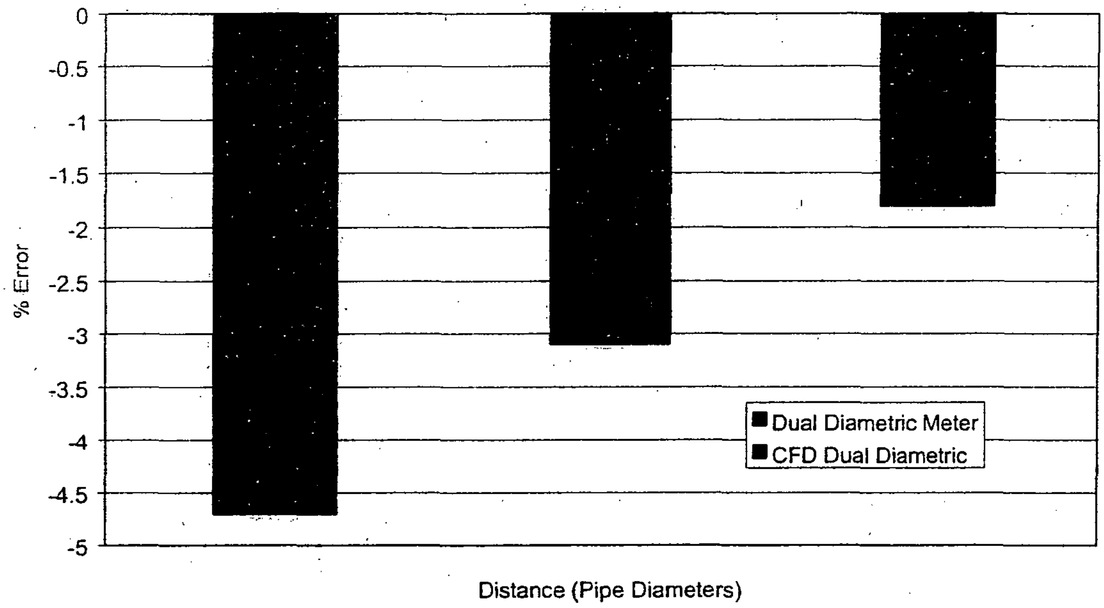


Figure 41 Comparison of predicted and measured error characteristics of a dual diametric ultrasonic meters (average of two similar meters) downstream of a twisted double bend (1D bend radius)

As with single bends, the error responses of dual-diametric meters are well predicted and the sensitivity of dual-mid-radius meters to these installations tends to be exaggerated.

Both multiple-bend installations generate swirl and an oscillating error characteristic. The CFD predictions have been shown to predict the swirl magnitude very well and the oscillating behaviour is seen in the simulations. The response of individual paths is also reasonably well represented. However, high frequency fluctuations in the path predictions, which do not occur in reality, combine to cause larger, spurious oscillations in the predicted flow rate measurement. The CFD simulations of dual-path meters therefore tend to show oscillations in the error characteristic that are higher in amplitude, and at a higher frequency, than would be seen in reality.

Flow Conditioners

Recent Flow Programme work has assessed the ability of CFD techniques to simulate flow conditioner plates [3]. It was found that, provided care is taken in defining the disturbed inlet flow into the conditioner and boundary conditions, such as the pipe roughness, these techniques will give good predictions of the velocity profile downstream of the conditioner. Based on this work it is reasonable to assume that the improvement in performance of an ultrasonic meter caused by a flow conditioner plate will be well predicted.

Downstream of Gate Valves

To the author's knowledge, no CFD simulation work has been done to model ultrasonic flowmeters downstream of gate valves. However, work performed in the Flow Programme on electromagnetic meters [5] suggests that CFD models of ultrasonic meters immediately downstream of partially closed gate valves should produce a reasonable error prediction provided the valve is less than 30% closed.

It should be noted that it is unlikely that an ultrasonic meter would be deliberately used in such an installation.

Complex Installations

The simulation of ultrasonic meters in a complex installation, typically seen in fiscal oil and gas metering stations was described in Section 5. In this case the behaviour of the flow was well modelled. The CFD simulations correctly simulated the transient behaviour of the flow, although in one of the three cases modelled, the relative difference between the path velocities was not correctly reproduced. However, it should be noted that the error in the flow rate measurement for both the real and simulated flowmeters was small.

In general, based on the performance of this technique with individual flow disturbances and the exercise in Section 5, it is believed that the CFD techniques outlined in this work should give reasonable estimates of flowmeter error in more complex installations.

6.2 Conclusions

Based on the information summarised in Section 6.1, the following conclusions have been drawn:

1 It is reasonable to use CFD methods to

(a) identify problems and the causes of problems with ultrasonic flowmetering installations,
(b) assess the magnitude of installation errors,
(c) assess the effectiveness of different remedial measures,
(d) extrapolate laboratory results for application to field problems,
(e) assess the relative merits of alternative path configurations in flowmeters for a particular application, and
(f) assess how factors such as pipe wall roughness, manufacturing tolerances, contaminants and unusually operating conditions affect ultrasonic flowmeters.

2 The CFD methods outlined in this report consistently reproduce the flow behaviour seen in the laboratory and in the field. In most cases a good quantitative match between predictions and measurements has been achieved. However, for some installations, although trends are well represented, there can be differences of a few percent between measured and calculated meter errors. This occurs with both dual-diametric and dual-mid-radius meters. It is therefore not possible to conclude that CFD techniques are better at modelling one design of meter than another.

As CFD simulations cannot always predict metering errors to within 1%, their predictions should not be used to correct K-factors of fiscal metering stations without substantial test and field data to confirm the validity of the predictions.

7 ACKNOWLEDGEMENT

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