North Sea FLOW Measurement Workshop

Paper 7.3

Use of Dual-Modality Tomography for Complex Flow Visualisation

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nel technology for life

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1 INTRODUCTION

The development of new flow metering techniques and the use of existing flow meters in more challenging applications requires more data than just bulk flow calibration measurements. The flow structure and its impact on the meter performance are vital pieces of information, without which the value of experimental research data can be limited. This is particularly true for complex flow characterisation.

With the development of more sophisticated technologies to measure increasingly complex flows there is a need for additional knowledge of flow patterns in National Standard flow facilities, as well as accurate measurement of the individual phases which constitute the multiphase mixtures.

Tomography systems have developed rapidly over the last 10 years, culminating in the recent development of multi-modal tomographic systems which are aimed at overcoming some of the limitations of single-modal systems. The UK is the leading centre for industrial process tomography in the world; whilst the pharmaceutical sector is already firmly engaged with the technology and reaping benefits, more general uptake has been limited. However, there is a need to develop tomography systems that will provide the capability to image complex multiphase flows, such that fundamental research can be undertaken on detailed flow structure phenomena, and how they relate to multiphase measurement performance. This is particularly timely in view of developments from several flow meter manufacturers.

As part of the 2008-2011 Engineering and Flow Programme for the UK's National Measurement Office, TUV NEL Ltd carried out an evaluation of commercially-available tomography systems to assess their suitability for use in flow standard facilities. The successful implementation of a tomographic flow characterisation capability would improve the capability of the UK national multiphase flow measurement facilities [1, 2] and help the facilities keep pace with new and emerging requirements for flow measurement of complex fluid systems, like that for high viscosity multiphase flows. Much of the research performed on these facilities would benefit from the ability to fully understand the fluid dynamics and flow structures. In addition, the use of modelling as a predictive tool in complex flows is well established, and the ability to visualise a real flow stream would have a major impact on the validation of modelling software, allowing users to have confidence in the use of the codes in more challenging flow systems.

2 BACKGROUND

No longer is oil extracted as a single phase, instead it arrives at the well head along with water, gas, sand, waxes, and other fluids used for well optimisation such as glycols. This has driven the need for better understanding of flow regimes and phase interactions.

Multiphase meters use mathematical models to try and predict the flow regime they are encountering at any moment in time. Getting the answer wrong can lead to significant over or under reading [3]. Many multiphase meters are installed vertically as this reduces the number of potential flow patterns from seven (stratified, stratified wavy, plug, slug, bubble, annular and mist) to four (bubble, slug, churn and annular). Often a blinded tee is installed directly upstream of the meter in an attempt to remove slip and homogenise the flow but this does not always work. As the world moves into an era where oil supplies are becoming more viscous, flow patterns are changing meaning a greater understanding of them is required.

The determination of flow regimes in pipes is not easy. Some techniques used include analysis of fluctuations of local pressure and/or density or by direct visual observation if a length of transparent pipe is installed in the line. This means that depending who is interpreting the results or looking at the pipe, one can get different answers. What one observer may classify as slug flow could be considered as plug flow if viewed by someone else. This means that descriptions of flow regimes are to some extent arbitrary [4].

A major source of error in multiphase flow metering is fluid properties. Over the course of its lifetime, the fluids coming from the well change, meaning the fluid properties will also change. Sampling is used to combat this so that the fluid properties being used by the meters can be updated. But how representative is the sample? Where should it be taken from? A technique enabling one to see inside the pipe, used in conjunction with sampling, will give more confidence in the samples collected, therefore more confidence in the fluid properties, leading to more confidence in the meter readings. In principle, tomography is a suitable technique to provide visualisation of what is happening inside a pipe.

Tomography is a technique for displaying a cross section through an object. Tomographic measurement technologies involve the acquisition of measurement signals from sensors located external to the object under investigation. It is necessary to gather projection data from multiple directions which is then processed by an image reconstruction algorithm to produce a tomographic image. This can achieved by rotating the object within the sensor field or rotating the sensors around the object. Tomography is perhaps most associated with medical imaging as illustrated by techniques such as Computed Tomography (CT) which uses rotating X-ray sources and detectors and Magnetic Resonance Imaging (MRI) which uses a powerful magnetic field. In both cases, the sensors can rotate at high speed around the human body thereby delivering the necessary projection data from multiple directions. The sensor can also scan in the orthogonal direction allowing a full 3D image to be obtained.

However, it may not always be possible to rotate the object or the sensors due to physical constraints or because the time required may exceed the time available due to time-dependent effects associated with the object under investigation. This is particularly the case with process tomography where the processes under investigation are often changing rapidly, for example, multi-phase flow.

3 DUAL-MODALITY TOMOGRAPHY

The defining feature of any tomographic measurement technology is the sensor system that is deployed. There are a number of sensor systems available based on transmission, acoustic and electrical technology and the key to determining which system is appropriate is to consider the properties of the process that can be exploited to deliver the required information. Most tomographic measurement technologies employ a single sensor system and this does limit the range of potential applications. Table 1 summarises various tomography techniques that can be applied to process applications [5].

Electrical tomographic measurement techniques are suitable for imaging multi-phase flow processes. The attributes associated with these techniques are high temporal resolution, ability to operate in opaque systems and generally low-cost (certainly when compared to radioactive tomographic techniques). Electrical Resistance Tomography (ERT) exploits differences in conductivity (or resistivity) within the sensing space and Electrical Capacitance Tomography (ECT) exploits differences in electrical permittivity. Individually, these techniques are popular for studying 2-phase flow processes. In the case of ERT it is necessary for the continuous phase to be electrically conducting such as in hydraulic conveying (liquid-solid flow), [6 - 7]. On the other hand, ECT works best with non-conducting materials (or at least where the continuous phase is non-conducting). Popular applications of ECT include pneumatic conveying [8], fluidised beds [9] (both gas-solid systems) and oil continuous flow, [10 -11] (oil-gas systems).

Table 1 - Tomography Techniques for Process Applications

Principle	Spatial Resolution (% of diameter of cross-section)	Practical Realisation	Comment
Electro-magnetic Radiation	1%	Optical	Fast Optical access required
		X-ray and γ-ray	Slow Radiation containment
		Positron emission	Labelled particle Not on-line
		Magnetic resonance	Fast Expensive for large vessels
Acoustic	3%	Ultrasound	Sonic speed limitation Complex to use
Electrical Properties	10%	Capacitance Resistance Impedance	Fast Low Cost Suitable for large or small vessels

Electrical capacitance sensors have been used to measure the component fraction of multi-component flow processes [12]. In this application, the sensors consist of two electrode plates and the capacitance measured is determined by:

$$C = K\varepsilon_m \qquad (1)$$

In order to improve the measurement quality of such systems, the size of the electrodes can be increased since the measured capacitance is proportional to the electrode surface area. The requirements for tomographic imaging are different since projection data must be gathered at multiple directions. This is achieved by arranging multiple electrodes around the boundary of the region and the capacitance between all the combination pairs of the electrodes should be measured. Typically twelve electrodes are mounted on the periphery of an insulating pipe with an overall outer earthed screen as shown in the schematic of an ECT sensor in Figure 1(a). This arrangement has the advantage that the electrodes are not in contact with the fluid inside the pipe so the sensor is non-intrusive and non-invasive. The capacitance between all independent pairs of electrodes is measured using a stray-immune circuit which is insensitive to the stray capacitances between the selected electrode and the redundant electrodes and those between the selected electrode and earth. This involves applying an alternating voltage (typical frequency = 1 MHz) from a low impedance supply to the selected electrode. The detection electrodes are all earthed and the current is measured sequentially on each of these electrodes. The second electrode is then selected and the sequence is repeated until all independent pairs of electrodes have been measured.

