NORTH SEA FLOW MEASUREMENT WORKSHOP 2001

BENEFITS AND LIMITATIONS OF ULTRASONIC METERS FOR UPSTREAM OIL AND GAS PRODUCTION

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Ultrasonic meters have a number of recognised potential benefits relative to more traditional methods of flow measurement. Recent years have seen the beginning of acceptance of ultrasonic meters for custody transfer applications in the oil and gas industry. A new generation of ultrasonic meters has emerged to service these applications which require high accuracy measurement or single-phase oil or gas. In production from marginal fields it is not uncommon that production streams are shared between a number of wells with allocation of production being performed either before or after first-stage separation. In these metering applications significant quantities of secondary fluids may be present in the flow. Depending on the situation it may be necessary for the flow meter not only to function properly in these conditions but also to give a measure of the component fractions.

This paper presents results of two-phase tests on liquid ultrasonic meters. The data covers oil flows with gas volume fractions (GVF) of up to 70% and oil/water flows of across the water-cut range. Factors affecting performance are discussed and prospective methods for multiphase metering using ultrasound are introduced. The results show the performance of transit time ultrasonic meters to be seriously affected by the presence of free gas in a manner that is dependent on the flow velocity and regime. Further results demonstrate the feasibility of multiphase flow measurement using ultrasonic techniques.

1 INTRODUCTION

Effects of secondary flow components on the performance of ultrasonic meters have long been recognised as being of importance in measurement of oil and gas production. In the 1980's, work was carried out to evaluate the performance of a cross-correlation ultrasonic meter in oil flow with gas volume fractions of up to 25 % [1]. Although the performance of the meter was promising given the state of the art at the time, there has been no further development or exploitation of the technique in the oil and gas industry.

Improvements in the performance of transit time ultrasonic meters led to greater industry acceptance of the technology in the 1990's. In 1993 a paper was presented at the North Sea Flow Measurement Workshop describing tests commercial transit time liquid ultrasonic meters to evaluate their suitability for oil flow measurement [2]. Tests were carried out where small quantities of gas were introduced into the oil. None of the meters tested were able to function with gas volume fractions greater than 0.1% by volume.

This paper presents the results of tests conducted at NEL on a range of ultrasonic flowmeters. Transit time and Doppler liquid ultrasonic meters have been tested in two-component flows at various velocities and component fractions in the 1993-1996 and 1996-1999 DTI Flow Programmes. Tests on a transit time ultrasonic flowmeter in oil/water flows and oil/water/gas flows are also presented. These tests were conducted in NEL's multiphase flow facilities.

2 FLOWRATE ACCURACY IN OIL FLOW WITH LOW GAS VOLUME FRACTION

Tests conducted by NEL on a range of transit time meters using oil with gas volume fractions of up to 20% were presented at the 1996 and 1997 North Sea Flow Measurement Workshops [4, 5]. The results demonstrated that at low liquid velocities of around 1 m/s the meters could tolerate significant gas fractions of up to about 10%. However, at velocities higher than 1 m/s significant errors occurred at between 0.5 and 2 % GVF. It was observed that the meter behaviour was related to the gas distribution in the cross-section. At high velocities of around 10 m/s none of the meters could make valid transit time measurements at these gas volume fractions due to the highly attenuating nature of the well-mixed bubbly flow. During the tests it was observed that diagnostic parameters could be used to indicate measurement problems under certain flow conditions.

In the 1996-1999 Flow Programme both reflective and transit time meters were assessed for flowrate measurement across a common range of liquid flowrates and gas volume fractions spanning the range of the previous tests. The aim of these tests was to identify conditions most suited to each instrument. During these tests diagnostic parameters were logged for subsequent analysis.

The tests were conducted using a circuit of the NEL oil flow primary standard by introducing metered nitrogen into the test line on the downstream side of a reference positive displacement (PD) meter. The test section and meters were orientated horizontally. The tests were conducted using nitrogen gas and oil of viscosity nominally 25 cSt at test conditions. Operating temperature and pressure were nominally 20°C and 1 bar gauge respectively. The matrix of nominal test conditions is shown in Table 1.

Table 1 Nominal Conditions for the low gas volume fraction tests

Nominal Liquid Flowrate (l/s)	Liquid Superficial Velocity (m/s)	Nominal Gas Volume Fraction (%)				
5	0.5	0	2	5	20	40
9	1	0	1	2	5	10
17	2	0	0.5	1	2	5
40	5	0	0.5	1	2	5
55	7	0	0.1	0.5	2	
80	10	0	0.1	0.5		

3.1 Transit Time Meter Results

The transit time meter used in these tests was a 4-inch Danfoss Sono3000/3300 installed with its two mid-radius paths in horizontal planes. This same meter model had been tested in the 1993-1996 flow programme and it was observed that erratic behaviour occurred when the gas interfered with signal transmission in the upper path [5]. Therefore, for these tests, the upper measurement path was purposely disabled.

Figures 1 to 6 show the results in terms of error relative to liquid and total volumetric flowrate versus gas volume fraction. If the gas were travelling at the same velocity as the liquid the error would be equal to the gas volume fraction. Also shown on the graphs is a dotted line indicating error equal to GVF.

At 0.5 m/s liquid superficial velocity the meter measures velocity in the liquid at all gas volume fractions tested. At gas volume fractions of 5% and less the errors in liquid flowrate are less than 2 %. At 27 % GVF the errors are less than 9 % and at 40 % GVF the error is approximately equal to the gas volume fraction. At 1 m/s superficial liquid velocity the errors are within ± 2.5 % at all gas volume fractions tested.

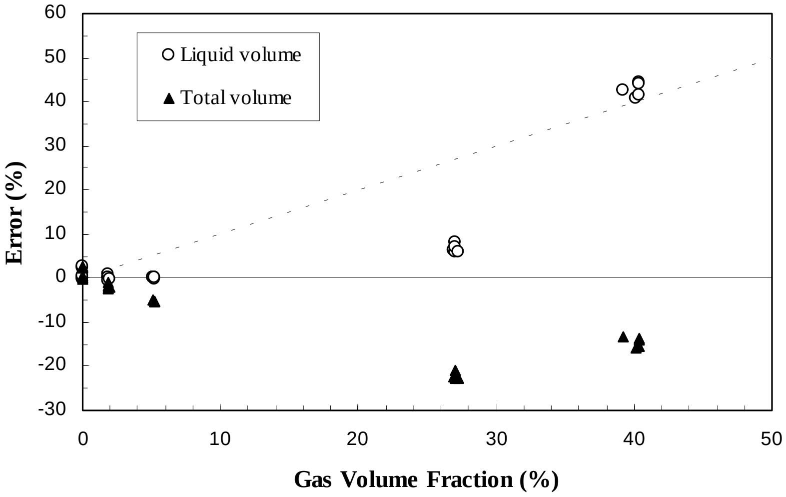

Figure 1 Low GVF results at 0.5 m/s (transit time)

