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1. Executive Summary

Introduction

The world will be dependent for many decades to come on the production of oil and gas for its underpinning energy needs. Over half of the world's energy demand is satisfied from oil and gas. When oil is extracted from a well it typically exists as a multiphase flow, comprising time-varying ratios of oil, water and gas. Measuring the flow rate of each component is an underpinning metrology requirement of sub-sea production, a direction in which the industry has been moving for a number of years.

The Problem

Typical multiphase flow measurement systems can have an uncertainty on component flow rate of 20 % or greater under field conditions. The financial exposure alone from this uncertainty is difficult to quantify but thought to be in the region of many $ billions. There is also the cost of production inefficiencies and sub-optimal decision-making that can result from the stated measurement uncertainty. Despite this, the industry has struggled to improve upon these levels of uncertainty.

Beside the intrinsic complexity of the fluids and the relative infancy of the technology, lack of standardised facilities (and procedures) for testing MPFMs for either development or evaluation purposes, is seen as a major barrier to the ongoing development and improvement in multiphase metering technology. Based on the above, a harmonisation initiative for multiphase reference measurement facilities (laboratories) is urgently needed

The Solution

The project has addressed the problem by creating the world's first multiphase measurement harmonisation between two globally-renowned multiphase flow laboratories, NEL and DNV-GL. These laboratories are now able to demonstrate measurement comparability through the adoption of common protocols and the completion of intercomparison testing and rationalism programme. The protocol and capability for conducting inter-laboratory harmonisation is now established and is transferrable, with minor adaptation, to any number of industry-scale multiphase flow laboratories operating worldwide.

Part of the solution was the development of complementary methods to aid our understanding of the harmonisation data and therefore interpret these in the most robust way. These include flow pattern observation and characterization using optical and tomographic techniques and modelling of the flow using small scale experimental and computational fluid dynamics (CFD) methods.

Impact

The ultimate impact of the project was on industrial practice and behaviour but it required a measurement harmonisation network that was enlarged to include a 'critical mass' of players. The project helped to achieve this in three ways:

- It established and implemented the protocol and capability for conducting inter-laboratory measurement harmonisation, as described above.
- During the course of the project, EURAMET approved the funding of a follow-on project MultiFlowMet II, whose aim is to achieve measurement harmonisation across an enlarged network of multiphase test laboratories. It will do so by rolling-out and trialling the findings of the first project to a wider network of test laboratories, also deploying a wider range of MPFM technologies in the transfer standard. All of the achievements of the project will be taken forward by the new project.
- Work on a new ISO Technical Report on Multiphase Flow Measurement (ISO/TR 21354) commenced during the timeframe of the project. This is a significant vehicle by which the findings of the project can inform future industrial practice in multiphase flow measurement. It is intended that TR will cite the project's Best Practice Guide relating to Intercomparison Testing. The expectation is that the TR will also continue to be influenced by findings from the follow-up project.

2. Project context, rationale and objectives

2.1 Context

The world will be dependent for many decades to come on the production of oil and gas for its underpinning energy needs. Over half of the world's energy demand is satisfied from oil and gas. The world economic value of oil and gas production is vast – around $3,000bn p.a. for oil (2014) and $500bn p.a. for gas (2013) [1,2].

When oil is extracted from a well it typically exists as a multiphase flow, comprising time-varying ratios of oil, water and gas. As larger reserves dwindle in number, the new reserves being exploited year after year are smaller in size, larger in number, more remote and in deeper water. This has necessitated the development of subsea production, where new wells are increasingly produced and metered, on the seabed, prior to commingling into shared pipelines leading to the nearest processing facility. Measuring the flow rate of each component is a metrology requirement that is vital for operational decision-making and resource efficiency. It is also a prerequisite for custodial and fiscal measurement [3].

Multiphase metering is relied upon for the monitoring of production changes within reservoirs and for process control of downstream fluids. In such situations, metering accuracy is critical to optimal decision-making as regards process control and production efficiency. Multiphase metering is also required for allocation purposes (where produced fluids from more than one field are co-mingled into a shared pipeline) and for fiscal reporting at minimal financial exposure (the financial value associated with measurement uncertainty).

At the moment, field-based multiphase flow measurement is subject to high levels of uncertainty (up to and sometimes above 20% on individual component flow rates), which has serious ongoing financial implications in all these areas of application. This project has not set out to directly improve uncertainty in the field but will provide an enabling platform for continuous gradual improvement.

In a review of major global multiphase flow loops, Falcone et al [4,5] noted that the need to validate and test multiphase flow meters and to assess their range of applicability had caused a significant rise in the number of multiphase flow loops around the world. There is considerable diversity in specifications, in terms of operating pressure and temperature, phase flow rates, fluid properties, pipe diameter, length of the test section, and available instrumentation and equipment. The facilities can also be configured in a variety of ways to reflect different flow conditions such as pipe inclination and the inclusion of known upstream flow-disturbances. Thus, flow loops are used intensively to test and validate the performance of multiphase flow meters (MPFM's), but there are limits to what can be achieved, even comparatively, when there are so many stand-alone facilities with little or no cross-referencing of measurements or procedures between them [5,6].

2.2 Rationale & Objectives

The lack of standardised facilities (and procedures) for testing MPFMs for either development or evaluation purposes, is seen as a major barrier to the ongoing development and improvement in multiphase metering technology. Significant differences are known to result when instruments are commercially tested between different multiphase test laboratories under similar parametric conditions. No single flow loop can recreate multiphase flow conditions that are representative of all possible field situations. Even when experiments in a given flow loop are believed to be sufficiently exhaustive for a specific study area, the conditions that will be encountered in a real application can be very different from those recreated in the research facility [4,5]. It therefore follows, that there is no 'one best way' of conducting laboratory-based calibrations, or performance measurements, for multiphase flow meters. Which leads to a need for harmonisation of multiphase flow methods and measurements, in order to provide comparability of measurements taken from different laboratories.

A high-level technical aim of this project (reflected largely in Objective 1, reiterated later) was to develop an approach to such harmonisation that could be piloted across a small number of multiphase flow laboratories. To achieve harmonisation, existing measurement comparability first has to be quantified through an intercomparison testing programme. This, in turn, requires the design and provision of a mobile suite of instrumentation that can be moved around the different laboratories to enable the comparison measurements to be taken. To understand any variances in the laboratory datasets requires understanding of the factors that influence the measurements, such as the geometrical features of each laboratory, the fluids used and the structure of the flow that develops in each set of flow conditions. Finally, it is necessary to apply these findings to the intercomparison data, to see what insights can be developed that will lead to the maximum possible level of harmonisation between the laboratories.

2.2.1 Flow measurement reference infrastructure

There are in excess of twenty industry-scale multiphase test loops existing world-wide and this number is growing.

Operational norms are many and varied. Prior to this project, there existed no networked reference infrastructure of significance; various stand-alone multiphase test loops existed around Europe and the world which use different sets of standards. Some observations at the outset were:-

- Most measure each constituent phase upstream of the mixing point – i.e. single-phase measurements. Technologies for this vary from loop to loop.
- Each operates over a specific set of flow rates, pressures and temperatures.
- Each uses a specific set of fluids for each phase e.g.
  - Oil phase varies from tightly specified grades of known physical properties to relatively variable 'live crude'.
  - Water phase varies from freshwater to 'produced' salt water
  - Gas phase varies from benign (e.g. nitrogen) through high-density gas (SF_6) to natural gas.
- Each facility has its own geometric characteristics with regard to flow inclination ranges, test section lengths, pipe diameters etc.
- Each follows a different specific set of test standards and procedures.

There therefore existed a need to put in motion a harmonisation initiative. This would begin with the formation of a small reference network of multiphase flow-loops able to demonstrate measurement comparability through the adoption of common protocols and a programme of intercomparison testing and rationalisation.

2.2.2 Flow Pattern Mapping

Because of the variable nature of multiphase flow and the variety of test facilities, it was considered important in terms of any harmonisation initiative that flow conditions should be described as comprehensively as possible. This means not only measuring the conventional parameters like component flowrates, pressure, temperature and so forth, but also describing the flow structure at the test location. It was recognised that this would be enormously challenging.

Flow pattern maps are fundamental to the understanding of multiphase flow measurement. The flow pattern through any given flow meter fundamentally affects, to some degree, the relationship between the meter outputs and the actual flow rates in each of the three components, water, oil and gas. Empirical flow pattern data already existed, with some degree of theoretical extrapolation, but only for a very select range of flow conditions, thus greatly restricting their applicability.

In particular, there was a lack of data for the flow conditions that characterise many of today's multiphase measurement applications in oil and gas. Therefore, the desire with regard to flow pattern mapping was to extend theoretical and experimental capability in this area, leading to better mapping of the flow conditions of greatest current industrial interest, particularly those that may be agreed upon for intercomparison testing.

2.2.3 Modelling and simulation

Computational fluid dynamics (CFD) flow modelling is a well-established useful tool in single-phase flow metering. More recently, advances in computing power has made multiphase models viable. A range of modelling approaches are available, each having its individual advantages and disadvantages. The basic approaches include:-

- Homogeneous flow approximation – in which the flow is regarded as 'well-mixed'. This is limited to cases where the 2nd phase is very well dispersed
- Lagrangian Particle Method – in which a carrier fluid is modelled as a single-phase CFD model and a second phase modelled as individual spherical particles that are tracked step-by-step. This is limited to low fractions of the 2nd phase
- Volume-of-Fluid Model – in which, in addition to the normal single-phase flow parameters, the liquid fraction between each cell is calculated. This is applicable mainly to stratified flow.
- Eulerian model – in which each cell contains one of the two possible phases, one of which is modelled as a 'cloud' of bubbles in a carrier fluid.

These are available in commercial and open-source packages including ANSYS Fluent, ANSYS CFX, Adapco STAR-CCM+, Flow3D and OpenFOAM.

There is a relative dearth of published information regarding CFD approaches to modelling multiphase flow, though it is known that there is much unpublished commercial activity in this area. A desire of the project was to evaluate different approaches and develop an optimal approach to CFD modelling of multiphase flows that would lend greater mechanistic understanding to the data likely to be generated in the intercomparison testing. Ideally, it was desirable for this to include modelling aimed at better understanding the influence of parametric variances (flowrates, pressure, temperature, viscosity, geometry and so on) on both flow structure and elementary physical aspects of metering, such as Venturi pressure drop.

It was further postulated, over-ambitiously as it would turn out, that combining state-of-the art computational fluid dynamics modelling techniques with *polynomial chaos method*, would lead to a much-improved basis for the determination of uncertainty in multiphase modelling and measurement. The desire was to enable closer comparison between modelling and experiment by quantifying the uncertainties associated with the former.

2.2.4 Flow visualisation

In recognition of the desire for extended flow-pattern mapping (described above), it was considered desirable to have available a means of observing (and quantifying if possible) the flow structure developing for a given set of measured parameters. A number of experimental flow visualisation techniques existing prior to the project and these were briefly reviewed in terms of their applicability, these included:

- Laser Doppler Velocimetry (LDV) – whose application range was limited only to small liquid volume fractions
- Fast X-ray tomography – which would not be readily transferable between labs.
- Ultrasonic multi-beam - under commercial development, therefore proprietary but not yet ready
- Magnetic resonance imaging (MRI) – which did not work well with magnetic conduits present.
- Optical (view-port) – an established method but challenging in terms of data capture and quantification.
- High-speed electrical capacitance tomography (ECT) – noted for high frame-rate data capture but applicable only to oil-rich flow.
- Dual-modality electrical tomography (ECT + ERT) – known for having provided verifiable data for stratified (horizontal) three-phase flow but in need of further development to resolve more complex flow patterns.

It was considered appropriate to take forward a combination of optical (view-port) methods together with high-speed ECT and dual modality electrical tomography. It was recognised that none of these methods were ideally placed to yield all the information required about flow structures. It was therefore decided to incorporate some development of the technologies into the project, with the prospect that they could be applied at later stages of the project and/or in subsequent work that the project may help to stimulate.

2.3 Objectives

The scientific and technical objectives were:

1. *To develop an accurate and validated metrological reference network*, using existing test and calibration facilities for multiphase flow. The objective is to achieve comparability between labs, using agreed test devices that is consistent with the respective uncertainty budgets. This agreement will establish, and take account of, cause and effect regarding variances in physical measurement methods, as well as in test, analysis and reporting procedures.
2. *To improve upon current theoretical and experimental determination of flow pattern*s (bubble, finely dispersed bubble, slug, churn, annular, stratified or wave) as a function of field variables such as pressure, temperature and component fluid properties and velocities. In particular, to extend the flow pattern data for the high pressure regime (at least up to 25 bar) that characterises many of today's multiphase measurement applications in oil and gas. A related objective is the development of synergistic modelling and experimental techniques that will allow flow patterns to be mapped using fewer experimental data points.
3. *To provide an improved basis for determining uncertainties*, by combining state-of-the art computational fluid dynamics modelling techniques with polynomial chaos method. The scientific

objective is to develop a method that enables closer comparison between modelling and experiment by quantifying the uncertainties associated with the former. Furthermore, this will allow modelling techniques to be developed for simulation of field conditions, where deterministic data are of only limited value without knowledge of the associated uncertainties. As a result an improvement by a factor of two in modelling uncertainty will be strived for, but should be regarded as an arbitrary target in the absence of prior data.

4. *To evaluate and improve experimental methods of flow visualisation* using dual modality electrical tomography for vertical multiphase flow pattern determination. In particular, we aim to develop this technique as a tool that can be used in multi-phase flow loops for investigation and verification of flow patterns. Measurement methods will be developed to help quantify the flow pattern(s) observed (currently methods are partly-subjective). A specific objective is for real-time cross and through-sectional imaging with flow pattern recognition to be developed for mixtures and flow velocities appropriate to multiphase production. Flow pattern recognition and quantification is the objective. Improvements in spatial and time-domain resolution are regarded as strong contributing factors and a ‘factor of two’ improvement will be sought in each, unless a more optimal way is identified

3. Research results

3.1 Developing a metrological reference network

3.1.1 Introduction

The objective here was to achieve harmonisation between two or more commercial test laboratories, using agreed test devices, consistent with the respective uncertainty budgets. This agreement was to establish, and take account of, cause and effect regarding variances in physical measurement methods, as well as in test, analysis and reporting procedures.

Prior to the project, a reference network consisting of test and calibration facilities for *multiphas*e flow meter testing simply did not exist. This was in contrast to the broad network of accredited laboratories for calibration of *single phase* liquid and gas flow meters. Project partners DNV GL, NEL, OneSubsea and Shell set out to establish such a ‘world first’ reference network for multiphase flow reference measurement. In the end, Shell was unable to t ake part experimentally in the project owing to changing business priorities.

3.1.2 Methodology

Uncertainty calculation for multiphase test facilities

Prior to the project, each laboratory partner had an existing uncertainty budget. These were presented to the neutral party, VSL, for independent review and to ensure comparability during intercomparison testing. It was found that the uncertainty budgets varied in terms of potential sources contributing to the overall uncertainty and how these are accounted for. However, as the facilities had different operating principles, varying uncertainty budgets were to be expected. Typical sources of uncertainty are those related to instrumentation (temperature, pressure, density, and reference flow rates measurements), single phase contamination oil-in-water, water-in-oil, liquid carry over and gas carry under) and calculation models for fluid densities, phase interactions and equilibriums. Recommendations were made to maximise comparability during intercomparison testing, which were implemented as far as was practicable.

Intercomparison transfer standard

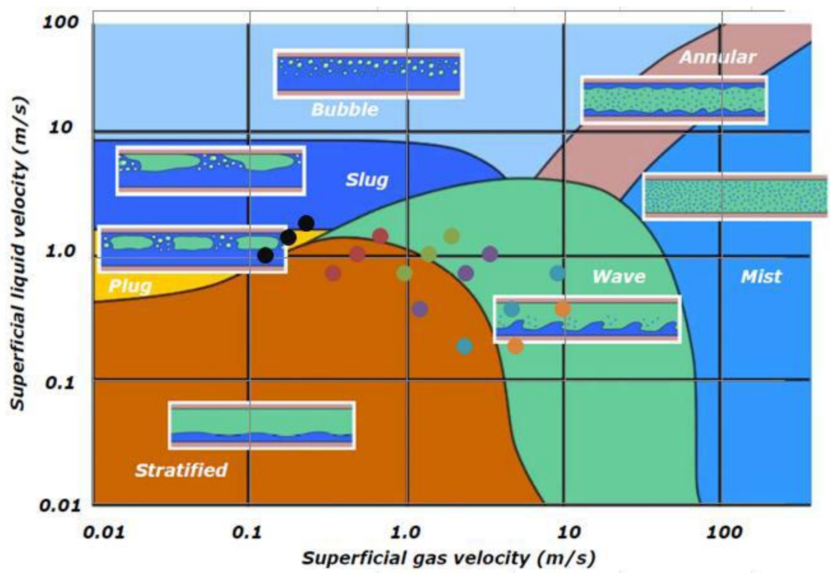
The intercomparison transfer standard consisted of a multiphase flowmeter, a PhaseTester Vx52 supplied by OneSubsea, a Schlumberger company, a 10 meter straight pipe length (100D = 100x the pipe internal diameter) upstream of the meter and a transparent spool piece (video camera normally incorporated but missing in photograph, for clarity), to capture the flow regime for each test point. The meter has an inlet pipe diameter of 104mm and the Venturi throat diameter is 52 mm (i.e. beta = 0.5). In the configuration supplied, the MPFM was skid-mounted with a 90-degree bend preceding the MPFM proper.

