The Effects of Salinity Variation on Dual Energy Multiphase Flow Measurements and Mixmeter Homogeniser Performance in High Gas and High Viscosity Operation

P. Harrison,
Melverley Consultants Ltd, UK

S.J. Parry
TH Huxley School of Environment, Earth Science and Engineering
Imperial College, Silwood Park, Ascot, UK

G.L. Shires
Department of Chemical Engineering & Chemical Technology
Imperial College, London, UK

It is a continuing concern of those involved with multiphase flow meters using dual energy X-ray/gamma phase fraction measurement that changes in the properties of the fluids being measured will cause errors. Density changes are accommodated through known PVT relations but changes in the chemical composition of the flowing fluids must be corrected for if errors are to be avoided. While significant changes in overall hydrocarbon composition are not usually encountered, salinity of the water fraction can vary over time for some wells and this changes not only the physical density but also the mass absorption of the water. In the first part of this paper the effects of fluid property changes on dual energy measurements are discussed in relation to the energy levels most commonly used for measurement.

The second part of the paper presents recent results from the Mixmeter homogeniser which continues to demonstrate excellent characteristics as a differential pressure meter in multiphase flow. Data for high gas fraction operation is presented together with work using high viscosity emulsions.

1. INTRODUCTION

Following the successful completion of the MIXMETER development project and the transfer of the technology to Jiskoot Autocontrol Ltd., study of the performance of the two key components of MIXMETER has continued.

Essentially MIXMETER consists of a specially developed homogeniser together with a dual energy densitometer (Figure 1). The homogeniser has a very stable differential pressure characteristic. This allows it to provide reliable multiphase velocity information over a wide range of flow conditions in addition to giving homogeneous downstream conditions for the X-ray/gamma dual energy densitometer. The dual energy instrument is also unusual in using a single beam and single source (Cs 137) to providing both energies for the measurement (32keV and 661keV).
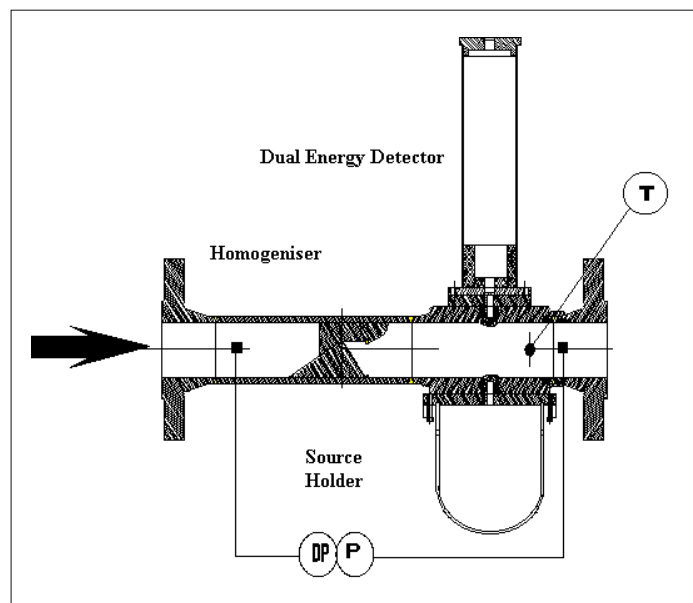

Figure 1: Mechanical Layout of MIXMETER

In relation to the dual energy system work has focussed on the sensitivity of the instrument and in particular changes in its performance which result from changes in fluid properties.

With regard to the homogeniser a detailed study of the NEL Multiflow test results has enabled a more sophisticated DP characteristic to be derived to extend the range of operation. Further, work at the Texaco facility at Humble has confirmed the ability of the device to provide reliable differential pressure velocity data when operating with high viscosity emulsions.

2. SENSITIVITY

2.1 Introduction
Dual energy phase fraction instruments can only provide accurate fraction measurements if the absorption of the individual fractions is known. The measurement parameter used for calibration is the absorption ratio which is the product of the density, the atomic mass absorption and the beam length (pipe diameter). If absorption ratio values change then measurement errors will occur. The atomic mass absorption is dependent on the atomic composition of the phase. Fortunately the overall composition of the hydrocarbon is not likely to change and density variations are taken account of through PVT corrections. Also, in many applications, the composition of the produced water is either unlikely to change or it is possible to take occasional samples for analysis. However there are applications where sampling is not convenient and where water composition may change dramatically; eg where water injection is used or where water driven downhole pumps are installed. Such changes are particularly significant as the atomic mass absorption changes (eg due to addition/subtraction of sodium, potassium, calcium, chlorine atoms etc.) aswell as the physical density.

To allow investigation of uncorrected changes in fluid composition a computer model of a full multiphase matrix has been used together with absorption ratios from laboratory measurements.

2.2 Salinity Variations
The effect of a change in salinity will be most apparent in the water cut measurement. An increase in salinity will increase the water absorption and will result in a perceived increase in water cut. Liquid fraction will increase slightly and oil fraction will decrease. A reduction in salinity will have the opposite effect and these changes will alter the measured oil flowrate by an amount which will depend on the original water cut and GVF.

The sensitivity depends on the energies used in the dual energy instrument and in addition to the 32keV and 661keV pair from Cs 137 used in MIXMETER, absorption measurements were been made for 59keV (Am 241 or W x-ray) and 80keV (Ba 133 or Pb x-ray).