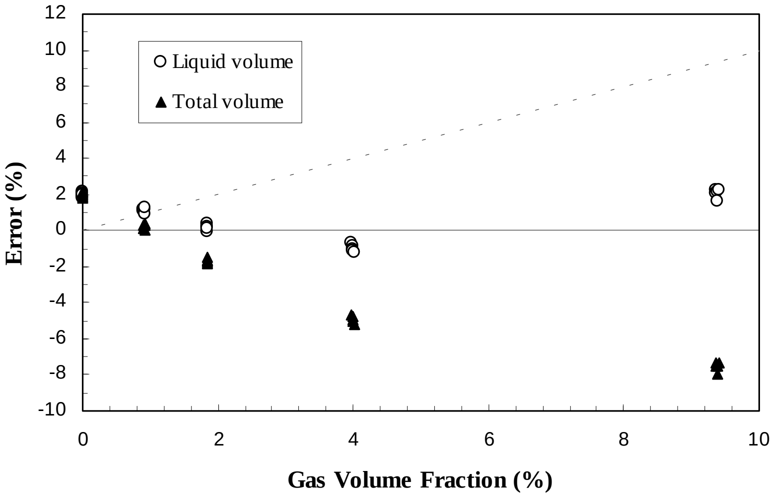

Figure 2 Low GVF results at 1 m/s (transit time)

At 2 m/s superficial liquid velocity the errors are within ± 0.5 % at all gas volume fractions tested. At 5 m/s the errors are less than ± 2 % at up to 1 % GVF. At 2 % gas volume fraction the performance of the meter is beginning to deteriorate with errors reaching 5 % in magnitude and when the GVF is approaching 5 % the repeatibiity is very poor with errors spaning from –12 to +20 %.

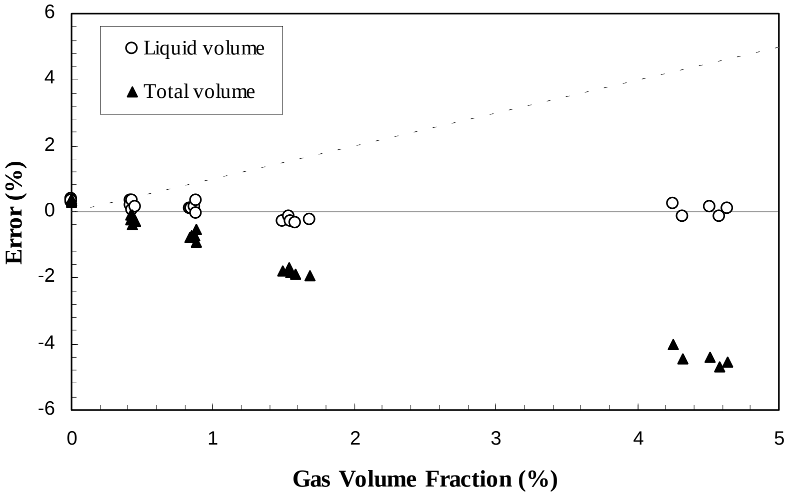

Figure 3 Low GVF results at 2 m/s (transit time)

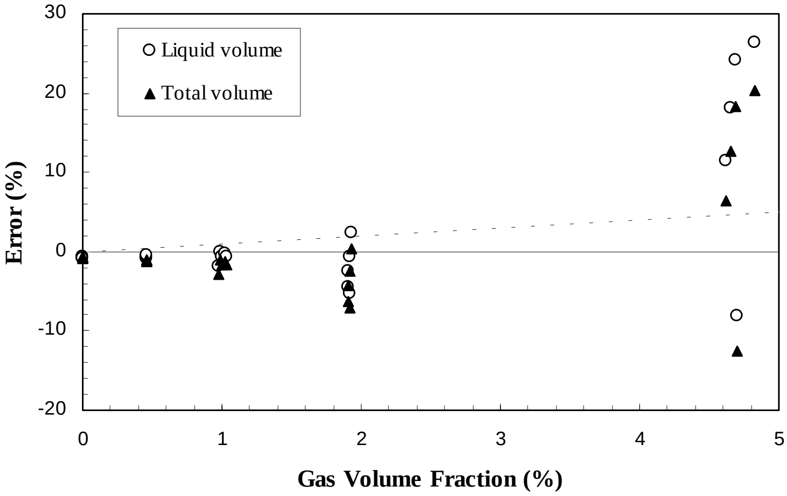

Figure 4 Low GVF results at 5 m/s (transit time)

At 7 and 10 m/s the ability of the meter to cope with entrained gas is seriously limited. The black shaded areas indicate gas volume fractions above which the meter could not measure. The gray shading indicates areas of uncertainty between test conditions. At 7 m/s the highest gas volume fraction tested at which the meter continued to function was 0.5 %. At 10 m/s the measurement failed between 0.1 and 0.5 % GVF.

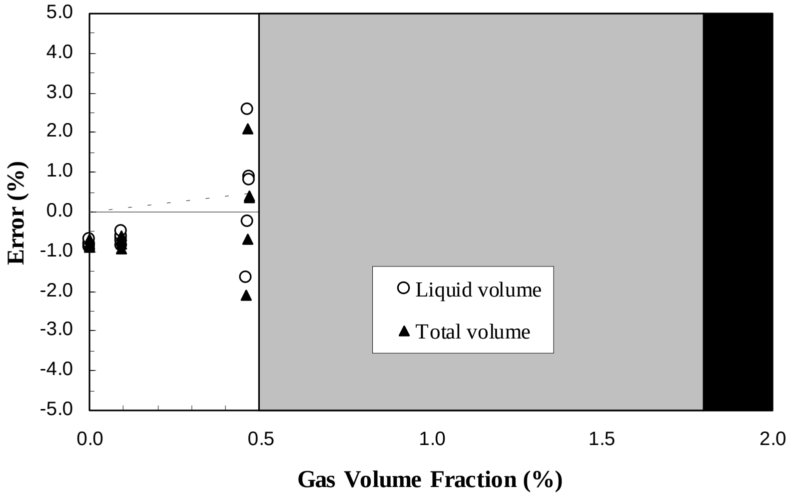

Figure 5 Low GVF results at 7 m/s (transit time)