The flow meter and transparent section (minus camera for clarity) are shown in Figure 1.1(a) while 1.1(b) shows the general layout including the 10m (100D) upstream straight section. An illustrative flow pattern map is shown in Figure 1.1(c) – this is a very broad indication only and should not be relied upon for accurate flow pattern prediction. Specific flow pattern evidence was acquired on video from the transparent spool piece, throughout the intercomparison tests. The frame rate used was 240 fps, which permitted flicker-free replay at one eighth of live speed, for flow pattern identification.

The measurement uncertainty of the transfer meter is specified as 3 % for liquid volume flow rate and 12 % for gas volume flow rate, both for a Gas Volume Fraction (GVF) below 90 % and line pressure above 5 bar. However the repeatability and reproducibility of the meter was believed to be typically better than 1 % for most measurements. This latter number is the most important value for the intercomparison.

(a) MPFM and optical section at NEL

(b) Overall setup at DNV-GL with 10m straight section



(c) Illustrative flow pattern map with some intercomparison test points superimposed

Figure 1.1 - Transfer standard set-up at NEL and DNV-GL, and typical flow pattern map.

Test protocol and test matrix

A standard test protocol was developed detailing the required meter set-up and procedures to be followed – these are detailed elsewhere [6] and reflect best measurement practice from those deployed individually at each of the participating labs. A flow meter operator from the manufacturer configured the meter at the start of each test and manufacturers operating procedures were followed throughout. To further ensure good data quality, a systematic audit was done of the MPFM data by VSL, DNV-GL and NEL, after completion of intercomparison testing. Some data reprocessing was performed following this – to account for differences in fluid properties for example – these being agreed between all the participating parties including VSL, the independent arbiter.

The intercomparison test matrix, containing all the test points in terms of flow rates, is given in Table 1.1. Test temperatures, pressures etc. were also specified throughout. The matrix was based on the combined operational envelope of the flow meter and the participating multiphase laboratories. The intercomparison measurements are based on average values obtained during at least 10 minutes flow recording.

Table 1.1 - Selected multiphase test points. Symbol meaning: X: Points carried out at WLR of 25, 45, 70 and 90 %. O: Points carried out at WLR of 0, 25, 45, 70, 90 and 100 %.

Liquid Flow m³/hr	Gas Volume Fraction %					
	25	55	70	84	92	96
9					x	O
18				X	O	x
35		x	X	O	x	
50	O	x	O	X		
70	x	O	X			
90	O					

The intercomparison has been possible with 4 sets of data recorded over 18 months. More than 300 data points were recorded, and the comparison is made over the full range of WLR and GVF values.

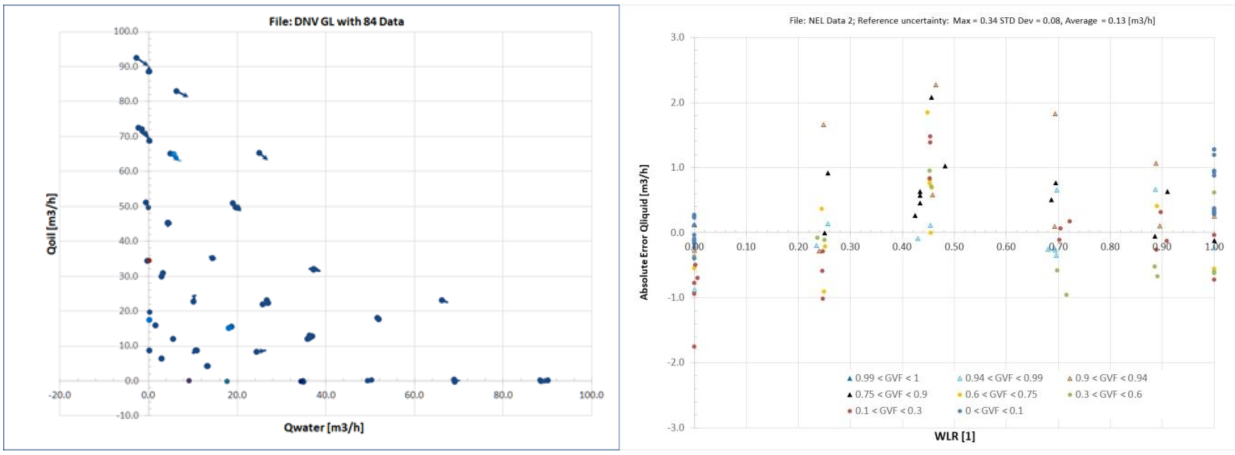
Data analysis method

One of the main challenges was to consolidate the data in the appropriate format and to develop a comparison procedure independent of the MPFM technology used (and its associated uncertainty). It was established that only four independent parameters should be considered - oil, water, gas and liquid flow rates (and consequently, the derived parameters Gas Volume Fraction, GVF and Water-Liquid Ratio, WLR). Any metering "system" (combination of flowmeter and test facility) has its own combined uncertainty and this should be taken into account in the comparison as it is instrumental to the analysis. It was assumed that the setting of the actual flow conditions for test each point on the test matrix, based on laboratory reference instruments, were identical between the different laboratories. In reality, there will be small deviations from set-points.

The analysis method developed was as follows:

i. A first stage in the analysis was to look at the 'fingerprint' of the transfer package on the facilities, i.e. the difference between the MPFM reading and the flowloop in the Qliquid vs. Qgas and Qoil vs. Qwater domains. This helps demonstrate the robustness of the transfer package, and measurement response versus WLR and GVF – see illustration below.

ii. The second step in the analysis was to look at the deviation for oil, water, liquid and gas flow rate versus GVF and WLR, see illustration below. This highlights the response for the "system" deploying the given MPFM technology without looking at the meter performance in isolation. This step is important in cases of deviation in the intercomparison proper, which is the third step of the analysis.



(a) (b)

Figure 1.2 - Illustration of analysis Stages 1 and 2. (a) Fingerprint of transfer package on facility, (b) Deviation of flow rate against WLR

iii. The final comparison (which is the actual intercomparison) developed examined the difference in the response of the MPFM between any two given flowloops. This analysis is done for oil, water, total liquid and gas flowrate measurements as a function of GVF and WLR, as appropriate.

For each set-point on the test matrix, if we look at the flow rate for any given component (liquid, water, oil or gas) there are three variables that are measured;

$Q1$ = MPFM reading in lab 1

$Q2$ = MPFM reading in lab 2

$Q_{ref}1$ = test matrix set-point

$Q_{ref}2$ = reference meter reading in lab 2

The reference meter readings are adjusted by the labs to obtain the given set points on the test matrix, therefore we can approximate $Q_{ref}1 = Q_{ref}2$ for any given test point.

It is then possible to establish the difference between the MPFM and the reference flowloop measurement. Let's call this derived measurement ΔQ_1 for Flowloop 1 and ΔQ_2 for Flowloop 2 with the same MPFM.

Now let $\overline{\Delta Q_1}$ and $\overline{\Delta Q_2}$ = the average values of ΔQ_1 and ΔQ_2 respectively

We can then define a comparability parameter ζ, that relates the measurement difference $\left(\overline{\Delta Q_1} - \overline{\Delta Q_2}\right)$ to the uncertainty of measurement, σ, for Q_1 and Q_2 respectively.

Thus,

$$\pm \zeta = \frac{\overline{\Delta Q_1} - \overline{\Delta Q_2}}{\sqrt{\sigma^2(\Delta Q_1) + \sigma^2(\Delta Q_2)}} \qquad \text{(Equation 1)}$$

The approach given above takes into account the uncertainty of the equipment (flowloop + reference meter + transfer package). However, the *repeatability* of the transfer package has not been taken into account in this analysis and should be highlighted in one way or another. The expression should therefore be re-written as:-

$$\pm \zeta_{global} = \frac{\overline{\Delta Q_1} - \overline{\Delta Q_2}}{\sqrt{\sigma^2(\Delta Q_1) + \sigma^2(\Delta Q_2) + Ur^2_{(TP)}}} \qquad \text{(Equation 2)}$$

Where $ur_{(TP)}$ is the uncertainty associated with the repeatability of the transfer package.

This expression highlights the fact that it is the *repeatability* or *reproducibility* of the transfer package that is critical rather than the *absolute* measurement performance of the MPFM used.

Unfortunately, in the present work, due to multiple constraints, it was not possible to determine $Ur_{(TP)}$ with great accuracy. However, it is believed that the repeatability of the meter used is small, such that the Ur^2 term was therefore also small in comparison to the other two uncertainties. In future work, special provision should be made in the experimental programme to accurately determine Ur^2.

For now, therefore, we are reporting the analysis based on the basic ζ value rather than ζ_{global}. This will lead us to a slightly *pessimistic* analysis of the intercomparison data.

If the MPFM readings in the two labs are the same then, clearly, $\zeta = 0$ and we have a ‚perfect' match. If the difference in the MPFM readings between the two labs is less than or equal to the combined uncertainty of measurement, i.e. $\zeta \leq 1$, then we can say that we have good statistical agreement between the laboratories based on the transfer meter readings. For ζ values above 1, comparability depends on whether there is an alternative explanation for the lack of a good stochastic agreement. The ζ - scoring system can then be summarised as follows:-

Table 1.1: ζ -score and criteria of validation for the intercomparison

ζ -Score	=0	<1	<2	>2	>3
Comparison Criteria	Perfect match	Good statistical agreement	Possible comparability depending on other factors	Poor comparability	Failed

As identified earlier this means now that it is possible to look at the ζ -score for liquid, water, oil and gas.

3.1.3 Findings of intercomparison study

The test facilities that participated in the core of the intercomparison were NEL and DNV-GL. Two rounds of testing were conducted at NEL, before and after the DNV-GL tests, with more than one year between the rounds. OneSubsea also ran tests using the same flow meter at their own Horsoy flowloop. However, the remainder of the transfer package was not installed, which resulted in a radically different inlet geometry. The line pressure was also at significant variance to those encountered at NEL and DNV-GL, which also masks comparability. Therefore, for consistency and rigour, only the NEL and DNV-GL data are reported here.

Consistency checks between NEL Round 1 (2015) and NEL Round 2 (2016)

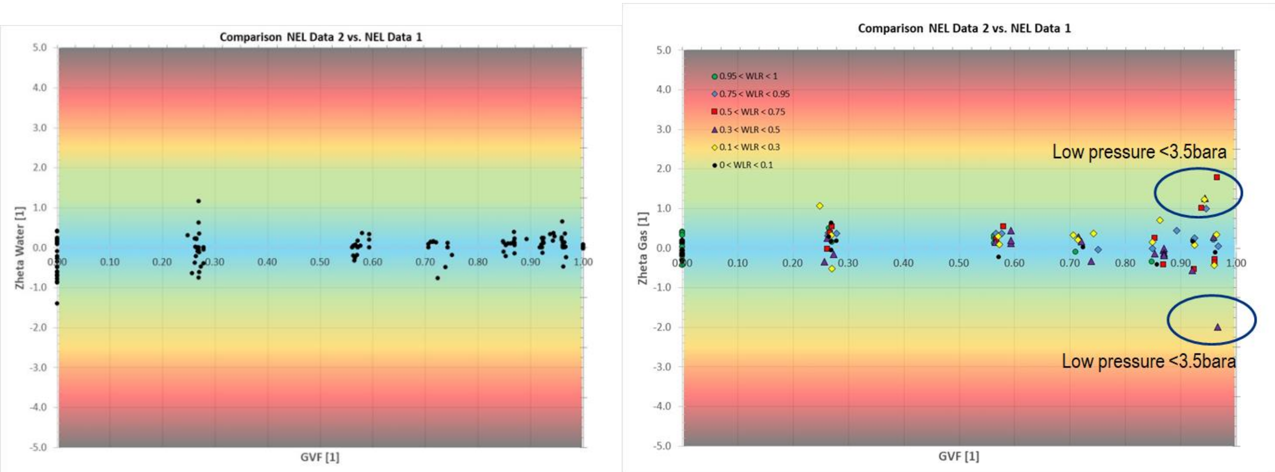
The NEL facility was used to record data in 2015 and 2016, to provide some measure of consistency of the intercomparison transfer package. Between those dates, the baseline fluid properties were altered slightly due to an oil change. However, the operating temperature was altered in order to achieve the same oil viscosity in NEL round 2 as in NEL round 1. 115 test points were recorded in NEL Round 1 and 143 points in Round 2.

Total liquid, oil and water comparisons.

These data showed overwhelmingly good statistical agreement throughout the entire range of GVF and WLR's considered. Only six points exhibited a ζ value above 1. All six of these exhibited ζ values well below 2. Five occured in monophasic oil or water flow conditions, the remaining one being at GVF = 25%. The water comparison data with GVF are reproduced below, for illustration. The fact that the poorest scores were recorded for monophasic liquid flow is an observation we will return to later in the NEL vs. DNV-GL intercomparison.

Gas comparison

The gas comparison between NEL round 1 and round 2, shown below, is good (ζ < 1) on the entire range of GVF except for a few points at very high GVF and low pressure. There was no trend observed with respect to WLR. The discrepancy occurs at high GVF and line pressures below 3.5 bara. It is clear based on this analysis that low line pressure is problematic from the point of view of producing good comparability. Further analysis of data acquired at line pressure around 3.5 bara showed significantly more variability of line pressure between NEL Round 1 and 2 at high GVF values than at lower GVF values. We will return to this finding in the intercomparison between NEL and DNV-GL below.



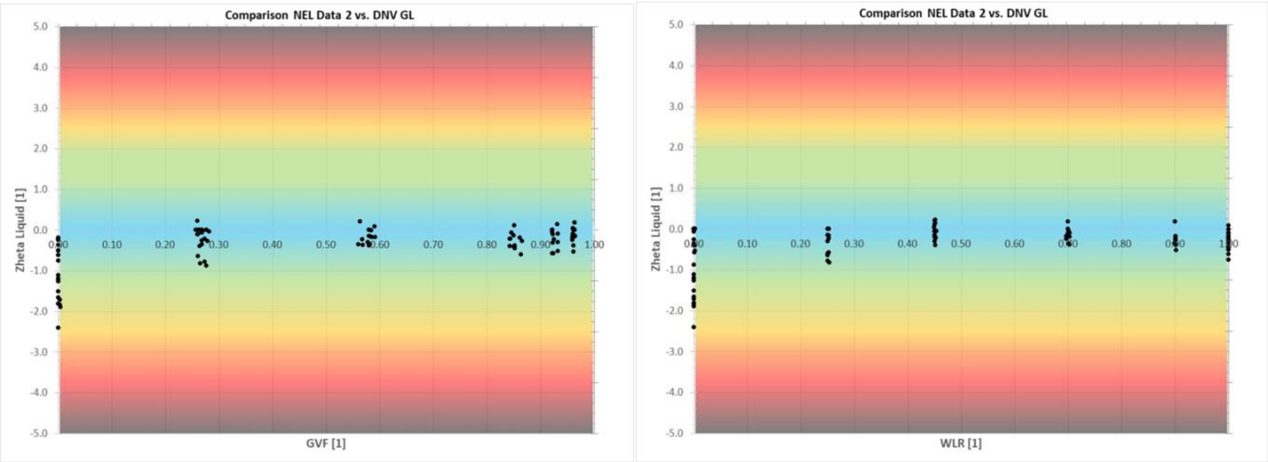
(a) **(b)**

Figure 1.4 - ζ values for (a) water and (b) gas, as a function of GVF for comparisons between NEL Round 1 (2015 and Round 2 (2016).

Intercomparison between NEL and DNV-GL

It should be noted that the gas used is the same for both flowloops (i.e. nitrogen). The oil and the water are slightly different in terms of density and salinity.