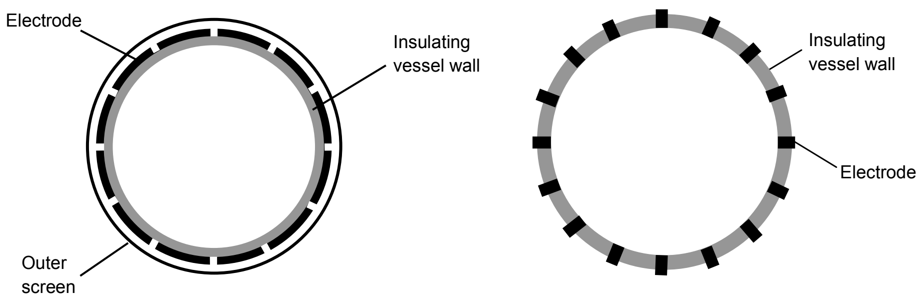


Fig. 1 - Sensor schematic - (a) ECT and (b) ERT

An ERT sensor consists of multiple point electrodes on the periphery of a pipe as illustrated in Figure 1(b). As with ECT, the electrodes are positioned equidistantly around the periphery but unlike ECT they make contact with the fluid inside the pipe. The electrodes are usually designed to be flush with the vessel wall so that the technique is considered invasive but non-intrusive. An alternating current (typical frequency = 10 KHz) is applied to a source and sink electrode and the generated voltages between other electrodes pairs measured according to a pre-defined measurement strategy. The injection pair is changed and other measurements taken until all independent measurements for the particular strategy have been taken.

In order for a tomographic measurement device to be suitable for imaging flows where the continuous phase may be electrically conducting (water) or electrically non-conducting (oil) it is necessary to deploy both ERT and ECT. This was the main driver behind the development of the dual-modality electrical tomography system. This system originated from the UK Government's Office of Science and Technology Foresight Challenge Project 'Process tomography - a new dimension in advanced sensor technology' (EPSRC Ref **GR/L37434/01),** which ran from 1997 to 2001 involving the Universities of Manchester, Leeds and Exeter and 10 companies. The hardware and software developed during the project were later licensed and then commercialised.

Hoyle et al. [13] discusses the design concept of the multi-modal tomography system and highlights the primary identified application area of multi-phase flow. Multi-modality systems inherently encourage a systematic approach in contrast to current single modality tomographic systems that are complex, expensive and designed primarily for laboratory use. A successful multi-modality system must allow individual sensor data to be collected and combined effectively and it must exploit opportunities for rationalization and sharing of resources, and deal with hazards of mutual interference. The platform proposed by Hoyle et al. [13] supports capacitance, resistance and ultrasound modalities although only capacitance and resistance were used in this study.

4 TECHNICAL APPROACH

4.1 The TUV NEL Multiphase Flow Facility

The TUV NEL multiphase facility consists of a three-phase separator and test loop section (Figure 2). The oil is supplied from the separator to the main oil pump and then to the oil flow metering section. A side-stream sampling loop and a main bypass loop are fitted on the delivery side of the pump. The same configuration exists on the water side.

The bypass loops permit control over the pressure and flow rates of the phases in the test section. The sampling loops provide information on any cross contamination in the oil and water process streams. Heat exchanger circuits stabilise the temperature of the working fluid, which is generally kept between 40°C and 42°C during tests.

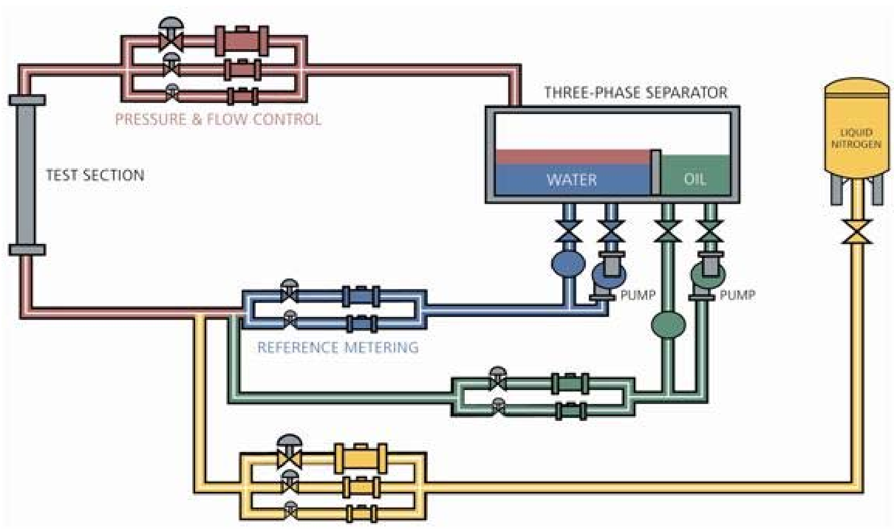


Fig. 2 - TUV NEL multiphase test facility

The oil and water pass through the reference metering stage and are then combined in the mixing section. The nitrogen, which is produced from a liquid nitrogen supply tank external to the building, is injected into the test section after passing through the gas reference metering section. The mixture in the test section runs horizontally to the test meter. Downstream, control valves are used to control the test section pressure. The flow then returns to the separator where the oil and water are separated, and the gas exhausted to atmosphere.

The oil used in the test loop is a mixture of stabilised Forties/Oseberg crude and Exxon D80. The oil phase has a density of around 867 kgm^{-3} at 20°C. The oil viscosity is approximately 23cP at 20°C and 9cP at 40°C. The water phase is a magnesium sulphate solution with an adjustable salinity/density.

4.2 The Dual-Modality Tomography System

Only one potentially suitable tomography system was identified for evaluation. This dual-modality electrical tomography system comprises two integrated modules; electrical resistance tomography and electrical capacitance tomography operated by a single software interface. A dual-modality sensor was designed and fabricated in accordance with the Pressure Systems Directive (97/23/EC) as shown in Figure 3. The sensor was made from a 5" Nominal Bore section of steel pipe connected to 4" Class 150 flanges. The pipe was lined with PVDF (Polyvinylidene Fluoride) to match the bore of the 4" pipe at the NEL Multi-phase flow facility. The 12 ECT electrodes are located within a cavity between the PVDF linear and the steel pipe). The 16 ERT electrodes are located around the external continuous ring welded to the pipe to provide pressure integrity.

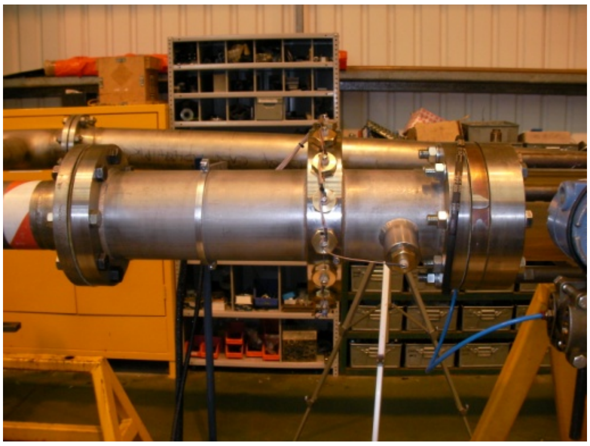


Fig. 3 - Dual-modality sensor

The dual-modality electrical tomography system is capable of operating a maximum of 32 ERT electrodes arranged as with sensors having 8, 16 or 32 electrodes and a maximum of 24 ERT electrodes with sensors having 8, 12 or 24 electrodes. The ECT module utilises an ac-based sinusoidal excitation method which produces good signal to noise performance and the ERT module produces sinusoidal currents to excite a pair of electrodes and the resulting potential difference is measured between other pairs of electrodes.

The software enables the design of flexible excitation strategies for both modalities. In this study a conventional ECT strategy was employed whereby the capacitance was measured between electrodes 1-2, 1-3, 1-4, …., 1-12, then 2-3, 3-4, …., 2-12 until finally 11-12. For a 12-electrode ECT sensor there are 66 capacitance measurements when this strategy is followed. The adjacent strategy was used for ERT whereby current is injected between an adjacent pair of electrodes (e.g. 1-2) and then the potential difference is measured between all other adjacent pairs not including the excitation pair (3-4, 4-5, 5-6, 6-7, 7-8). For an 8-electrode ERT sensor there are 24 independent measurements according to this strategy.

