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DEVELOPMENT AND TESTING OF THE "MIXMETER" MULTIPHASE FLOW METER

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DEVELOPMENT AND TESTING
OF THE
'MIXMETER' MULTIPHASE FLOWMETER

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SUMMARY

The MIXMETER multiphase flow meter has been developed over the last three years by Imperial College and SGS Redwood through a project sponsored by the UK Offshore Supplies Office (OSO) and a consortium of oil companies.

This paper traces the development of MIXMETER from pre-project studies through to tests of a 3" (76mm) laboratory prototype on the Imperial College WASP multiphase flow rig and on the National Engineering Laboratory (NEL) multiphase flow facility. Test results from NEL are presented.

A 4" (100mm) field prototype has now been built and will undergo trials at an oilfield test site early in 1996.

Performance to date is extremely encouraging, patents have been applied for and discussions are in hand with potential commercial manufacturers.

GENERAL DESCRIPTION

MIXMETER comprises a specially developed static mixer (homogeniser), a dual energy gamma phase fraction instrument and a second gamma instrument for cross correlation velocity measurement. Velocity is also determined from the mixer differential pressure.

A schematic of the laboratory prototype is shown in Figure 1.

MIXMETER DEVELOPMENT

Background

The commercial advantages to the industry of a proven multiphase flow meter have been well documented in the past:

Reduced need for separate well test lines

Reduced need for test separators and hence
weight saving on offshore structures

Improved reservoir management

Although the potential cost savings for a subsea installation are most striking a meter of sufficiently low price would also find application for topsides and land based installations. A phase fraction meter would also appear to have commercial possibilities in its own right.

Pre-project Studies

By the mid 1980's a number of techniques had been tried and various groups across the oil industry together with some manufacturers were pursuing R&D projects with the aim of developing a metering system. However, it was becoming apparent that there would be no quick and easy solution. Therefore, the UK Department of Energy through the Offshore Supplies Office (OSO) and the Offshore Energy Technology Board (OETB) commissioned two studies in order to review the technical and commercial situation and hopefully to identify a technical route which had the best chance of success in addressing industry requirements.

Both reports were commissioned through Imperial College but other organisations working in multiphase flow were involved (The National Engineering Laboratory, SGS Redwood, AEA Harwell) in addition to potential users, particularly Texaco and Shell.

OETB report OTN 88-195 reviewed an extensive range of methods for mass metering of multiphase flows with emphasis on techniques which would be suitable for eventual subsea application. This report demonstrated the significant advantages of homogenising the flow prior to making measurements and identified a number of measurement techniques which could be expected not only to provide the performance required but also to result in a device which was commercially viable.

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The second report, OETB No.OTN 90-175, was a project definition study for a meter based on homogenisation. This confirmed that homogenisation was feasible in terms of the basic physical ability to retain a homogenised mixture of oil, water and gas over sufficient length in a pipeline to allow measurements to be made without at the same time having to use so much energy that stable emulsions would be formed. The report also investigated further the measurement techniques which offered the best opportunity to achieve the desired results.

Techniques selected for further evaluation through an R&D project were:

Multi-energy gamma for phase fraction

Gamma cross correlation for velocity

Alternative methods selected were:

Neutron interrogation for phase fraction

Weighing for mean density

Venturi for velocity

The basic technical key to substantially simplifying the multiphase measurement problem was seen to be to homogenise the components, removing 'slip' such that only three instruments are required to determine the individual flows of the three components. In this case the preferred instruments were three gamma beams; two for oil/water/gas fractions and one for velocity determination.

Due to the success of the primary techniques the alternatives have not been investigated in depth. Initial work using a venturi was halted when the homogeniser pressure drop was found to provide a very good indication of multiphase velocity.

MIXMETER Stage 1

Introduction

The MIXMETER project (Stage 1) was launched in November 1992 to evaluate the above methods theoretically and through laboratory testing with the aim of proving a system and producing a design brief for a prototype meter.

Project policy was controlled by a steering group which comprised representatives from all the sponsoring organisations.

The project was carried out under the direction of Imperial College acting through its consultancy arm, IC Consultants Limited (ICON). The Project Director was Professor Geoff Hewitt.

Overall administrative and financial control was provided by Mr Paul Docx of ICON. Detailed project management was provided by Mr Paul Harrison of SGS Redwood.

Other members of Imperial College were involved, principally Professor George Shires who provided analytical support and Dr Susan Parry who contributed the appropriate nuclear instrumentation expertise.

ICI Tracerco provided general consultancy throughout the project.

SGS Redwood were heavily involved in the homogeniser development and also provided the practical flow measurement expertise necessary throughout the project and particularly related to the rig trials.

Funding was obtained from Brasoil, British Gas, Mobil, Texaco, Total and the OSO and the work ran through a 22 month period.

This first intensive programme resulted in a 3" (75mm) NB laboratory meter comprising:

> A specially developed homogeniser/flow
> conditioner.
>
> A dual energy X-ray/gamma phase fraction meter.
>
> A second gamma device for cross correlation
> velocity measurement.

The complete assembly is less than 1m in length.

The development of each of the system components is discussed below.

Homogeniser

Background
If the nuclear instruments are to function as required it is essential to provide effective homogenisation to remove 'slip' (gas travelling faster than the liquid components) and to produce an even distribution of the flowing components across the pipe diameter where the nuclear absorption is being determined. This becomes more critical as the width of the gamma beam reduces.

As the gas separates from the liquids very quickly it was realised that traditional in-line mixers which comprise a series of flow separation and twisting elements were unlikely to be successful. A much more abrupt device is required.

SGS Redwood had developed such a mixer based on the twin cell rotation principle and this had been successfully tested in two phase flow by SGS and during an earlier development project at the National Engineering Laboratory.

This SGS Redwood plate type (MkI) mixer (see Fig 2) has also been evaluated by Christian Michelsen Research (CMR) and was found to provide good flow conditioning over a wide range of two phase flows.

Development and Testing
A streamlined version of this mixer (MkII) was developed by SGS for MIXMETER (see Fig 3). This was refined following initial tests on the Imperial College WASP rig. Final comparative tests confirmed that the MkII design was superior to the MkI and to a commercial Statiflo mixer in terms of its ability to condition two phase flows.

Tests were carried out with horizontal flow as is the case for all tests to date and air/water only was used at this stage.

In early trials a broad gamma beam from an Americium source was used with two detectors to determine the vertical distribution of liquid after the mixer. Later work used a fine beam scanning gamma densitometer to measure water hold-up across the pipe downstream of the mixers.

Comparisons were made of a number of characteristics but the basic requirement was for a mixer which would give reliable homogenisation at some defined downstream position where the dual energy instrument would be located. The homogenised region is also required to extend further downstream to a position where the single energy gamma instrument would be installed for cross correlation velocity measurements.

A key parameter therefore is the centreline liquid hold-up as it was planned to use a narrow gamma beam across the centre of the pipe for the measurements. Fig 4a compares the centreline liquid hold-up with the homogeneous hold-up calculated from rig figures. The superior performance of the MkII mixer is clear, producing a centreline hold-up at 4D downstream of the mixer very close to the homogeneous value. Also, the higher correlation coefficient, r, indicates more consistent performance than the other designs.

At 8.3D downstream of the mixer (Fig 4b) the liquid has begun to drop out but homogeneity is still better than the other designs and performance is more consistent. This was considered adequate for the cross correlation measurement at this point.

The above tests were carried out over a range of total velocities from 2m/s to 6m/s. However subsequent system tests indicate that the mixer will continue to work well down to velocities of 1m/s.

Fig 5 compares the pressure drop for the three designs and it can be seen that the MkII is the most efficient.

The MkII design was therefore selected for system tests of the 3" laboratory meter and has now been carried forward into the 4" field prototype.

Dual Energy Gamma Phase Fraction Meter

Source Selection

Previous studies by others Ref (1) had indicated that Americium 241 (59keV) and Caesium 137 (661keV) would provide a good working combination and these sources were selected for initial evaluation. However, during initial tests this combination was found to be much too susceptible to error due to its extreme sensitivity to very small errors in counting or calibration.

A detailed theoretical study was performed and it soon became clear that the key factor is not the simple difference between the energy levels but the difference between the absorption ratios for oil and water. This is illustrated by Fig 6 and it can be seen that the system is relatively unaffected by the high energy selected which simply needs to be greater than about 100keV. The low energy however should be as low as possible and at 59keV Am241 was simply not low enough. These conclusions were confirmed by static testing. An alternative to 59keV Am241 was required and a range of alternative isotopes and energy levels were assessed.