Liquid comparison



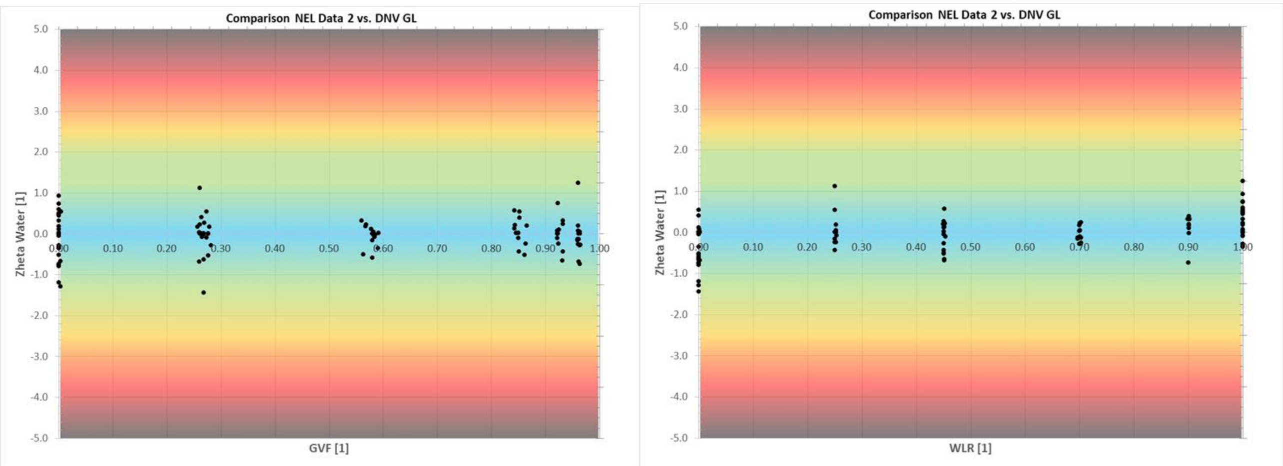
(a)

(b)

Figure 1.5 - ζ values for liquid, as a function of (a) GVF and (b) WLR, for comparisons between NEL and DNV-GL.

The liquid was shown to match very well over the entire range, i.e. ζ < 1, except for discrepancies where there is monophasic flow of oil. This was also observed in the NEL Round 1 vs. NEL round 2 comparison. Further analysis is considered under the Oil Comparison (below).

Water comparison



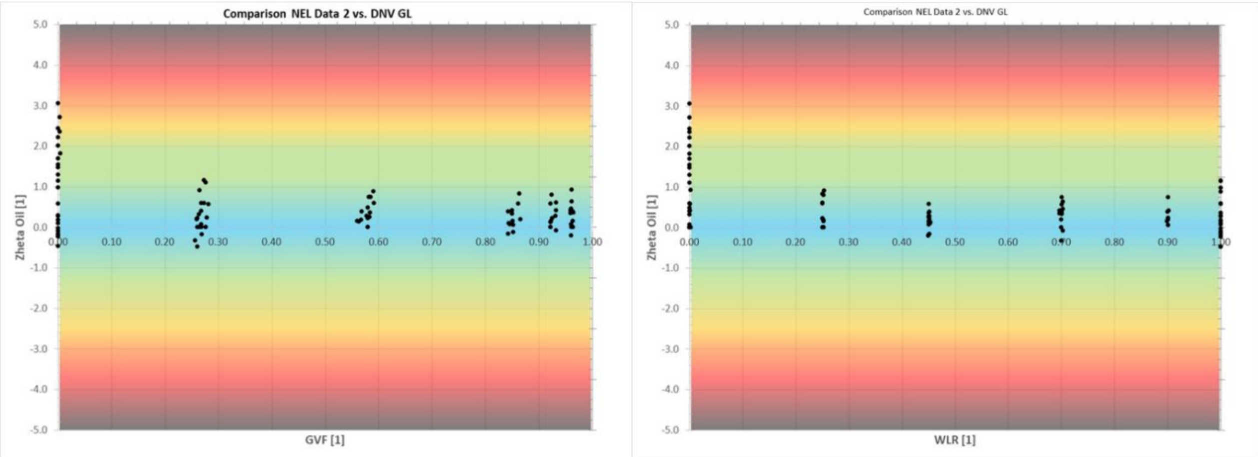
(a)

(b)

Figure 1.6 - ζ values for water, as a function of (a) GVF and (b) WLR, for comparisons between NEL and DNV-GL.

The ζ-score for the water showed good statistical agreement for most of the data (ζ < 1), with the small number of exceptions still exhibiting ζ values quite close to 1.

Oil comparison



(a)

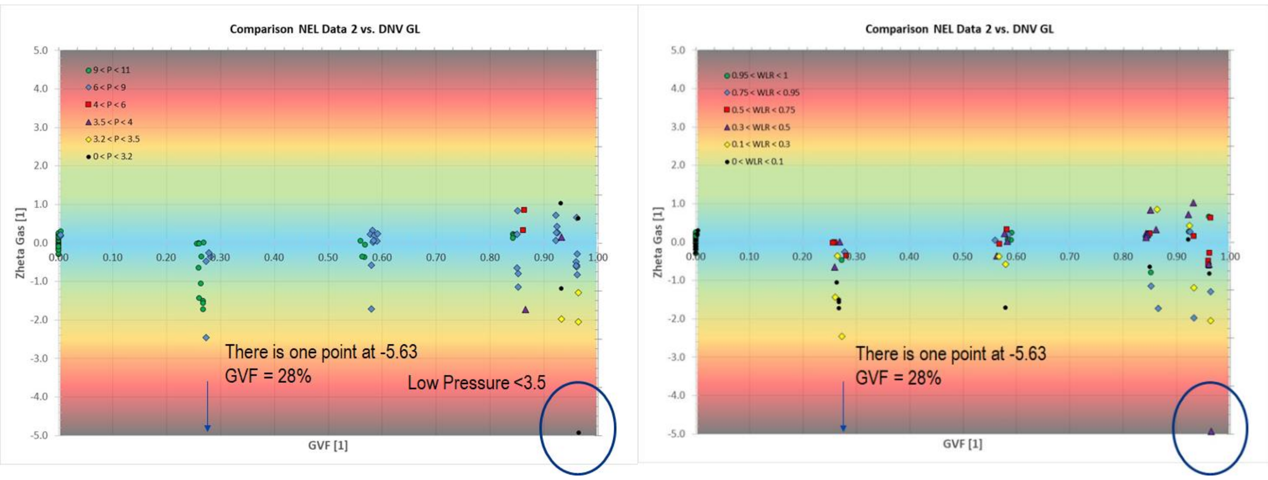
(b)

Figure 1.7 - ζ values for oil, as a function of (a) GVF and (b) WLR, for comparisons between NEL and DNV-GL.

The ζ-score for the oil shows good statistical agreement for the entire range of GVF except for the case of GVF = 0 or monophasic oil flow. The comparison against WLR was similar or better across the entire range, with again only the monophasic oil flow case (WLR = 0) being problematic.

The issue with monophasic oil was also observed in the NEL Round 1 vs. Round 2 comparison and is therefore consistent. It is, however, an unexpected finding. There exists the possibility that the assumed uncertainty in the measurement ‚system' (reference meters + MPFM) was over-optimistic for monophasic flow conditions, as this would lead to a calculated value for ζ that is over-pessimistic (Equation 1). However, this does not explain the bias that is also observed in the ζ values. For now, therefore, it is not possible to be conclusive about the cause of these monophasic measurement variances between the flowloops. They are, however, in the minority, the vast majority of the liquid data showing very good intercomparability between the laboratory measurements.

Gas comparison



(a)

(b)

Figure 1.8 - ζ values for gas, as a function of GVF with (a) line pressure and (b) WLR being indicated for each point, for comparisons between NEL and DNV-GL.

The intercomparison for gas between both facilities was less than satisfactory. Specific observations are that:

- At 85 to 95% GVF, the ζ score was very good when line pressure was kept high (unfortunately, in the high GVF tests at NEL, line pressure dropped from 9 bara to below 3.5 bara).
- The ζ values at around 60% GVF - where the flow is usually quite intermittent – are very good, except for one point, which still has a ζ value below 2.
- At 25% GFV, when the flow is relatively bubbly and stable, the ζ-score is highly variable.

The first observation above emphasises again the role of the line pressure, as observed earlier in the consistency checks between NEL Round 1 and NEL Round 2. This underlines the need to keep line pressure as consistent as possible in intercomparison testing.

The second and third observations above run contrary to expectations on the basis of the flow patterns – relatively stable bubble flow being predominant at GVF = 25% but intermittent flow occuring at GVF = 60%. The bubble flow (25% GVF) should result in less stochastic noise than the intermittent flow (GVF = 60%), yet the opposite is reflected in the recorded measurement data.

To investigate these anomalies further, differences of geometry between the two laboratories were considered next. In the DNV-GL facility, the mixing point location is more upstream than in the NEL one (when the same 100D straight section is deployed). A number of additional tests were arranged at NEL aimed at seeing whether the injection point significantly alters the flow pattern, with other variables held constant. In addition to the standard injection point 100D upstream, the injection point was moved to 10D and 500D respectively and further tests carried out.

Footage of the flow patterns taken at the optical section where the flow enters the meter were examined as part of the analysis. The table below summarises the findings for WLR = 0% and GVF = 25%. The flow pattern characteristics tabulated were based on extensive examination of the video footage. Stills from the footage are reproduced further below, for illustration only.

Table 1.3 – Flow pattern observations for different upstream injection points, at WLR = 0% and GVF = 25%.

Injection point, upstream of meter	*Description of flow pattern observed*
10 D	Stable flow, no section of the pipe totally dry. Gas flowing more in the upper half of the pipe but always in the presence of oil.
100 D	Gas slugs observed of average frequency ~ 0.5Hz. Remainder of structure similar to above.
500 D	Larger slugs of gas than above, at lower average frequency of ~0.25 Hz.

(a)

(b)

(c)

Figure 1.9 – Stills from video footage at WLR = 0% and GVF = 25%, for illustration. Injection point was (a) 10D upstream, (b) 100D upstream and (c) 500D upstream.

Given that these data are all from the same flowloop, they clearly show the injection point influencing the flow pattern, with other variables held constant. This leads to the *possibility* of the differences of injection point between the two laboratories contributing to the measurement variances in some way. Unfortunately, there are insufficient data to lead to a more conclusive finding. For now, the measurement variance between the NEL and DNV-GL facilities at low and high GVF, is not fully resolved.

What is clearly underlined is the importance, in intercomparison testing, of ruling-out as many potential sources of measurement variance as possible. These include matching not only the oil, water and gas flow rate and line pressure as closely as possible but also other factors such as the setting of the injection point.

3.1.4 Intercomparison conclusions & recommendations

- A transfer standard was developed and successfully deployed, incorporating a single MPFM (based on mass flow measurement), standard upstream straight pipe length and optical section for observation of flow pattern. Looking toward the MultiFlowMet II project, complementary flowmeter technologies are recommended to strengthen the intercomparisons in wide-ranging flow conditions. Mass flowmeters are particularly suited in cases of low GVF. Volumetric flowmeters, by contrast, are more tailored to high GVFs. Additionally, a flowmeter tailored to give low uncertainty in areas of low overall flowrate will extend the intercomparison test envelope to the lower flowrates that may be appropriate for some facilities.

- A standard testing protocol was established and implemented. This will also be taken forward, with minor refinements. It was concluded that a 10-minute sampling time is sufficient when the associated standard deviations are available.
- A set of principles was established by which uncertainty budgets from different facilities can be reviewed for comparability and subsequent use in the intercomparison data analysis. A data comparison methodology has been developed that combines facility and MPFM uncertainties in a way that allows facilities to be compared against one another without explicit reference to the performance of the flowmeter deployed. Objective success criteria have also been proposed for intercomparison validation, based on a ζ-score which compares variances against the “system” uncertainty for each facility pairing and MPFM combination.
- Based on the work carried out, a successful intercomparison was performed between NEL and DNV-GL, across a wide-range of four parameters oil, water, gas and liquid flow rates (and the parameters WLR and GVF derived from them). There were some unresolved anomalies in a minority of cases:
- In the liquid comparisons, liquid single-component flow conditions exhibited some interlaboratory measurement variance. These variances were not worryingly high, but they were significant. Several possible causes exist but none have been proven conclusively. It is recommended that, in future tests (MultiFlowMet II), the MPFM should be coupled with a single-phase meter (such as a full-bore ultrasonic meter) to provide better insight into this anomaly.
- There was significant variance observed in a small minority of data in the gas comparisons. This was not fully resolved, though some possible causes were proposed. To rule these out in future intercomparison testing, it is recommended that the line pressure is matched as closely as possible between facilities, together with other factors that may affect flow pattern/regime, such as the injection point location relative to the test location. This includes consideration of geometry and injection point locale further upstream from the standard 100D straight section.
- The findings of the intercomparison represent the foundation of a future standard guideline to provide intercomparison between flowloops, though further work is required. The above recommendations should be followed in future work. Finally, the rolling-out of the intercomparison protocol and capability to an increasing number of participating flowloops, will not only expand the harmonisation network but will lend greater confidence to the robustness and relevance of the methods deployed.

3.2 Improving on theoretical and experimental determination of flow patterns

The development of multiphase flow patterns has important implications for many industrial processes. For example in oil and gas production, sophisticated flow assurance software and dedicated process equipment are employed to mitigate the negative effects of slug flow, which include pressure pulsations, accelerated wear of process equipment and decreased efficiency of separator vessels. One aim of this work was to make better sense of historical flow pattern data (bubble, finely dispersed bubble, slug, churn, annular, stratified or wave) as a function of field variables such as pressure, temperature and component fluid properties and velocities. Another was to acquire and publish many new data through the experimental observation and modelling carried out in the project.

3.2.1 Validation of established flow pattern maps and models against independent flow loop data for flowrates/pipe sizes relevant to industry

Flow pattern prediction and mapping has been the subject of extensive study in the academic literature. Understanding of the distribution of phases in multiphase systems is necessary to accurately model various aspects of fluid behaviour. For example, two major drivers for flow pattern research were for pressure drop prediction in long distance transport of mixed oil, water and gas streams and heat transfer research in the nuclear industry.

It is a common criticism of flow pattern maps; particularly the older empirical maps; that they perform poorly for flow conditions other than air-water flow at low or near atmospheric pressure, and in applications where pipe sizes exceed 2-inch in diameter. In the project, established flow pattern maps from the literature were evaluated against experimental data from the NEL multiphase flow facility. The conditions tested are much closer to “realistic” conditions with mixtures of oil, water and gas in 4-inch pipe and with flowrates more representative of those encountered in the field.

A large number of flow pattern maps and models have been produced, seven of which were evaluated using experimental data collected in the project.

These maps and models were selected because they are well established in flow pattern research and each of them were derived from a substantial volume of experimental data. Flow patterns were determined in the project experimental tests with the aid of a Perspex viewing window and video recordings at 240 fps.

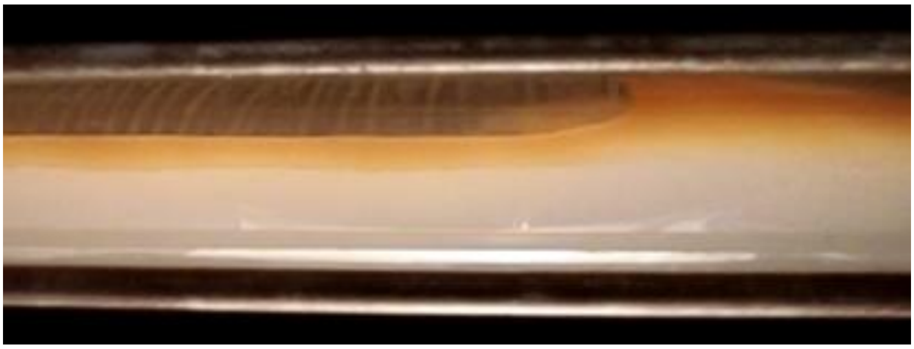


Figure 2.1 - Still from Flow Pattern Video Footage from NEL. Low Frequency Slug Flow with Separated Oil and Water Layers

An example of the evaluation of a flow pattern map using NEL experimental data is shown below.

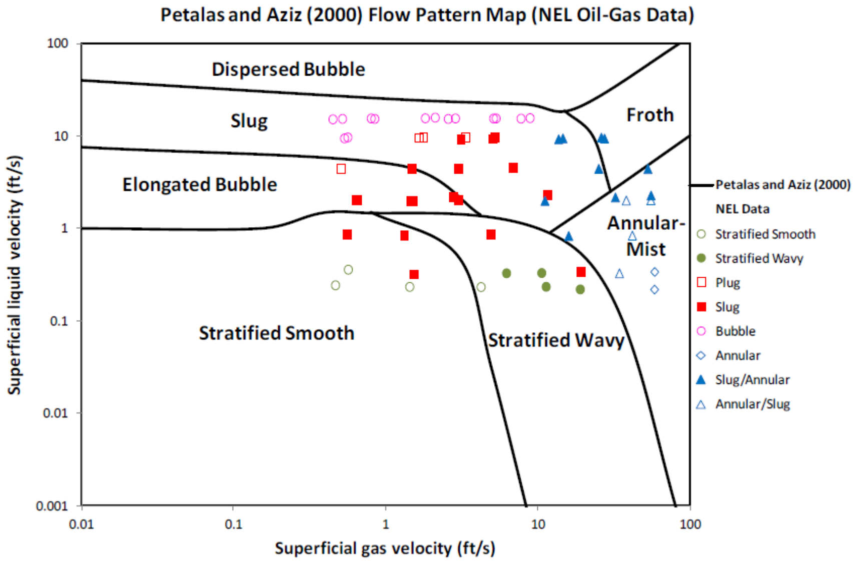


Figure 2.1: Evaluation of Flow Pattern Maps, Comparison with Experimental Data

Table 2.1 – Predictive accuracy of well-established flow pattern maps from the open literature.