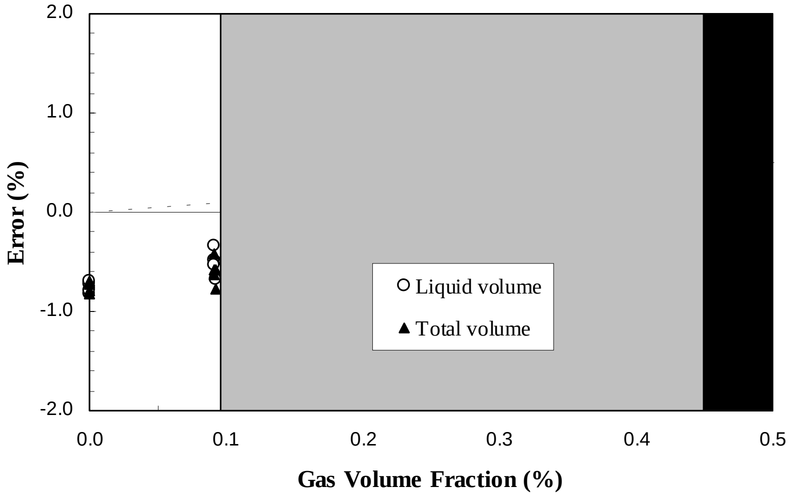

Figure 6 Low GVF results at 10 m/s (transit time)

3.2 Doppler Meter Results

The Doppler meter used in these tests was a clamp-on Buhler-Montec Zytec 7400 installed on a length of steel pipe of 4-inch nominal bore. The two clamp-on transducers were attached to the pipe at 45 degrees above and below the horizontal on the same side of the pipe. On transducer acts as the transmitter operating at 2 MHz. The other transducer acts as the receiver and picks up the transmitted signal and the Doppler-shifted signal. The Doppler-shifted signal and the transmitted signal are mixed to produce a high frequency signal with a low-frequency amplitude modulation. The Doppler frequency is determined by passing the signal through a low-pass filter and feeding the resulting signal into a zero-crossing detector. In this particular model the cut-off frequency of the low pass filter was set such that the maximum Doppler frequency that could be detected was equivalent to a velocity of 5 m/s. Owing to this limitation, the Doppler meter results do not extend to the 7 and 10 m/s velocities used for testing the transit time meter.

Figures 7 to 10 show the results in terms of error relative to liquid and total volumetric flowrate versus gas volume fraction. At 0.5 m/s liquid superficial velocity the Doppler meter did not return a velocity reading until gas was introduced in to the liquid. At 2 % GVF the errors were within ± 5 % of the liquid volumetric flowrate. At higher GVF the errors relative to the liquid flowrate were greater than the gas volume fraction. Relative to the total volumetric flowrate the errors were within ± 30 %. At 1 m/s liquid superficial velocity the meter returned a velocity reading at zero GVF and the repeatibility of the results improved. All of the results fell within a band of ± 23 %

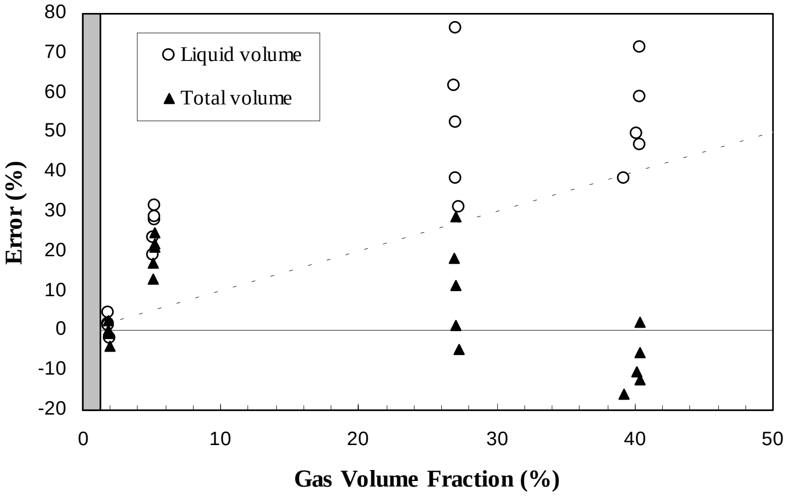

Figure 7 Low GVF results at 0.5 m/s (Doppler)

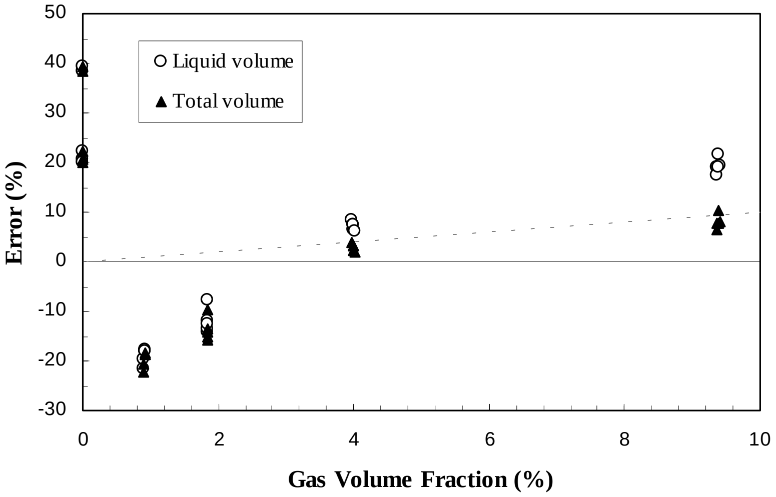

Figure 8 Low GVF results at 1 m/s (Doppler)

At 2 m/s liquid superficial velocity all of the results fell within a band of ± 9 % with the exception of the zero GVF results which included errors of up to –37 % (Note: these points are not shown on the graph below). At 5 m/s liquid superficial velocity the Doppler meter tended to under-read with the errors at 0.5 to 5 % GVF lying within a band between zero and –12 %. At zero GVF the errors were less than 6 %.

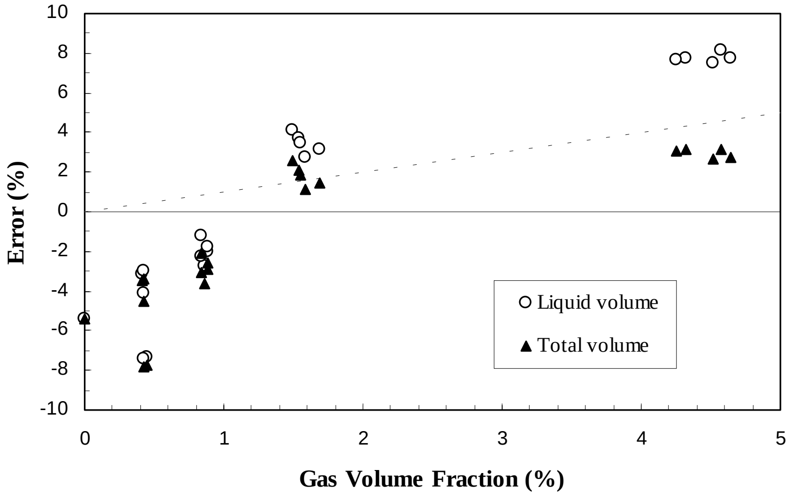

Figure 9 Low GVF results at 2 m/s (Doppler)