The problem is illustrated by Fig 7a which shows the very narrow working area afforded by the Am/Cs combination.

The use of the lower energy of Am at 18keV was considered impractical due to its limited penetrative power. Barium has a peak at 30keV which could have been used in combination with one of its other peaks at 302 or 356keV. However the Barium spectrum is fairly complex and 'full' which would have resulted in further difficulties with background correction and count rate limitations. Barium is also relatively expensive and supplies are limited. It was finally decided that the best option was to use the two energies of Cs 137, 32keV and 661keV. Advantages of this choice are seen to be:

> The lower energy has sufficient penetrative power to traverse liquid filled pipes of diameters typically used for flowlines without the need to use unusually high strength sources. (Special 'windows' in the tube wall are seen as unavoidable)

> The use of both energies from the same source removes any doubts regarding differences between fluids 'seen' by the two beams.

> Caesium 137 is a relatively common isotope and readily available.

> The Cs 137 spectrum is simple with only two peaks.

Fig 7b shows the improvement in working area available if Cs 137 (32keV/661keV) is used.

Calculation Method

As it has no retained volume the mixer mixes only spatially and not temporally and therefore in most multiphase flow situations and particularly in slug flow the density of the flowing fluids passing the instruments changes rapidly (this allows the cross correlation system to function).

Due to the exponential nature of photon absorption, counting the activity detected over a long period when flow is fluctuating does not give a correct indication of the average density. A technique was therefore developed where counts are collected over a series of very short periods (dwell times), between 5ms and 30ms. These measurements are collected over a 'measuring period' during which several thousand individual counts are made. These counts are then sorted into 10 or more bands and determinations are made on individual average band values before calculating average values for the measurement period.

This routine was developed theoretically using data obtained from initial tests on the WASP rig. It has been tested successfully over a very wide range of flow conditions on WASP and at NEL and shows negligible sensitivity to the statistical errors which can be associated with gamma counting.

Source Size

Cs 137 is normally supplied in stainless steel capsules which cut out the majority of the 32keV emissions. Special 'thin window sources' are therefore required. However, the 661keV peak remains considerably larger than the 32keV peak and for the system to operate well the empty pipe counts should be approximately equal. Detectors used are relatively standard sodium iodide (NaI) photomultiplier tube type. The correct peak balance is achieved by specifying a thinner crystal which allows many of the 661keV photons to pass through undetected whilst allowing capture of most of the 32keV emissions.

The power of the source must be carefully selected so as to provide sufficient counts in each peak over the very short dwell time when the pipe is full of water but not to exceed the maximum total count rate which the detector can accept when the pipe is empty. The need for this balance will put a practical limit on the largest pipe diameter for which MIXMETER is suited of around 150mm to 200mm. High power sources are not necessary. For the 3"(75mm) meter a 50mCi is used and a 100mCi source will be adequate for the 4"(100mm) meter.

Beam Geometry

A single vertical beam was chosen. Collimation was found to be critical as is background (scatter) correction. Suitable arrangements were determined through a series of static tests using flat sided test cells, perspex pipe sections and, to study the effect of fluid distribution, a layered test cell which allows oil, water and air samples to be positioned in any order in the gamma beam. Accurate background correction was achieved using a combination of fixed, proportional and measured values to subtract from the measured peak values.

Cross Correlation Velocity Measurement

Cross correlation of density measurements between one of the dual energy sources/energies and a second downstream instrument should in theory provide a perfectly adequate measure of velocity of the bulk fluid once the slip has been removed by the homogeniser.

To avoid the need for a second set of 'windows' in the pipe wall at the downstream position the absorption of the high energy 661keV is used. It is important to use the same energy range and general geometry at both positions to avoid introducing errors.

Maximum separation of the instruments was determined using the fine beam traversing gamma device to confirm persistence of flow conditioning downstream of the mixer. Mixing effects were found to persist to about 10D. However, to ensure good performance for the 3" laboratory meter 500mm (6.5D) was chosen. The 4" field prototype has a separation of 600mm (6D).

To provide a signal for correlation it was convenient to use the same dwell time as for the dual energy calculations. The correlation is therefore performed on two series of counting figures with dwell times typically of 10ms over a 40 second measurement period. The combination of dwell time and instrument separation gives a fairly coarse measurement step. Also the instantaneous velocity of the homogenised fluid can vary by a factor of at least two during slug flow. Individual velocity measurements therefore exhibit a fair degree of scatter. However, accurate results are obtained by averaging successive measurements and as few as 10 are found to produce acceptable results.

Differential Pressure Velocity Measurement

The MkII SGS mixer has been found to have the added advantage that pressure drop correlates evenly and precisely with the product of the total velocity and the liquid velocity. This relationship holds over all test conditions run to date on WASP and at NEL and provides a second determination of velocity to compliment the cross-correlation measurement.

This redundant measurement is used to reduce the overall uncertainty of velocity determination.

Also, more importantly, in situations where the cross correlation system will not function due to lack of sufficient density perturbations in the flow the differential pressure velocity continues to be valid, extending the range of the instrument.

NATIONAL ENGINEERING LABORATORY TESTS

Following component development and successful component and system tests on the Imperial College WASP rig the 3" laboratory prototype meter was taken to NEL in September 1994 for more extensive testing.

These tests are described below:

Test Fluids

The test fluids used at the NEL were:

Magnesium sulphate solution to simulate produced water.

Stabilised crude oil cut with a little kerosene to produce typical wellhead viscosity.

Nitrogen from a liquid nitrogen supply.

Test Conditions

All tests were carried out with the instrument horizontal. Flow conditions were predominantly slug flow though entering the stratified and annular conditions at the extremes.

These conditions have been selected as being most common and also possibly the most difficult to work in. They do not indicate any perceived limits of operation.

Tests were carried out using water/nitrogen, water/oil/nitrogen, and oil/nitrogen.

Total velocity was varied between 0.75 and 7.7m/s.

Liquid fractions were from 5 to 85% and water/oil ratios from 6 to 0.1 in three phase tests.

The test point matrices are shown in Figs 8 and 9.

All tests were carried out at a nominal pressure of 10bar and at ambient temperature.

All MIXMETER results are calculated from a maximum of 400 seconds of data.

The instrument was calibrated at Imperial College CARE near Ascot prior to shipment to NEL and no changes were made to calibration constants throughout the tests.

Errors quoted below are relative errors and are not based on maximum or total fractions.

Results

Cross Correlation Velocity
Cross correlation results for all runs are plotted against rig total velocity in Fig 10.

Predicted total velocity is plotted against Rig total velocity. An average error of -0.67% is obtained over the whole range with a standard deviation of 7.14%.

There is still clearly some remaining statistical scatter due to the 400 second limit on data collection time. For longer determinations errors will be reduced further, certainly to within 5% and possibly to the order of 1%.

Differential Pressure Velocity
Fig 11 shows the mixer differential pressure plotted against the square of rig total velocity multiplied by the dual energy liquid fraction.

The fluids involved in each test are indicated and it can be seen that the correlation is not noticeably dependant on the fluid properties.

Fig 12 shows this correlation used to predict the rig total velocity. Average error is -0.04% and standard deviation is 7.17%.

By taking a simple average of cross correlation and differential pressure results and removing one 'rogue' result average error is becomes 0.99% and standard deviation is reduced to 4.22%. Fig 13 shows the relative errors.

Dual Energy Liquid Fraction

Fig 14 shows liquid fraction, determined by adding the dual energy water and oil fractions, plotted against the rig total liquid fraction for all test points. The fluids used in each test are indicated. It can be seen that the data is consistent throughout the range from 5% to 85% liquid.

Figs 15 and 16 show the individual oil and water fractions from all 3-phase runs plotted against rig data. Both plots correlate reasonably with the straight line though there is noticeably more scatter with the oil fraction results.

In addition to the statistical scatter resulting from using only 400 seconds of data a small amount of electronic drift occurred during the tests. The results are found to fall into groups according to test date (tests were run over three weeks).

Fig 15 uses different symbols to distinguish the three groups of data. The effect of the drift can clearly be seen with results 17-21 and 61-63 showing a positive bias. Runs 41-49 are evenly scattered about the ideal line with an average relative error of only 6%.

This problem of drift has been overcome with the purpose built electronics designed for the field prototype.

Conclusion

The test results show that the instrument is capable of giving multiphase velocities and liquid fractions with average errors within the 5% target which was originally set for the project.

This is achieved over run times of only 400 seconds in predominantly slug flow regimes. Scattering will certainly be reduced when running times are extended beyond this limit.