Flow Pattern Map	% Predictive Success vs. Experimental Data	
	Oil-Gas	Water-Gas
Baker (1954) (1)	61	61
Beggs and Brill (1973) (2)	82	86
Beggs and Brill (Revised Transitions)	80	82
Mandhane (1974) (3)	62	84
Taitel-Dukler (1976) (4)	64	61
Weisman (1979) (5)	84	63
Barnea (1987) (6)	77	61
Petalas and Aziz (2000) (7)	62	63

The overall predictive accuracy of the flow pattern maps tested was good, with every map achieving more than 60% predictive accuracy for both oil-gas and water gas flows. In some cases, predictive accuracy was greater than 80%.

3.2.2 Influence of water-liquid ratio, liquid viscosity and entrance length on flow pattern transitions

In the academic literature, there are various studies concerned with different parametric influences on flow pattern transitions. This includes the influence of fluid properties; such as gas and liquid density, liquid viscosity and surface tension; as well as the influence of pipe geometry; pipe diameter, inclination and upstream length. In some cases, the findings of these studies have been applied to flow pattern maps and models in the form of correction factors, which can be used to shift the flow pattern boundaries to match operating conditions. In other cases, the findings have formed the basis of generic guidance. However there is still some dispute regarding the influence of certain parameters on flow pattern. For example, there are many conflicting reports on the influence of liquid viscosity, particularly at very high viscosities.

In facility testing at NEL, the influences of water-liquid ratio, oil viscosity and entrance length were all investigated. It was found that when the liquid phase was changed from oil to water, the majority of the flow patterns transitions were not shifted, but a noticeable change was observed for the transition between annular and slug flow. This transition occurred at higher gas velocities as water-liquid ratio was increased.

Another parameter investigated was entrance length. A common rule-of-thumb in flow pattern research states for multiphase flow patterns to fully develop, a minimal straight pipe length equivalent to 100 pipe diameters must be provided upstream. NEL tested this guidance by generating a wide range of flow conditions using two entrance lengths; both 100D and 500D. The flow patterns observed were unchanged for the vast majority of tested flow conditions, with only minimal differences observed at some of the flow pattern transitions.

NEL investigated the influence of liquid viscosity through testing of oil-gas flow at viscosities of 8 and 16 cP. A change in liquid viscosity of this magnitude did not have a noticeable influence on any of the flow pattern transitions. This finding; together with the observation made on the influence of water-liquid ratio; suggests that the transition between slug and annular flow is sensitive to liquid density, surface tension or a combination of both.

3.2.3 Standardised flow patterns between two flow loops despite fundamental differences in loop configuration and operation

A primary task within the project was the intercomparison testing of several multiphase flow test facilities. The success of the intercomparison was predicated on standardisation of flow conditions between each participating test facility. At each facility it was necessary to establish the same multiphase flow patterns, which are influenced by a range of parameters including component flowrates, fluid properties and installation geometry.

An intercomparison of independent, industry scale multiphase flow facilities had never previously been carried out. Successfully standardising flow patterns required careful research of the relevant literature and sharing of the knowledge and past experience of the various project partners. The multiphase flow test facilities of NEL and DNV GL feature significant differences in operation, fluid properties and test section geometry. Fluid property differences were minimised by testing at the same static pressure and selecting appropriate temperatures to bring oil viscosities into a similar range. Perhaps the biggest difference between the loops would be the entrance length of straight pipe upstream of the test device. Piping was supplied with the test device in order to provide exactly 100 pipe diameters of straight pipe between the gas injection point location and the test meter at both facilities.

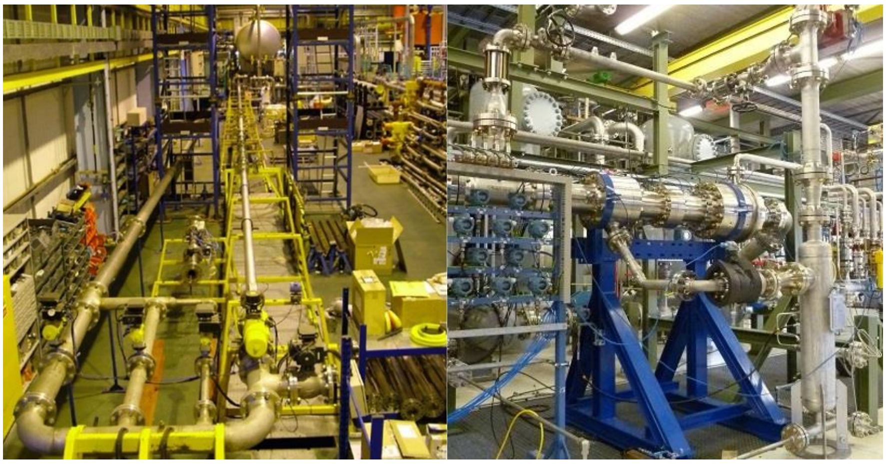


Figure 2.2: The multiphase flow test facilities of NEL (left) and DNV GL (right) differ greatly in design and operation

The outcome was that flow patterns were successfully standardised, in terms of the predominant flow pattern (slug, bubble, stratified etc.) at any given set of flow conditions. Flow pattern maps generated for testing at NEL and DNV GL were almost identical in this regard. Note, however, that owing to the vast number of data involved, this analysis did not further breakdown the characteristics of the flow. For example, in slug flow, the slug lengths or frequencies were not quantified as part of this objective. Some quantification in this area was carried out however, specifically to investigate measurement variances that were highlighted under the main intercomparison investigation. These additional flow pattern analyses are reported in Section 3.1 above.

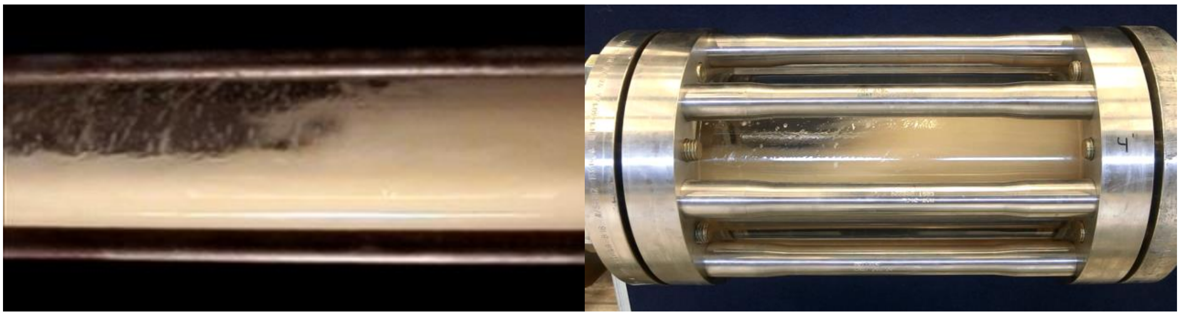


Figure 2.4: Flow pattern footage from each test facility showing Slug flow for the same test condition

3.2.4 Comparison of CFD studies and experimental work

Laboratory experiments and CFD simulations were conducted in order to investigate the influence of installation geometry on flow pattern. Cranfield University developed CFD models with geometrical variations that represented the configuration of test facilities used in the lab intercomparisons. The CFD models were validated using experimental test data from Cranfield University experimental test facilities.

The simulation results were in close agreement with flow pattern observations from the experimental work. It was found that the entrance length was an important consideration in both the experimental and modelling work. A minimum length of 200 pipe diameters was required for simulations to run successfully.

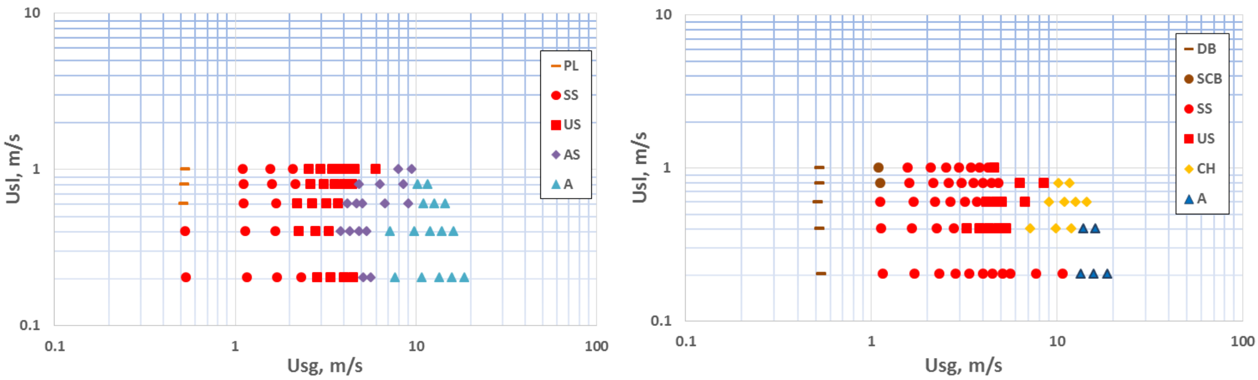


Figure 2.5: Flow pattern maps generated from experiments at Cranfield University. Left: Horizontal flow patterns. Right: Vertical flow patterns

PTB; with support from CMI; performed CFD simulations to investigate the influence of fluid properties on flow pattern. Two CFD packages were used; OpenFOAM and ANSYS Fluent. Numerical simulations with Fluent were able to reproduce the following different flow patterns: stratified, wavy, slug, and plug. When applied to the cases from the intercomparison test matrix, all cases were successfully reproduced.

OpenFOAM was capable of reproducing all of the flow patterns observed from the literature data. However the success of correct flow pattern prediction appeared to be highly sensitive to fluid properties (more so than had been indicated by the experimental data). The correct flow patterns were not always reproduced when fluid properties from the full-scale intercomparison tests were used.

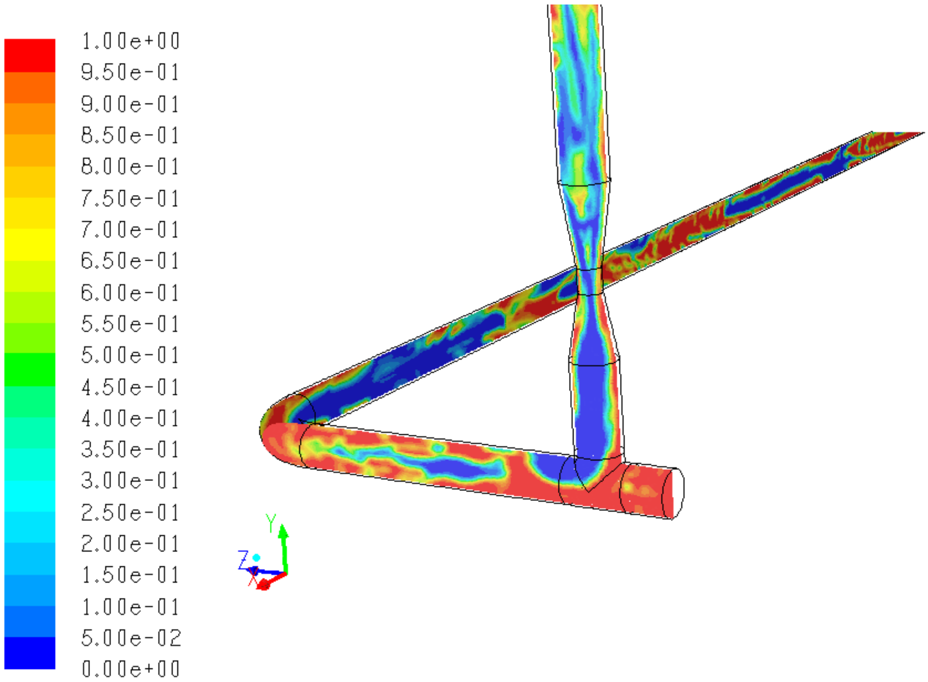


Figure 2.6: Example of contour plot from CFD simulation

3.3 Improving the numerical modelling of multiphase flow in pipes and Venturi tubes

The original headline objective for the above work – *To provide an improved basis for determining uncertainties, by combining state-of-the art computational fluid dynamics modelling techniques with polynomial chaos method* - proved to be over-ambitious in view of the complexities and enormous computational expense of the CFD simulations required. This meant that insufficient numbers of simulations were possible in the timeframe of the project to support the use of the polynomial chaos method. This can be regarded as an important finding. The project did, however, make significant progress in methods for deterministic CFD modelling of multiphase flow, an essential prerequisite for the achievement of the headline objective in the longer term.

3.3.1 Numerical modelling of multiphase flow in horizontal pipes

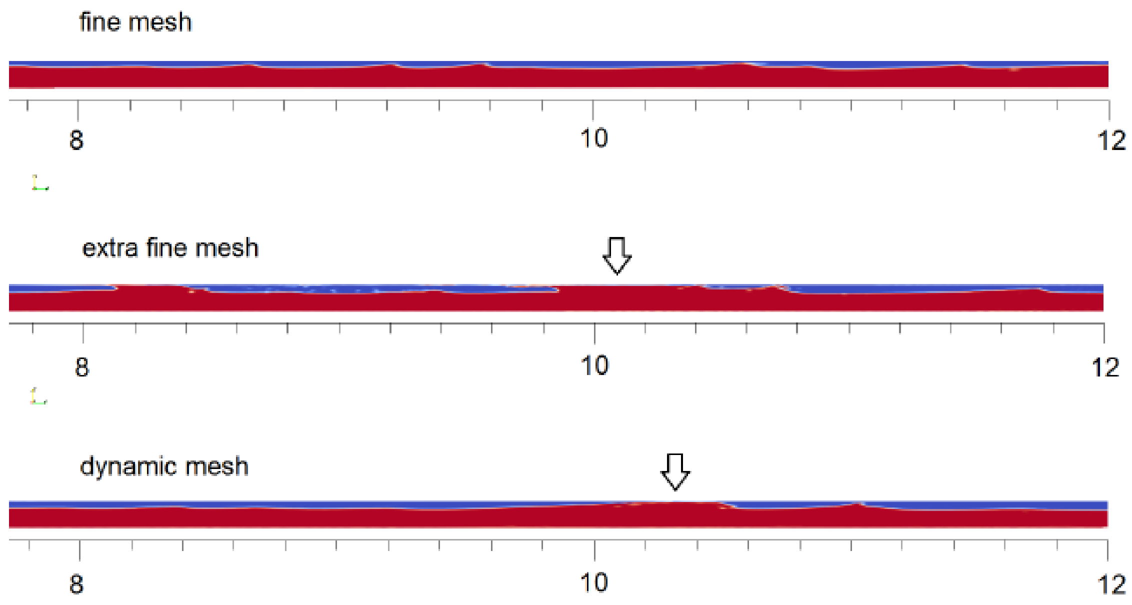


Figure 3.1: Development of different flow patterns depending on the refinement level of the mesh used for the simulation for a transitional test case. Top: solitary waves for fine mesh, middle and bottom: slug flow for extra fine and dynamic mesh.

Within the project, CFD models have been developed that allow a close comparison between simulation and experimental results. The investigations showed that, at least for transitional cases between two flow patterns, the mesh, the numerical settings as well as the boundary conditions (especially on the inflow boundary) can have an influence on the observed flow pattern. Fig. 3.1 shows simulation results for one of the test cases obtained with the freely available CFD solver OpenFoam [14]. One can see the fraction of oil (red colour) and gas (blue colour) in a horizontal pipe between ca. 8 and 12 metres downstream of the inlet for three different meshes. For the extra fine as well as for the dynamic mesh (where the elements close to the interface between the two phases are refined) slug flow is found, whereas for the coarser meshes (coarse, medium, and fine, whereof only the latter one is depicted in Fig. 3.1) only solitary waves touching the wall in one point are observed. In order to model the high velocity gradients at the interface between the different phases appropriately, turbulence damping should be used [15]. In CFD, the inflow boundary conditions are usually much smoother compared to realistic inflow conditions in the experiments. Hence, it might be necessary, at least for transitional cases, to perturb the inflow profile in order to stimulate the Kevin-Helmholtz instability. In the project, several perturbations have been implemented improving the simulations so that the expected flow pattern could also be reproduced for transitional cases. Nevertheless, from the experiences made in the project, the conclusion was drawn that the set-up of the experiment and the simulation should go hand and hand to ensure that the same boundary conditions are used wherever possible.

The CFD models have been validated by comparison of the results with test cases that are described in the papers by Oddie et al. [16], Frank [15], and Vallée and Höhne [17] as well as with several test points investigated in the experimental intercomparison of the project. Fig. 3.2 shows kerosene-nitrogen slug flow for one of the test points as observed in the simulation with the commercial CFD code Fluent [18] (on the left) and in the experiment at NEL (on the right). A comparison of the results shows a very good qualitative agreement. The structure of the slug is reproduced very well by the numerical simulations. Furthermore, also the time differences between the beginning, middle, and end of the slug match quite well with the experimental observations. Both in the numerical simulation and in the experiment, one observes smaller waves behind most of the slugs. Further details can be found in [19].

