

FINAL PUBLISHABLE REPORT

Grant Agreement number 16ENG07
 Project short name MultiFlowMet II
 Project full title Multiphase flow reference metrology

Project start date and duration:		01 June 2017 (36 months)
Coordinator: Anna Pieper, NEL Tel: +44 (0) 7885 464 396 E-mail: anna.pieper@tuv-sud.co.uk		
Project website address: https://www.tuvsud.com/en-gb/industries/chemical-and-process/flow-measurement/research-and-development/multiflowmet---multiphase-flow-reference-metrology/		
Internal Funded Partners: 1. NEL United Kingdom 2. CMI, Czech Republic 3. PTB, Germany 4. VTT, Finland	External Funded Partners: 5. NORCE, Norway 6. CU, United Kingdom 7. DNV GL, Netherlands 8. ITOMS, United Kingdom 9. OneSubsea, Norway (withdrawn from March 2018) 10. PSL, United Kingdom 11. Roxar, Norway 12. UCov, United Kingdom 13. ULE, United Kingdom 14. UofG, United Kingdom	Unfunded Partners: 15. Rosen, Germany
RMG: -		

TABLE OF CONTENTS

1 Overview 3

2 Need 3

3 Objectives 3

4 Results 5

5 Impact 20

6 List of publications 21

7 Contact details 22

1 Overview

Europe, and the world, will be dependent for many decades to come on the production of oil and gas for its energy needs. Multiphase flow measurement is a fundamental enabling metrology in oil and gas production. However, field measurements exhibit high measurement uncertainty, costing industry billions of euros in financial exposure and production inefficiencies. To improve this situation requires a reference measurement capability that is consistent and comparable across different test laboratories that offer this service. Therefore, this project addressed this need by establishing harmonisation of measurements between different multiphase flow reference laboratories. The project achieved metrological comparability for 94 % of all test points for gas volume flow and 87.5 % of all test points for liquid volume flow. This means that end users and manufacturers of multiphase flow meters (MPFMs) can now be assured that their meters will perform comparably at the three different European multiphase test facilities that participated in this project's intercomparison (i.e. partners NEL, DNV GL and NORCE). These results mean that, end users of these multiphase test facilities can now use them to help refine their MPFM technologies further and hence provide better measurements with decreased uncertainty.

2 Need

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 \$1860bn p.a. for oil for 2017 and 2080bn p.a. for 2018. When fluid is extracted from a well it typically comprises time-varying ratios of oil, water and gas. Multiphase flow measurement, where each component is individually metered, is a key enabling metrology that is vital for operational decision-making as well a prerequisite for allocation and fiscal measurement. However, currently field-based multiphase flow measurement is subject to high levels of uncertainty (up to c. 20 %, greater in some conditions), which has serious ongoing financial implications in all these areas of application. The previous lack of standardised facilities (and procedures) for testing MPFMs led to variances in test results between laboratories which eroded confidence in the measurement system, and hence confidence in the meters themselves. Which in turn led to a need for harmonisation of multiphase flow measurement methods and data.

The preceding project ENG58 MultiFlowMet developed and piloted an approach for such harmonisation. However, in order to achieve better harmonisation and comparability of MPFM measurements this approach needed application across an enlarged network of laboratories and a wider range of different MPFM types via an extended intercomparison testing programme. But in order to be able to execute this intercomparison, it needed the design and provision of a mobile suite (i.e. transfer package) of instrumentation that could be moved around different laboratories in order to enable comparison measurements to be taken.

To be able to understand any variances in the datasets gained in such an intercomparison, an understanding of the factors that influence the measurements was urgently needed. Such factors included the geometrical features of each participating laboratory and the structure of the flow that develops in each set of flow conditions. Finally, the intercomparison's data needed to be carefully analysed and interpreted, to ensure the maximum possible level of harmonisation and comparability between laboratory measurements.

3 Objectives

The overall goal of this project was to establish an enduring multiphase flow measurement capability to end users.

1. To optimise, and fully prepare for, the intercomparison testing programme by building a transfer package whilst taking into account leading-edge methods of flow pattern visualisation and the production of a comprehensive set of test matrices and protocols.
2. To carry out intercomparison testing across a network of laboratories with appropriate facilities in order to significantly extend the test envelope, in terms of flow rates (4 to 100 m³/hr for liquid and 3 to 300 m³/hr for gas), pressure (4.5 to 9 bar; extended to > 24 bar in complimentary research tests), and fluid properties (oil viscosity including the range of 5 cSt to 8.5 cSt). The intercomparison testing will include appropriate leading-edge methods of flow pattern visualisation and will be done with a meter that incorporates a Venturi, cross-correlation, gamma ray absorption and electrical impedance sensing.