4.3 Imaging Equipment

4.3.1 Direct Visual Observation

During the test programme a Perspex viewing section was installed directly upstream of the tomography system to enable visual observation of the multiphase flow patterns generated. The flow patterns observed were recorded in High Definition using a JVC Everio GZ-HD7 HD Camcorder.

4.3.2 Gamma Densitometer

In fluid flow measurement, gamma densitometers are often used to calculate fluid densities, interface level and slug frequencies. A gamma densitometer was installed immediately downstream of the tomography spool. The densitometer functions by emitting a beam diametrically across the pipe to a detector. This essentially measures the height of the liquid-gas interface rather than the cross-sectional area of the pipe filled with liquid or gas. Consequently, the measured density differs slightly from the actual average density in the pipe.

4.4 Test Programme

The dual-modality tomography system was initially installed horizontally in a straight section of the flow loop (Figure 4a and 4b). In this set up, gravity produces separation of the liquid and gas phases, which can in turn leads to phase slip and localised liquid hold-up.

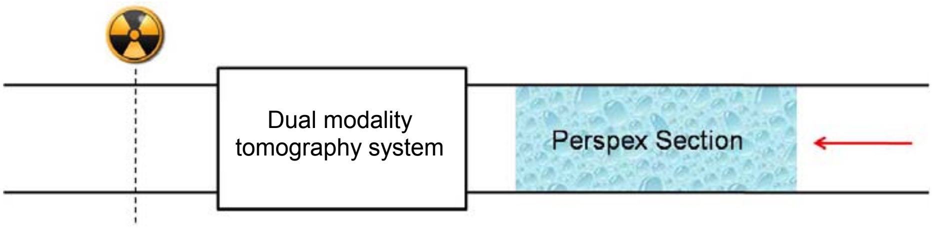


Fig. 4a - Horizontal test set up

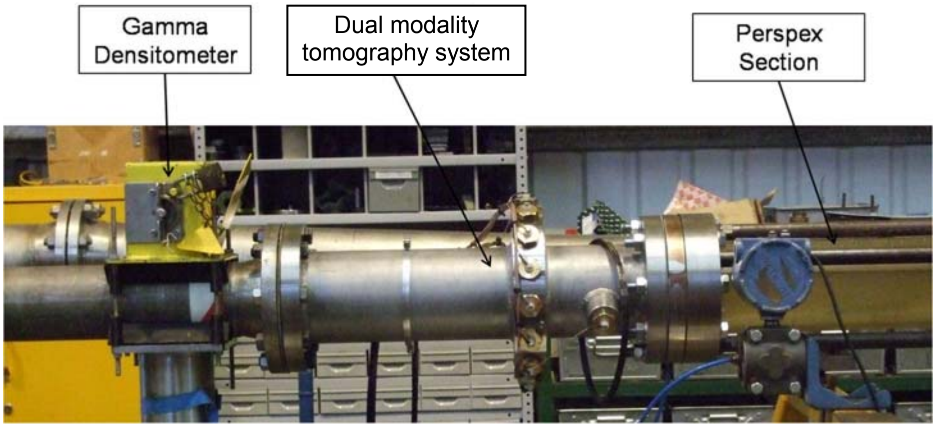


Fig. 4b - Photograph of horizontal test set

On completion of the horizontal tests, the tomography system was installed in a vertical orientation directly downstream of a blinded tee with vertical up-flow, as shown in Figure 5. Many multiphase flow meters are installed this way in an attempt to homogenise the flow and remove/reduce slip. Flow visualisation testing could help quantify how successful using a blinded tee actually is.

4.4.1 Test Matrices

The nominal test matrix developed to cover the three-phase flow map of interest in horizontal flow is shown in Table 2. In addition to covering the range of liquid flowrates and gas volume fractions (GVFs) specified, the test programme intended to cover water cuts of 0, 5, 25, 40, 50, 60, 65, 75, 90, and 100%.

The nominal test matrix developed to cover the three-phase flow map of interest in vertical flow is shown in Table 3. In addition to covering the range of liquid flowrates and GVFs specified, the test programme intended to cover the same water cuts as for the horizontal tests.

The aim of the test matrices was to see how the dual-modality tomography system would cope with a full range of test conditions achievable in the multiphase facility. The most common horizontal flow patterns encountered in the TUV NEL multiphase test loop are bubble and slug, with some stratified and wavy stratified at very low flow rates whilst the most common vertical flow patterns are slug and churn, with annular at high gas flow rates with low liquid content.

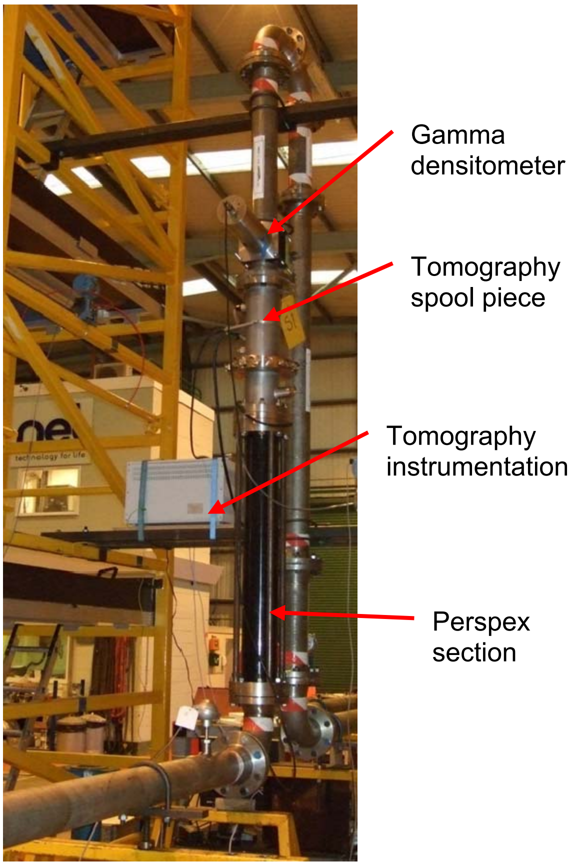


Fig. 5 - Vertical test set up

4.4.2 Procedures

For each test run, the flow loop was set up for the required conditions (pressure, temperature, and flow rates) and allowed to stabilise for several minutes.

Test points were initially run from 2 to 10 minute intervals to find the best length for evaluating the system. From these tests it was decided that logging both the multiphase reference instruments and the dual-modality tomography system for 5 minutes at a time was the most suitable option. Video footage was captured during the data collection period where appropriate.

Table 2 - Nominal Two-phase Gas-liquid Test Matrix for Horizontal Tests

Q_l m^3 hr^{-1}	GVF / %										
	5	10	20	30	40	50	60	70	80	90	95
3.6											
7						x	x	x	x	x	x
15				x	x	x	x	x	x	x	
25			x	x	x	x	x	x	x		
35		x	x	x	x	x	x				
45		x	x	x	x	x					
55		x	x	x							
63		x	x	x							
72		x	x								
90	x	x									

Table 3 - Nominal Two-phase Gas-liquid Test Matrix for Vertical Tests

Q_l m^3 hr^{-1}	GVF / %								
	15	30	50	70	80	90	95	98	99.5
1.8						x	x	x	x
15			x	x	x	x	x	x	
40		x	x	x	x				
70	x	x	x						

5 RESULTS AND DISCUSSION

5.1 Test Matrices

Figures 6 and 7 below shows the test points completed. In the horizontal orientation, the flow regime primarily observed was slug flow with a few points with bubble flow. In the vertical orientation slug and churn flow were observed, with one instance of annular flow. This agrees with the observations made through the Perspex viewing section directly upstream of the tomography spool piece for both orientations.