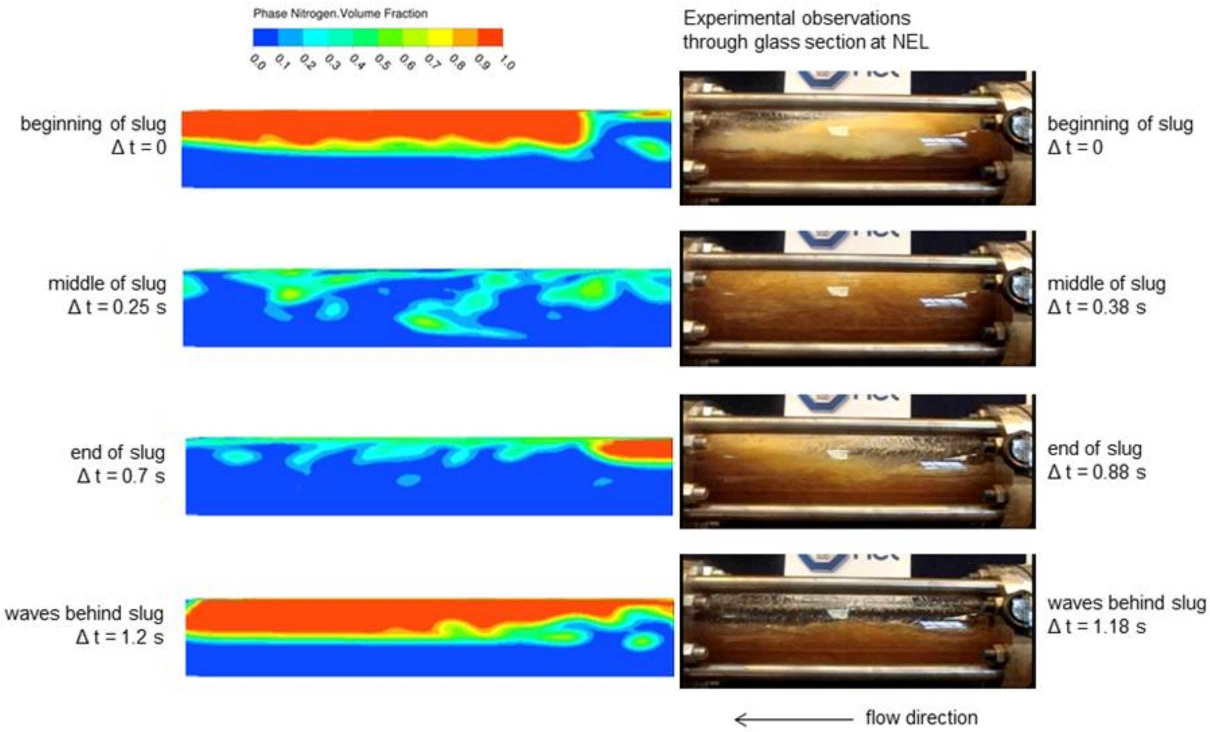


Figure 3.2: Comparison between simulation results obtained with Fluent (left) and experimental observations of the flow pattern through a glass viewing section at NEL (right).

3.3.2 Numerical modelling of multiphase flow in vertical Venturi tube

In order to investigate the influence of several operational parameters on the pressure measurement, not only a horizontal pipe, but the whole transfer package used in the experimental intercomparison of the project was considered also in the CFD simulations. Therefore, a high-quality, block-structured, hexahedral mesh was created, see Fig. 3.3. The corresponding CFD model gives insight into areas, which can hardly be observed in the experiments. Fig. 3.4 shows the flow pattern for one of the test cases of the intercomparison simulated with Fluent. One observes the change from slug flow in the horizontal inflow section towards annular-like flow in the vertical Venturi section. As expected the blind-T leads to a mixture of the two phases.

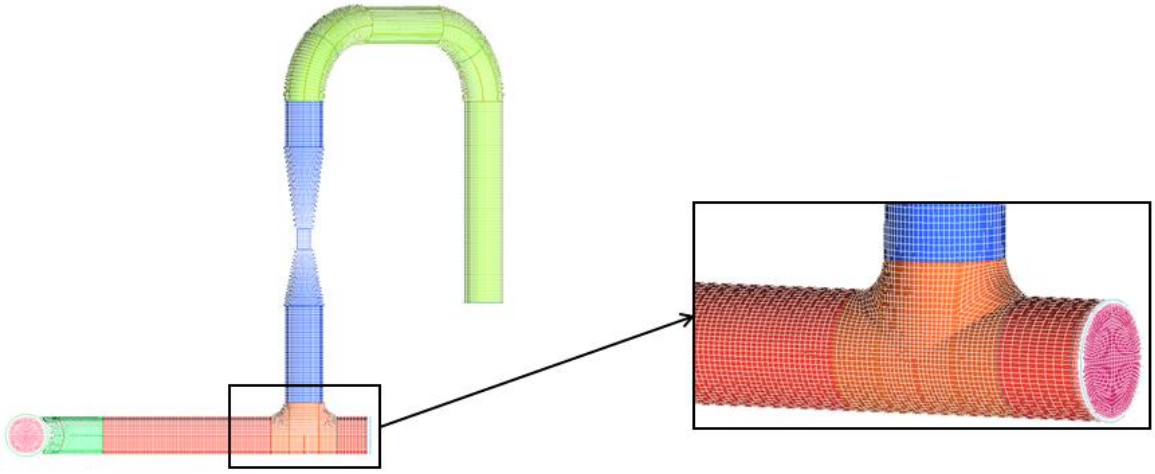


Figure 3.3: Block-structured hexahedral mesh used for the simulation of the Vx52 geometry with Fluent (left) and enlargement of the blind-T section (right).

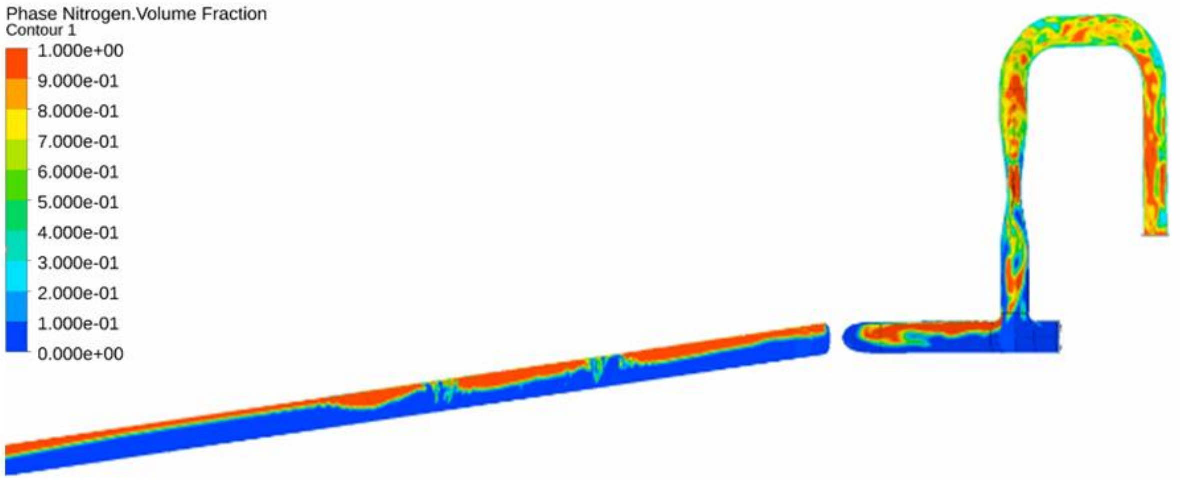


Figure 3.4: Simulation of one of the test cases: Development of slug flow in the horizontal inflow section (left) and mixture of the phases due to the blind-T (right).

For the comparison with experimental data from the intercomparison, the pressure difference over the Venturi was calculated from the simulation results. Fig. 3.5 shows the computed extreme and mean values of the pressure differences for several cases from the test matrix in comparison with experimental results. One observes a good agreement of the mean values for both, the OpenFoam results (red and blue) and the Fluent results (green).

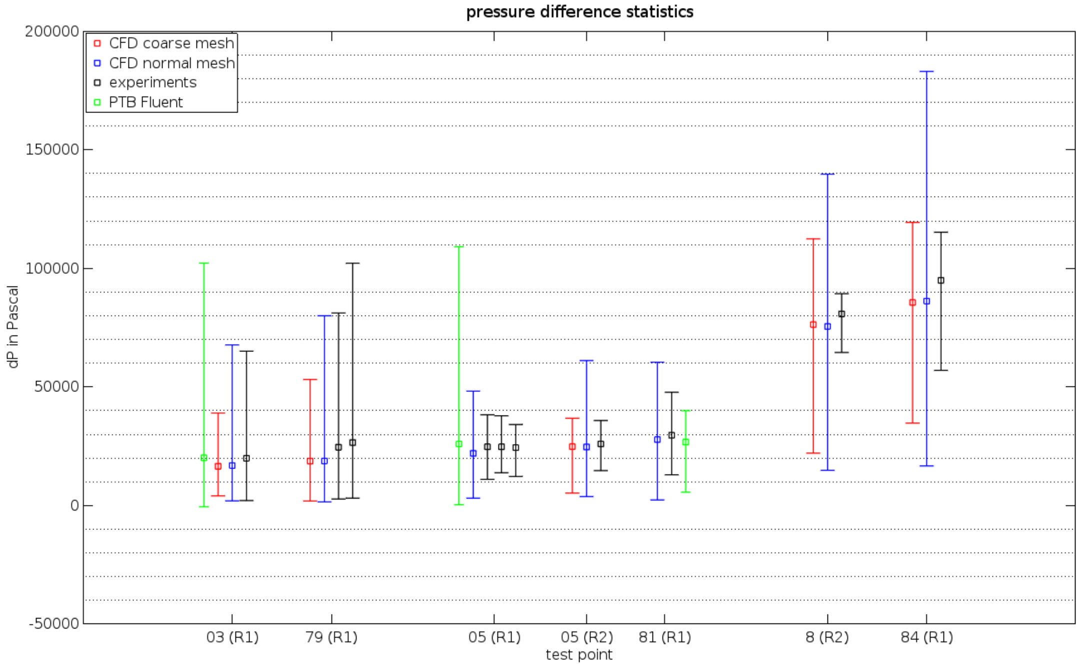


Figure 3.5: Comparison of extremal and mean dP values by CFD predictions and by experimental observations for several test cases.

Table 1.1: Volume flow rates of the test cases shown in Fig. 3.5.

Test case no.	***Oil flow rate in m^3/s***	***Water flow rate in m^3/s***	***Gas flow rate in m^3/s***	***Total volume flow rate m^3/s***	***GVF %***	***WLR %***
03	0.00972	-	0.01188	0.0216	55	0
79	-	0.00972	0.01188	0.0216	55	100
05	0.01389	-	0.00463	0.0185	25	0
81	-	0.01389	0.00463	0.0185	25	100
08	0.02500	-	0.00833	0.0333	25	0
84	-	0.02500	0.00833	0.0333	25	100

The results obtained with OpenFoam underpredict the mean pressure difference slightly for all cases. The Fluent results, on the other hand, show a much wider spread between minimum and maximum pressure difference than observed in the experiment (see green lines for test point 03 and 05 in Fig. 3.5). The reason for this is that much smaller time steps are used for the numerical simulations compared to the sampling rate of the Venturi meter. In order to resolve this difference, the simulation data have been re-sampled with the same frequency as the experimental data have been recorded. The corresponding results are shown in Fig. 3.5 for test point 81 leading to a much smaller range of dp values.

Note that for test point 03 and 79 the same liquid and gas flow rates have been prescribed. The difference between the cases lies in the water cut: the liquid phase for test point 03 is pure oil, whereas for test point 79 pure water is used. The same applies for cases 05 and 81 as well as for test points 08 and 84. Since the density of water is higher than the density of oil, a higher pressure difference is expected for the water cases 03, 05, and 08 compared to the corresponding oil cases 79, 81, and 84. Similarly, a higher dp value is expected for test point 05 (R2), where the oil density has been increased, compared to test point 05 (R1). Fig. 3.5 shows that the numerical results are in good agreement with these expectations.

The influence of several more parameters (like oil / gas density, oil / gas viscosity, surface tension, gas volume flow rate) has been investigated during the project, see also [20]. An advantage of the simulations is that it is possible to change only one of the parameters and keep the others constant, which can often hardly achieved in experiments. Thus, the influence of the different parameters can be investigated separately. As expected, the pressure difference in the Venturi increased with increasing liquid or gas density. On the other hand, a clear dependency on liquid or gas viscosity was not observed. This latter result is consistent with observations made in the intercomparison testing experiments, see Section 3.1.

3.3.3 Data analysis and comparison with experimental data from electrical capacitance tomography (ECT)

As basis for a quantitative comparison with experimental data, the simulation data have been condensed so that the main features of the flow can be extracted. Therefore, each grid point was classified as either part of the liquid phase, the gas phase or the interface between them, depending on the value of the gas volume fraction at this point. If the thresholds for the classification algorithm are chosen properly, this allows a good comparison with data from electrical capacitance tomography (ECT). Fig. 3.6 shows slug flow observed by ECT (top row) as well as by simulation and classification (bottom row). A very good qualitative agreement can be observed. However, further analysis of the classified data allows also the extraction of characteristic values (like slug frequency), which can then be used for a quantitative comparison with experimental data. This will further be investigated in the follow-up EMPIR project “Multiphase flow reference metrology”.

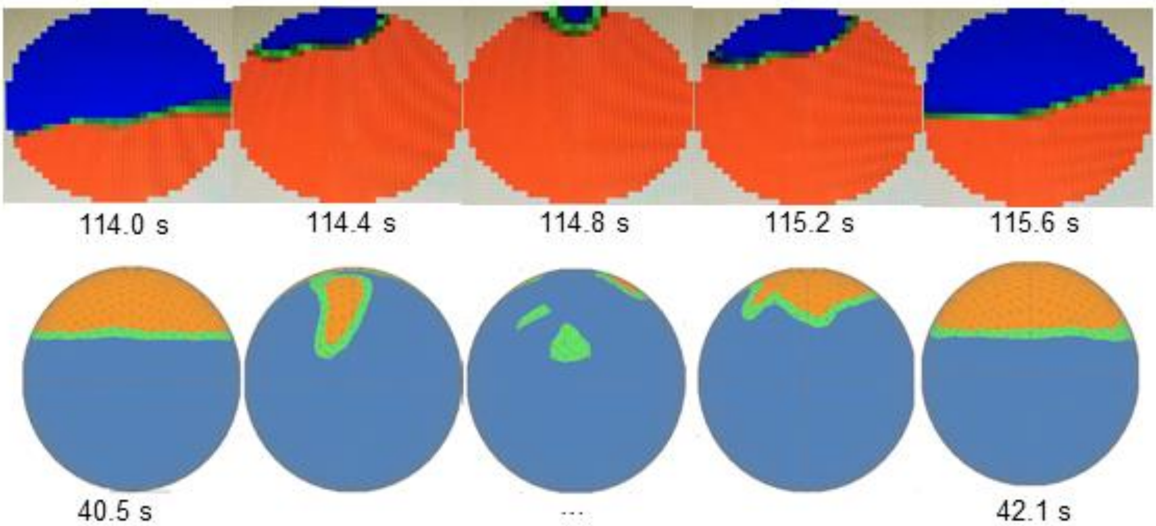


Figure 3.6: Electrical capacitance tomography (ECT) data in comparison with simulation results for one of the slug flow test cases.

3.4 Evaluating and improving experimental methods of flow visualisation

3.4.1 Dual modality electrical tomography

The visualisation of three-phase flow has attracted much attention from researchers and engineers. It, however, is extremely challenging to measure and visualise such phenomenon, due to the complex interactions among each phase, resulting in over 20 different flow regimes having been described. In order to provide insights into gas-oil-water flow, many techniques have been commercially applied and scientifically proposed in the past few decades, among which multi-modality tomographic systems have been suggested to be effective in several multiphase flow applications, with the advantages of being low cost, non-intrusive/invasive, and robust.

In this research, a number of tomographic methods were developed for analysing flow dynamics of gas-oil-water flows in horizontal pipeline, particularly, the threshold-based method [21] and the bubble mapping capability for flow regime visualisation [22], the flow regime recognition method based on the Boolean logic and statistic methods [23] and a Proper Orthogonal Decomposition (POD) method [24]. In this section, the first and most successful of the newly developed flow visualisation methods are briefly addressed.