3. To further develop modelling (e.g. computational fluid dynamics (CFD) techniques) for the significant improvement of the metrological characterisation of multiphase flows, using small and full-scale experimental testing. Improvements will come from new data that will allow flow regime map(s) to be extended and/or new one(s) created. This will include additional research to understand geometrical influences and the influence of gas phase activity.
4. To make statistical cross-comparisons between the measurements undertaken in each intercomparison laboratory with a view to establishing comparability of measurement between test laboratories. The analysis will compare findings, identify anomalies, deduce their method of investigation and state the resolutions achieved.

4 Results

Objective 1 - To optimise, and fully prepare for, the intercomparison testing programme by building a transfer package whilst taking into account leading-edge methods of flow pattern visualisation and producing a comprehensive set of test matrices and protocols.

The transfer package was designed by NEL, NORCE, DNV GL, Rosen, Roxar, PSL, UofG, UCov, VTT, ITOMS, CU and ULE, to minimise the potential geometrical differences between the laboratories (i.e. partners NEL, NORCE and DNV GL), so that the item under test was as consistent as possible across all laboratories. The transfer package was also designed to accommodate the instruments required for objectives 3 and 4. The transfer package consisted of the following main components (shown in detail in Figure 1):

Description	Supplier
1 Multiphase meter + instrumentation	Roxar
2 Tomography system 1 + instrumentation	Atout
3 Tomography System 2 + instrumentation	ITS
4 Perspex viewing spool	NEL
5 Video recording equipment + instrumentation	NEL
6 High Speed Pressure Logger + instrumentation	NEL
7 Pipework + nuts, bolts and washers	NEL