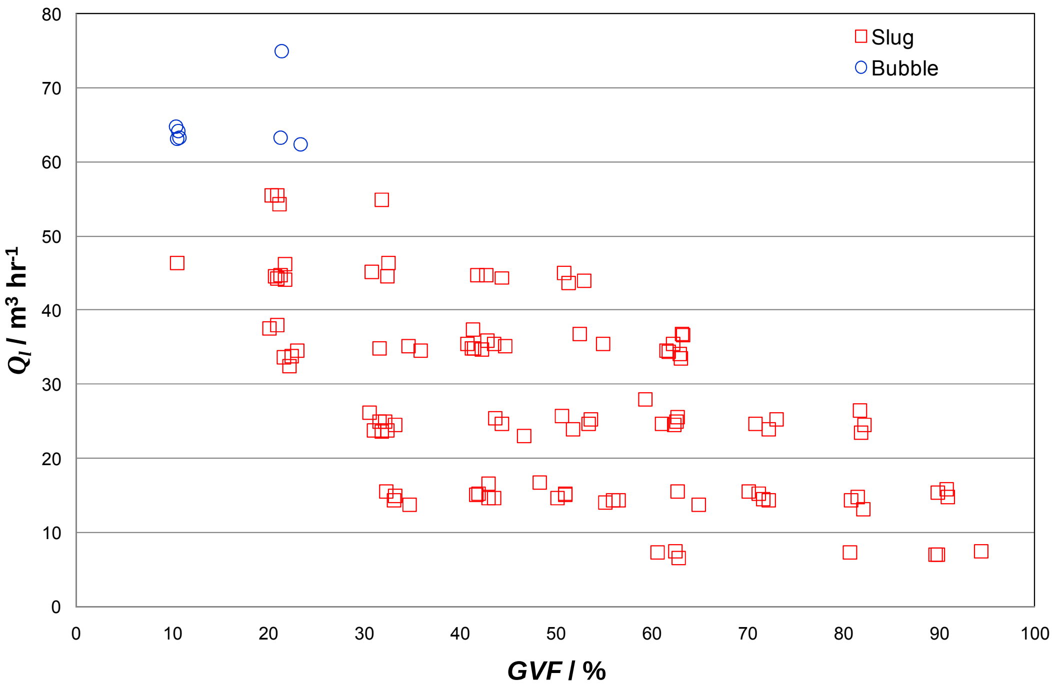


Fig. 6 - Horizontal tests completed

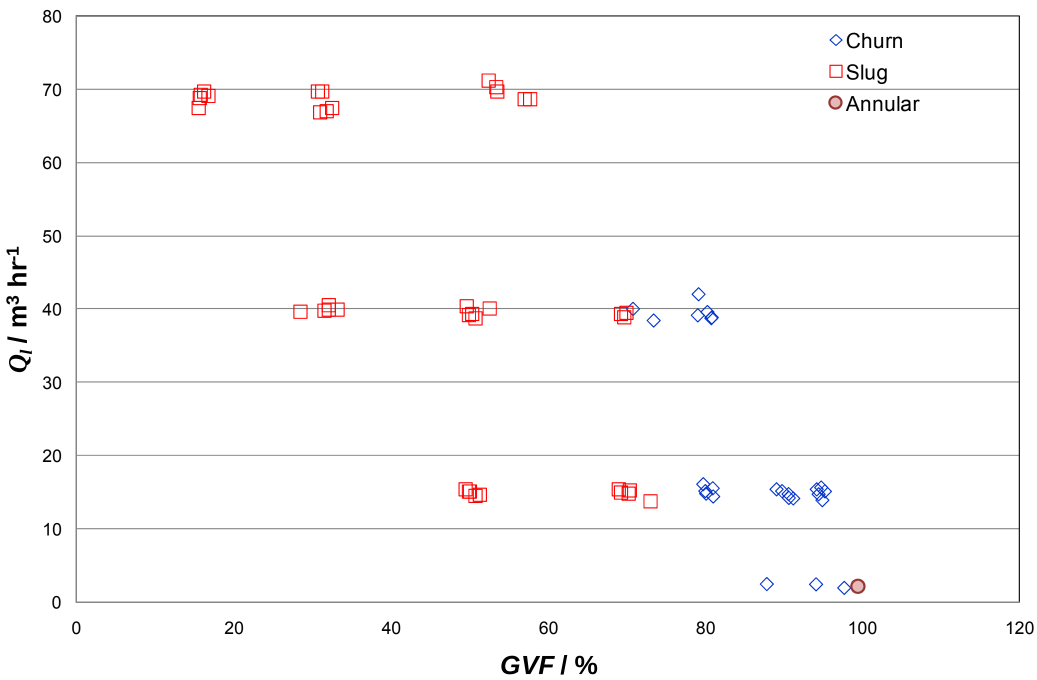


Fig. 7 - Vertical tests completed

5.2 Void Fraction Comparisons

As noted in Section 4.3, a gamma densitometer was used to record the average mixture density downstream of the tomographic spool piece. By assuming that the density recorded by the gamma densitometer is a simple line average along the gamma beam vertically down the pipe diameter, as shown in Figure 8, it is possible to calculate the height of the liquid to gas interface and hence the void fraction.

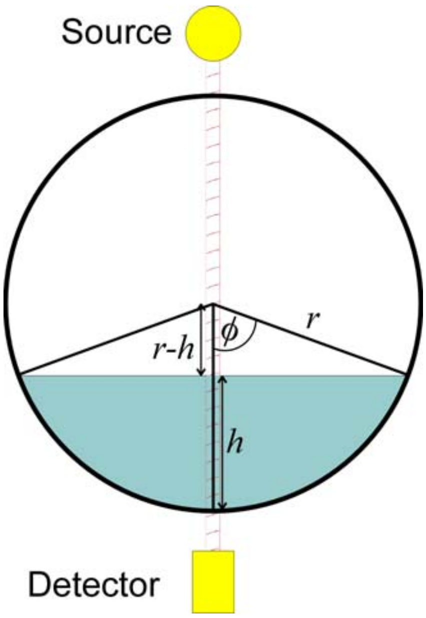


Fig. 8 - Void fraction calculation from gamma densitometer data

With reference to Figure 8, the average density recorded by the gamma densitometer will be

$$\rho_{gamma} = \frac{h}{d}\rho_{liquid} + \frac{(d-h)}{d}\rho_{gas} \tag{2}$$

where h is the height of the interface above the bottom of a pipe of diameter d, the lower part of which is filled with a liquid of density ρ_{liquid}, above which is gas of density ρ_{gas}. Equation 2 can be rearranged to give

$$h = \frac{d\left(\rho_{gamma} - \rho_{gas}\right)}{\rho_{liquid} - \rho_{gas}} \quad . \tag{3}$$

Application of basic trigonometry enables the area of the pipe occupied by liquid to be calculated from

$$A_{liquid} = \phi r^2 - r\left(r-h\right)\sin\phi \tag{4}$$

and hence the void fraction, ε, can be obtained from

$$\varepsilon = 100\left(1 - A_{liquid}/A_{pipe}\right) \quad . \tag{5}$$

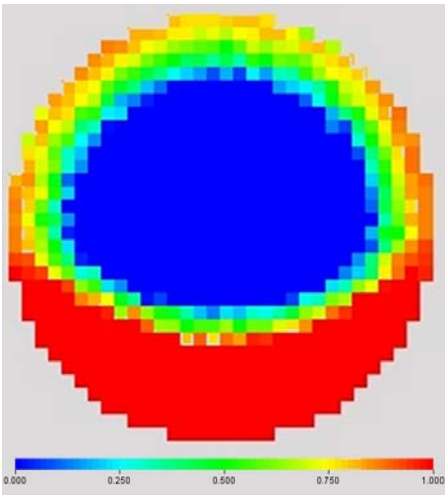


Fig. 9 - Typical ECT image

The software supplied with the dual-modality tomography system enabled the export of "relative permittivity" data from ECT images, from which true area-based void fractions can be calculated. Figure 9 shows a typical ECT image, representing one frame from a test run. The relative permittivity is 0 for an air-filled sensor and 1 for an oil-filled sensor so the mean permittivity is an estimate of the liquid hold-up.