Figures 2 and 3 show the effect on water cut for salinity changes from a base level of 50g/l for a 32keV/661keV dual energy combination and for a 59kev/661keV combination.
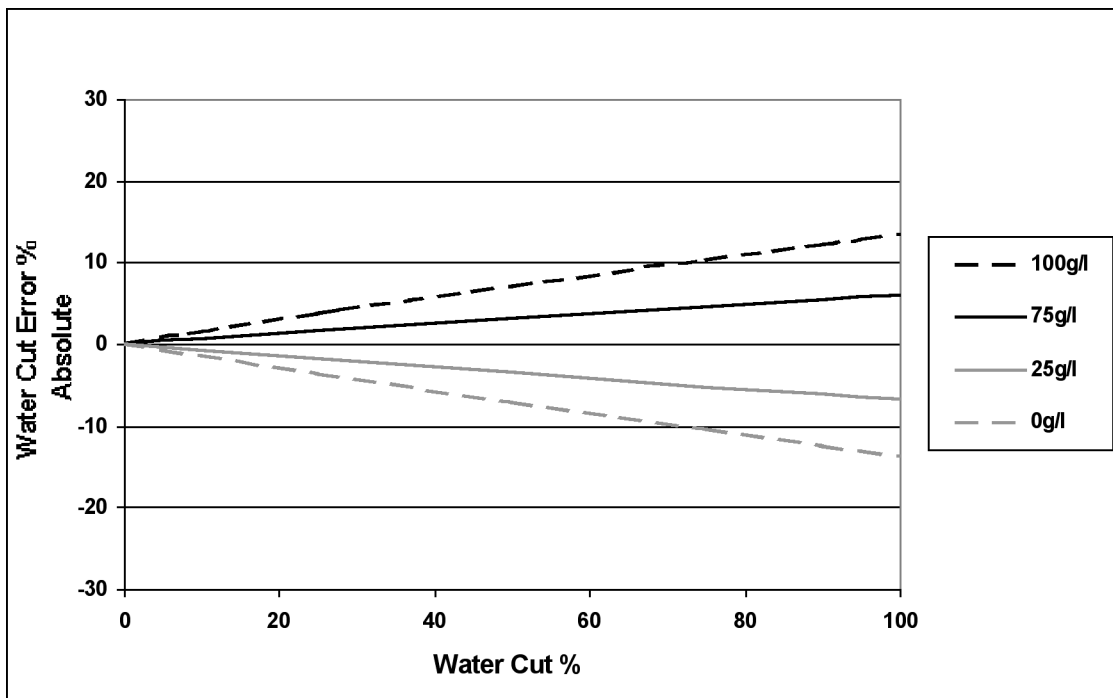
Figure 2: Water Cut Error due to Salinity Changes from 50g/l 32keV/661keV Dual Energy Gamma
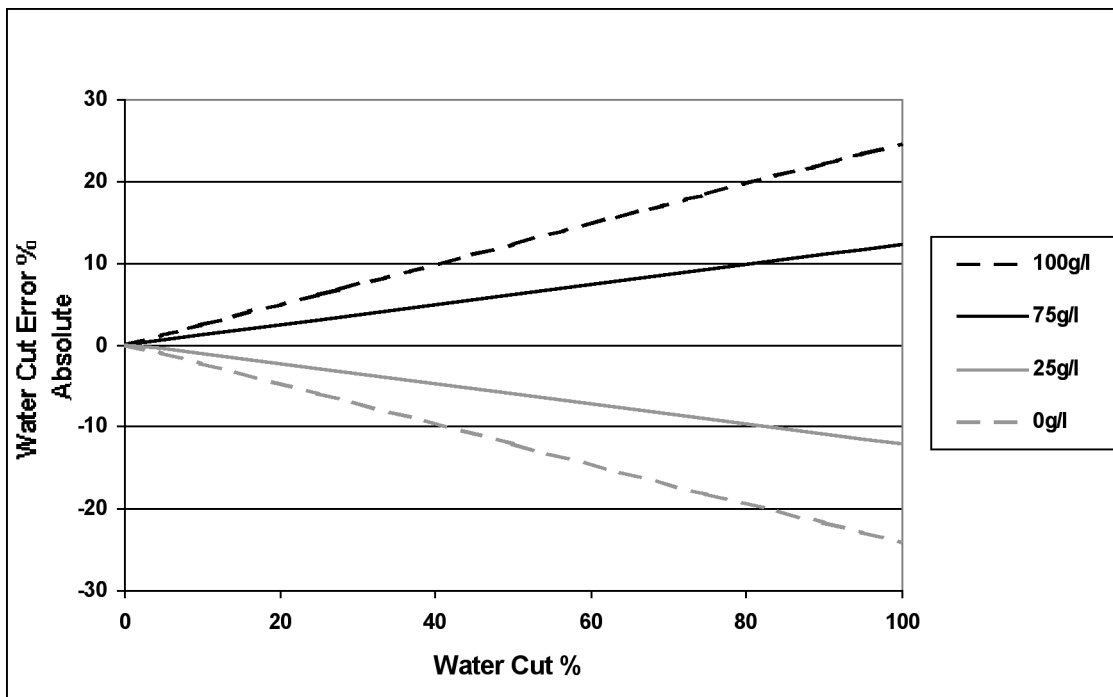

Figure 3: Water Cut Error due to Salinity Changes from 50g/l 59keV/661keV Dual Energy Gamma

It should be noted immediately that large changes in salinity have been used to produce the errors shown. Calibration errors will normally be less than 1g/l and will have a very small effect.

The effect is linear with respect both to initial water cut and to the change in salinity.

It can be seen that the 59/661keV combination appears to be more sensitive to salinity changes than the 32/661keV combination.

A third combination of energies commonly used in dual energy work is 30/350keV from Ba 133. As absorption under these conditions is very similar for all energies above 100keV this combination will respond in a similar manner to the 32/661kev combination.

The magnitude of the errors also depends on the density of the oil phase. The absorption ratio for a light oil (800kg/m3) has been used to generate the figures above. If a heavier oil is present (900kg/m3) the errors reduce by a factor of approximately 1.15.

The effect of the changes in salinity on the oil fraction and hence the final oil flowrate will depend on the water cut and the GVF. Figures 4 and 5 show the absolute oil fraction errors resulting from the 50g/l to 100g/l salinity changes shown in Figures 4 and 5.

The errors shown are absolute and, as may be expected, the errors in oil fraction become greater as water cut increases and as GVF decreases. However, once again, a large increase in salinity (50g/l – 100g/l) has been used to generate these changes.
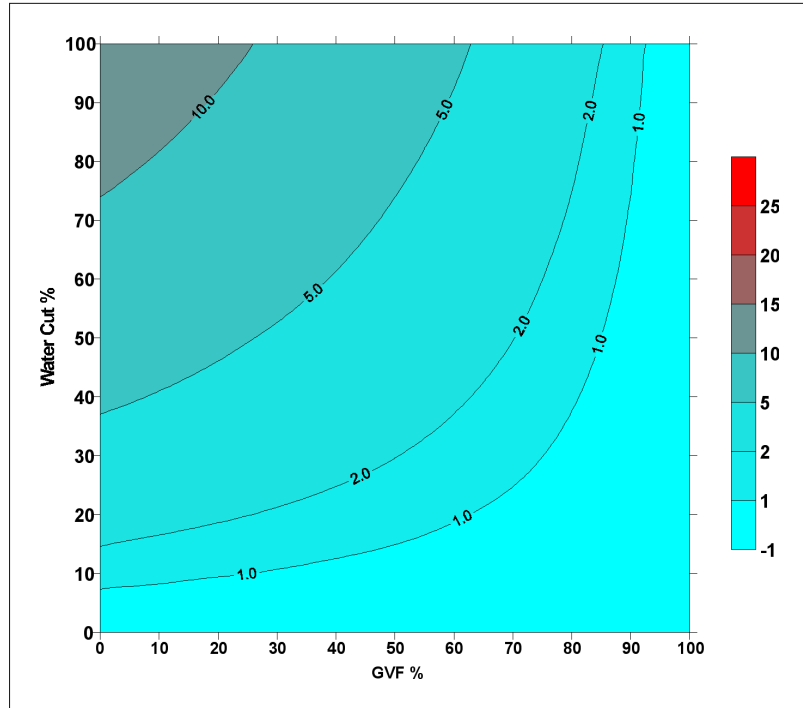
Figure 4: Absolute Oil Fraction Error due to Salinity Change from 50g/l to 100g/l 32keV/661keV Dual Energy Gamma
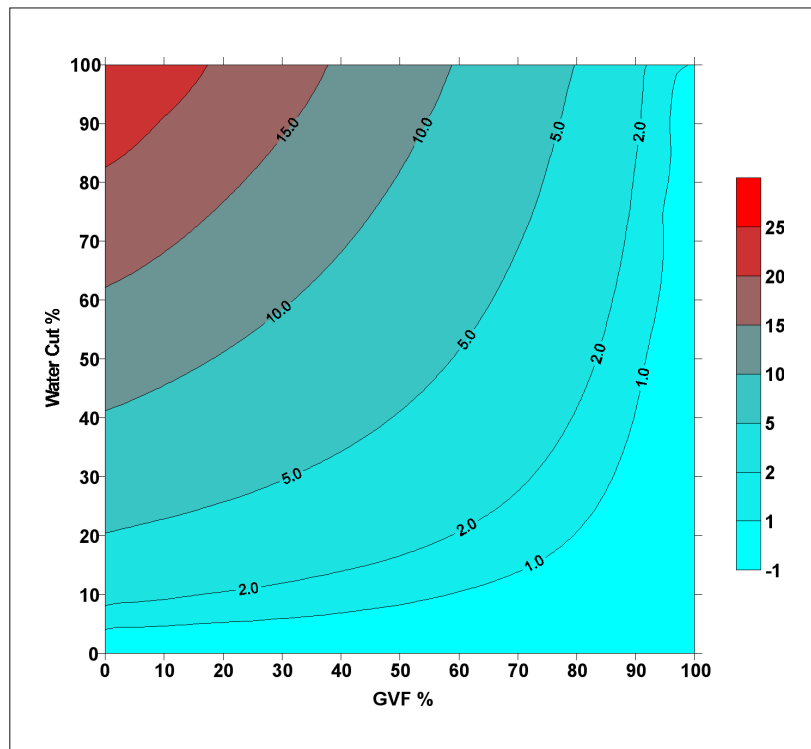