PRESENT AND FUTURE PROGRAMME

MIXMETER project Stage 2 is now well underway and comprises the following tasks:

Detailed design of a 4" (100mm) NB field prototypemeter.

Procurement/construction of the meter.

Rig trials (probably again at NEL).

Field trials at a suitable onshore test site.

The mechanical design and construction of the meter including the pipe wall windows has been carried out by Cambridge Advanced Technologies Ltd. who have also provided the communications electronics and the software. A general arrangement of the 4" meter is shown in Fig 17.

ICI Tracerco have developed stabilised counting electronics and are providing the detectors, sources and source holders.

Although the meter is eventually targeted at subsea applications it is considered essential to prove the device on the surface before advancing to a subsea system. However, the subsea application has been kept in mind during the development so that marinisation planned for 1996 will be a natural progression which will not involve a complete redesign.

Main advantages of MIXMETER are seen as follows:

* Potential for high performance measurement

* Wide application range

* Simplicity - wide use of components which are already field proven

* Compact design

* Use of basic physical principles removes the need for complex calibration or theoretical flow models

* Low cost

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1. Abouelwafa MSA and Kendall EJM "The measurement of component ratios in multiphase systems using gamma ray attenuation" J.Phys.E.: Sci. Instrum, 131 341 345 (1980)

MIXMETER MULTIPHASE FLOW METER
LABORATORY PROTOTYPE

Source ②
High energy
only

Source ①
High and
low energy

3" N.B. Pipe

Mixer

FLOW

②

①

Pressure & Temperature
Transducers loop
powered.

Upstream Pressure 4-20mA

4-20mA Temperature

Mixer Downstream Pressure 4-20mA

DETECTOR ①

HV

XTAL
Thin

PM

Pre
Amp

O/P Low Channel

O/P High Channel

I/P 12V DC

I/P 12V DC

12V DC
Power
Supply

P.C. E_W V_{XC}
E_O V_{DP}
E_B

DETECTOR ②

HV

XTAL
Thick

PM

Pre
Amp

O/P High Channel

Fig 1
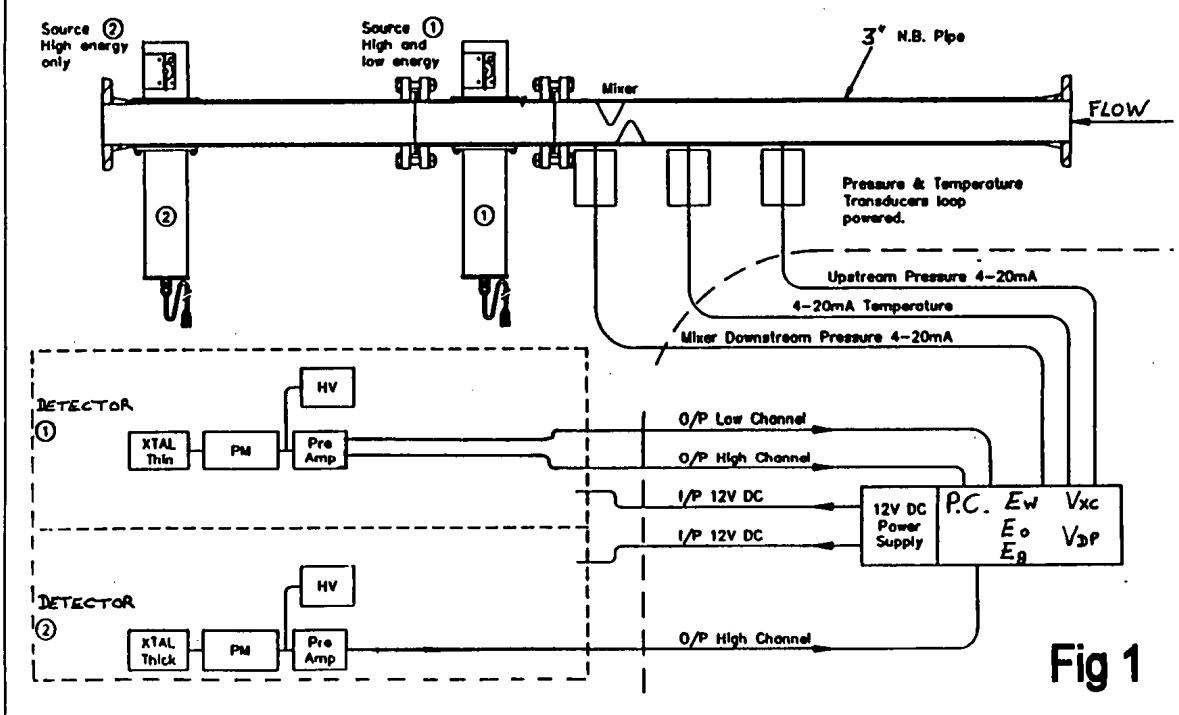
MIXMETER MULTIPHASE FLOW METER
SGS REDWOOD MkI MIXER
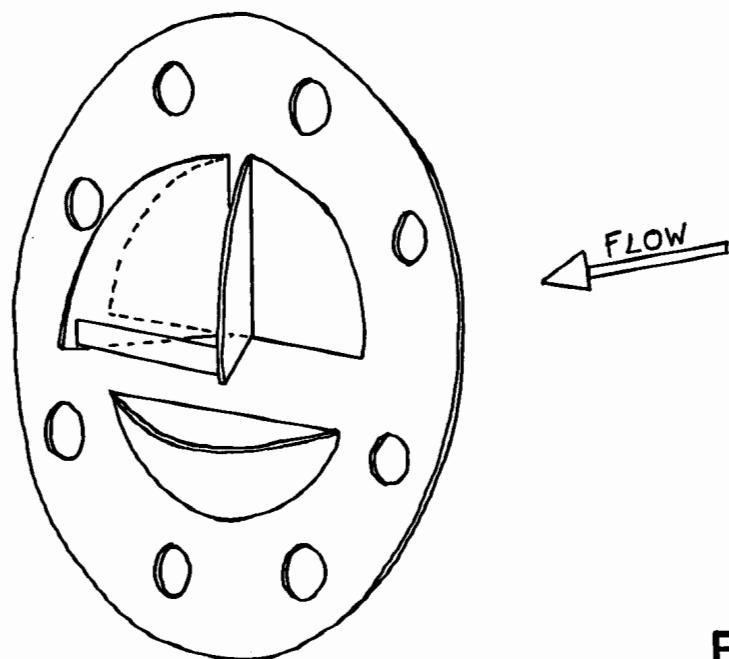
FLOW