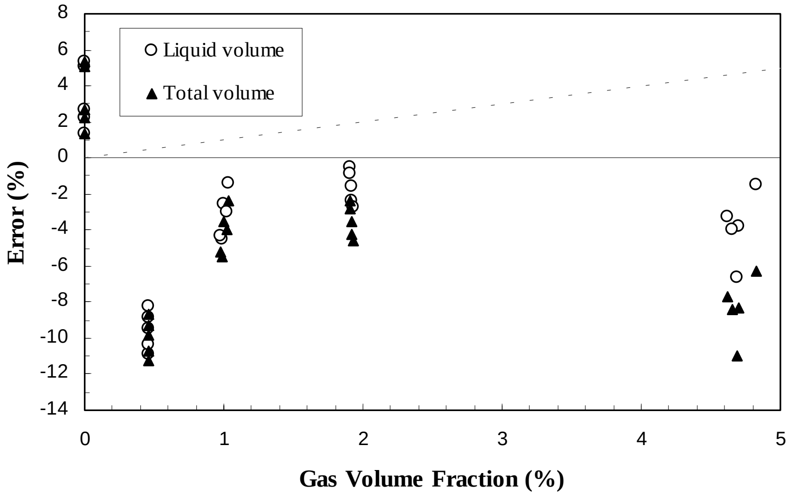

Figure 10 Low GVF results at 5 m/s (Doppler)

Comparing the results from the two meters, it is clear that the Doppler meter is generally less accurate than the transit time meter. However, as illustrated in Figure 11, the Doppler meter is more accurate and repeatable at 5 m/s when the GVF exceeds 1 %. This is the point at which the transit time meter was beginning to experience serious difficulties due to attenuation. It is unfortunate that the Doppler meter could not be tested at higher velocities to determine if Doppler measurements could be made under conditions where the transit time meter had failed.

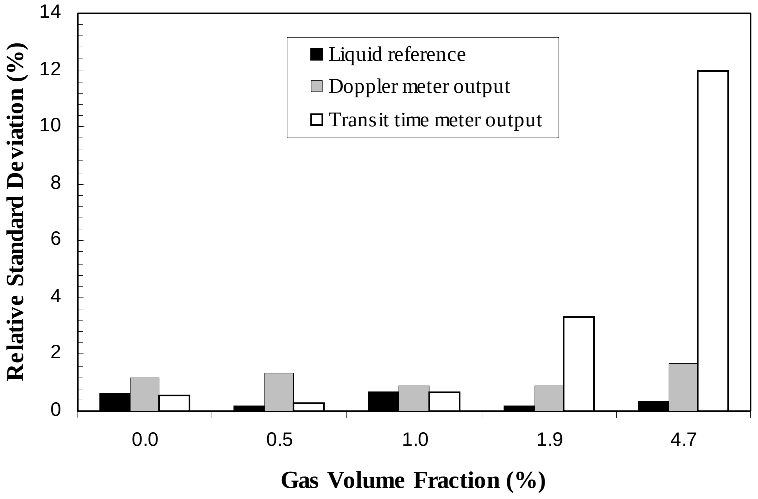

Figure 11 Comparison of Doppler and transit time results at 5 m/s

4 FLOWRATE ACCURACY IN OIL FLOW WITH HIGH GAS VOLUME FRACTION

As the transit time meter had performed with reasonable accuracy at liquid superficial velocity up to 2 m/s and was continuing to function at the highest GVF in each case, further tests were conducted at higher GVF. For these tests both measurement paths were activated and signal diagnostics were recorded. The test facility was set up as described in the previous section. The matrix of nominal test conditions is shown in Table 2.

Table 2 Nominal conditions for the high gas volume fraction tests

Nominal Liquid Flowrate (l/s)	Liquid Superficial Velocity (m/s)	Nominal Gas Volume Fraction (%)					
5	0.5	10	25	50	60	65	70
9	1	10	20	40	50	55	60
13	1.5	10	20	30	40	45	50
17	2	10	15	25	35	40	45

The results are presented in Figures 12 to 15 in the same style as in the previous section. The grey-shaded points show results obtained when the measurement of velocity in the lower path is also failing (corresponding to a signal-to-noise ratio of less than 20).

The results show that the GVF at which the velocity measurement on the lower path fails reduces as the liquid superficial velocity is increased. The limit of operation is 60 % GVF at 0.5 m/s, 45 % GVF between 1 and 1.5 m/s, and 35 % GVF at 2 m/s. The relationship between error relative to volumetric flowrate of total fluid and GVF is approximately linear with the total volumetric flowrate being systematically underestimated. This implys that the gas and liquid in the upper part of the pipe move at a higher velocity than the velocity of the liquid being measured by the functional lower path. The gradient of the line varies with liquid superficial velocity. This is the combined effect of variation of velocity slip between the fluid phases and changes in the liquid velocity profile.