During the test programme the logging frequency of the gamma densitometer was 5 Hz whereas the dual-modality tomography system logged at between 5 and 20 Hz, depending on the mode of operation, with most data being collected at 20 Hz.

An initial comparison of gas void fractions from the ECT data with the gas void fractions calculated using the gamma densitometer for the horizontal orientation showed that the gamma densitometer values tended to be greater as a general rule but not always. The difference appeared to be related to the flow rate of the gas and/or the gas volume fraction, as can be seen in Figures 10 and 11.

Those points where the void fraction determined by the tomography system was significantly greater than the value determined from the gamma densitometer data correspond to water-continuous conditions. The TUV NEL multiphase facility uses a brine substitute consisting of magnesium sulphate crystals ($MgSO_4.7H_2O$) dissolved in mains water. The ECT side of the dual-modality tomography system initially used a lower limit based on the permittivity of gas and an upper limit based on the permittivity of oil to distinguish the gas phase from the liquid phase. The permittivity of the brine substitute used during testing was so much greater than that of the oil that the water can block the capacitance, so that water appears as gas on the tomogram. Initially there were issues with the brine substitute on the ERT side as well but this was rectified using a network resistance adaptor. The effects of water with high conductivities on electrical tomography systems have been investigated by Jaworski and Bolton [14].

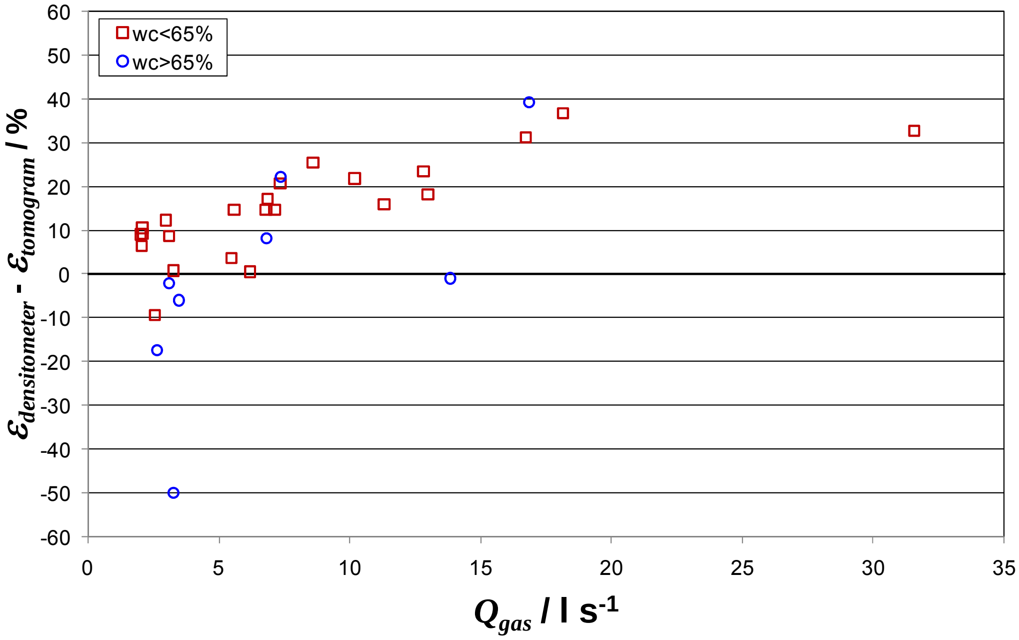


Fig. 10 - Difference in gas void fractions vs gas flow rate, horizontal orientation, initial references

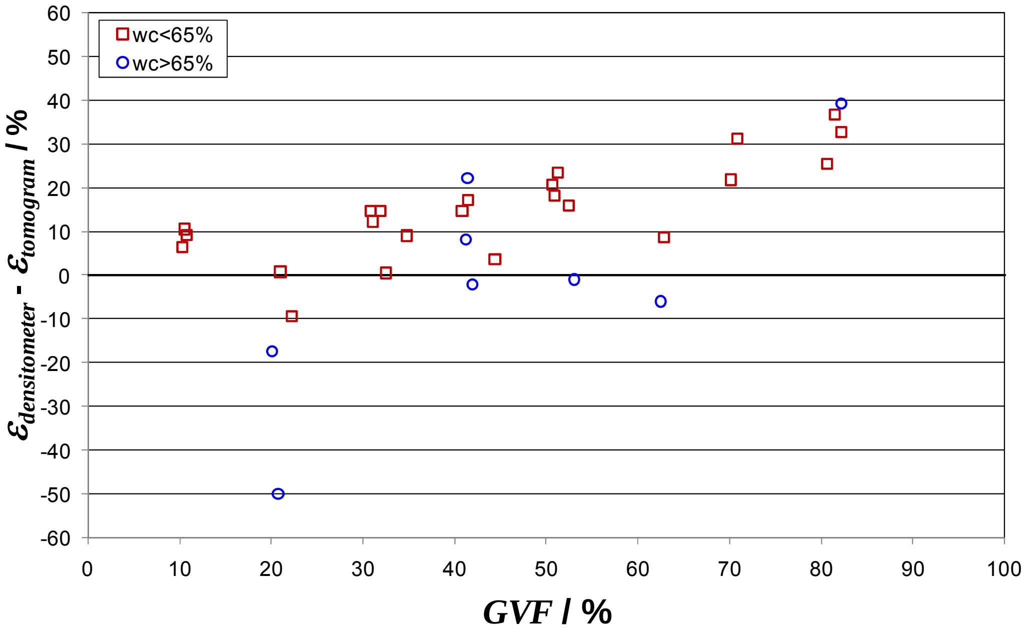
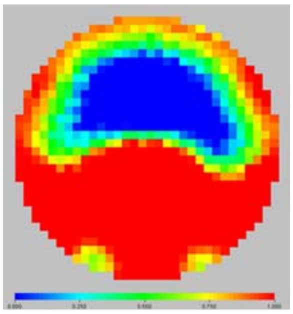
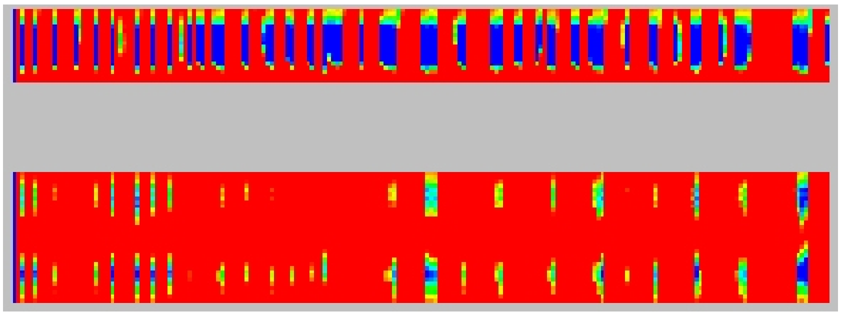


Fig. 11 - Difference in gas void fractions vs GVF, horizontal orientation, initial references

It was initially assumed that for points in the oil-continuous region, the difference could possibly be attributed to the flow regime, which is partly determined by the gas flow rate. Figures 12a and 12b show the cross-sectional view of the pipe and the stacked images respectively of slug flow taken by the ECT in horizontal orientation. The red part of the tomogram represents liquid and the blue part is the gas. The cross-sectional tomogram image shows a curved interface between the gas and the liquid as well as some liquid hold-up at the pipe wall. This gives a larger liquid hold-up than the gamma densitometer and its single path measurement, and hence a smaller gas void fraction.