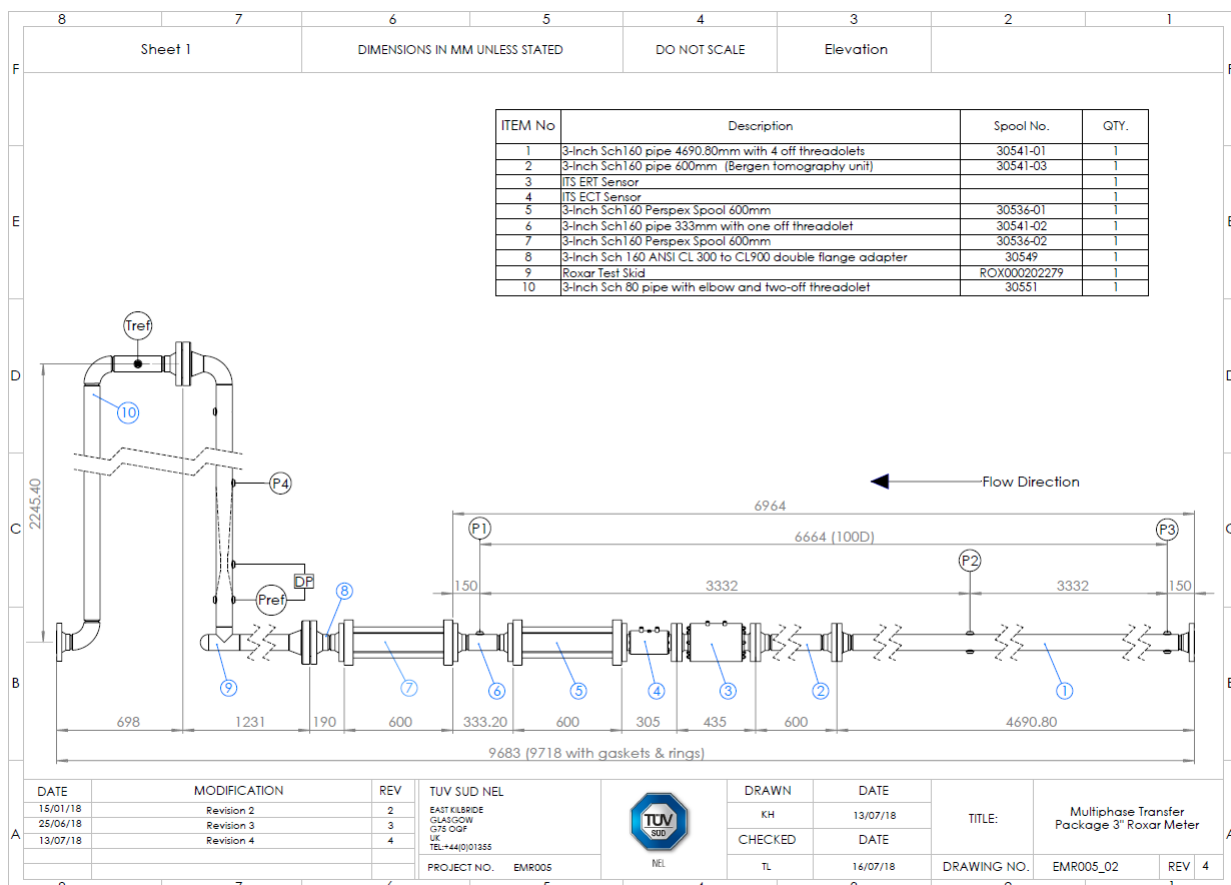


Figure 1. 3-in Transfer package with Roxar 2600 ID67mm MPFM

The bespoke transfer package was an improvement upon that from the previous ENG58 project's transfer package as it used a state-of-the-art MPFM, with an operating envelope that was able to cover the entire test matrix specified across all three partners (NEL, DNV GL and NORCE) participating in the intercomparison.

The improved and bespoke transfer package shown above consisted of a Roxar Multiphase flow meter (from partner Roxar), item 9 in figure 1 above.

Items 3 and 4 in the figure above are the ITOMS tomography sensors (from partner ITOMS) used to collect flow visualisation data. Item items 5 and 7 above (shown in more detail in Figure 2 below) are the Perspex spool sections which were used for recording high speed video footage and for mounting the Atout tomography sensors which were also used to collect flow visualisation data.