Data fusion method for visualisation of gas-oil-water three phase flow with ERT-ECT dual modality tomography systems

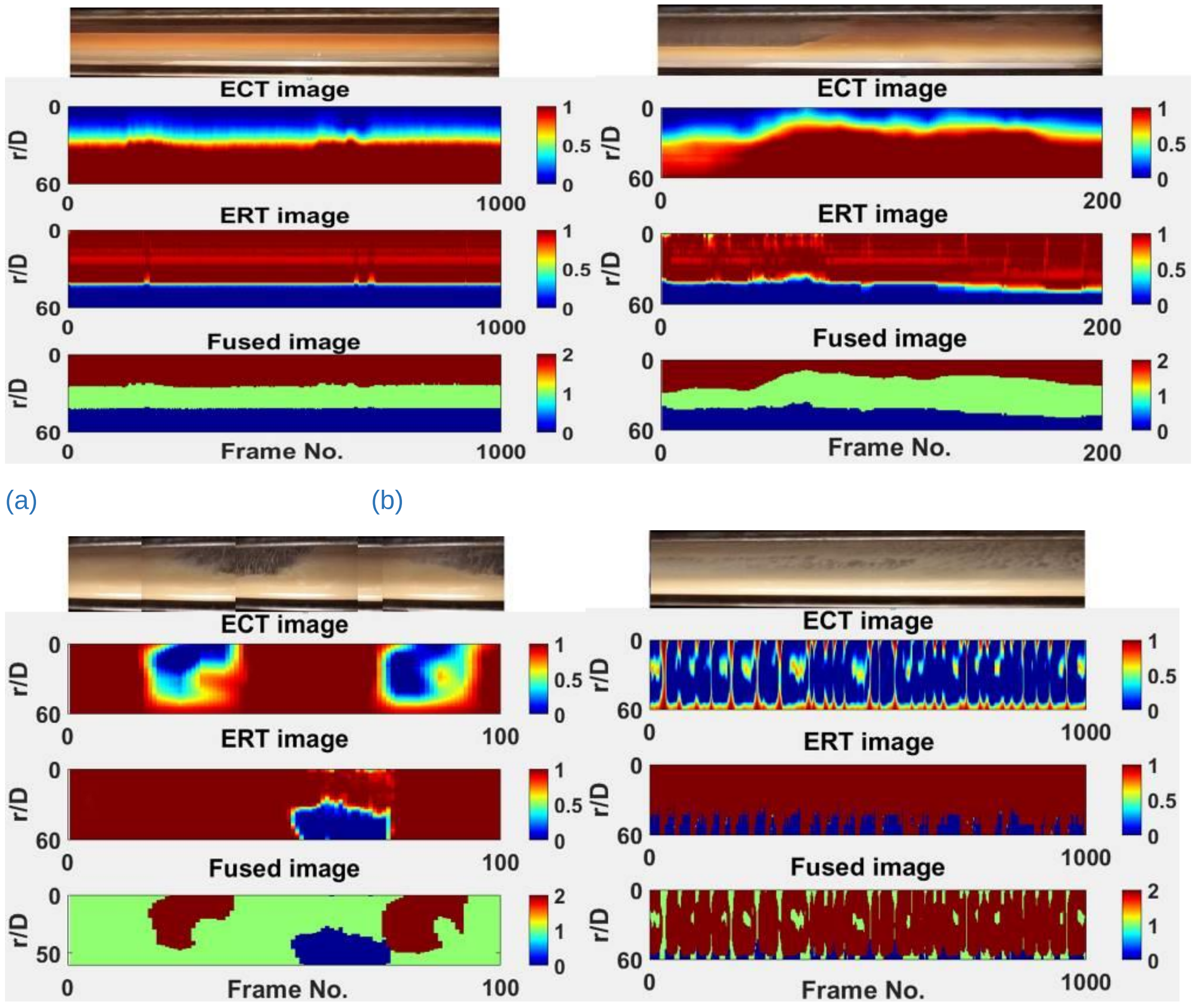
Varieties of dual-modality tomographic systems were previously reported for the characterisation of multiphase flow, however, the capability of systems was only demonstrated under simplified flow conditions, such as stratified flow and slug flow. Conventional ERT-ECT systems offer cross-sectional images of high temporal resolution but relatively low spatial resolution. A major barrier for the systems is that they are unable to identify small bubbles, as well as produce sharp interfaces between large bubbles and liquid phase within multiphase flow due to the non-linear distribution of electrical field for sensing and associated ill-conditioned inverse problems in image reconstruction. Although multi-modality tomographic systems have attracted much attention, the data fusion methods are still at an early stage of research and development.

A threshold-based data fusion method was developed in the research and deployed for visualisation of industrial-scale, horizontal gas-oil-water three-phase flow facility at TUV NEL. A commercial dual-modality electrical tomographic system provided by ITS was applied to carry out the visualisation. Experimental conditions covered water-to-liquid ratio (WLR) from 0% to 100% and gas volume fractions (GVF) from 0% to 100%, which produced a variety of flow patterns, typically stratified flow, slug flow, plug flow, bubbly flow, and annular flow. Tomography visualisation is compared with optical photographs, which demonstrated that the electrical resistance tomography (ERT) system is able to visual water continuous flow with WLR higher than 40%, providing good agreement with previous reports. The electrical capacitance tomography (ECT) system is able to manage WLR from 0% to 90%, which is far beyond the conventional knowledge in literature. The fusion of data obtained from the dual-modality system is able to visualise these typical flow regime over full flow conditions under the investigation.

As the purpose of the demonstration, the visualisation of flow regimes under selected flow conditions (Table 1) at 50% WLR is presented in Figure 4.1, in terms of ECT, ERT, and fused images, referenced with the stacked photographs taken with the video logger at 240 fps. From the visualisation perspective, the figures demonstrate a promising capability of the systems for imaging gas-oil-water flow at WLR 50%. There are small deviations from conditions as seen by the reference video logger as in Figure 4.1d, where the top liquid film is too thin to be detected by either modality. The system is unable to image bubbly flow in Figure 4.1e, due to the incapability of both ERT and ECT systems to identify small bubbles. It is worth noting that bubble flow is notoriously difficult to measure for the optical imaging as well. This issue has been addressed in next section.

Table 1: Selected flow conditions for visualisation at WLR 50%.

	GVF (%)	Q_{water} (m^3/h)	Q_{oil} (m^3/h)	Q_{gas} (m^3/h)
Stratified flow	60	3.790	3.860	10.978
Slug flow	60	9.031	9.030	27.896
Plug flow	25	42.520	40.626	27.841
Annular flow	75	42.451	40.974	254.034
Bubbly flow	5	70.327	69.061	7.606



(a) (b)

(c) (d)

Figure 1: Visualisation results of WLR 50% for (a) stratified flow; (b) slug flow; (c) plug flow; and (d) annular flow.

Bubble mapping method for visualisation of gas-liquid flow

Colour mapping is the most widely utilised method for visualising gas-liquid flow by electrical tomographic systems. A well-known limitation of the systems is the relatively low spatial resolution to identify individual small bubbles, due to the ill-conditioned problems and limited number of measurements in inverse solution. As a result, the visualisation by the systems conveys limited information regarding multiphase flow dynamics, e.g. bubble size and distribution.

A novel approach, namely bubble mapping, has been proposed to overcome the problem. The algorithmic approach will be fully described in reference [25]. Figure 4.2 demonstrates the results of the approach applied to gas-liquid horizontal flow, with the flow regimes of stratified flow (Figure 4.2.a.), bubbly flow (Figure 4.2.b.), plug flow (Figure 4.2.c.), slug flow (Figure 4.2.d.), and annular flow (Figure 4.2.e.) [23]. Compared to its counterpart by conventional colour mapping, the new approach is able to reveal extra information. For example, due to the gravitational force, the bubbles in horizontal pipe tend to accumulate at the top of the pipe, and the closer the bubbles are to the top, the larger the bubbles are, which are not fully reflected by conventional method.

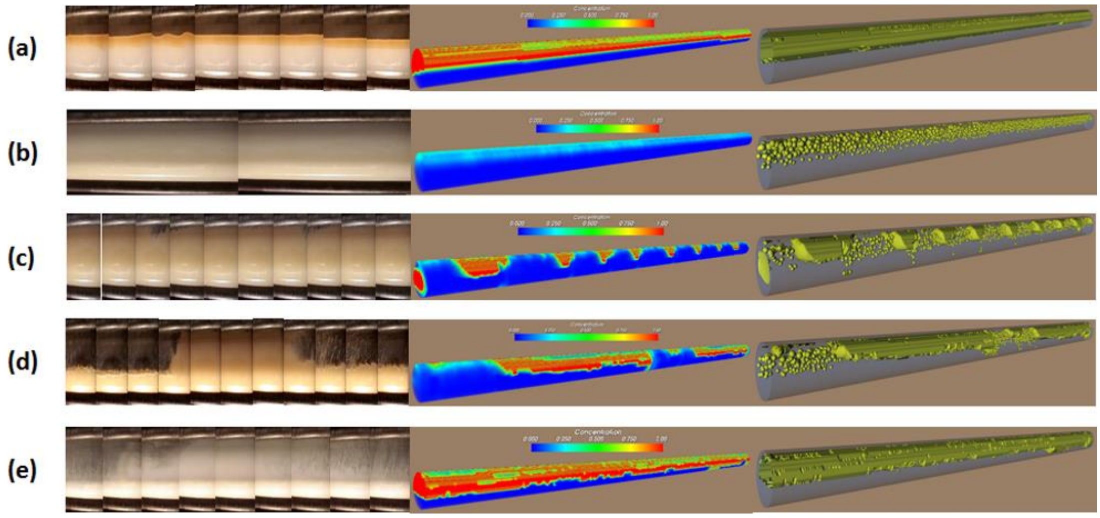


Figure 2: Flow regimes for gas-oil-water flow in horizontal pipeline and flow is from right to left (the left part is taken by photo, the middle one is by conventional colour mapping, and the right one is by newly developed bubbly flow mapping); (a) stratified flow; (b) bubbly flow; (c) plug flow; (d) slug flow; and (e) annular flow.

3.4.2 Single-modality electrical tomography

Electrical Capacitance Tomography (ECT) has a well-established reputation as a research tool and has been used in a number of industrial applications including dry solids flows, gas-liquid flows and wet gas flows. Whilst being primarily limited to the study of gas with an oil-continuous liquid phase, ECT can give detailed flow structure information that has been experimentally validated against other techniques. Prior to this project, little was understood about how best to use ECT in horizontal gas-liquid flows for flow regime identification.

Through this work it has been shown that there are 6 primary parameters available from single-modality electrical imaging which are the key indicators of flow structure:

1. average concentration (holdup) of the liquid phase,
2. spatial distribution of the concentration over the pipe cross-section – for example stratified, annular or bubbly,
3. level, range and balance of the probability density function of average concentration for example (a) primarily liquid with gas bubbles present, (b) primarily gas with liquid structures passing or (c) fully intermittent slugs or waves.
4. frequency distribution – number of structures passing in a given period,
5. primary structure velocity,
6. length-scale of primary structure.

Our recommendation for best practice in flow regime identification is to use cross-sectional images as an aid to visual interpretation of flow regime structure and to measure and record the 6 key parameters for future automation and study. We also propose that the definition of such key parameters should enable clearer and more quantitative comparison between experimental measurements and CFD results.

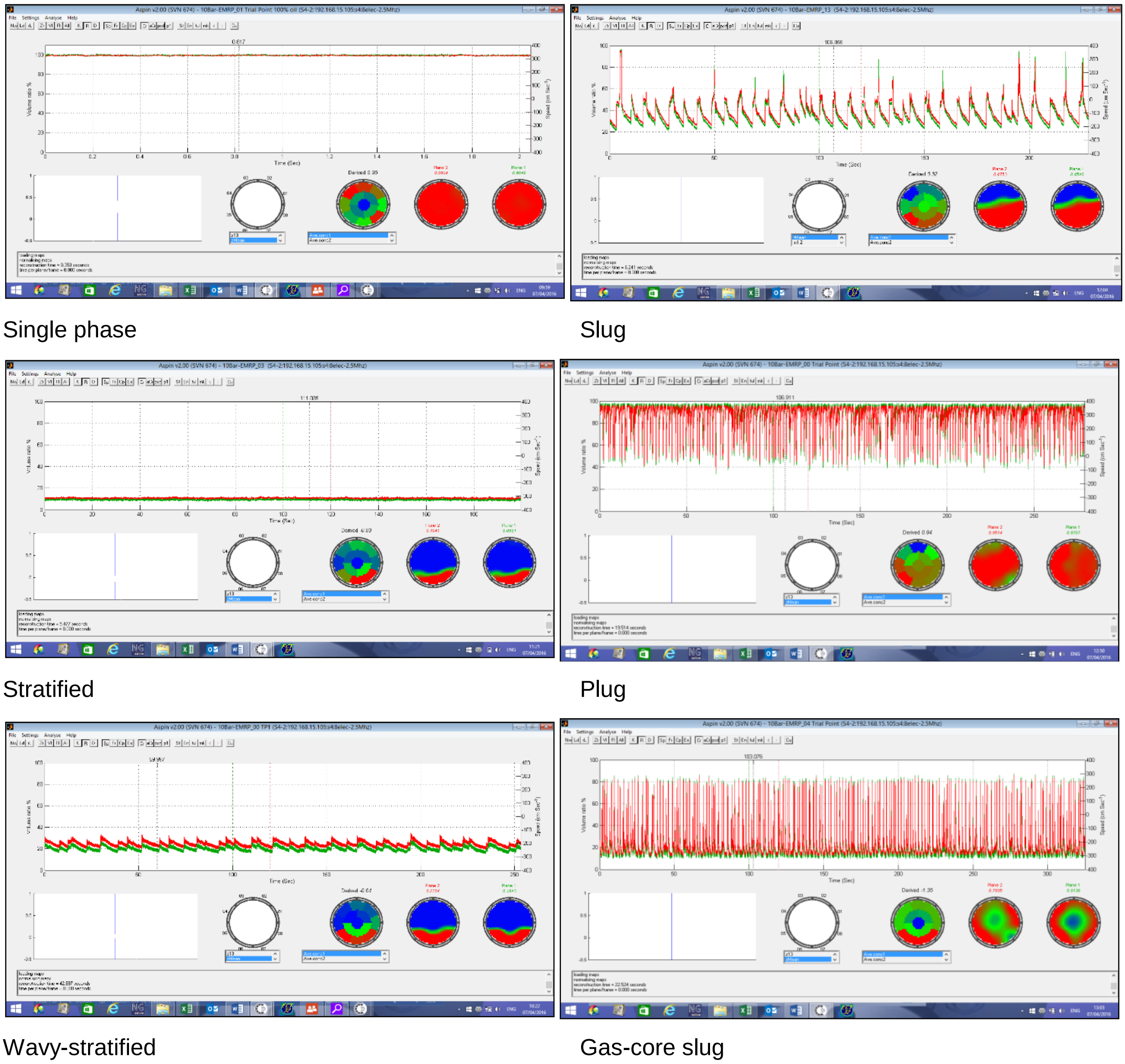


Figure 4.3. ECT overview screens from different flow regimes. Red and green lines are the time series average concentration (holdup) of oil in plane 1 and 2, while the circular images in the bottom right of each screen show the instantaneous cross-sectional concentration image at the time of the cursor.

Figure 4.3 shows ECT overview screens from 6 different flow regimes. The characteristics of each are clearly different:

- Single-phase flow – ‘full’ red images, no periodic structure, average concentration 100%,
- Stratified flow – stratified images, no periodic structure, average concentration low and steady,
- Wavy stratified flow – stratified images, periodic structures, average concentration low and variable,
- Slug flow – stratified images alternating with full images, highly periodic structures, average concentration varying from high to low over a wide range,
- Plug flow – variable images with gas pockets visible principally at the top of the pipe, high frequency periodic structures dominant, concentration predominantly high with rapid excursions to low values,

- Gas-core slug flow – primarily annular images with some stratified, high frequency periodic structures dominant, concentration predominantly low with rapid excursions to high values.

Future best practice will follow from widespread agreement on the nature and details of the primary parameters, while developing an extensive data base and proving POD and other statistical measures on them. At some point this should enable the implementation & test of automatic flow regime identification techniques.

Figure 4.4. ECT sensor mounted on NEL national standard multiphase flow facility, East Kilbride. Close-up view of ECT sensor showing slim-line clamp-on design fitting under tie-rods around existing 140mm diameter sight-tube.

3.4.3 Evaluation & Summary

Calibrations of multiphase flowmeters should contain a quantitative assessment of the flow regimes used for calibration as well as the bare details of fluid physical properties and flowrates. This is because the regimes may vary between calibration facilities and impact the accuracy and validity of calibration. Electrical tomography offers a good vehicle for that quantitative assessment in two and three-compnent flows.

Two distinct techniques were explored in the work – dual-modality (ERT+ECT) and high-speed single-modality (ECT). Each of these has strengths and weaknesses for different areas of application. Two significant findings in this regard were:-

- For dual-modality tomography, multiphase flows can be visualised across the entire range of water cuts and gas volume fractions. However, great care is required in the fusion of data from the two sensor arrays. The work showed that significantly greater detail can be revealed using advanced data processing techniques such as bubble mapping, that were further developed in the course of the work.
- For high-speed single-modality (ECT), multiphase flows can be visualised in significant detail, but only at low water cuts. The work showed that six key parameters may be derived that are key indicators of the flow structure.