The upper part of the stacked tomogram is the image of the top half of the pipe at the centre-line, viewed from the side. This gives an indication of the frequency and size of the slugs. The lower tomogram is the image at the mid-plane of the pipe, viewed from above. These images confirm that for the flow conditions in this test the slugs are relatively regular in size and that the liquid / gas interface is curved.





(a) (b)

Fig. 12 – Tomograms for test point FGRE310501 (horizontal orientation)

Figure 13 shows the calculated gas void fractions over a 20 second period. It would appear that the ECT shows more events, i.e. slugs, due to its faster sampling rate of 20Hz compared to the 5Hz sampling rate of the gamma densitometer. Whilst it may be thought that this would lead to the ECT-based void fraction being higher, it appeared to be the case that the ECT was detecting more of the liquid, including the significant amounts accounted for by the curved interface, than detected by the gamma densitometer.

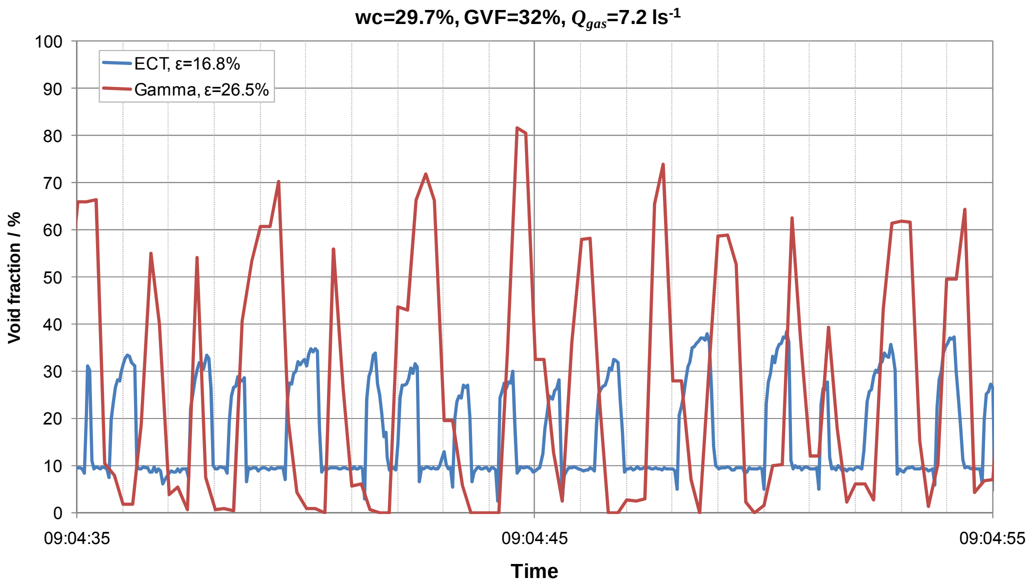
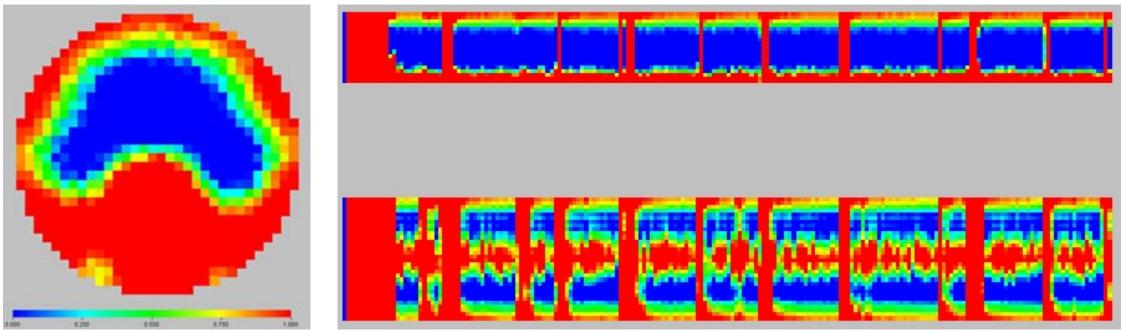


Fig. 13 - ECT and gamma void fractions for test point FGRE310501 (horizontal orientation)

Figures 14a and 14b show the cross-sectional view and stacked images for a test point with much higher gas flow rate and gas volume fraction than the previous example in horizontal orientation, representing a more extreme instance of slug flow.

As can be seen in Figure 14a, the liquid / gas interface is extremely curved, with significant liquid hold-up on the upper part of the pipe. Although the plot of the gas void fractions for this test point over a 20 second period (Figure 15) shows that the ECT is detecting even more events (slugs) than the gamma densitometer, the significant amounts of liquid hold-up and curved interface contribute to the ECT-derived void fraction being smaller than that derived from the gamma densitometer data. Furthermore, the conditions in this test resulted in relatively small, fast-moving liquid-filled regions of the pipe between the large gas slugs. Previous (qualitative) experiments with the gamma densitometer using a liquid-filled phantom indicated that that faster the phantom (slug) was moved through the gamma densitometer beam, the less it was recorded [15]. For the conditions pertaining in this test it appeared that the gamma densitometer was not seeing all of the liquid and hence the calculated void fractions were higher than those derived from the ECT data.



(a) (b)

Fig. 14 – Tomograms for test point FGRE310512 (horizontal orientation)