Fig 2

MIXMETER MULTIPHASE FLOW METER
SGS REDWOOD MkII MIXER

FLOW

Fig 3
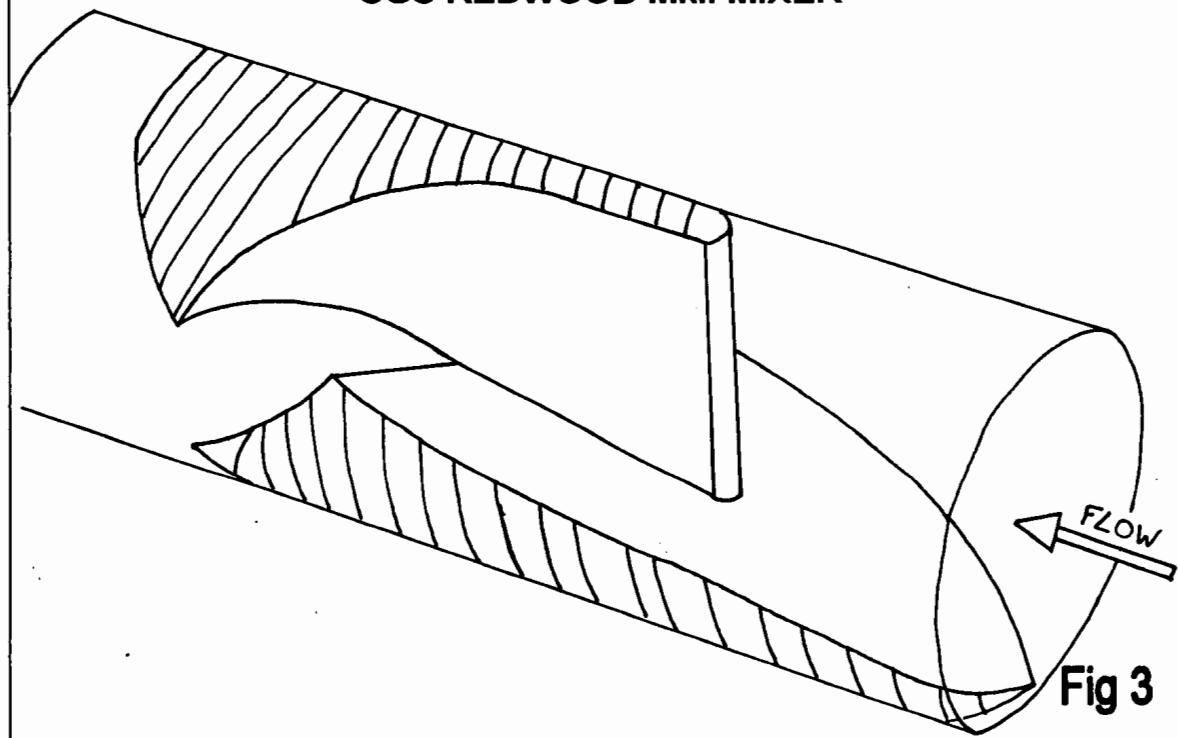
MIXMETER MULTIPHASE FLOW METER
MIXER TESTS - HOLD-UP AT 4D
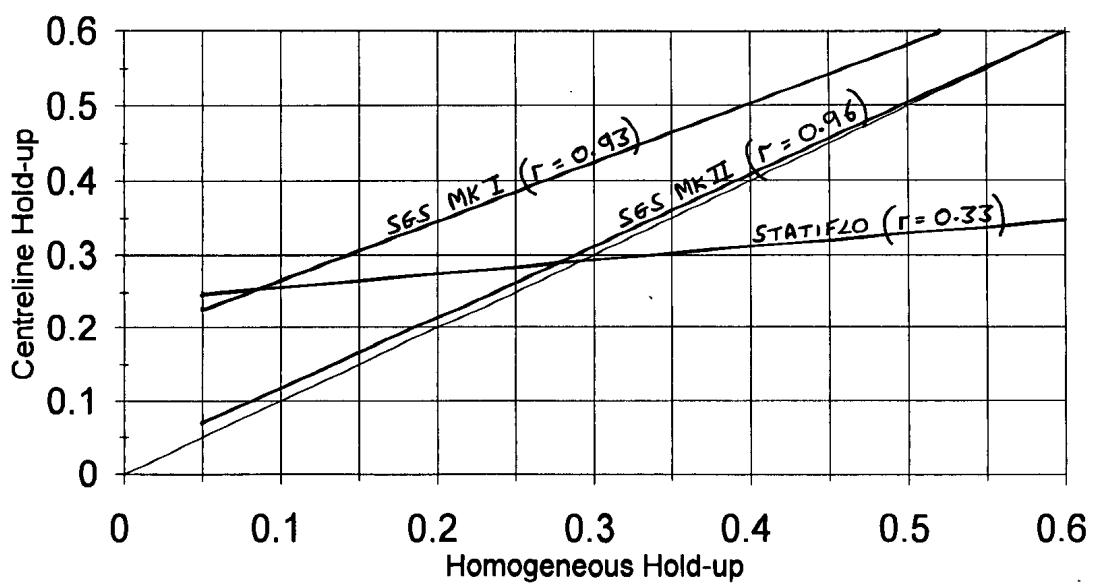
Fig 4a

MIXMETER MULTIPHASE FLOW METER
MIXER TESTS - HOLD-UP AT 8.3D
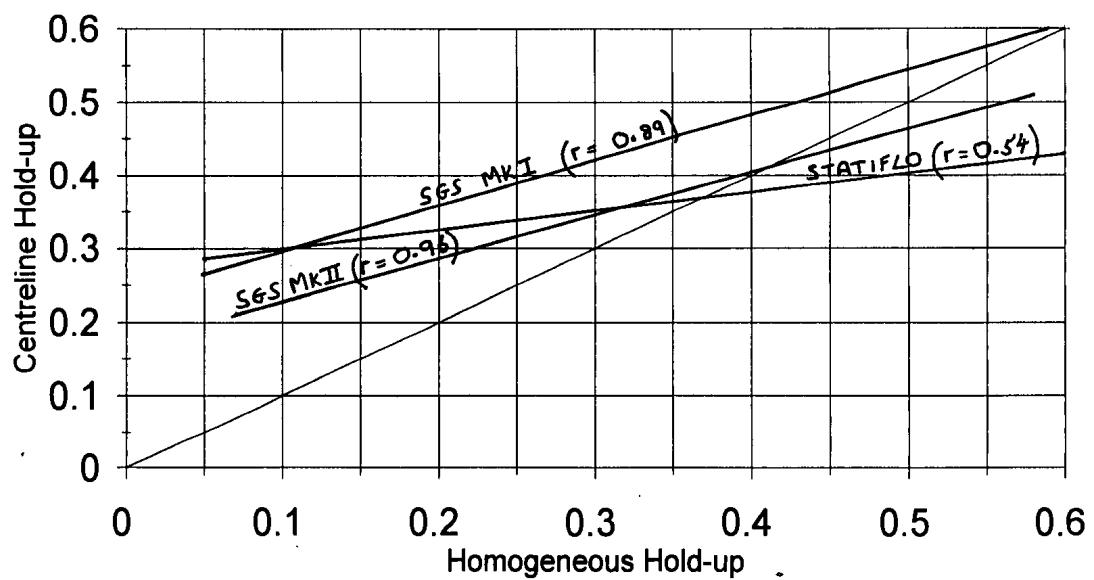
Fig 4b

MIXMETER MULTIPHASE FLOW METER
3" MIXER TESTS - PRESSURE DROP
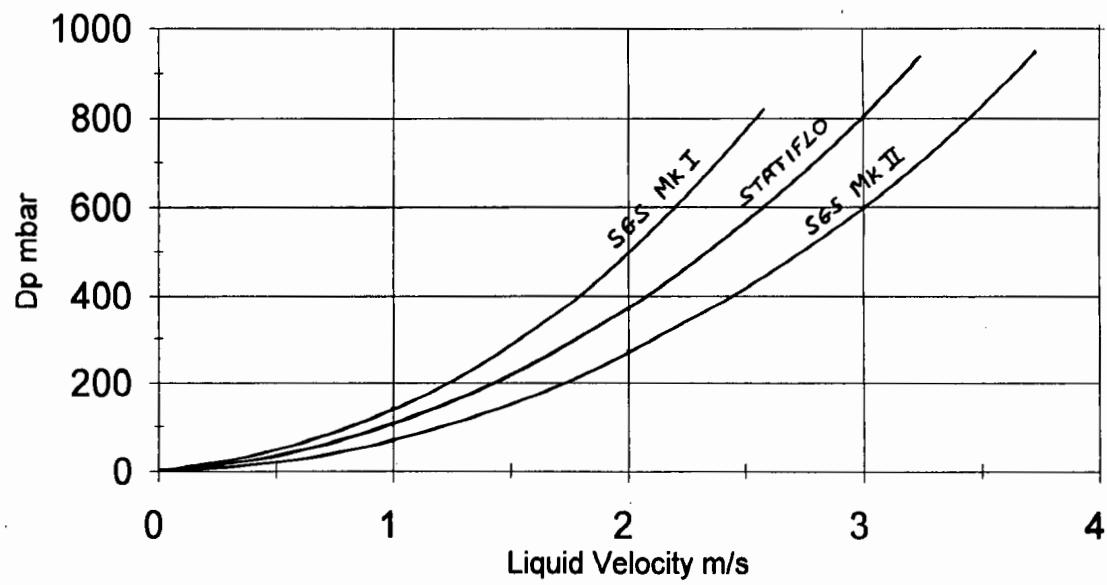
Fig 5