Figure 5: Absolute Oil Fraction Error due to Salinity Change from 50g/l to 100g/l 59keV/661keV Dual Energy Gamma

The reasons for these performance differences become apparent when the responses of the energy level pairs to oil/water/gas mixture are considered. The following Figures 6 and 7 show graphically how the responses interact. Figure 6 is for 32/661keV combination. The hatched lines show the 661keV energy absorption ratio for the full range of phase combinations and the plain lines show the 32keV absorption ratios. The resolution of the measurement depends upon the angle of intersection of the two sets of response lines and the precision depends on the range of the absorption ratios.
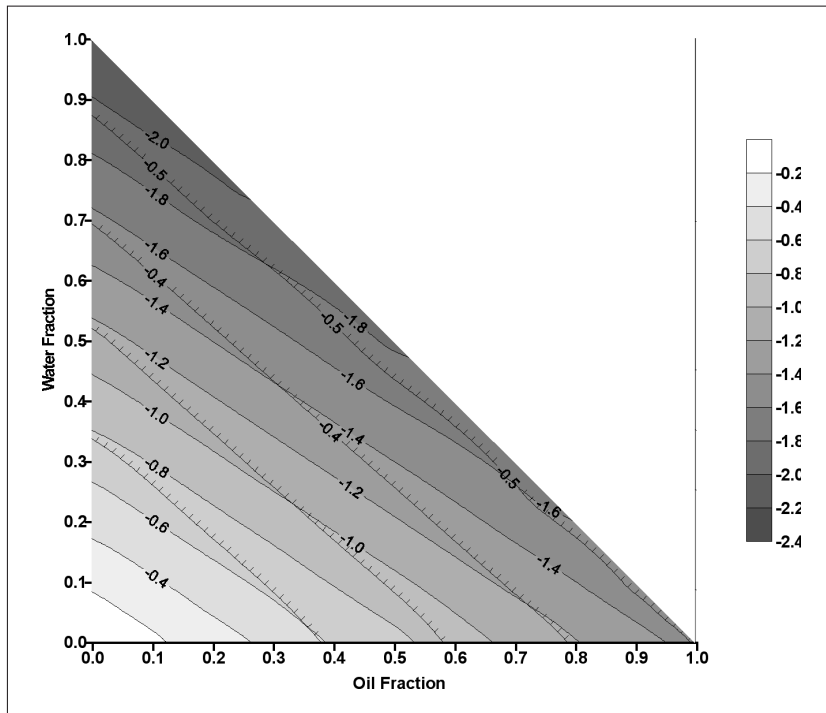

Figure 6: 32keV/661keV Dual Energy Response

Figure 7 shows the same plot for the 59/661keV energy combination. It is clear when comparing the two figures that the angle of intersection of the absorption lines is less for the 59/661 combination and also that the range of 59keV absorption ratio is less than for the 32keV. The 32keV/661keV combination offers better resolution and precision than the 59/661 keVenergy pair.
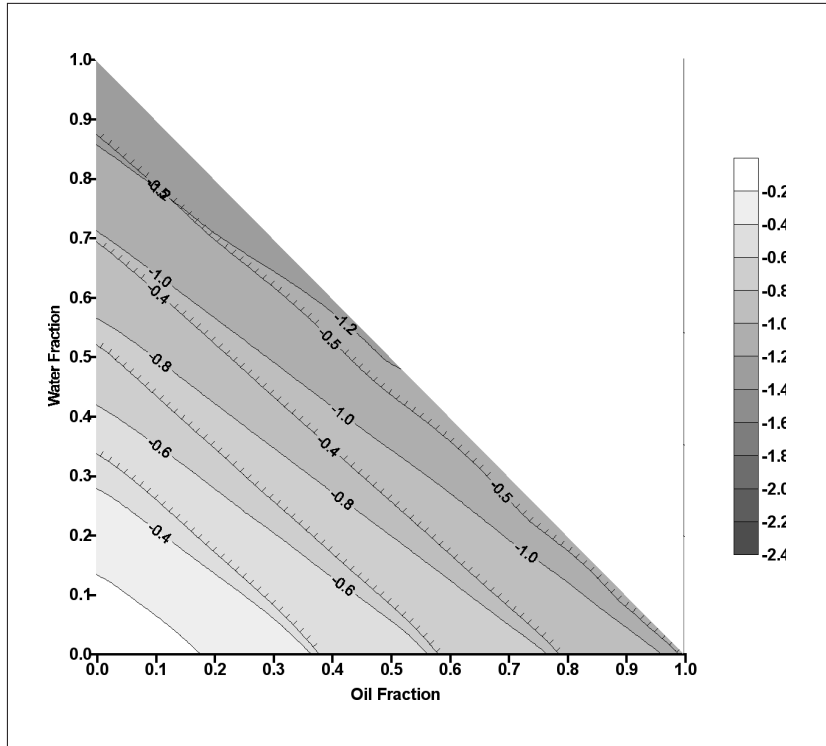
Figure 7: 59keV/661keV Dual Energy Response

2.3 Oil Density Variations

As noted in 2.1 above uncorrected variations or errors in oil density have a much smaller effect on dual energy measurements. Figure 8 shows the oil fraction error resulting from an uncorrected 5% increase in oil density imposed on a system with 50g/l salinity. Errors shown below are absolute oil fraction errors. These errors increase exactly in step with increasing oil fraction such that the relative error is constant at 5%. That is to say that an error in oil density calibration or an uncorrected change in oil density due perhaps to PVT error will be reflected in an almost exactly similar error in the oil measurement.
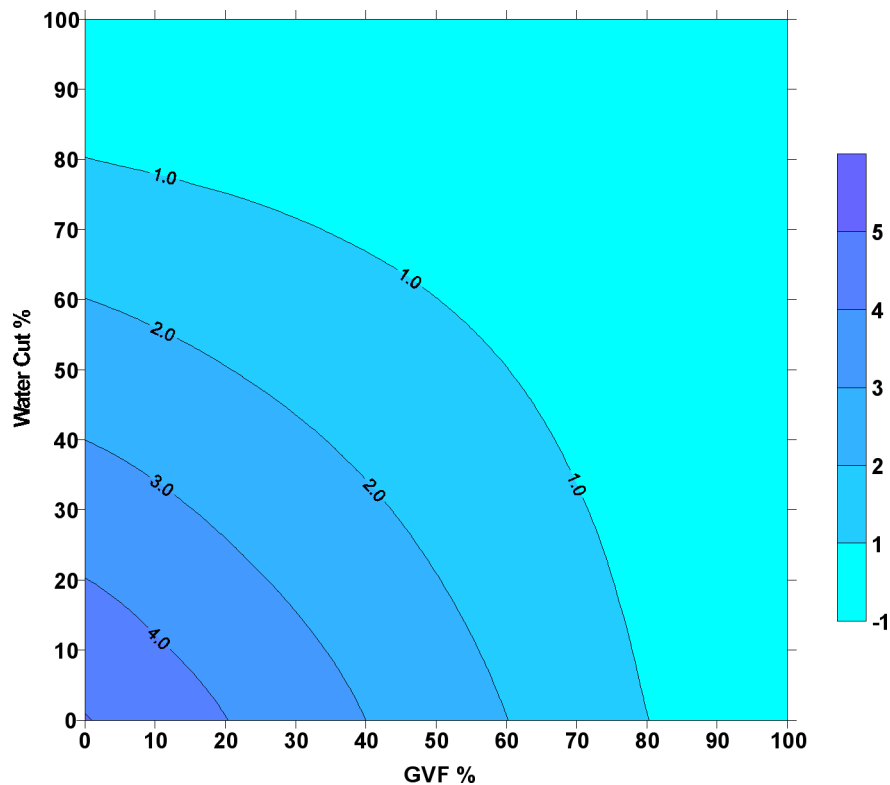
Figure 8: Absolute Oil Fraction Error due to Oil Density Change from 800kg/m3 to 840kg/m3 32keV/661keV Dual Energy Gamma

2.4 Conclusions

The work briefly described above shows some examples of how the effects of individual and combined uncorrected errors in calibration of dual energy instruments can be modelled and studied. By using data for intended applications field behaviour of the instrument under 'upset' conditions can be predicted.