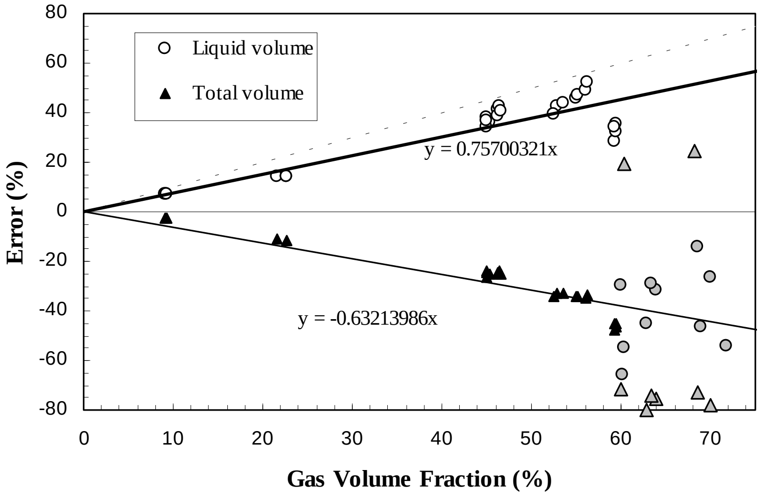

Figure 12 High GVF results at 0.5 m/s

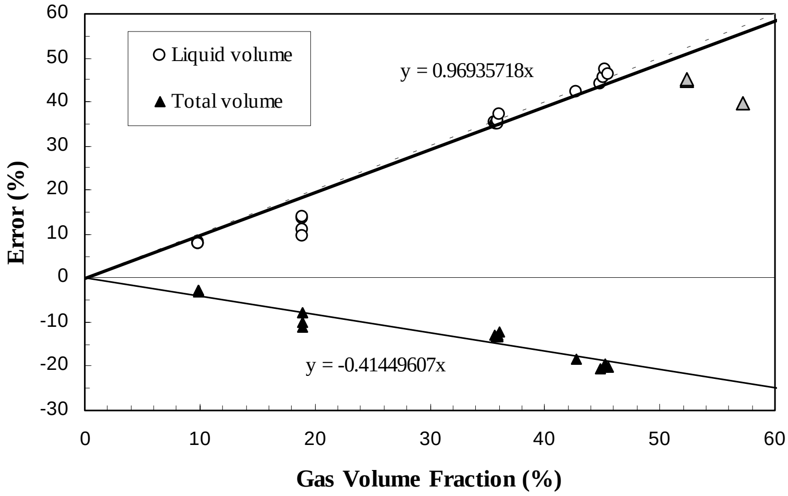

Figure 13 High GVF results at 1 m/s

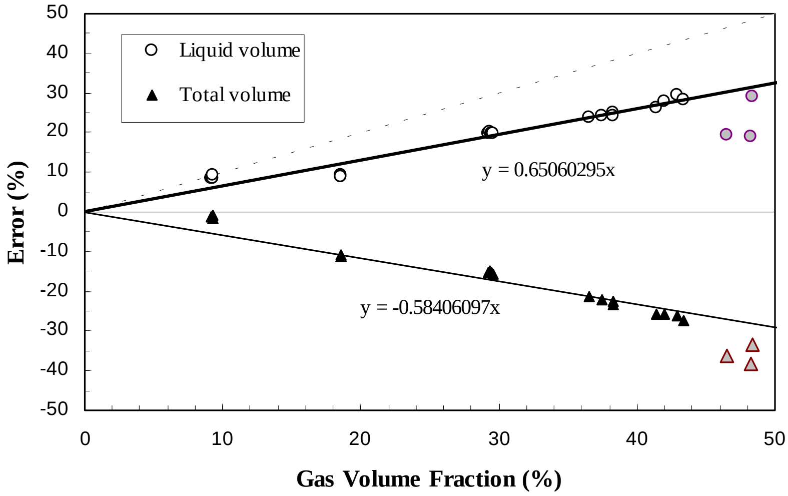

Figure 14 High GVF results at 1.5 m/s

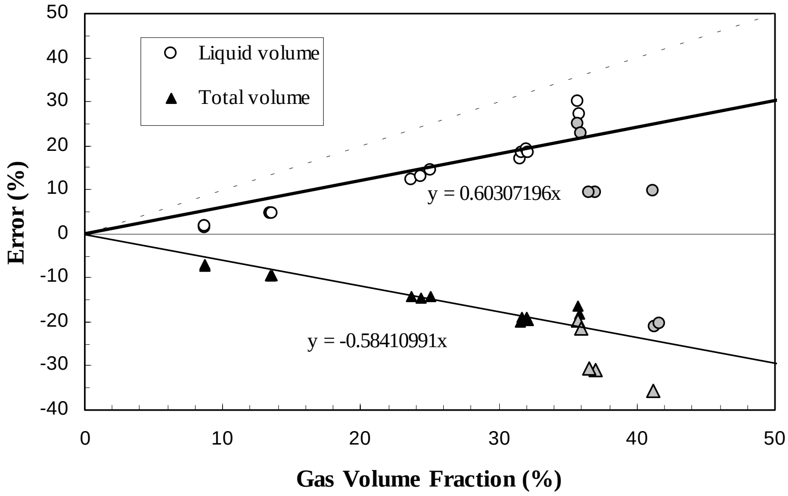

Figure 15 High GVF results at 2 m/s

5 GVF ESTIMATION IN OIL FLOW WITH HIGH GAS VOLUME FRACTION

In the previous section it was shown that the error in measurement of the total volumetric flowrate is linearly related to gas volume fraction. This relationship can be used to estimate the flowrates of both liquid and gas using the transit time ultrasonic meter if an estimate of the gas volume fraction can be obtained for use with the velocity measurement.

Two approaches were taken in an attempt to make this measurement using ultrasonics. For the first approach additional equipment was used to try and make on-line measurements of the gas-liquid interface. For the second approach the diagnostic data provided by the ultrasonic meter was analysed for usable relationships.

To achieve measurement of the interface position, a system comprised of pulser/pre-amplifier, digitising oscilloscope, and commercial 1 MHz ultrasonic transducer was utilised. The digitising oscilloscope was connected to a PC with data acquisition software in order to capture and process the raw ultrasonic signals. The system configuration is illustrated in Figure 16 below. The pulser/pre-amp excites the transducer with a high-voltage transient that generates an ultrasonic pulse that is transmitted into the adjoining medium. Returning ultrasonic signals (echoes) are converted to electrical signals by the transducer and amplified to a suitable level by the pre-amp. The amplified signals are captured by the oscilloscope, the pulse repetition rate and synchronisation being controlled by the pulser/pre-amp unit. The arming of the oscilloscope and data transfer is controlled by the PC, where subsequent processing of the raw signal is performed using software written specifically for the application.

The ultrasonic transducer was coupled to the outer wall of a block-shaped Perspex flow cell with a 100 mm nominal bore as illustrated in Figure 17. A mineral oil based couplant was utilised to improve transmission efficiency between the Perspex and the transducer face by eliminating the air gap that would otherwise be present as a result of surface imperfections.

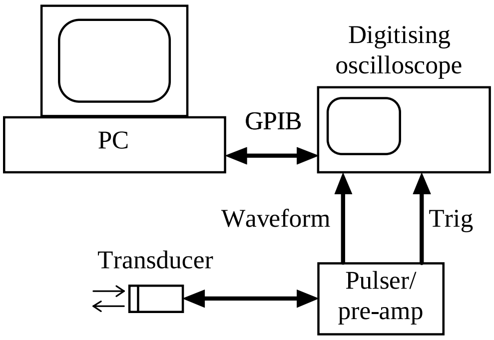

Figure 16 A schematic diagram of the interface measurement system

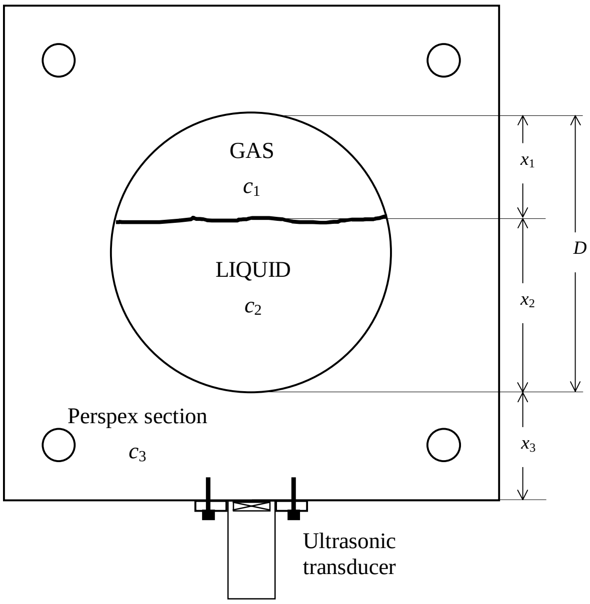

Figure 17 A schematic diagram of the interface measurement flow cell

5.1 Interface Measurement Results

Trials were carried out using the interface measurement system in parallel with the tests on the transit time ultrasonic meter described in the previous section. The round-trip transit times corresponding to the distances x_1 plus x_2 (as shown in Figure 17) were recorded at intervals of about 0.5 seconds. An example of the interface level data recorded at conditions with a superficial liquid velocity of 0.5 m/s and gas volume fraction of 46 % is shown in Figure 18.