MIXMETER MULTIPHASE FLOW METER
ABSORPTION RATIO vs ENERGY
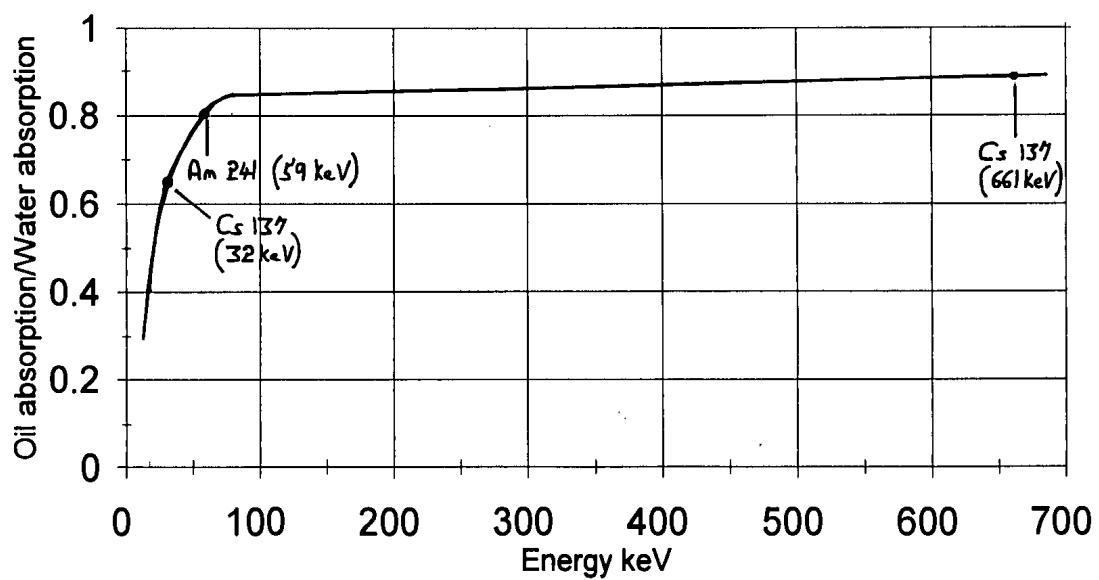
Fig 6

MIXMETER MULTIPHASE FLOW METER
CALIBRATION Am(59)/Cs(661)
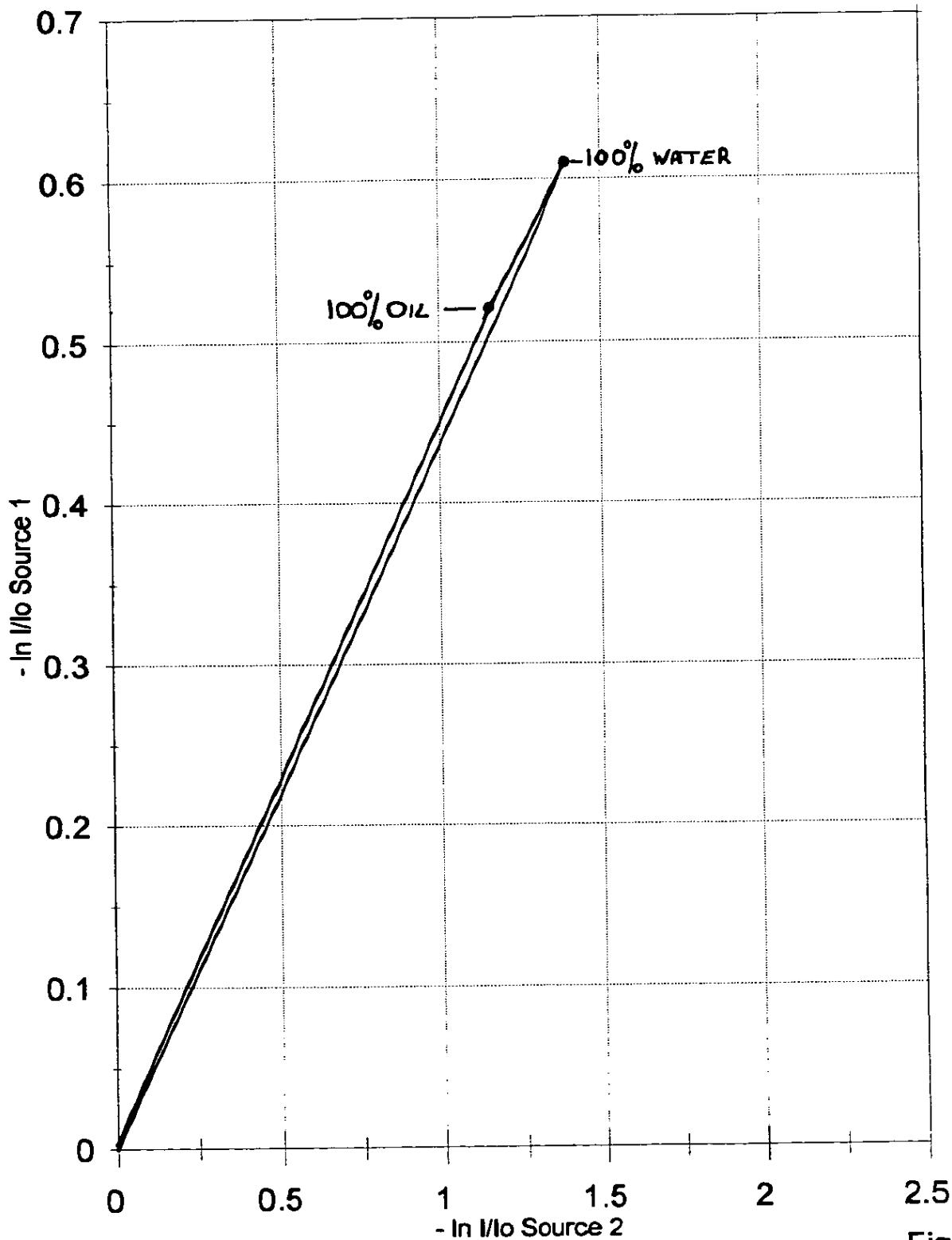
Fig 7a

MIXMETER MULTIPHASE FLOW METER
CALIBRATIONS Am(59)+Cs(32)/Cs(661)
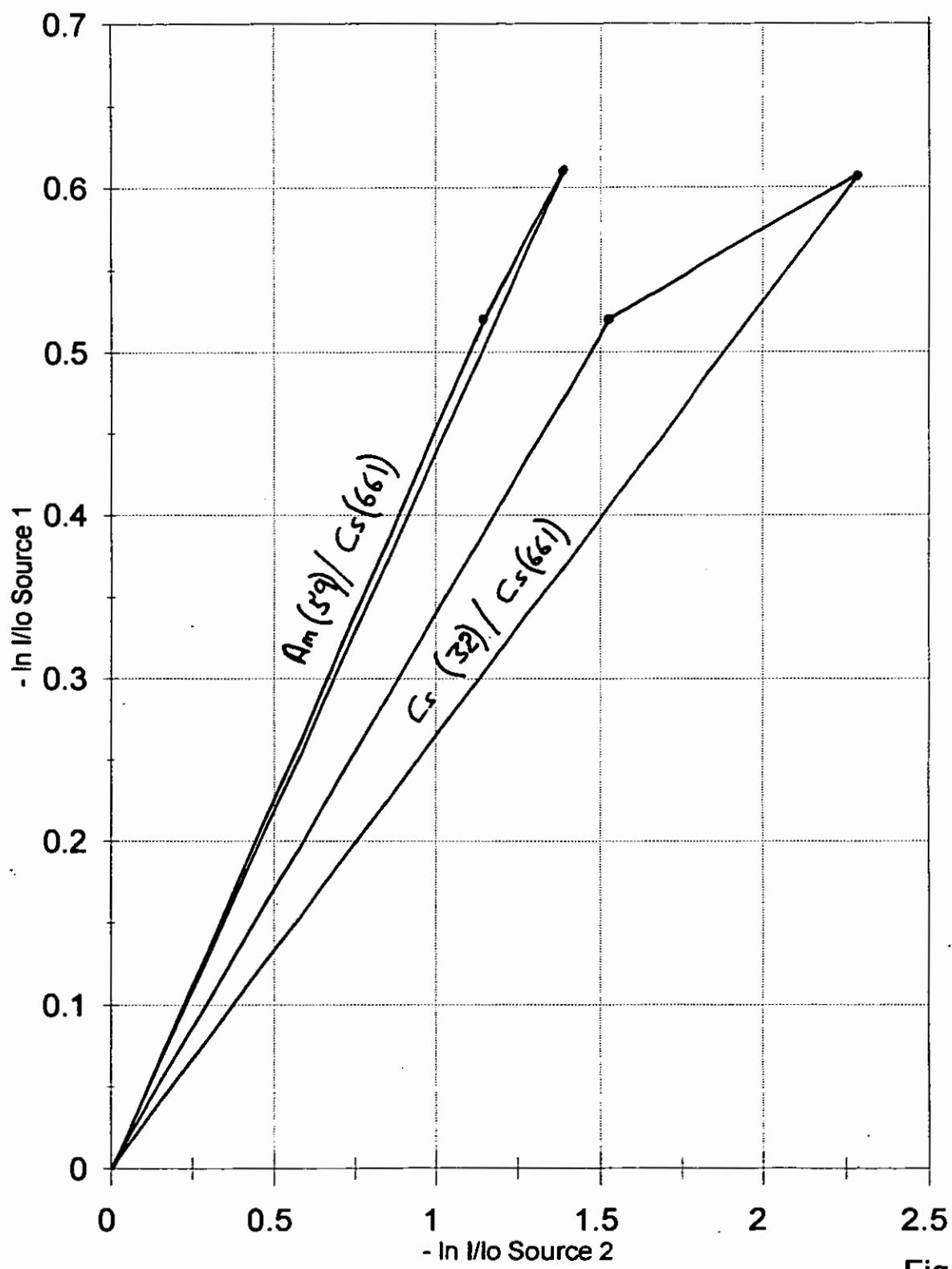
Fig 7b