Errors of this type will be systematic and will add to any random errors which may be present.

As noted from earlier work the small errors in oil density which may arise from PVT calculations will have a relatively small effect on the instrument. Also, small changes in salinity do not lead to large errors in absolute water cut. However the errors are systematic and where the salinity change and water cuts are high the effect on oil rate will be severe.

There are however a number of quite simple safeguards. The most obvious of these is the stability of the liquid fraction or GVF measurement. In the most extreme case of salinity change noted above (50g/l to 100g/l) the GVF error moved by less than 1% relative. Any rapid step changes in salinity such as injection breakthrough will therefore be apparent as a large swing between oil and water flows with total liquids staying the same. Basic trending enables this type of occurrence to be flagged easily. As a consequence of the same GVF stability, in situations where water cut is high increased salinity will rapidly lead to negative oil fractions being noted by the instrument, again indicating a change in fluid propertes and a need to recalibrate.

3. SALINITY MEASUREMENT

3.1 Introduction
Ideally an on line measurement of salinity is required in order to allow automatic correction for any changes. The addition of more instruments is not desirable and a solution where the existing dual energy system can be enhanced to include the additional measurement seems most attractive.

In simple terms the current systems with two energies allow three fractions or components in the pipe to be measured: two directly and the third by difference. A third energy will allow the additional salinity measurement to be made.

This idea is not new and is a simple extension of the dual energy method. A discussion of the principle was given by Scheers Ref (2). However practical implementation is difficult due to the need to obtain three energies of radiation of the correct levels to provide discrimination and of sufficient intensity to allow penetration of the fluid to be measured. The three energies of Am 241: 18, 26 and 60keV proposed in Ref (2) work well but the penetrating power of the two lower energies restricts application to very short path lengths and low liquid fractions.

3.2 Test Work
During the last few months work has been carried out using an additional 59keV energy peak added to the 32keV and 661keV peaks used in MIXMETER. The following Figure 9 shows that this is about the ideal triple energy system to use with the salinity calibration lines for the three energies evenly spaced. Previous tests with a 75keV peak proved unsuccessful as the response of this higher energy peak was too similar to that of the 661keV peak.
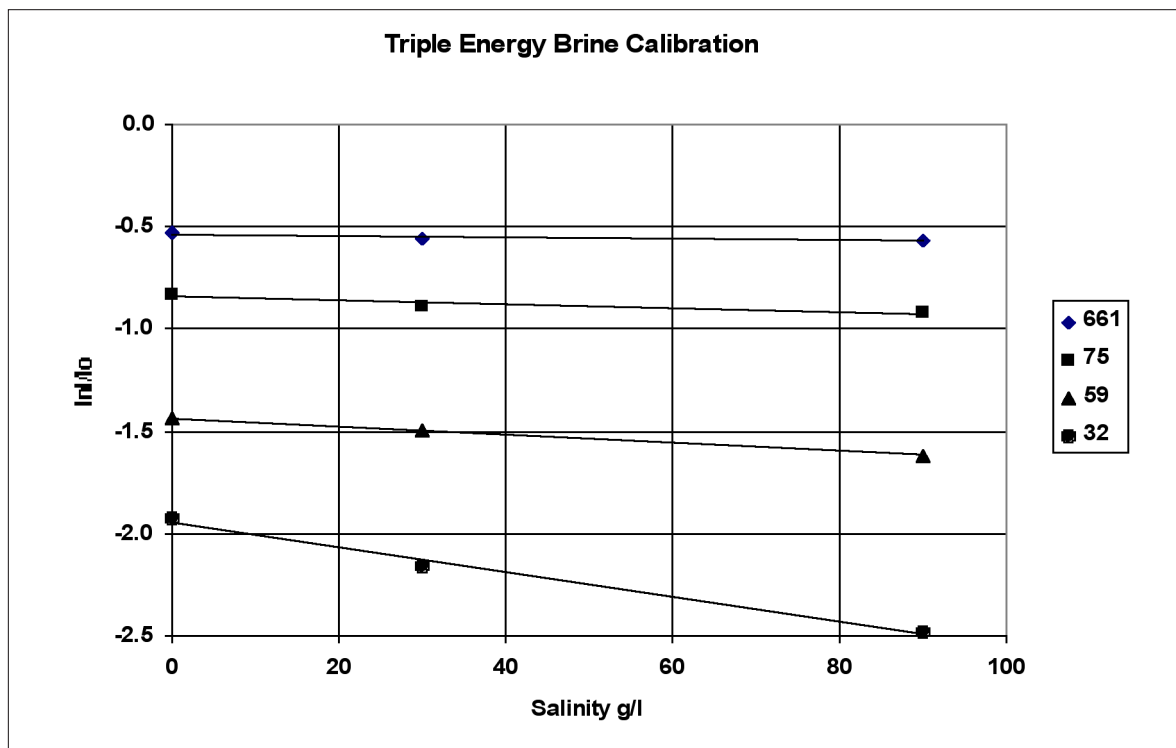

Figure 9:   Brine Calibration, 661, 75, 59 and 32keV X-rays

Even with this 'optimum' combination it is very difficult to obtain consistent salinity measurements due to the need for extremely high precision for the measurement and calibration data. This can be appreciated by referring back to Figures 6 and 7 and considering the difficulties in working with the 32 and 59keV absorption grids. The MIXMETER system normally operates with measurement and calibration uncertainties to around 0.1% whereas to work with three energies and over a range of GVF's and water cuts a further order of magnitude of precision is needed. It seems most unlikely that this can ever be achieved when the various sources of uncertainty are considered. However the opportunity remains to detect salinity changes when significant quantities of water are present and this will be pursued.

4. HOMOGENISER PERFORMANCE

4.1 Differential Pressure Velocity Measurement
The performance of the mixer as a multiphase differential pressure meter is crucial to the operation of MIXMETER and the unique ability of the device to maintain the same calibration characteristic over a wide range of liquid fractions was discussed in a previous paper (Ref 1).

The relationship used is

$$\Delta p = k\, U^2\, \varepsilon_L \tag{1}$$

Where U is the total superficial velocity, k the resistance factor of the mixer and ε_L is the total liquid fraction in the homogenised region ($\varepsilon_{L} = \varepsilon_{O} + \varepsilon_{W}$).

ε_O and ε_W are the (measured) phase fractions in the homogenised region downstream of the mixer.
l
This relationship approximates the homogenous model where $\rho_G \ll \rho_O$ or ρ_W and $\rho_W \approx \rho_O$ but has been found to be more accurate as liquid properties vary. Indications are that density and viscosity effects offset each other.

Clearly the relationship will break down at some point as ε_L approaches zero in high gas and, generally, high velocity situations.

Limitations of available test rigs resulted in earlier work with the 4" meter being restricted to a maximum velocity of around 10m/s. Also, little work had been carried out at liquid fractions less than 10%. The claimed operating range of MIXMETER was therefore quoted as being within these limits. However the NEL Multiflow tests using a 3" meter allowed collection of a considerable amount of data at higher velocities and at lower liquid fractions and it was hoped that the results would allow some extension of the operating range of the meter.