Figure 19 shows the reference gas volume fraction plotted versus the area fraction calculated from the measured interface level. This graph shows that the measured area fraction is always less than the volume (flowrate) fraction, suggesting that the gas is flowing with higher mean velocity than the liquid.

The relationship shown in Figure 19 can be used to estimate the gas volume fraction from the measured interface level for 0.5 m/s liquid superficial velocity. The calculated GVF can then be used to estimate liquid and gas flowrates and to allow correction of these by plotting the volume flowrate correction factor as a function of GVF. Using the data shown in Figures 12 and 19 corrected liquid, gas and total flowrates were calculated from the ultrasonic measurements of velocity and interface level. The residual errors are generally less than ± 10 % relative to volume flowrate as shown in Figure 20.

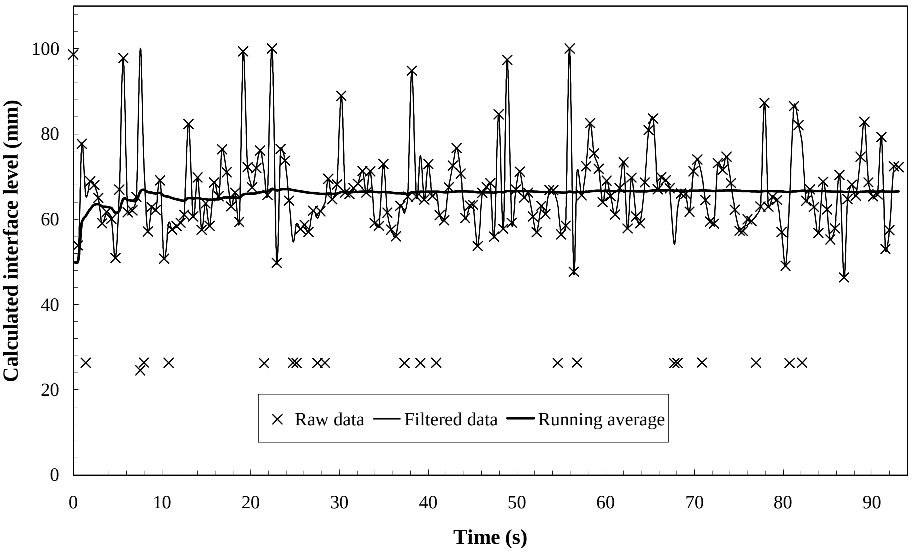

Figure 18 An example of data recorded using the interface measurement system

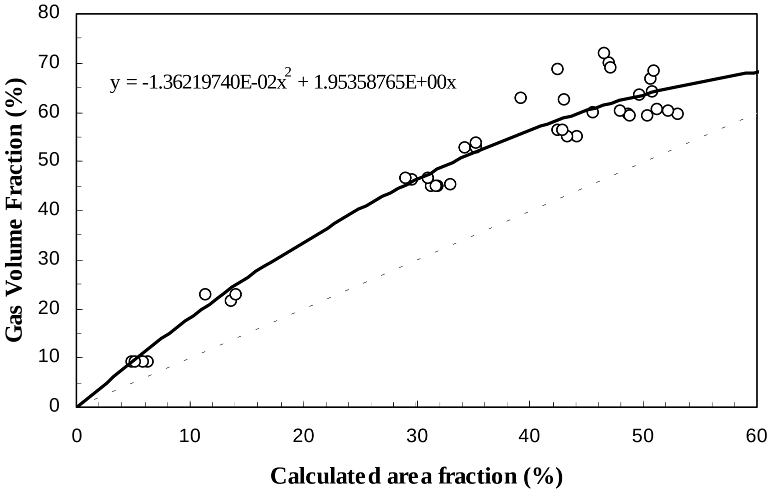

Figure 19 GVF versus area fraction calculated from ultrasonic measurements

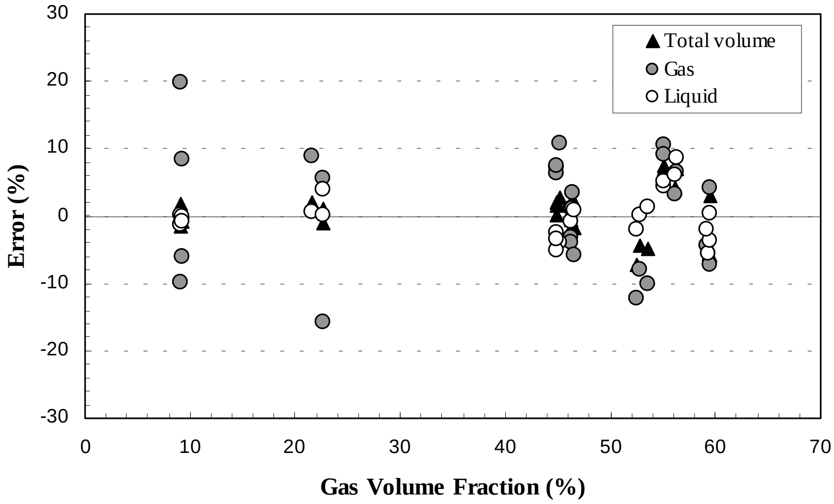

Figure 20 Error in individual phase flowrates versus GVF at 0.5 m/s liquid superficial velocity

At liquid superficial velocity of 1 m/s reasonable measurements of the gas/liquid interface could still be made. However, at 1.5 m/s and 2 m/s, the interface measurement results were not reliable as the interface was less distinct and there were increasing quantities of gas in the liquid layer.

5.2 Diagnostic Measurement Results

Various diagnostic parameters were available from the transit time ultrasonic meter. These include signal detection coefficients, apparent VOS, signal-to-noise ratios and automatic gain control values. The relationship of variations in these parameters to gas volume fraction was investigated and the most useful correlation was found to exist in the automatic gain control values. Figure 21 shows GVF plotted against a normalised automatic gain control parameter from data obtained during tests at 1.5 m/s liquid superficial velocity.