MIXMETER MULTIPHASE FLOW METER
NEL TESTS - TEST POINT MATRIX
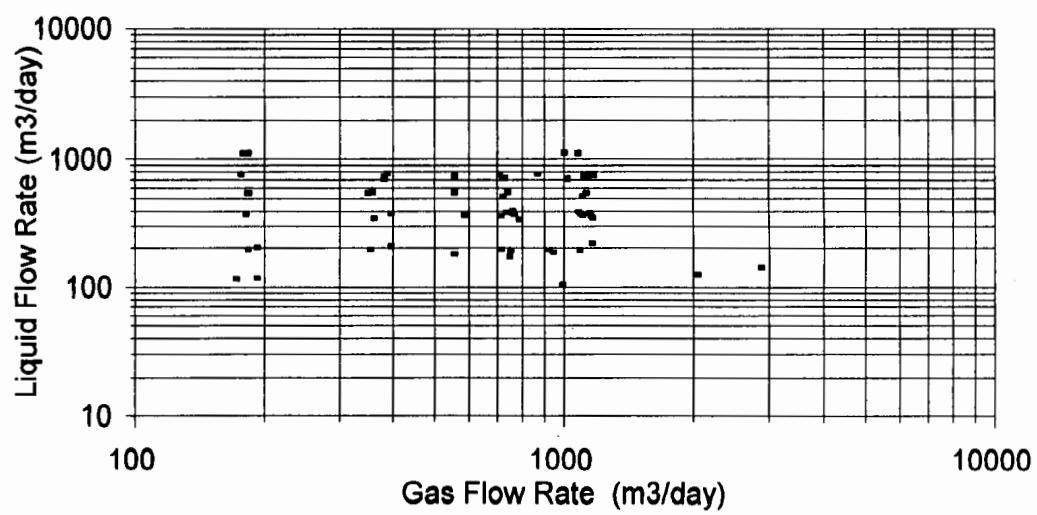
Fig 8

MIXMETER MULTIPHASE FLOW METER
NEL TESTS - MULTIPHASE COMPOSITION MAP
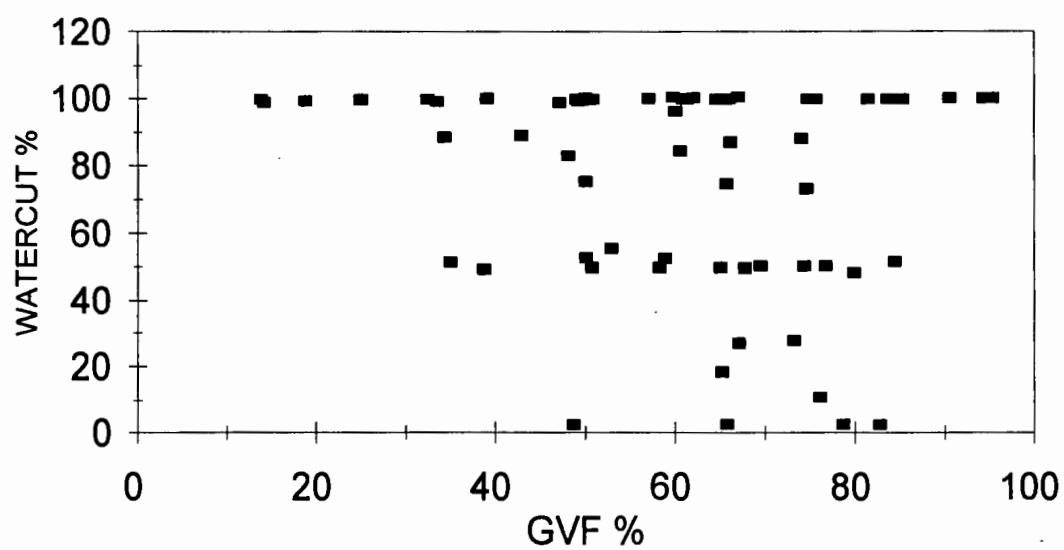
Fig 9

MIXMETER MULTIPHASE FLOW METER
NEL TESTS - CROSS CORRELATION

Fig 10

MIXMETER MULTIPHASE FLOWMETER
NEL TESTS - MIXER DP VELOCITY (1)

Mixer Differential Pressure bar

Rig Velocity^2 x Mixmeter EI

▪ Water/Gas   ▲ Oil/Gas   ▾ Water/Oil/Gas
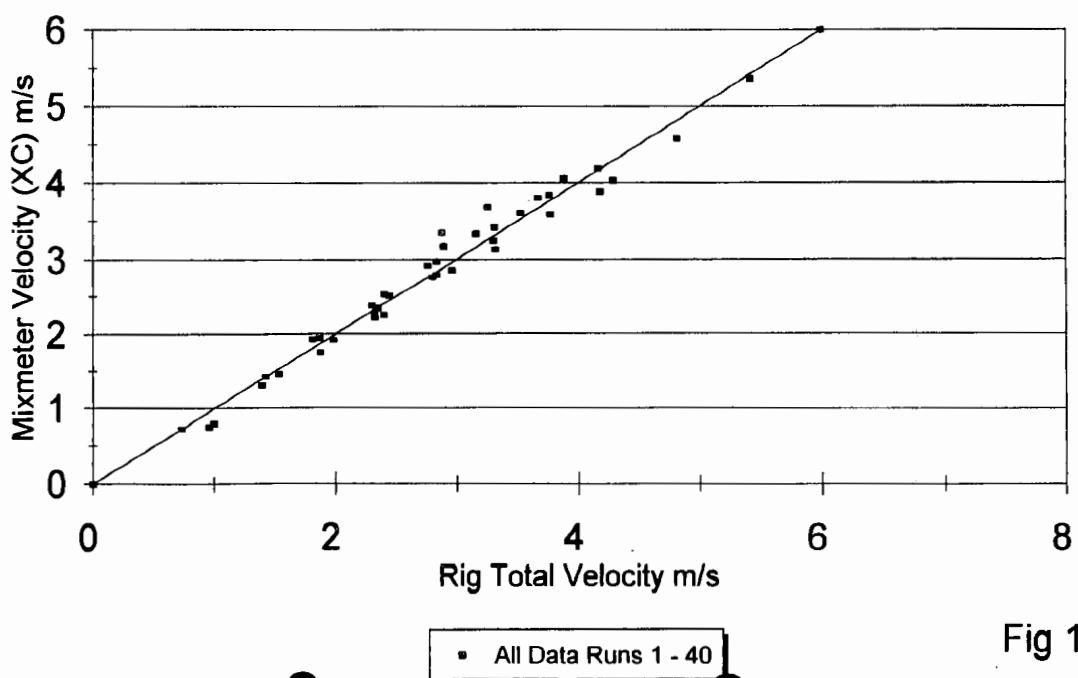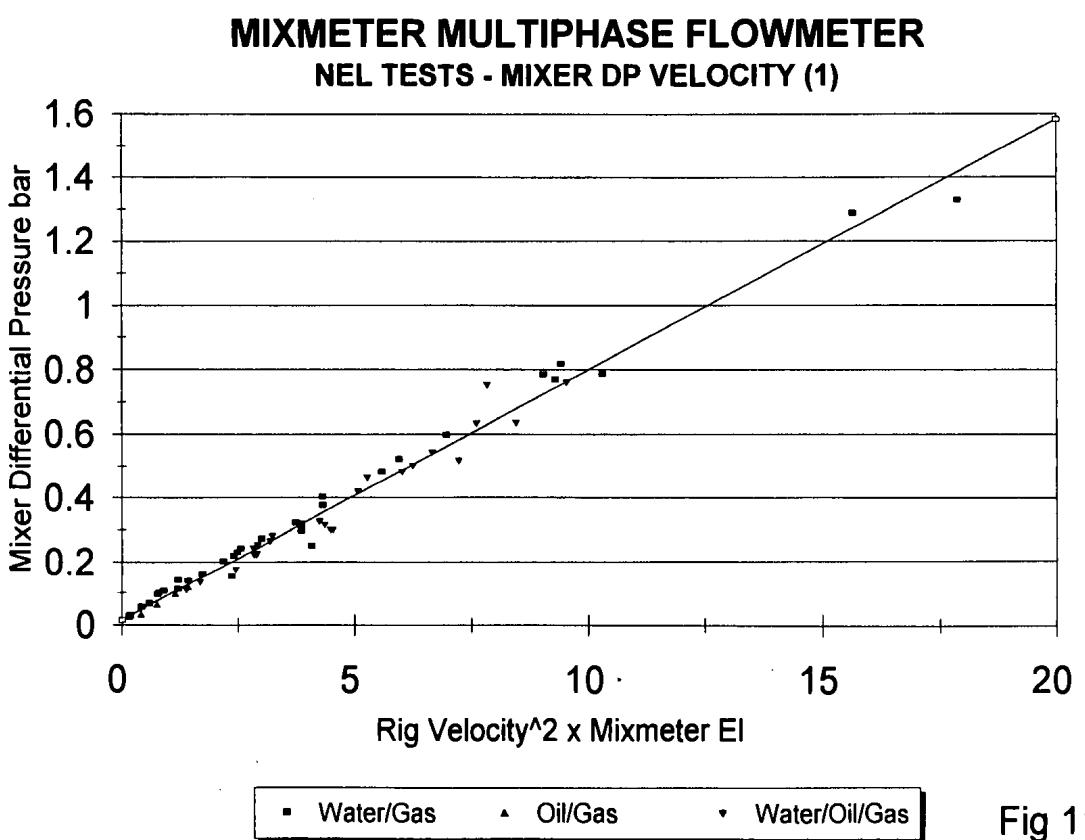
Fig 11