A common finding for each of the systems deployed was that the raw data acquired from the existing sensor arrays is very rich in information. Whilst considerable advances have been made in the course of the work in the interpretation of sensor outputs from both types of system, there would also appear to be significant potential for further development in data processing methods before the limits of the existing hardware systems are reached.

4. Actual and Potential Impact

Dissemination of results

Eleven papers and six posters were presented at international conferences and workshops including *International flow measurement, Offshore technology asia,* and *Flow measurement institute conference*.

Four peer-reviewed papers were published in journals such as *Flow measurement and instrumentation* and *Journal of hydrodynamics* and a further four have been submitted for publication.

The following Best Practice Guides were produced, and are available on the project website:

- Objective criteria for defining flow patterns using electrical tomography
- Numerical modelling of multiphase flow
- Test protocol and approach to multiphase test facility intercomparisons utilising a MPFM transfer standard

The following case studies were produced, and are available on the project website:

- Multiphase test facility performance improvements and reduction in measurement uncertainty
- Determination, mapping and prediction of multiphase flow patterns
- Multiphase flow in horizontal tube
- Setting up a test matrix in a multiphase flow laboratory comparison

The project findings were incorporated into various training products including training courses that are run regularly by NEL, Cranfield University and Coventry University.

In addition, three webinars were delivered – 'Fundamentals of Multiphase & Wet Gas Flow' and 'From the Lab to the field: how do we validate a multiphase meter' (an update of the latter was run just over a year after the original, incorporating further JRP findings), with audience sizes averaging more than 70. Audiences included representatives of both small and large industrial organisations as well as academics.

Contribution to standards

The work of the project has provided input to the new ISO Technical Report on Multiphase Flow Measurement (ISO/TR 21354). This Technical Report will become, in due course, the de facto international guide to multiphase flow measurement (publication late 2018). The project's Best Practice Guide on "Test protocol and approach to multiphase test facility intercomparisons utilising a MPFM transfer standard" will be cited in the report. There are ongoing discussions regarding further influence of the project on meter testing aspects of the TR, which will continue after the end of the project.

Early impact Development & implementation of methods of measurement harmonisation for multiphase test laboratories

The lack of measurement harmonisation between laboratories used for testing multiphase flowmeters for either development or evaluation purposes, was seen as a major barrier to the ongoing development and improvement in multiphase metering technology. **This defined the most significant industrial need behind the project - the need to set in motion a harmonisation initiative for multiphase reference measurements.**

The project has addressed this through achievement of the world's first measurement harmonisation between two globally-renowned multiphase flow laboratories, NEL and DNV-GL (objective 1). These laboratories are now able to demonstrate measurement comparability through the adoption of common protocols and the completion of a programme of intercomparison testing and rationalisation. The protocol and capability for establishing such harmonisation is universally transferrable, with minor adaptation, to any number of industry-scale multiphase flow laboratories operating worldwide.

The findings of this initial harmonisation exercise represent the foundation of a future standard guideline to provide intercomparison between any two multiphase flow measurement laboratories.

Future potential impact

During the course of the project, EURAMET approved a follow-on project MultiFlowMet II, which will aim to roll-out and trial the findings of this project across a wider range of multiphase test laboratories, using a wider range of MPFM technologies in the transfer standard. All of the Metrology Achievements will be taken forward by the new project. Of the original eleven Partners, Researchers (REGs) and Collaborators in the first project, eight will participate in the new project as Partners. They will be joined by a further eight new partners, making a total of sixteen.

The work of this project has made a significant contribution toward the evaluation and development of multiphase metering technology. This is a fundamental enabling metrology for the economic exploitation of remote, marginal and deep-water oil and gas fields. These fields will make an increasing contribution in the coming decades in underpinning European and global energy needs as the world strives for a longer-term transition to a low carbon economy.

5. Project webpage

Project website:

https://www.tuv-sud.co.uk/nel/members-area/european-metrology-research-programme/multiphaseflowmet-i

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Publications list

1. Q. Wang, M. Wang, K. Wei, and C. Qiu (2017) Visualisation of Gas-Oil-Water Flow in Horizontal pipeline using Dual-Modality Electrical Tomographic System. IEEE Sensors Journal, Digital Object Identifier: 10.1109/JSEN.2017.2714686
2. Q. Wang, J. Polansky, B. Karki, M. Wang, K. Wei, C. Qiu, A. Kenbar and D. Millington (2016) Experimental tomographic methods for analysing flow dynamics of gas-oil- water flows in horizontal pipeline. Journal of Hydrodynamics, 28 (6). pp. 1018-1021
3. J. Polansky, M. Wang (2017) Proper Orthogonal Decomposition as a technique for identifying two-phase flow pattern based on electrical impedance tomography, Flow Measurement and Instrumentation 53, 126–132
4. Qiang Wang, Xiaodong Jia, Mi Wang (2017) Bubble Mapping: A Novel Approach for Three-Dimensional Visualisation of Gas-Liquid Flow by Electrical Tomography.
5. M. Wang, Q. Wang and B. Karki: Art of Electrical Impedance Tomographic Sensing, PHILOSOPHICAL TRANSACTIONS A of Royal Society, DOI: 10.1098/rsta.2015.032
6. A. Hunt, Novel fluid mechanics observations from ECT measurements of 3-phase flows containing water, International Journal of Multiphase Flow (To be submitted 2017)
7. Qiang Wang, Jiri Polansky, Mi Wang, Kent Wei, Changhua Qiu, Asaad Kenbar, David Millington, Capability of Dual-Modality Electrical Tomography for Gas-oil-water Three-phase Pipeline Flow Visualisation, Journal of Flow Measurement and Instrumentation, https://www.sciencedirect.com/science/article/pii/S0955598617300936?via%3Dihub
8. Liyun Lao, Patrick Verdin, Hoi Yeng, The experimental investigation of the interaction between multiphase flowmeter testing and flow loops, International Journal of Multiphase Flow (Submitted)
9. Andrew Hunt, Good Practice Guide, Objective criteria for defining flow patterns using electrical tomography, JRP website http://www.tuvnel.com/EMRP1/emrp1_project_home
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11. Gertjan Kok, Dennis van Putten, Terri Leonard, Richard Harvey, Lev Zakharov, Rick de Leeuw, Good Practice Guide, Test protocol and approach to multiphase testfacility intercomparisons utilising a MPFM transfer standard, JRP website http://www.tuvnel.com/EMRP1/emrp1_project_home

Annex A: Comparison of calibration and test facilities for multiphase flow

JRP-Contract number	ENG58
JRP short name	MultiFlowMet
JRP full title	Multiphase Flow Metrology in Oil & Gas Production
Version numbers of latest contracted Annex Ia and Annex Ib against which the assessment will be made	Annex Ia: 1.2 Annex Ib: 1.2
Period covered (dates)	From 1 June 2014 To 31 May 2017

JRP start date and duration:	June 2014; 36 months
JRP-Coordinator: Dr David Crawford, NEL, Tel: +44 (0) 1355 593737, E-mail: dcrawford@tuvnel.com JRP website address: http://www.tuvnel.com/EMRP1/emrp1_project_home	
JRP-Partners: JRP-Partner 1 NEL, United Kingdom JRP-Partner 2 CMI, Czech Republic JRP-Partner 3 PTB, Germany	JRP-Partner 4 VSL, Netherlands JRP-Partner 5 ITOMS, United Kingdom JRP-Partner 6 KEMA (now trading as DNV GL), Netherlands JRP-Partner 7 Shell, Netherlands
REG1-Researcher (associated Home Organisation):	Liyun Lao Cranfield University, United Kingdom
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REG3-Researcher (associated Home Organisation):	Jiri Polansky University of Leeds, United Kingdom

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1. Annex A

1.1 Introduction

This annex presents additional information on the work performed for objective 1 regarding *developing an accurate and validated reference network using existing test and calibration facilities for multiphase flow*. Whereas the presentation and analysis in section 3.1 of the main part of the document has been written by the coordinating lab NEL, this annex presents the analysis performed by VSL with support of DNV GL and OneSubsea. Points of view expressed in the main part of the document are not necessarily shared by the authors of this annex, and the other way round, points of view expressed in this annex may not be shared by NEL. It is hoped that publication of both analyses and points of view will encourage the scientific debate in this area of research.

1.2 Comparisons of test and calibration facilities for multiphase flow

In the ENG58 project three test and calibration facilities for multiphase flow have measured and reported the meter deviations of a 4 inch Vx multiphase flow meter provided by OneSubsea (MUT: Meter Under Test). Ideally, the measurements would have taken place under identical conditions. However, for a variety of reasons this was not possible. Table 2 lists the main differences in the characteristics of the facilities. In view of all differences and the limited set of measurements it will be difficult to draw definitive conclusions in the case divergences in measurement results occur. An interesting point is that the flow meter manufacturer claims that the 10 m long straight pipe with 90° elbow (part of the 'transfer package') is irrelevant for the results produced by the flow meter, as there is a blind-T at the inlet of the flow meter. Other multiphase flow experts disagree with this view point. Note that the mixing point of the three fluids at NEL is intermediate compared to those at DNV GL and OneSubsea.

Table 2: Some characteristics per facility, with a focus on the differences

Characteristic	NEL	DNV GL	OneSubsea
Pressure at MUT	2.1 to 9.5 barg (low P at high gas flow rates)	7.3 to 8.3 barg	15.9 to 17.1 barg
Temperature at MUT	38 to 42 °C (Round 1) 39 to 45 °C (Round 2) (pure gas down to 6 °C)	19 to 21 °C	11 to 17 °C
Oil viscosity	7.5 to 8.7 cP (Round 1) 7.5 to 9.1 cP (Round 2)	4.6 to 5.0 cP	1.7 to 1.9 cP
Water density (linked with temperature and salinity)	1015 to 1019 kg/m^3 (R-1) 1025 to 1029 kg/m^3 (R-2)	1029 to 1030 kg/m^3	999 to 1000 kg/m^3
Flow loop design	Open loop design, nitrogen gas is vented	Closed loop design	Closed loop design
Mixing point of fluids (oil, water and gas)	Almost immediately upstream of a 10 m long straight pipe followed by a 90° elbow followed by the meter.	About 20 m upstream of the meter. Directly upstream of the meter is a 10 m long straight pipe followed by a 90° elbow.	About 3 m upstream of the meter. Upstream of the meter are some bends, but no long straight pipe section.
Claimed expanded uncertainties	Single phase flow rates < 0.9 %, WLR < 0.23 %, GVF < 0.14 %	Single phase flow rates < 1.0 %, WLR < 0.17%, GVF < 0.24 %	oil & water flows: 1.5 %, gas flow: 5 %, WLR < 0.6 %, GVF < 1.3 %

In the next sections bilateral comparisons between NEL and DNV GL, and between DNV GL and OneSubsea will be presented. First the analysis method will be presented.

1.3 Analysis method

1.3.1 Validation of measurement points

The flow meter was installed and configurated by an operator of OneSubsea. VSL witnessed all tests. After the data had been collected various sanity checks were performed. This included following checks: correspondence of measured time period by MUT and facility, differential pressure in throat of Venturi of MUT above 50 mbar, physical conservations laws in the reported data, correspondence of measured density with theoretical density, consistency of the noise levels and standard deviations in the data, correspondence of actual flow rates, WLR and GVF with the nominal values prescribed by the test protocol. Points not respecting the quality criteria were removed. Data from NEL was reprocessed by the flow meter manufacturer in order to compensate for changing fluid properties (due to the open loop design) that could have affected the flow meter performance. This resulted in only small changes.

1.3.2 Consistency assessment

An important goal of the comparisons is to assess if the claimed uncertainties by the test facilities can be validated or not. The measurand is the absolute or relative deviation *d* of the MUT for various multiphase quantities like water oil and gas volume flow rates, total mass flow rate, GVF (Gas Volume Fraction) and WLR (Water Liquid Ratio). For example, let *d* be the relative deviation of the average MUT oil flow rate q_{MUT} with respect to the average reference oil flow rate q_{ref} provided by the test facility recorded during a test point, i.e. $d = (q_{MUT} - q_{ref}) / q_{ref}$. If the testing time was long enough the recorded average q_{MUT} has very small uncertainty, as the natural variability of the flow rate will be averaged out. In the case of relative small deviations between MUT and test facility, it can be verified that $u(d) \approx u^*(q_{ref})$, where $u^*(q_{ref})$ denotes the relative standard uncertainty of the reference flow rate provided by the test facility. For each facility *k,* and for each test point *i* and for each quantity of interest *j* a deviation d^k_{ij} with uncertainty $u(d^k_{ij})$ can be calculated. The results of two facilities *A* and *B* are consistent if

$$|d_{ij}^A - d_{ij}^B| \le 2\sqrt{u^2(d_{ij}^A) + u^2(d_{ij}^B) + 2\,u^2(r_j^{MUT})} \tag{1}$$

The term $u(r_j^{MUT})$ denotes the reproducibility uncertainty of the MUT for quantity *j*, which is assumed to be independent of the actual test point *i* (e.g. the overall reproducibility of the MUT for measured oil flow rates, as a number independent of the actual flow rate). Note that a dependence on GVF was observed (see Table 3), but in the overall consistency calculations the overall value has been used. The reproducibility uncertainty accounts for the fact that the MUT itself produces slightly different measurement results when a measurement is repeated under the same measurement conditions. It is present at both facilities *A* and B, which is the reason for the factor 2 before $u^2(r_j^{MUT})$ in equation (1). This uncertainty contribution has been assessed by analysing the data measured at NEL in two different rounds of measurement, which were separated by approximately one year in time. The fact that the MUT may produce different results in different operating conditions (see Table 2 for the differences) is not accounted for in this consistency assessment, as it is difficult to quantify. Thus, if results are inconsistent, either an uncertainty provided by (at least) one test facility is too low, or the flow meter has a higher reproducibility uncertainty between different facilities than the calculated value $u\left(r_j^{MUT}\right)$. Also note that it is impossible to thoroughly validate facility uncertainties $u\left(d_{ij}^k\right)$ which are smaller than $u(r_j^{MUT})$, as in that case potential inconsistencies are obfuscated by the flow meter reproducibility. It is therefore important the flow meter reproducibility is as low as possible, and a priori assuming a high value for $u(r_j^{MUT})$ makes the comparison a priori of little significance. The factor 2 before the square root in equation (1) is linked to the fact that the target is ‘consistency with a 95 % coverage probability (assuming a normal distribution for the uncertainties)’.

Multiphase flow patterns have a natural variability. Flow rates of oil, water and gas fluctuate over time. The reported mean values measured over a sufficient long time have been compared in this analysis. The standard deviation of the flow rates is seen as irrelevant as long as the averaging time is long enough, or, alternatively, if its effect on the uncertainty is incorporated in the uncertainty statements of the test facilities. If one would include these standard deviations in the analysis, a facility can claim any uncertainty and get consistent results as long at the natural variability in time of the multiphase flow pattern is high[1].

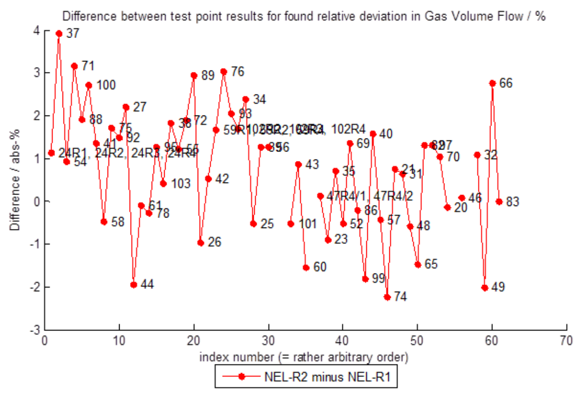
1.4 Flow meter reproducibility

In this section the results for the flow meter reproducibility $u(r_j^{MUT})$ are presented. This has been done by comparing the results of 56 multiphase test points measured at NEL in August 2015 and September 2016. The batch of single phase test points was not used in this analysis, nor some points with questionable quality (low dP values or timing error). The expanded reproducibility uncertainties U'_{repro}, where $U'_{repro} = 2\sqrt{2}\,u(r_j^{MUT})$, are presented in Table 3, split out to GVF range. These values are both affected both by flow meter and test facility reproducibility. The factor 2√2 has been included in order to present an expanded uncertainty (factor 2) covering the uncertainty of both measurement rounds (factor √2).

Table 3: Results of the reproducibility analysis, split out for different GVFs. The value *U'_repro* corresponds to $2\sqrt{2}\,u(r_j^{MUT})$ in equation (1). Its determination is affected by both flow meter reproducibility and facility reproducibility.