Figure 10 shows the velocity characteristic of the 4" meter as determined at NEL and Trecate. The mixer differential pressure is plotted against the square of rig total superficial velocity multiplied by the liquid fraction (see equation 1).
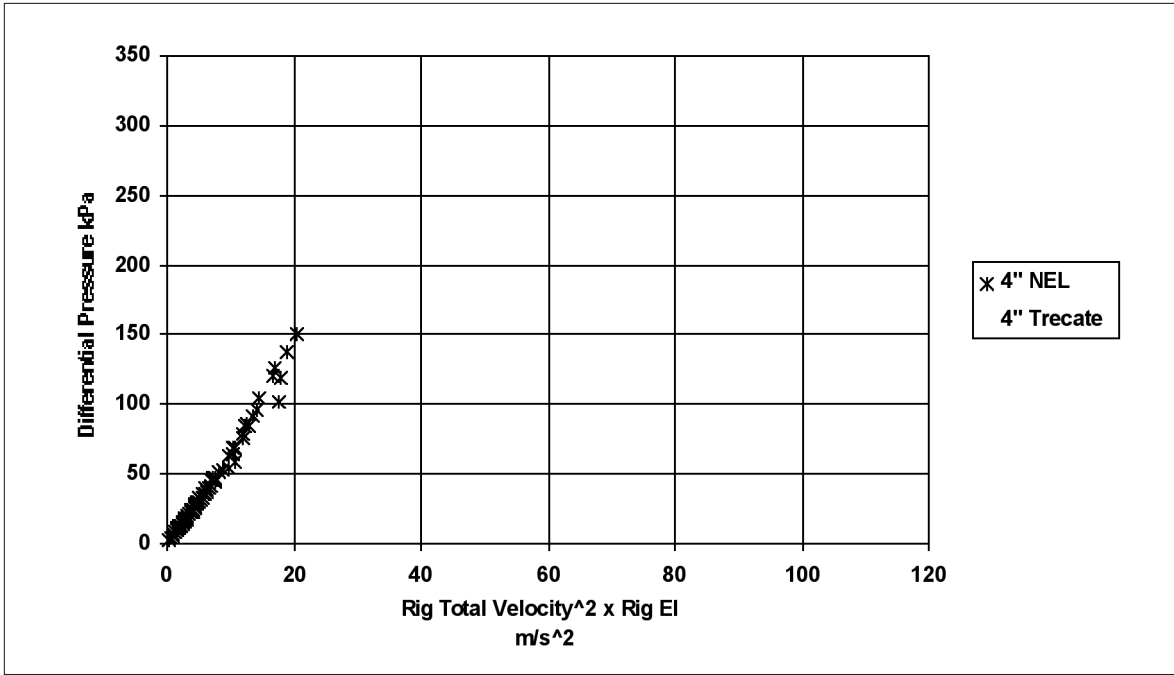
Figure 10: 4" Meter Differential Pressure Characteristic

Data is plotted on the same scale as later figures to allow comparison.

A similar plot for the 3" meter from Matrix 1 of the Multiflow tests is shown in Figure 11. A simple straight line calibration for the 4" meter is also shown for comparison.
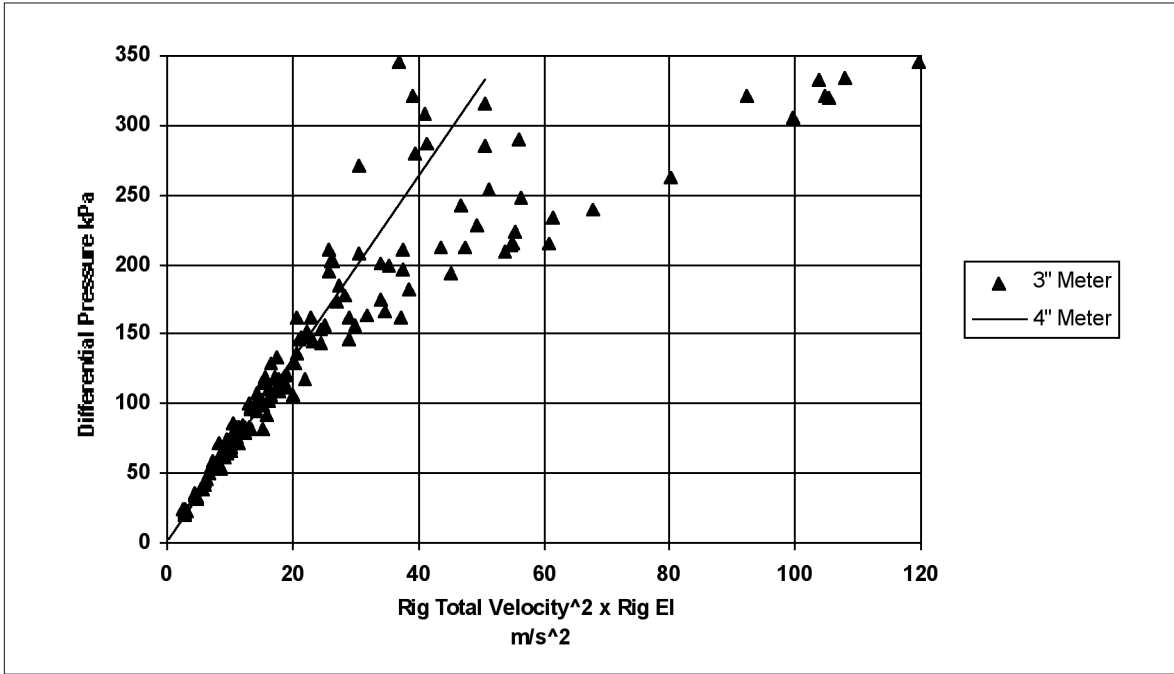

Figure 11: 3" Meter Differential Pressure Characteristic

The scattering as the velocity term increases does not look encouraging. However the data falls into groups based on liquid fraction allowing Figure 12 to be plotted to provide a basic family of calibration curves.
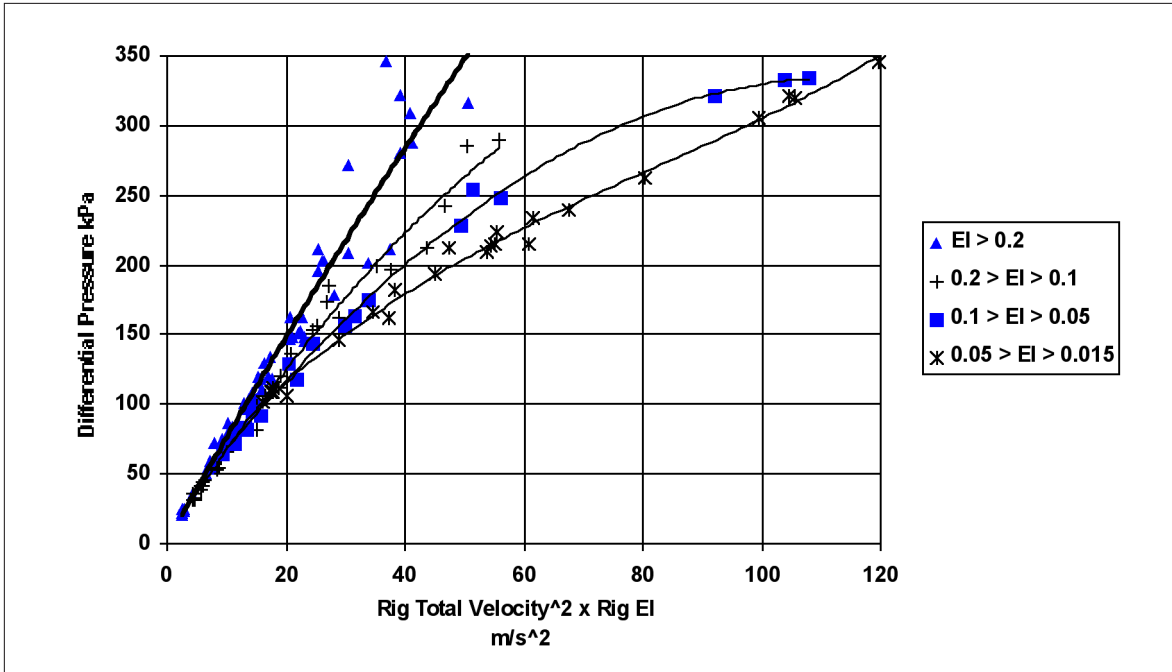
Figure 12: 3" Meter Differential Pressure Characteristic: 0.015 < El < 1.0

Figure 12 above shows that a reasonable characteristic can be derived even for liquid fractions down to below 2%. However it becomes increasingly difficult for the gamma instrument to determine liquid fraction at these levels.