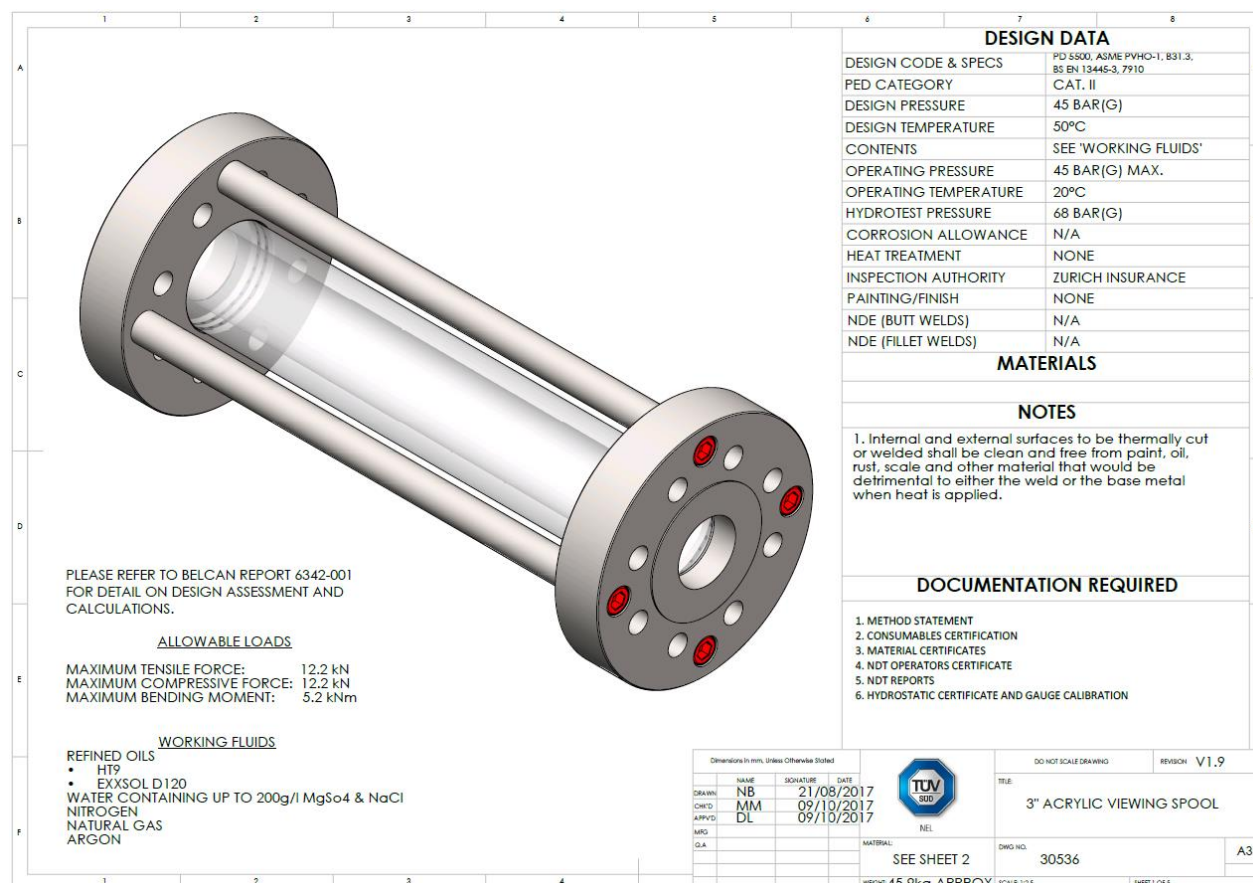


Figure 2. Perspex viewing sections for high speed video recording and Atout tomography sensor mounting.

Taking into consideration the different operating envelopes of the three different laboratories (i.e. NEL, NORCE and DNV GL), a test matrix, which defined the test points was developed and agreed between partners NEL, DNV GL, NORCE, UofG, PSL, VTT, UCov, ITOMS, Rosen, Roxar and ULE. The test matrix is shown in Table 1 below.

Liquid Flow m ³ /hr	Gas Volume Fraction %						
	10	30	50	67	80	90	95
5							X
15					X	X	
30			X	X	X		
50		X	X	X			
75	X	X	X	X			
100	X	X	X				

Table 1. Multiphase Intercomparison test matrix. All test point shown above were carried out at WLR or 0, 10, 25, 40, 60, 75 and 90%.

A test matrix defining the test points, in terms of laboratory flow conditions, for optimally selected permutations of test laboratories and MPFMs was developed by NEL, NORCE, DNV GL, ULE, CU, VTT, PSL, UCov and Rosen for the transfer package. Following this, a set of intercomparison testing protocols (methods) was agreed by the consortium for use first in objective 2 and then in objective 4. The test matrix built upon the previous ENG58 project's test matrix and improved it significantly by extending the test envelope, in terms of flow rates (4 to 100 m³/hr for liquid and 3 to 300 m³/hr for gas), pressure (4.5 to 9 bar, extended to greater than 24 bar in complimentary research tests), and fluid properties (oil viscosity including the range of 5 cSt to 8.5 cSt). In order to minimise variation in testing procedures across the three laboratories, the test protocol, outlining the test set up and configuration, was developed by the partners and the tests at each facility were witnessed by an independent arbiter from UofG who maintained daily logs.

The coordination of the logistics of this intercomparison was challenging as each of the laboratories had tight schedules, were all in different countries and the transfer package included a radioactive source. The logistics plan was primarily driven by NEL and included the testing schedules, shipping details, details of customs requirements by country and definition of special licensing and or certification requirements and the means of obtaining them were developed. Table 2 shows the test date schedules for each of the laboratories.

<u>Stage</u>	<u>Ship from/to</u>	<u>w/c (no.)</u>	<u>Transport</u>
1	Roxar/NEL	25 Feb (9)	Suppliers own
2	NEL/CMR	06 May (19)	Road/ Sea/ Road
3	CMR/DNV	10 Jun (24)	Road
4	DNV/NEL	22 July (30)	Road/ Sea/ Road
5	NEL/Roxar (owner)	09 Sept (37)	Road/ Sea/ Road

Table 2. Shipping and test date schedules for the Intercomparison testing.

Summary

The project successfully prepared for the intercomparison testing programme by building a transfer package and taking into account leading-edge methods of flow pattern visualisation. It also produced a comprehensive set of test matrices and protocols and a logistics plan that included all necessary aspects for successfully setting up and managing the intercomparison.

Objective 2 - *To carry out intercomparison testing across a network of laboratories with appropriate facilities in order to significantly extend the test envelope, in terms of flow rates (4 to 100m³/hr for liquid and 3 to 300 m³/hr for gas), pressure (4.5 to 9 bar; extend to 24 bar in complementary research tests), and fluid properties (oil viscosity including the range of 5 cSt to 8.5 cSt). The intercomparison testing will include appropriate leading-edge method of flow pattern visualisation and will be done with a meter that incorporates a Venturi, cross-correlation, gamma ray absorption and electrical impedance sensing.*

Test laboratory data - Component flow rates were measured for each test matrix point (from objective 1) by partners NEL, DNV GL and NORCE in turn. Reference meter outputs, pressure and temperature were measured and checked that they were appropriate for use in the intercomparison in objective 4.