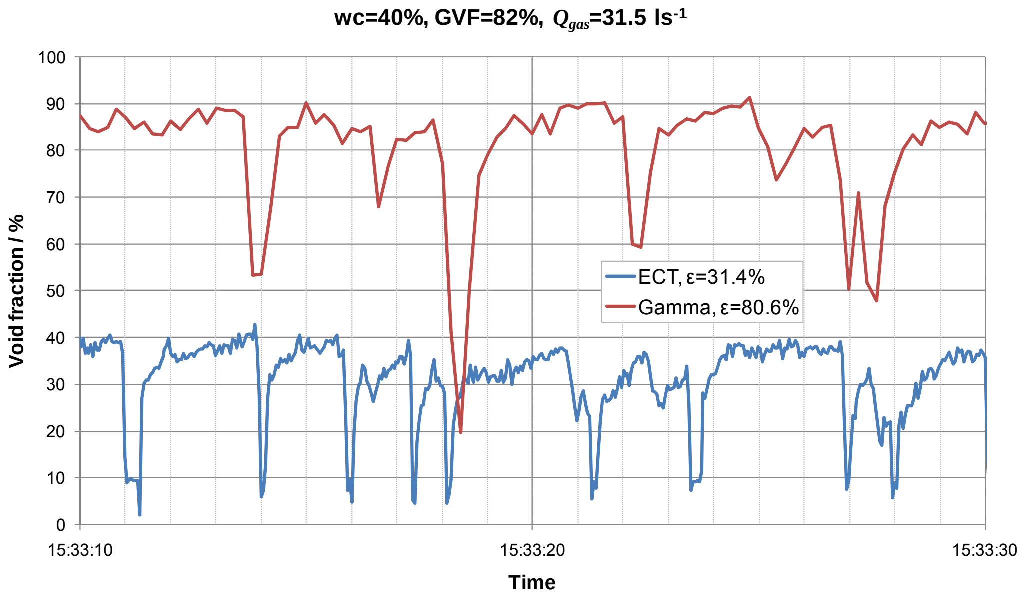


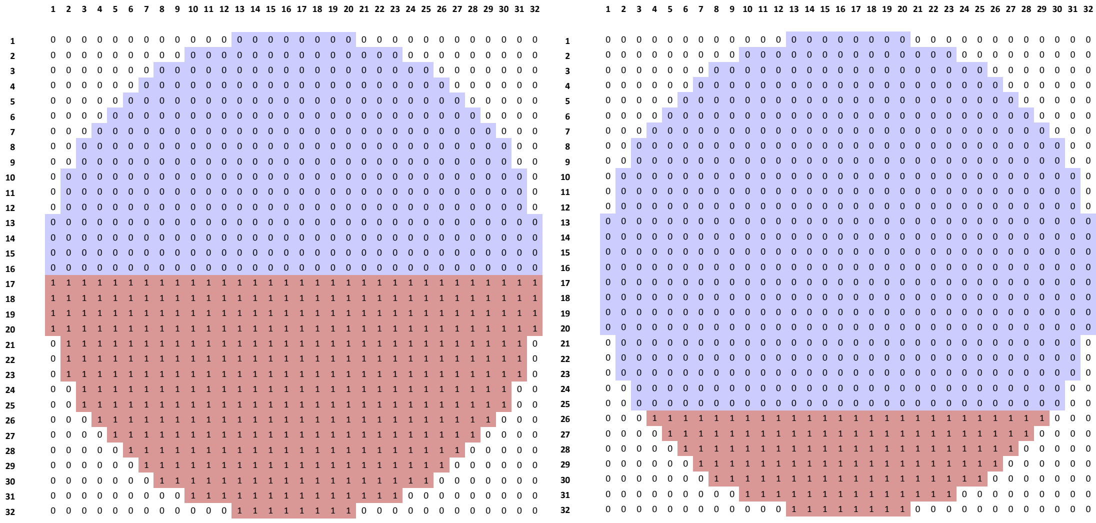
Fig. 15 - ECT and gamma void fractions for test point FGRE310512 (horizontal orientation)

A simple analysis was carried out to ascertain whether the shape of the interface and liquid hold-up at the wall could lead to the observed differences between the gamma densitometer- and ECT-derived void fractions.

Figure 16a represents a pipe filled with 50% liquid and 50% gas, on a 32 x 32 grid, corresponding to the pixel-based approach as used by the data analysis system in the ECT part of the dual-modality tomography system. Using a line-based void fraction calculation analogous to that used for the gamma densitometer gives a gas void fraction of 50.5%. An area based void fraction calculation of the type used by the tomography system gives an answer of 50%. The slight difference in answers is due to the difference in the calculated area of the pipe when treated as a circle of radius 16 (804) or by counting pixels (812).

Figure 16b represents a pipe filled mostly with gas, the line-based and area-based calculations giving answers of 84.0% and 83.7% respectively. Again the slight difference is due to the differences in the area calculations.

When the interface is a straight line, the line-based and area-based void fraction calculations tend to agree with each other. However, looking at an example which is more representative of Figures 12a and 14a with the curved interface and liquid hold-up at the pipe wall, the difference in calculation methods becomes more apparent. The image in Figure 17 gives a line based void fraction of 84.0% and an area based void fraction of 71.9%.



(a) (b)

Fig. 16 - Pixel representation of a pipe filled with gas and liquid - straight interface

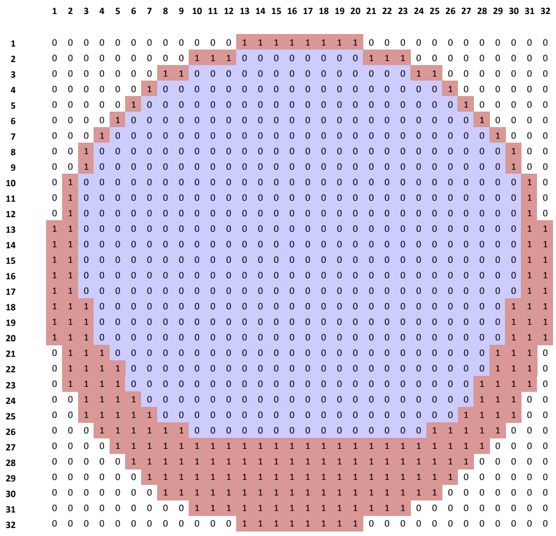


Fig. 17 - Pixel representation of a mainly gas-filled pipe with curved interface

As the line based method assumes a linear interface it is possible it has a tendency to under-estimate the liquid hold-up which in turn means the gas void fraction would be over-estimated. As the curvature of the interface increases with higher gas flow rates this is potentially an explanation for the differences observed in the test results.

However, this effect is not sufficient to explain the observed differences between the gamma densitometer- and ECT-derived void fractions. The tomography system supplier therefore re-examined the tomogram data processing method.

As noted above, the ECT side of the dual-modality tomography system processes the raw data using reference values. Initially a lower limit based on the permittivity of gas and an upper limit based on the permittivity of oil were used to distinguish the gas phase from the liquid phase. However, for the majority of flow conditions in horizontal orientation in the TUV NEL Multiphase Flow Facility, the oil and water effectively form a pseudo single phase with mixed fluid properties. Using the permittivity of pure oil as the upper reference limit may therefore lead to over-estimation of the liquid content (and hence underestimation of the void fraction) as even small amounts of water will significantly increase the measured permittivity, taking the value above the oil-based upper limit and hence appearing as all “liquid”. The tomography system supplier therefore suggested re-processing the data using theoretical mixed oil-water references, based on the known water cuts for each test point, since the permittivity of a homogenised two-component fluid mixture can be well approximated by a simple mole fraction average of the component permittivities.

Figures 18 shows the data from the oil-continuous horizontal orientation tests and Figure 19 shows the data from the vertical orientation tests re-processed using theoretical mixed oil-water references. However, with this approach it appears that the tomography data are now generally over-predicting void fractions compared with the values derived from the gamma densitometer data.

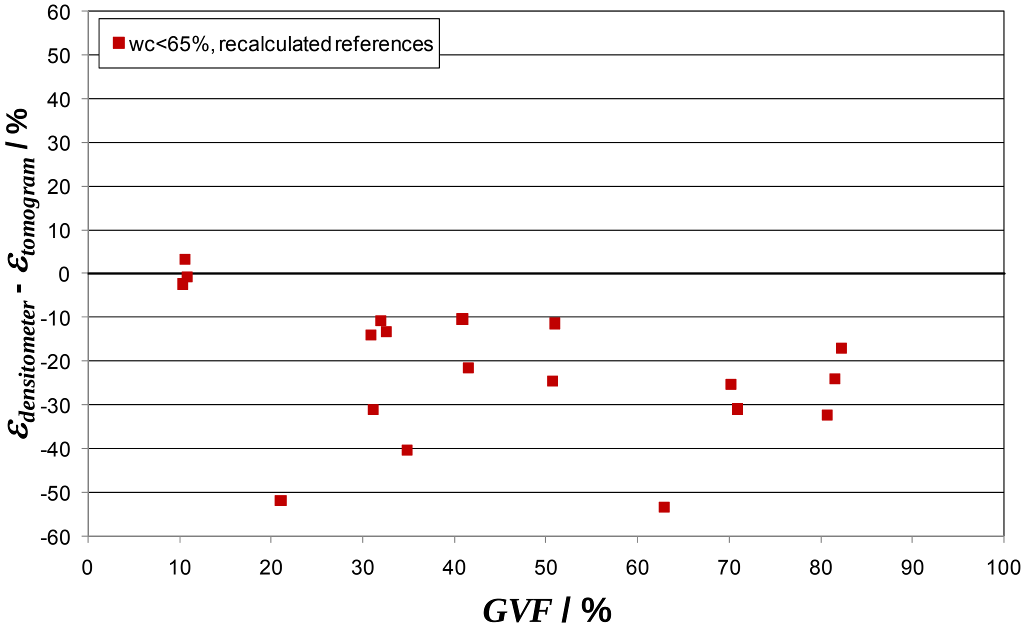


Fig. 18 - Difference in gas void fractions vs GVF, horizontal orientation, recalculated references