Selecting those test points with liquid fractions above 5% and by applying the above calibrations velocity measurements are obtained as shown in Figure 13.
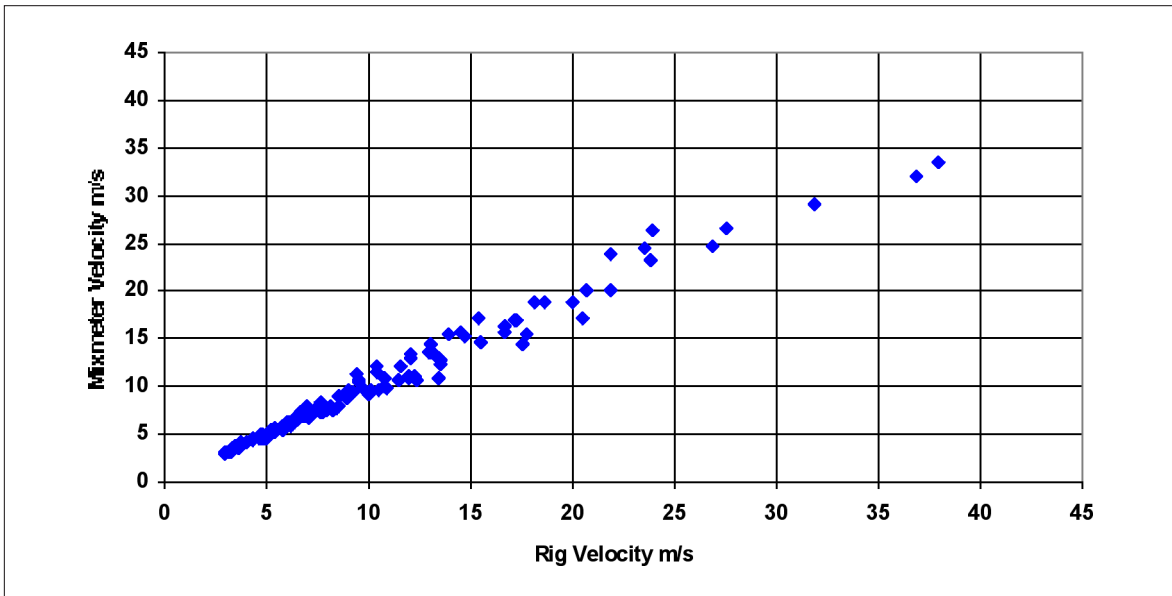

Figure 13: 3" Meter Total Velocity Measurements for Liquid Fractions above 5% NEL Multiflow Matrix 1

Figure 13 suggests that even with the increasing uncertainty of liquid fraction measurement at very low fractions MIXMETER can perform adequately at velocities up to 20m/s and with gas fractions up to 95%.

Enhanced Overall Performance

By using the improved DP calibration liquid and gas flowrate errors for the full NEL Multiflow Matrix 1 test range are as shown in Figs 14 and 15.

Errors are presented in the form of contour plots which allow the error to be plotted against two other variables, in this case reference water cut and GVF. This type of plot was used by the NEL Multiflow JIP and is very helpful in allowing three variables to be viewed together. However these plots can also be very misleading as the software extrapolates outside the data points. In this case there are almost no points below 25% GVF and the entire left hand quarter of the plot is therefore fabricated. It is seen as essential in using this type of plot that the data points are mapped onto the plot as has been done here so that the extent of the data can also be seen.

Liquid rates ranged from 3l/s to 23l/s and gas rates were between 5l/s and 75l/s.

For velocities up to 20m/s and GVF's up to 95% RMS error for liquid flowrate was just over 5% and for gas flowrate was 8.4%.
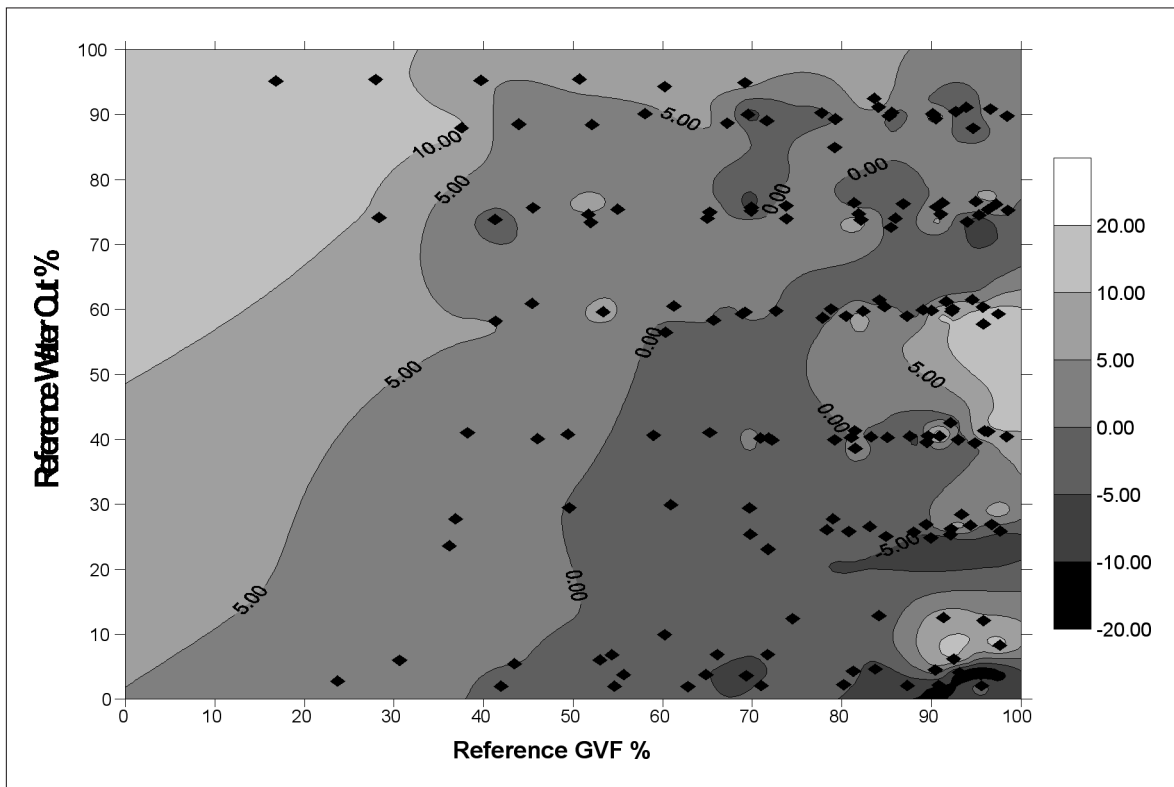