MIXMETER MULTIPHASE FLOW METER
NEL TESTS - MIXER DP VELOCITY (2)
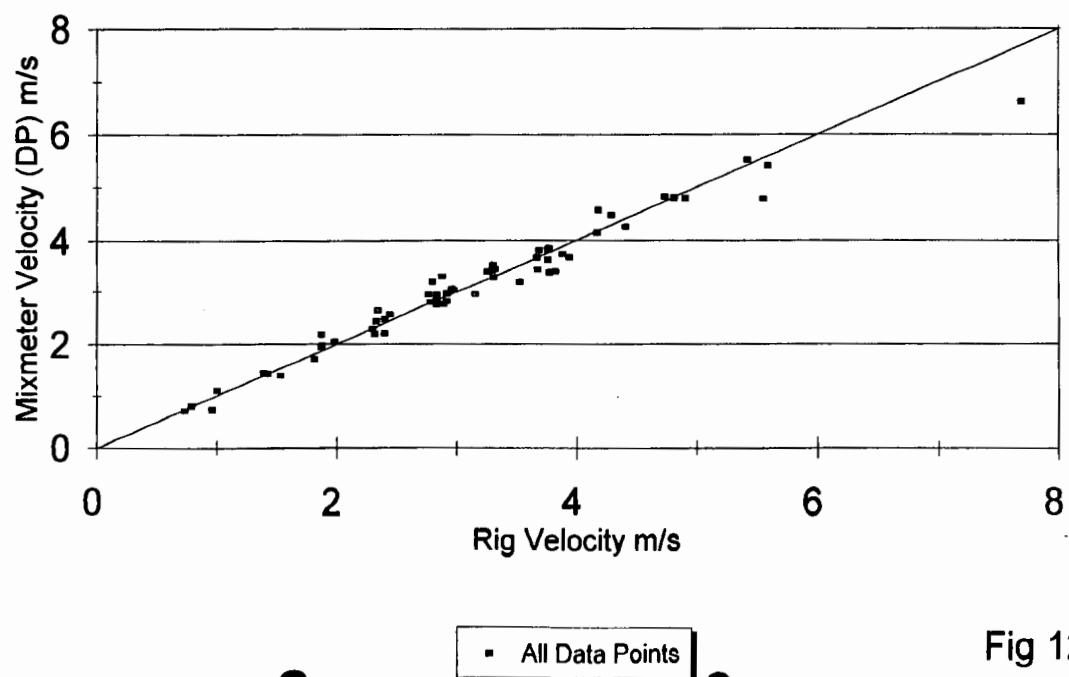
Fig 12

# MIXMETER MULTIPHASE FLOW METER
NEL TESTS - VELOCITY ERROR
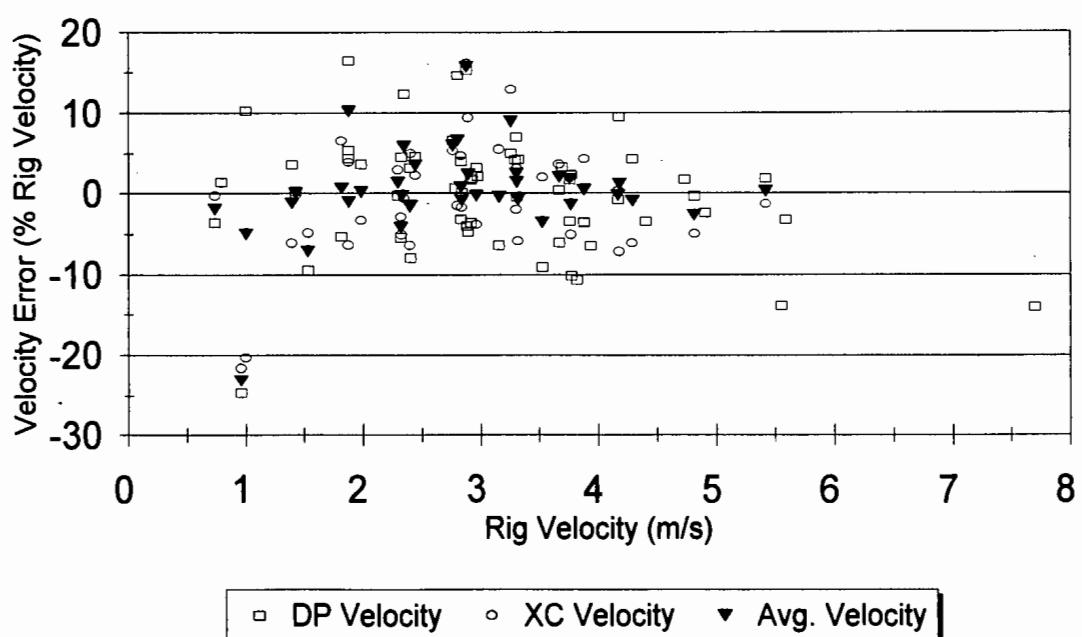
Fig 13

MIXMETER MULTIPHASE FLOW METER
NEL TESTS - LIQUID FRACTION

Mixmeter Total Liquid

Rig Total Liquid

■ Water/Gas   ▲ Oil/Gas   ▼ Water/Oil/Gas
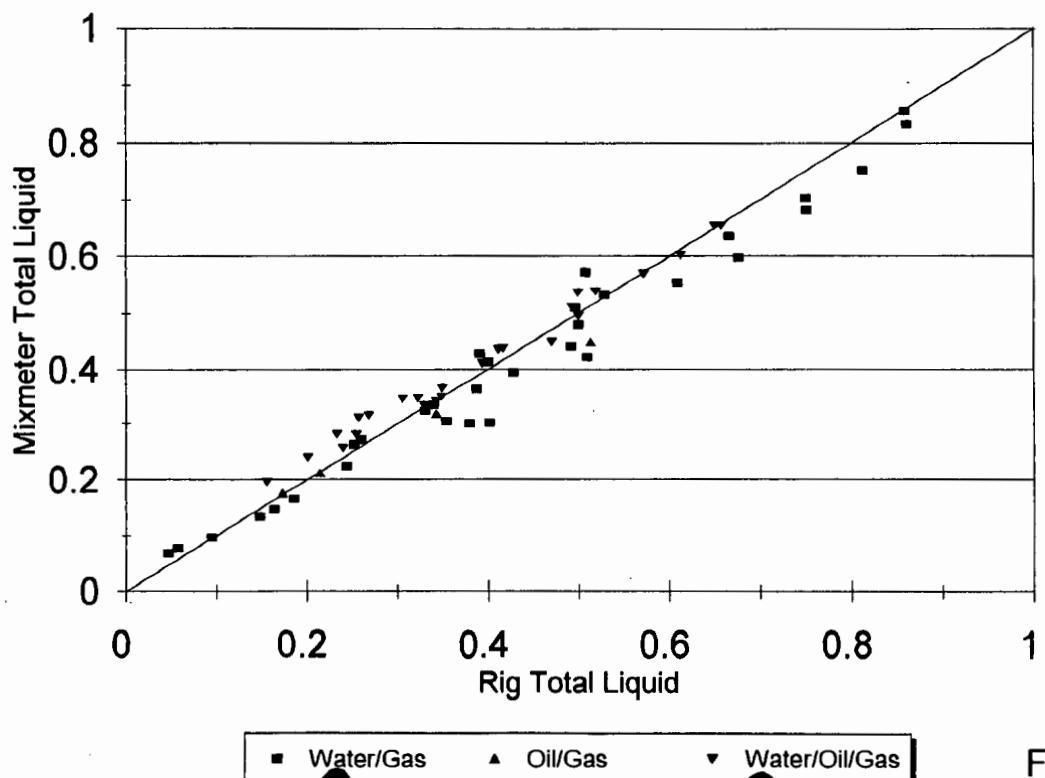
Fig 14