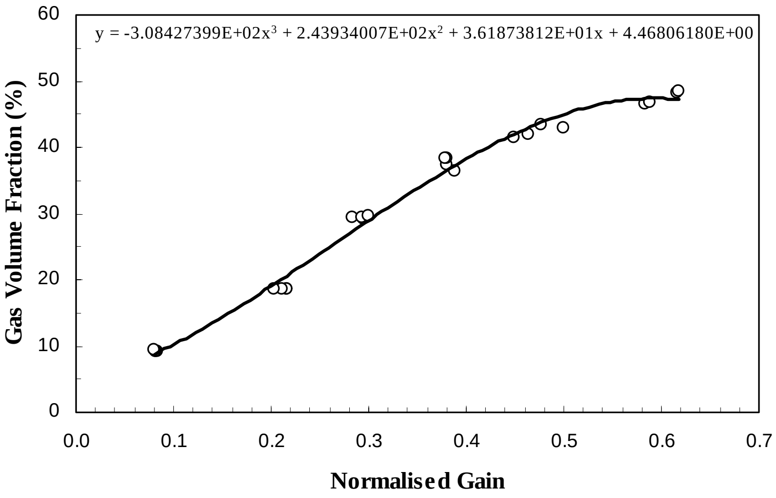

Figure 21 GVF versus normalised gain from the transit time meter

The relationship shown in Figure 21 can also be used to estimate the gas volume fraction and individual phase flowrates and to allow correction of these by plotting the volume flowrate correction factor as a function of GVF. Using the data shown in Figures 14 and 21, corrected liquid, gas and total flowrates were calculated from the ultrasonic measurements of velocity and GVF. The residual errors are less than ± 8 % relative to gas volume flowrate ± 8 % relative to gas volume flowrate as shown in Figure 22.

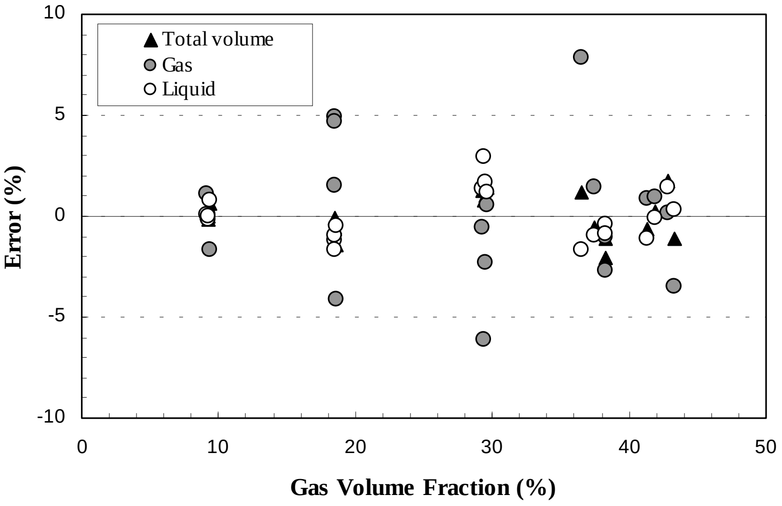

Figure 22 Error in individual phase flowrates versus GVF at 0.5 m/s liquid superficial velocity

6 FLOWRATE ACCURACY IN OIL/WATER FLOW

Oil flow tests with high gas volume fractions were conducted using the Danfoss Sonoflo flowmeter. Similar tests have been conducted previously and the aim of these tests was to collect diagnostic information for analysis with respect to performance and oil/water ratio measurement.

The results in Figure 23 show the total volume error for the meter in the oil/water tests at a nominal flowrate of 10 l/s. At 3.6% water cut the error was between 0.8 and 1.1%. At 25.6% water cut the error increased to between –0.1 and 2.9% and at 41.9% water cut the error increased further to between 1.8 and 3.3%, still with no error warnings apparent. At 59.5% water-cut the meter diagnostics indicated that the received signal on the lower path was weak and the error increased to between –3.7 and -10.5%. Between 69.5 and 75% water cut the meter indicated an intermittent upper path weak signal warning, the error reached a peak of between 3.9 and 25.8%. At 89.8% water cut the meter gave a continuous upper path weak signal warning and the error reduced again to between 3.9 and 5.3%. Finally at close to 100% water cut the meter gave no warnings and the error had dropped again to between –1.1 and +0.3%.

Also shown in Figure 23 is the average speed of sound as indicated by the meter diagnostics. As expected it shows the velocity of sound clearly increasing with increasing water cut.

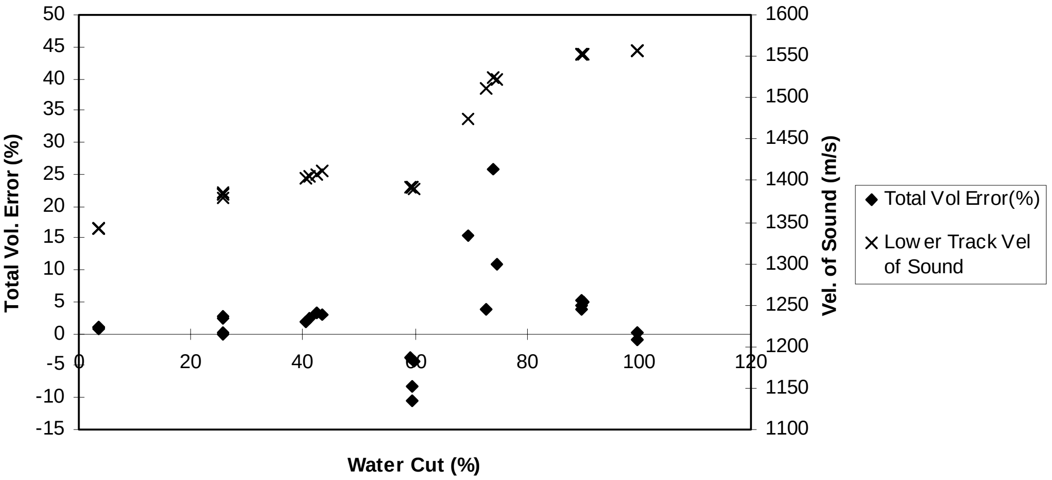

Figure 23 Meter Performance against Water Cut at 10 l/s

Figure 24 shows the total volume error at a nominal flowrate of 20l/s. No data was obtained for water-cuts between 3.6 and 60% as it was very difficult to separate the oil and water at these conditions and flowrates. At 3.6% water-cut the error was between –0.2 and –0.5%. At 60% water cut the error has increased to between –1.2 and +0.6%. At 76% water cut the error reduced to between –0.6 and +1%. At water cuts above 80% the error has reduced to between 0.1 and 0.8%. During these tests no error warnings were observed.