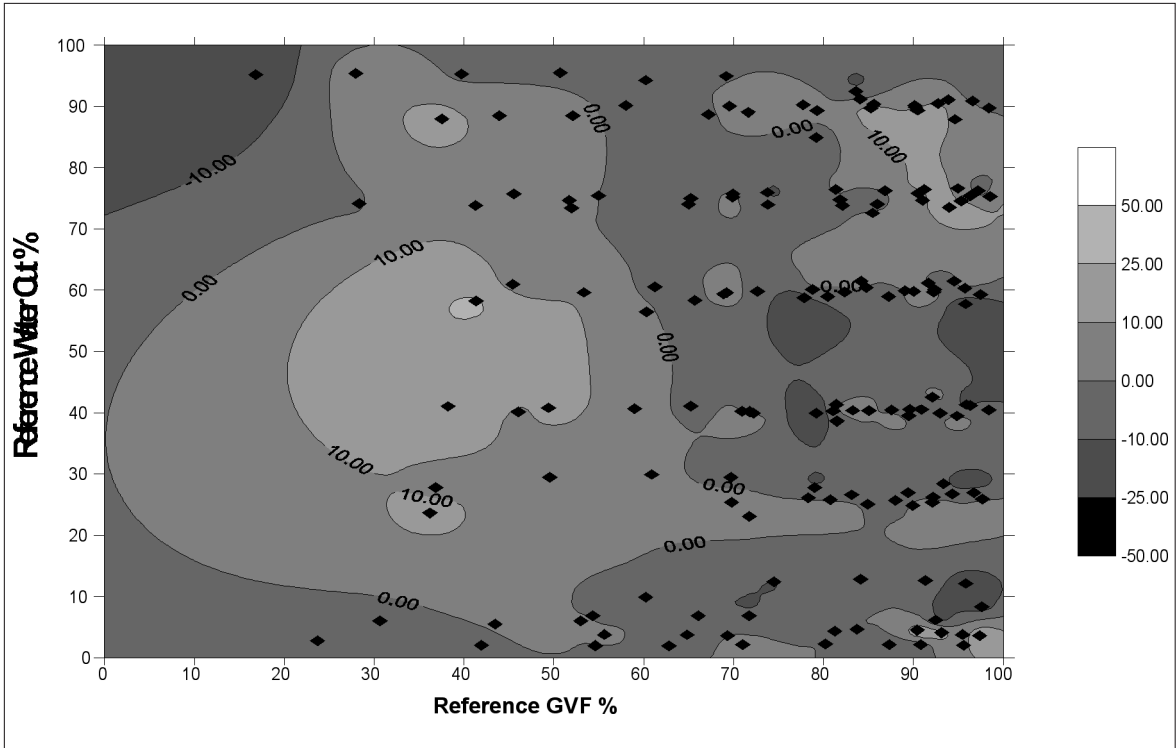*Figure 14:   3" Meter Liquid Flowrate Error vs Rig Water Cut and GVF*

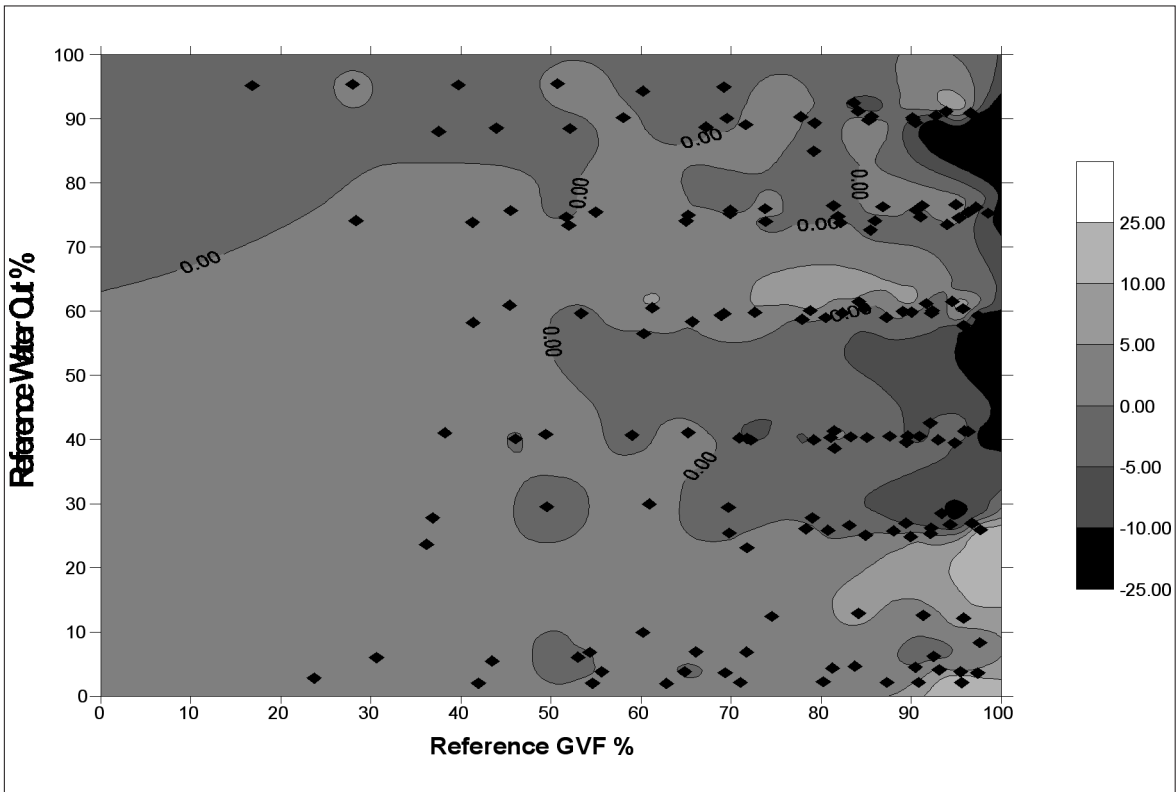*Figure 15: 3" Meter Gas Flowrate Error vs Rig Water Cut and Rig GVF*

Figure 16: Absolute Water Cut Error vs Rig Gas Fraction

Within the operating range noted above RMS absolute water cut error is 4%. This increases to 5% when only results with gas fractions over 80% are considered and to 6.2% for all results with over 90% gas fraction (ie 90% -95% gas).

4.2 Viscous Crude Tests

Late in 1998 the 3" Production Prototype meter was taken to the Texaco Flow Facility at Humble in Texas for tests with a heavy, viscous crude oil. For comparison these tests were followed by a second series using a much lighter crude corresponding closely to the oils used at NEL.

The heavy crude has an API gravity of 19 and density during the tests was typically 915 kg/m3. The oil forms viscous emulsion with water. At typical test temperatures, around 35degC, dead oil viscosity was approximately 300Cp rising to approximately 1300Cp at 50% water cut. Methane gas (typical density 8kg/m3 at test conditions) and a brine containing 26g/l of salts were used. 22 test points were run with water cut varying from 6% to 99% and liquid fraction from 0.03 to 0.90.

The lighter crude has an API gravity of 32 and typical density during the tests was 820kg/m3. Viscosity is estimated at around 4Cp. The gas used for the tests was a field gas (typical density 11kg/m3 under test conditions) and a brine solution containing 96g/l of salts was used for the associated water. 50 test points were run with water cut varying from 5% to 90% and liquid fraction from 0.03 to 0.90.

It had been hoped to run at higher pressures but tests were limited to around 12bar downstream of the mixer.