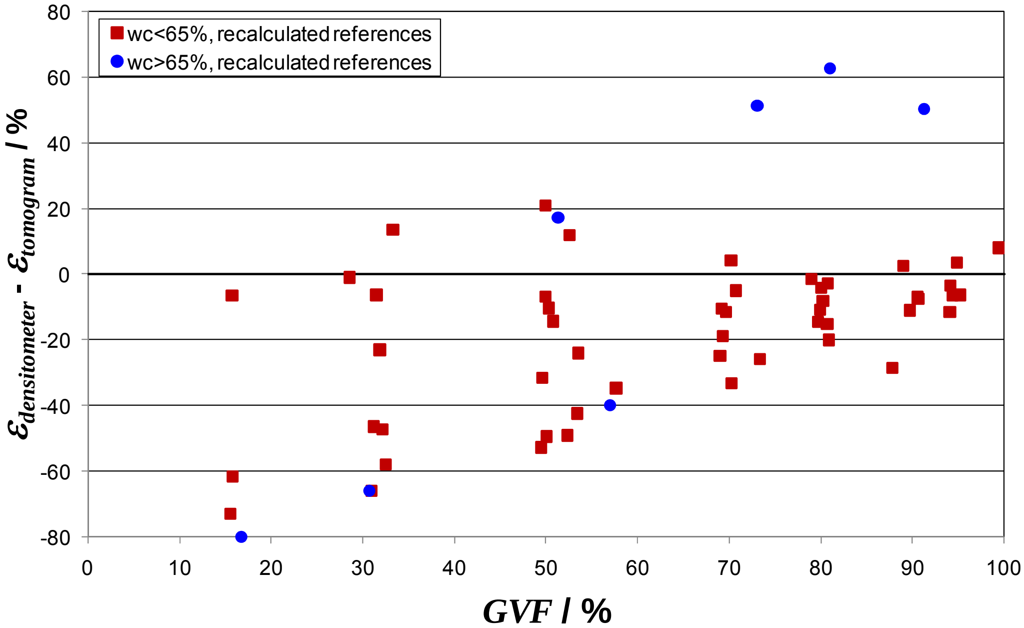


Fig. 19 - Difference in gas void fractions vs GVF, vertical orientation, recalculated references

Following further discussion with the tomography system supplier, a revised method of using experimentally determined mixed fluid-phase references was developed. So far, only a limited amount of data has been reprocessed using this approach but the results look promising, as shown in Figure 20.

5.3 Discussion

So far, efforts have been focussed on validating the ECT part of the dual-modality system. Further analysis will be carried out using the data collected by the ERT side. The images produced by the ERT will give additional visualisation information with regards to the oil and water distribution in the liquid phase.

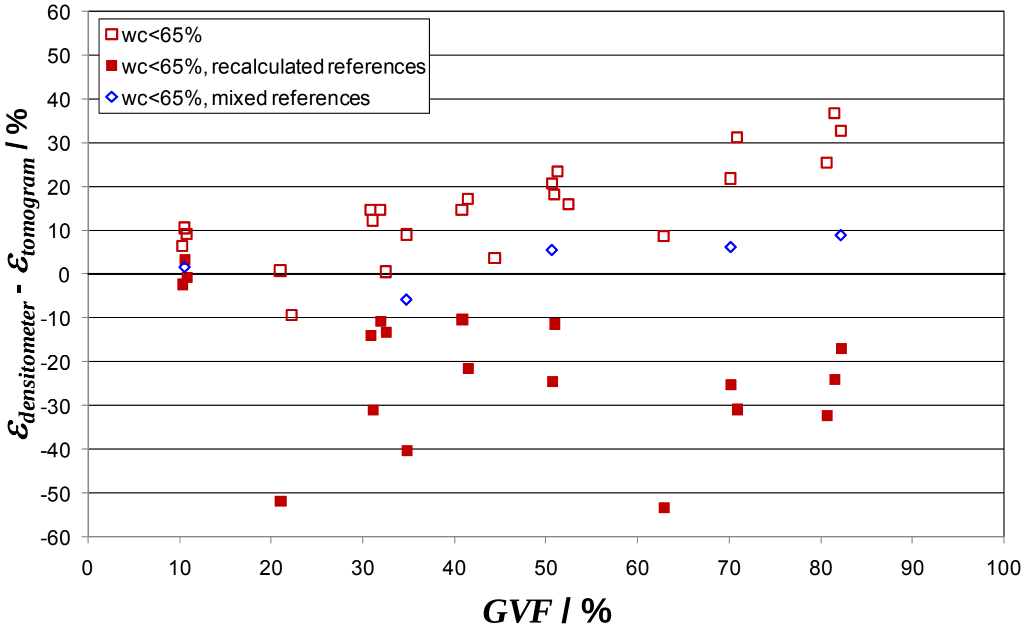


Fig. 20 - Effect of reference on difference in gas void fractions vs GVF, horizontal orientation

Whilst results so far show potential there is still the issue of data fusion. Being able to combine the ECT and ERT images in a single tomogram would make visualisation of complex flows easier.

The main issues encountered when the tomography system was installed in the multiphase test facility were the effect of the water salinity on the dual-modality system, and the need for good references.

Many tomography systems based on electrical properties are in use in universities around the world. Those that have tomography systems based on electrical properties use distilled water and in some cases triple distilled water. As noted previously, the TUV NEL multiphase facility uses a brine substitute consisting of magnesium sulphate crystals ($MgSO_4.7H_2O$) dissolved in mains water and appropriate references must therefore be used

The dual-modality tomography system relies upon the user to take good reference measurements, i.e. single phase water, oil, and gas, or other appropriate references. The better the references used, the better the data collected during testing. This is very similar to many multiphase flow meters in that their performance is heavily reliant on having good fluid property data. It is possible though to post process data with references taken after testing.

Tomography systems still appear to be aimed at more research-based work and as such offer considerable flexibility. Customisation of the user interface is generally required to simplify operation for more industrial applications.

6 CONCLUSIONS

The purpose of this project was to gain a better understanding of the TUV NEL multiphase test facility by using a dual-modality tomography system to visualise the complex flows. It must be stressed that the tomography system was to be used to characterise the flow patterns and not for flow measurement purposes. However, at its current state of development, the dual-modality tomography system evaluated as part of this project was not suitable for this application. TUV NEL has therefore decided not to install the system on the multiphase flow facility at present.

So far, testing has shown that there can be significant differences between the void fractions calculated using the ECT data and the gamma densitometer data, depending on the reference values used to process the raw data from the tomography system. By using appropriate references, it appears to be possible to obtain good agreement between the two techniques, at least over significant parts of the flow regimes.

Whilst it may be argued that comparing void fractions derived from an area-based technique such as tomography with those derived from a line-based technique such as gamma densitometry is unrealistic (due to the effects of a curved liquid / gas interface plus liquid hold-up not detected by the gamma beam), most commercially-available multiphase flowmeters rely on gamma densitometers to provide phase split information and hence there is a perception that gamma densitometer-derived phase information will always be correct. This may not always be the case. At the throat of a Venturi under ideal conditions, the fluid may be sufficiently well mixed that the phase splits derived from a line-based gamma densitometer will be close to the true phase splits. However, this will not be the case in highly chaotic flow situations such as slug and churn flow. In principle therefore, validation of any particular tomographic technique could strictly only be undertaken using another tomographic technique, which itself would have had to be validated.

Despite the difficulties alluded to above, electrical-based tomographic techniques have the potential to provide useful information on phase splits and flow structures in multiphase flows. In addition, the use of modelling as a predictive tool in complex flows is well established, and the ability to visualise a real flow stream would have a major impact on the validation of modelling software. It would allow users to have confidence in the use of codes in more challenging flow systems, bringing benefits to many industrial sectors.

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8 NOTATION

A	Pipe cross sectional area	m^2
C	Capacitance	Farad
d	Pipe ID	m
h	Liquid interface height	m
K	Sensor geometry constant	$Farad^{-1}$
r	Pipe radius	m

Greek symbols

ε_m	Average fluid dielectric within sensing volume	-
ε	Void fraction	-
ϕ	Angle	rad

Subscripts

gas	gas phase
gamma	gamma densitometer
liquid	liquid phase

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