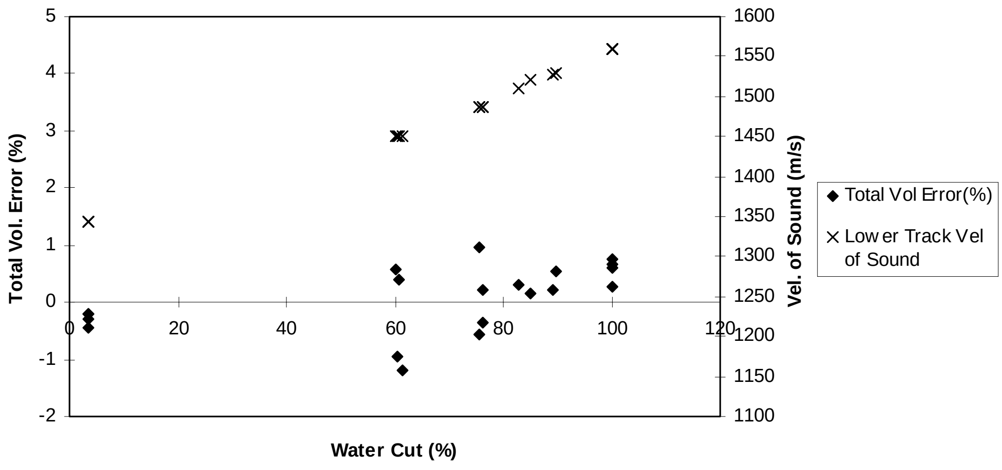

Figure 24 Meter Performance against Water Cut at 20 l/s

To demonstrate the usefulness of the observed relationship between velocity of sound and water-cut a simple linear fit to the data was made. As the data from the 10 l/s test was more complete than that of the 20 l/s test, the 10l/s test data was fitted. In order to exclude unreliable velocity of sound measurements only measurements that had a corresponding high signal-to-noise ratio (of greater than 20) were used. This condition removed measurements where a poor signal could have affected the result. The resulting meter characteristic for water-cut is shown in Figure 25.

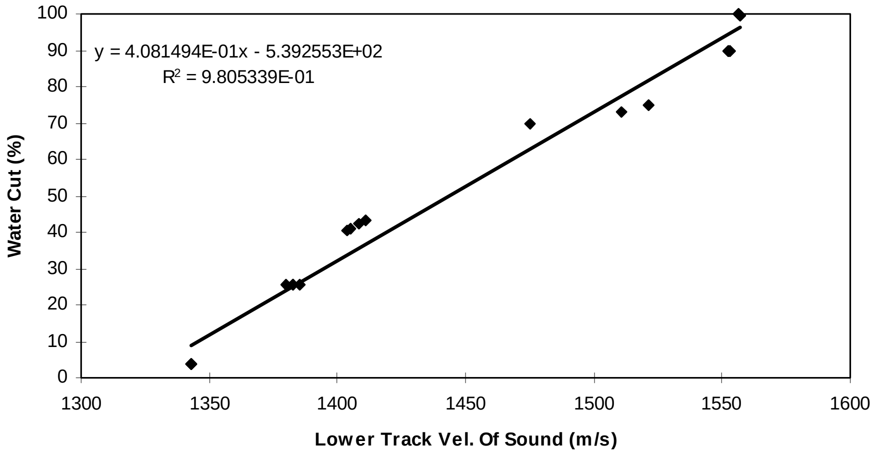

Figure 25 Linear relationship between water-cut and VOS

A linear best-fit equation was then applied to all valid (signal noise ratio greater than 20) velocity of sound measurements obtained in the during full multiphase oil/water/gas tests. The test matrix covered liquid flowrates of 5 to 16 l/s, oil/water ratios of 5, 40, and 75%, and gas volume fractions of 25 to 72%. The absolute errors in resulting water-cut predictions are graphed against the reference water-cut in Figure 26.

This graph shows that for water cuts of up to 70%, the water-cut can be predicted by the velocity of sound to within an absolute error of between –9 and +11% using a simple linear relationship.

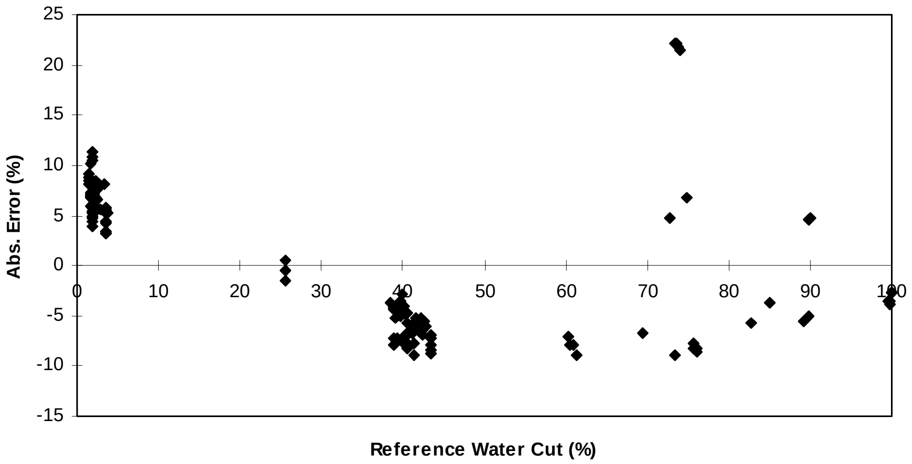

Figure 26 Water-cut error for simple linear relationship

7 CONCLUSIONS

Ultrasonic transit time measurements in liquids are adversely affected by the presence of secondary flow components. At low velocities the meter can continue to operate with high gas volume fractions but with relatively large error. At higher velocities small gas volume fractions (as little as 0.4%) can prevent the meters from measuring the velocity. At higher velocities signal-to-noise ratio or other diagnostic parameters can be utilised to indicate the onset of errors.

Reflective Doppler meters generally perform in a less accurate and less reproducible manner. However, at some conditions good results were obtained. The Doppler meter was not able to provide measurements under all conditions where transit time technique failed owing to a hardware limitation. In other conditions of application or with modification of the electronic hardware, reflective techniques may demonstrate more significant benefits.

Ultrasonic interface level measurements could be made in two-phase flows with high gas volume fractions. The measurements could then be applied to estimate the liquid and gas volumetric flowrates. This approach was limited in applicability to low velocities but could be improved upon by enhancing the level measurement instrumentation or making use of transit time signal diagnostics.

Signal diagnostics provided useful information throughout the tests giving information relating to the performance of the meters and the underlying mechanisms that affect performance. It was also demonstrated that additional information about the flow properties could be obtained.

Results from oil/water and oil/water/gas tests show promise for use of VOS measurements in determining water-cut in multiphase flows.

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