Results

Differential Pressure: The differential pressure characteristic for both crudes for liquid fractions above 0.2 is shown in Figure 17. It can be seen that there is very little difference between the two sets of data. Maximum velocity was limited by the rig and few points were run below a liquid fraction of 0.2. However these are plotted in Figure 18 and it can be seen that the trend for both crudes is moved to the right in the same way as the low liquid fraction results for the NEL tests discussed in Section 3.0 above.
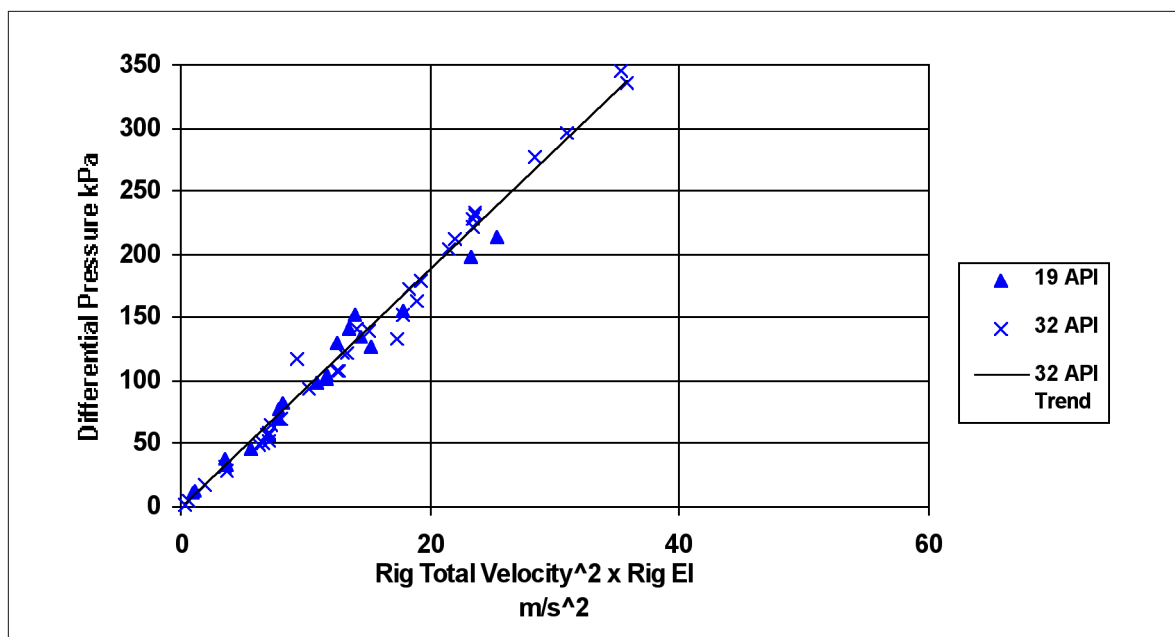

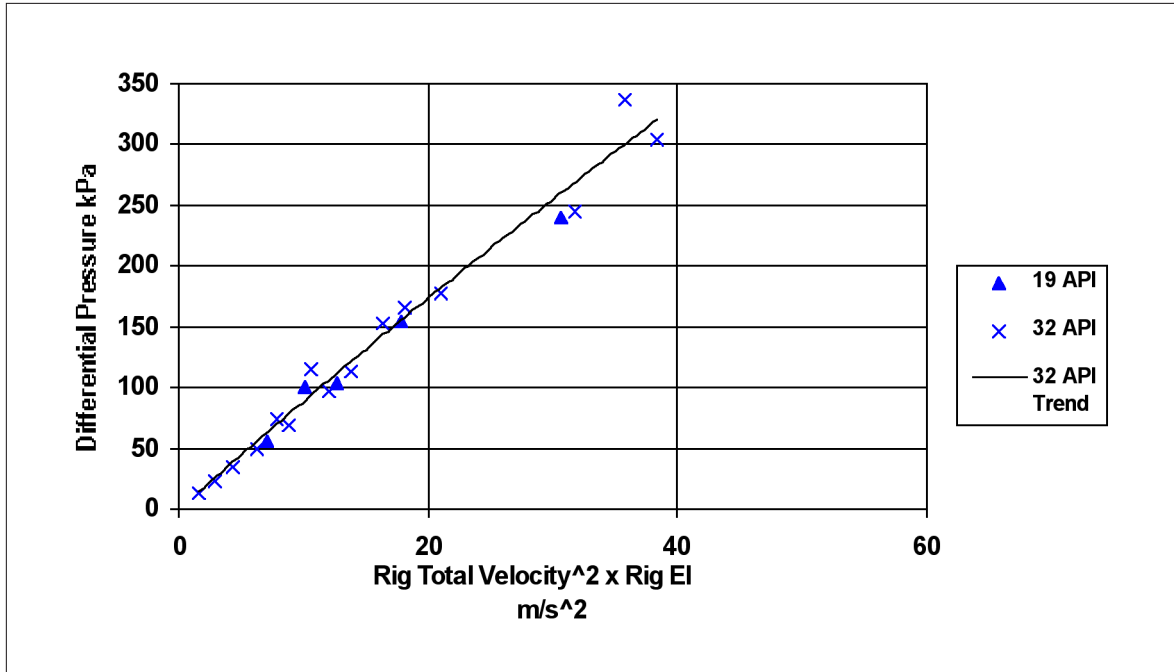*Figure   17: Differential Pressure Characteristic Humble Tests*
El > 0.2

Figure 18:   Differential Pressure Characteristic Humble Tests El < 0.2

4.3 Conclusions

Detailed analysis of the NEL Multiflow data suggests that use of a more sophisticated calibration for the homogeniser differential pressure will allow operation at total superficial velocities up to 20m/s and liquid fractions as low as 5% with no significant increase in errors.

The NEL tests provided very difficult conditions for MIXMETER due to the low pressure regime and the emphasis in the test matrix on high gas fractions. However results were very satisfactory with RMS errors for the main matrix based on original meter operating limits of 5.1% for liquid rate, 7.3 % for gas rate and 3.4% for absolute water cut.

It also seems clear from the test performed at Humble that the differential pressure characteristic is not sensitive even to fairly large changes in viscosity and density.

Full results are not presented here but as might be anticipated there were no problems with the dual energy measurements when using the heavy crude and the instrument functioned normally even when the line contents were transformed to a stiff 'mousse' at the end of a full day of circulation.

7.0 FINAL CONCLUSIONS

Systematic errors in dual energy gamma phase fraction instruments which can arise due to calibration errors or changes in fluid properties during operation can be predicted readily using a simple model together with absorption data for fluids which can be taken from laboratory measurements or calculated from chemical composition data.

For a 'typical' set of oil, gas and water properties errors in oil density lead to relative errors in oil fraction and flowrate of a similar size. eg a 5% increase in oil density will result in a 5% relative increase in measured oil fraction.

An error of this magnitude is unlikely and the instruments are generally very tolerant to anticipated errors in hydrocarbon properties.

Large changes in salinity can cause significant water cut errors to occur where water cuts are high. However the nature of these errors is such that GVF remains essentially constant so that it is possible to identify changes of this type through standard trending of the instrument output.

Use of a third energy to measure salinity offers a simple and direct method to avoid errors due to salinity changes. However, even using the best spread of energy levels within the range which is practical for normal pipe diameters the measurement is too sensitive to be of practical use. The method may be feasible if lower energies are used with small diameter lines or when liquid fractions are low. However, for applications where salinity is expected to vary and where sampling is not an option an alternative method of monitoring the water quality may be needed.

Data from the NEL Multiflow tests has enabled the MIXMETER homogeniser DP characteristic to be extended such that the operating range of the meter is now up to 20m/s and 95% gas fraction.

The mixer characteristic could be extended beyond 95% gas fraction but it becomes more difficult for the dual energy instrument to measure liquid fraction under these conditions.

Tests with a heavy crude forming a viscous emulsion have demonstrated that the homogeniser maintains its characteristic under these adverse conditions.

References:

(1) Hewitt, G.F., Harrison, P.S., Parry, S.J. & Shires, G.L. (1997) "The 'MIXMETER' flowmeter: Another Step Towards Routine Multiphase Flow Measurement?" Multiphase '97, Cannes

(2) Scheers, A.M. (1998) "Multiple Energy Gamma Ray Absorption (MEGRA) Techniques Applied to Multiphase Flow Metering" 4th International Conference on Multiphase Technology, London

(3) Hewitt, G.F., Harrison, P.S., Parry, S.J. & Shires, G.L. (1995) "Development and Testing of the Mixmeter Multiphase Flowmeter" North Sea Flow Measurement Workshop, Lillehammer