Quantity	U'_{repro} (all GVFs)	U'_{repro} (GVF ≤ 90 %)	U'_{repro} (GVF = 92 %)	U'_{repro} (GVF = 96 %)
Total mass flow rate	2.2 %	2.0 %	2.3 %	3.5 %
Total volume flow rate	2.2 %	2.1 %	2.1 %	3.0 %
Gas volume flow rate	3.2 %	3.3 %	2.1 %	2.9 %
Liquid volume flow rate	2.4 %	2.0 %	2.4 %	4.2 %
Water liquid ratio (WLR)	1.9 %-abs	1.2 %-abs	1.6 %-abs	4.4 %-abs
Gas volume fraction (GVF)	0.7 %-abs	0.8 %-abs	0.2 %-abs	0.2 %-abs
Oil volume flow rate[2]	5.6 %	4.3 %	8.7 %	8.5 %
Water volume flow rate	3.4 %	3.0 %	3.0 %	5.7 %

As an illustration to the calculation of the numbers in Table 3 the reproducibility calculation has been visualized in Figure 3. It is seen as important to present this in detail, in order to give the reader enough information to properly understand and judge the presented analysis results.



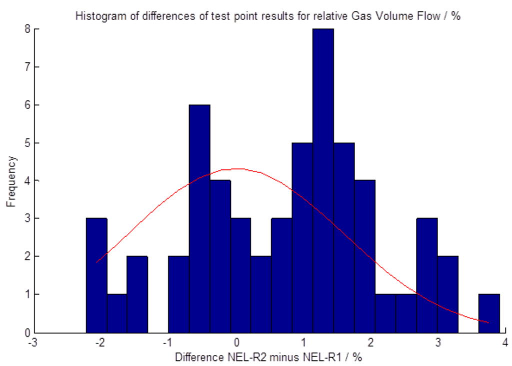


Figure 3: Visualization of reproducibility calculation for relative deviation in gas volume flow rate. Left: Difference between repeated test points per test point. Right: Histogram of differences together with the fitted (zero mean) normal probability distribution.

[1] It seems that this approach has been followed in the analysis in the main part of the document.
[2] One value with a difference of 36 % in measured flow meter oil volume flow rate deviation between the two test rounds was removed in this calculation.

1.5 Comparison between NEL and DNV GL

In this section the results of NEL and DNV GL are compared. These facilities claim the lowest uncertainties.

1.5.1 Measurement results

In this section the test results of NEL and DNV GL are compared. As a first step an overview of some of the main measurement results is given. Figure 4 shows the measured MUT deviation for gas volume flow rate (relative deviation in %) and for Water Liquid Ratio (WLR, absolute deviation in %), as determined by NEL (two rounds) and by DNV GL. The results for 100 % gas have been excluded from the plots and analysis.

Although the specifications regarding absolute accuracy of the manufacturer are strictly speaking not relevant in a comparison context, they have nevertheless been included, as it is still interesting to see how they compare with the results of the test facilities, and it can serve as a quality check of the MUT. It is seen that most points for WLR fall within specifications. For gas volume flow rate more points fall outside. For high GVF measurements at NEL this is not a complete surprise due to the low operating pressure.

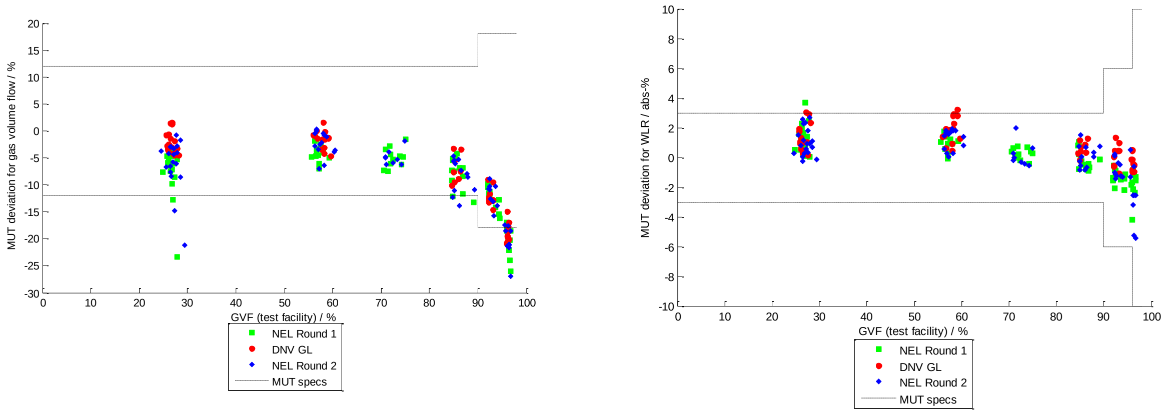


Figure 4: Measurement results at NEL and DNV GL for MUT relative volume flow deviation (left) and MUT WLR deviation (right). The manufacturer specifications of the MUT have been included as well.

1.5.2 Point-wise comparison

As a next step the test points have been compared point-wise, after checking that the actual flow rates corresponded sufficiently (and not only the nominal values). Some points were removed for this reason. It was observed that for WLR = 0 % the water volume flow rate reported by the MUT became sometimes slightly negative (down to -0.3 m^3/h), and for WLR = 100 % the oil flow reading became sometimes negative (down to about -3 m^3/h), together with an indicated WLR of almost 104 %. This deviation is possibly related to inconsistency between fluid properties as measured during the MUT setup vs. fluids properties, while actually flow testing. In Figure 5 the results for the test points at a total liquid flow rate Q_{liq} = 90 m^3/h and GVF = 25 % are shown for various WLRs. This is an interesting set of points as it contains some of the highest deviations between the facilities. The error bars indicate the expanded uncertainty reported by the test facilities. In order to judge consistency of the results the meter reproducibility (as estimated in Table 3) has to be included as well, and equation (1) has to be applied. For WLR the results are consistent in this case (as U'_{repro}(WLR) = 1.2 %). For gas volume flow rate ($U'_{repro}(Q_{gas})$ = 3.3 %) the results are consistent for high WLRs, but inconsistent for low WLRs, especially for an oil-gas mixture. In the absence of other information (e.g. other laboratories or identified errors) it cannot be said if the discrepancy is due to the MUT reacting differently at slightly different flow conditions (see also Table 2), of if one (or both) of the test facilities provides inaccurate reference values (or far too low uncertainties).

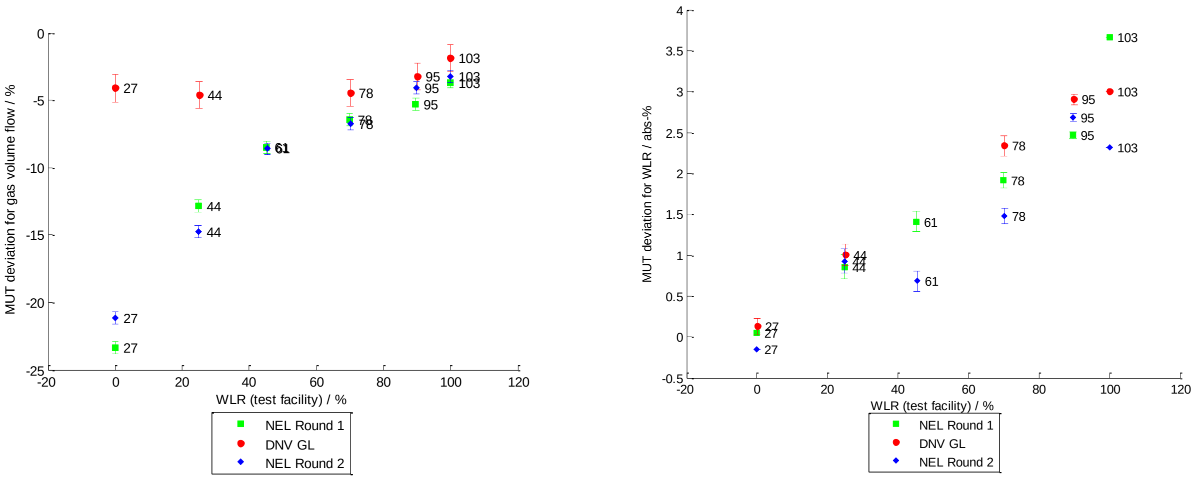


Figure 5: Examples of point-wise comparison of test point results for GVF = 25 % and Q_liq = 90 m3/h. Error bars indicate facility uncertainties only. Left: relative gas volume flow rate deviation (*U'*_repro = 3.3 %), right: absolute WLR deviation (*U'*_repro = 1.2 %).

1.5.3 Overall numerical consistency

To summarize all results with a few numbers, the fraction of the cases that consistency was achieved has been calculated for different quantities, as listed in the first row of Table 4. The large batch of single phase points has been excluded from this calculation. The row comparing NEL-R1 with NEL-R2 has a mean consistency of 95 %. This is as expected by the definition of U'_{repro} and also confirms that the assumption of a normal distribution for the uncertainty is not so bad (i.e. 2 standard deviations corresponds to 95 %). The consistency between NEL and DNV GL is about 80 %, where at least 95 % would be expected for complete consistency. It is slightly surprising that the consistency with NEL-R1 is higher, although in time the tests at DNV GL (July 2016) took place closer to NEL-R2 (September 2016). Without more information it is unclear if the fraction of inconsistent results is mainly due to a larger reproducibility uncertainty of the flow meter installed in different facilities (see Table 3), or to one or more facilities underestimating their uncertainty of measurement (or anything else being overlooked in this analysis).

Table 4: Consistency of the test results of NEL and DNV GL expressed as percentage of the number of test points. Consistency is calculated using equation 1, the values of Table 3 and the uncertainty values provided by the test facilities.

Comparison	Total mass flow rate	Total volume flow rate	Gas flow rate	Liquid flow rate	WLR	GVF	Oil flow rate	Water flow rate	Mean value
NEL-R1 with NEL-R2	91 %	95 %	98 %	93 %	96 %	96 %	92 %	96 %	**95 %**
NEL-R1 with DNV GL	89 %	78 %	69 %	87 %	95 %	71 %	88 %	90 %	**83 %**
NEL-R2 with DNV GL	85 %	75 %	75 %	90 %	93 %	79 %	84 %	86 %	**78 %**

1.6 Comparison between DNV GL and OneSubsea

In this section the results of DNV GL and OneSubsea are compared. A similar structure as for the comparison of NEL and DNV GL data is followed. Note that OneSubsea claims a higher uncertainty than DNV GL. DNV GL and OneSubsea have tested at different pressures. These facilities represent the extremes regarding the location of the mixing point of the three phase points with DNV GL having a mixing point far upstream and OneSubsea relatively close to the MUT.

1.6.1 Measurement results

In Figure 6 the results for gas volume flow rate and WLR are shown, together with the specifications of the MUT. For WLR all points lie within specification, for gas volume flow rate some points at high GVF lie outside the MUT specifications for DNV GL (note that the specifications go until GVF = 98%). It is not surprising that the MUT deviations as measured at OneSubsea's multiphase facility all lie within specifications, as OneSubsea is the manufacturer of the MUT. MUT results and OneSubsea's multiphase facility are thus most probably not independent. At high GVFs the results for the gas volume rate start to deviate. This is probably due to the difference in operating pressure at the test facilities. Note that is is known that the meter uncertainty specification increases at lower pressure for high GVF.

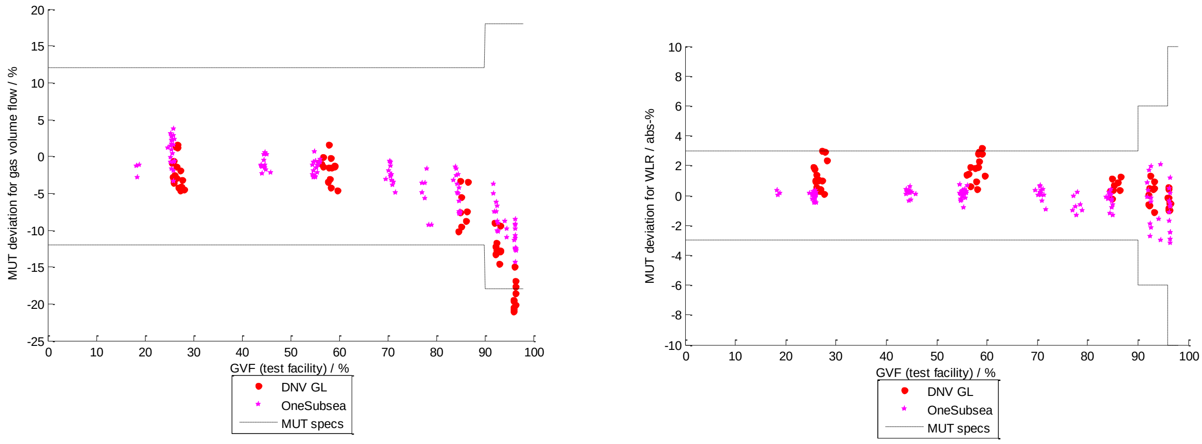


Figure 6: Measurement results at DNV GL and OneSubsea for MUT relative volume flow deviation (left) and MUT WLR deviation (right). The manufacturer specifications of the MUT have been included as well.

1.6.2 Point-wise comparisons

In Figure 7 point-wise comparisons of the results for the relative volume flow deviation and the WLR for the points at Q_{liq} = 90 m³/h and GVF = 25 % for different WLRs are shown. The gas volume flow rate results have good agreement, whereas the agreement for WLR is poor for this set of points.

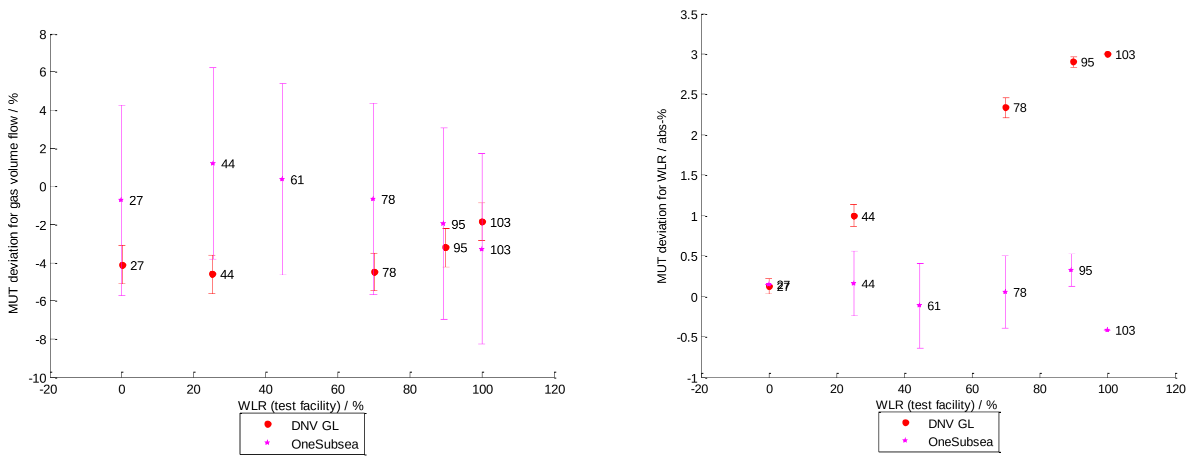


Figure 7: Examples of point-wise comparison of test point results for GVF = 25 % and Q_liq = 90 m3/h. Error bars indicate facility uncertainties only. Left: relative gas volume flow rate deviation (*U'*_repro = 3.3 %), right: absolute WLR deviation (*U'*_repro = 1.2 %).

1.6.3 Overall numerical consistency

The consistency of DNV GL and OneSubsea, respecting their claimed uncertainties and the assumed MUT reproducibility of Table 2 is shown in Table 5. The mean consistency is about 78 %, where a consistency of at least 95 % would be desirable. This may nevertheless be seen as a good result in view of the differences of operating pressure and inlet geometry.

Table 5: Consistency of the test results of DNV GL and OneSubsea expressed as percentage of the number of test points. Consistency is calculated using equation (1), the values of Table 3 and the uncertainty values provided by the test facilities.

Comparison	Total mass flow rate	Total volume flow rate	Gas flow rate	Liquid flow rate	WLR	GVF	Oil flow rate	Water flow rate	Mean value
DNV GL with OneSubsea	82 %	74 %	78 %	74 %	80 %	100 %	58 %	80 %	**78 %**

1.7 Conclusions

The results of two comparisons have been presented in this annex. Both comparisons resulted in an overall consistency of about 80 %, where ideally at least 95 % would have been attained. No conclusive answers have been found to explain the 15 % of unexpected inconsistencies, although some tentative studies have been performed. Due to space limitations nor these studies, nor a separate discussion of the single phase points could be included in this document. To remedy this situation following advices are given:

- make publicly available all measurement data of the ENG58 project to enable further investigations by any interested party;
- organize a new comparison with at least five partners, at least two different metering technologies, an extensive test protocol, data analysis by an independent party and open access of all the raw measurement data.

At a non-technical level some differences between the test facilities in the way of cooperating and communicating were observed as well. A party interested in multiphase flow tests is well advised also to consider these aspects, independently of the technical specifications a facility may possess.