MIXMETER MULTIPHASE FLOW METER
NEL TESTS - OIL FRACTION (Eo)
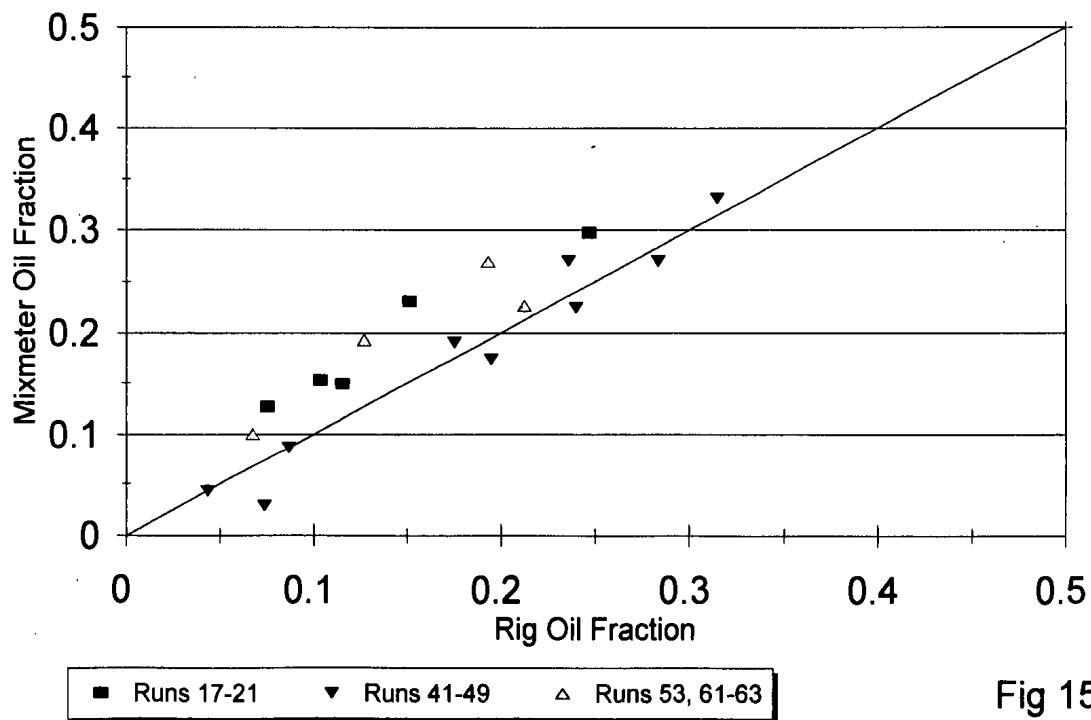
Fig 15

MIXMETER MULTIPHASE FLOW METER
**NEL TESTS - WATER FRACTION (Ew)**
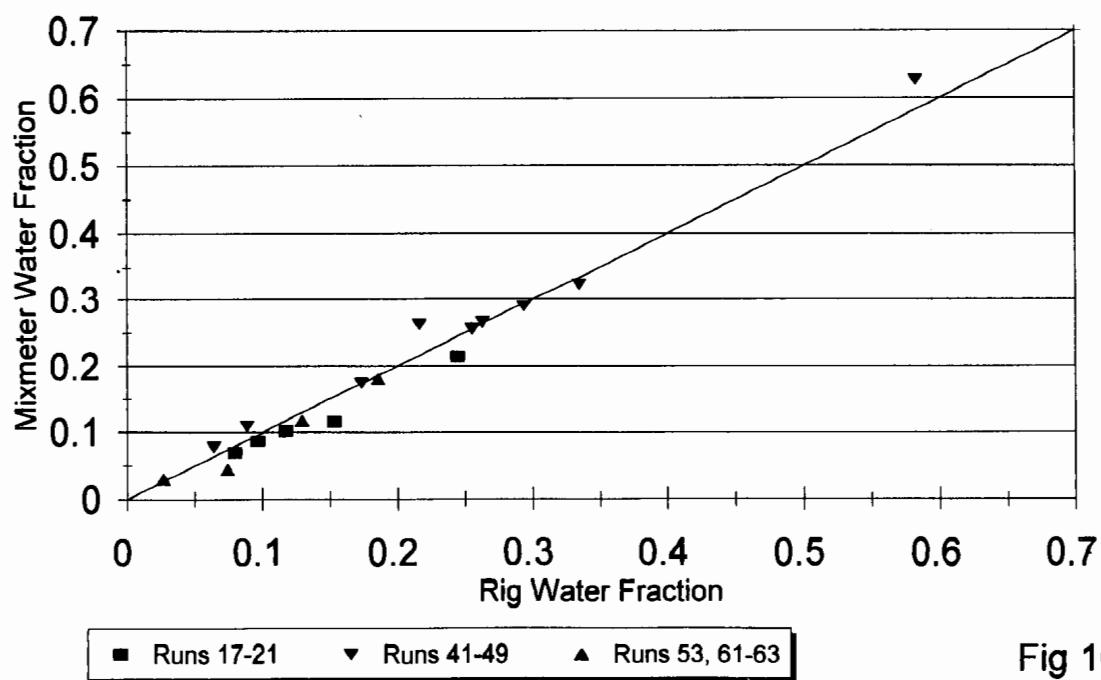
Fig 16

# MIXMETER MULTIPHASE FLOW METER
FIELD PROTOTYPE
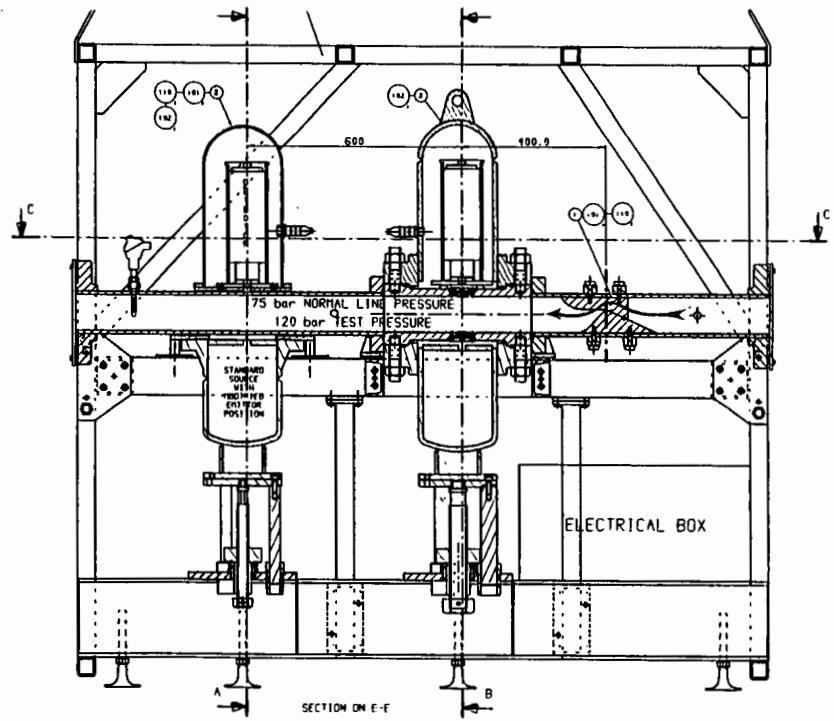
Fig 17

References

[1] Paper presented at the North Sea Flow Measurement Workshop, a workshop arranged by NFOGM & TUV-NEL

Note that this reference was not part of the original paper, but has been added subsequently to make the paper searchable in Google Scholar.