MPFM data – Using a MPFM that incorporated a Venturi, cross-correlation, gamma ray absorption and electrical impedance sensing, component flow rates and appropriate raw data outputs e.g. differential pressure were measured by ROXAR and were found to be appropriate for use in the intercomparison in objective 4.

Operating pressure - there was no cross over area of common ground in terms of operating pressure between the DNV GL and NORCE multiphase test facilities. This meant that it would be necessary for the project to conduct two separate comparison studies in objective 4, (1) one at high pressure comparing NEL and DNV GL facilities directly (9bar), and (2) one at low pressure (4.5 bar), allowing a direct comparison of the NEL and NORCE multiphase test facilities.

Conductivity measurements - were not collected in the earlier ENG58 project. Conductivity is an important measurement in determining the performance of the MPFM transfer meter. Partners NEL, DNV GL and NORCE agreed to match the water salinity at 4.8 wt% and at an operating temperature of 15 °C, 25 °C and 45 °C. These parameters resulted in conductivity measurements from 6 S/m to 10.3 S/m. The MPFM manufacturer confirmed that the conductivity is of the same order and within the preferred range of the MPFM (5 – 20 S/m), therefore these results demonstrated that conductivity would have minimal impact on the performance of the MPFM during the intercomparison.

Instrumentation drift - two sets of data (laboratory reference flow meters plus the MPFM) from the NEL facility were taken under identical conditions, at the start and end of the test programme. The data was used to, to rule out (or detect) drift in any of the instrumentation and quantify the reproducibility uncertainty. No drift was detected in the data which was an important result for the project.

Flow pattern - experimental evidence of the flow pattern was collected using tomography sensors and viewing section video footage. This data was used to further investigate test points that showed variation between laboratories after analysis (objectives 3 & 4). The data required subsequent analysis before yielding numerical or other results e.g. flow pattern categorisation. The flow patterns observed at partners NEL, DNV GL and NORCE were expected to differ due the parameters which are intrinsic to the laboratory and were thus impossible to standardise across the three laboratories with the transfer package. However, these phenomena were further investigated in objective 3.

Summary

The project carried out intercomparison testing across a network of laboratories with appropriate facilities and was able to extend the test envelope, in terms of flow rates (4 to 100m³/hr for liquid and 3 to 300 m³/hr for gas), pressure (4.5 to 9 bar; extend to 24 bar in complementary research tests), and fluid properties (oil viscosity including the range of 5 cSt to 8.5 cSt). The intercomparison testing was also set up to include appropriate leading-edge methods of flow pattern visualisation using UCov and ITOMS tomography sensors along with high speed video capture of transparent viewing sections. Two complementary electrical tomography methods, capacitance and resistance, were used to generate images of the distribution of oil, gas and water in 2- and 3-phase flows typical of oil and gas production. Having these accurate measurements of the phase distribution in space and time, several hundreds of times per second, enabled more accurate descriptions of the way the fluids flow and the nature of the waves, bubbles and other structures in the flows.

Objective 3 - To further develop modelling (e.g. computational fluid dynamics (CFD) techniques for significantly improving the metrological characterisation of multiphase flows, using small and full-scale experimental testing. Improvements will come from new data that will allow flow regime map(s) to be extended and/or new one(s) created. This will include additional research to understand geometrical influences and the influence of the gas phase activity.

An analysis of the inter-laboratory differences was carried out, including the geometrical variances, as a precursor to the full scale experimental research undertaken and NEL and DNV GL. Topics (i.e. measurement influence factors) identified from the analysis for further small-scale modelling and CFD simulations were (i) length, (ii) orientation and true ID of pipe upstream and downstream of transfer package, (iii) fluid mixing / injection point, (iv) internal geometry of mixing sections, (v) diameter changes or bends between the mixing, and (vi) the transfer package (objective 1).

Partner CU built a low pressure 3-in transparent 2 phase (gas and liquid) multiphase flow facility, which included the use of transparent blind tee, pressure transducers, electrical capacitance tomography sensors, a venturi meter and wire mesh sensors (WMS). Using this low pressure 3-in transparent 2 phase multiphase flow facility, CU were able to carry out different flow regime modelling analysis. Some of the key findings from their modelling analysis were;

- the combination of probability density function (PDF) plots of the venturi throat differential pressure (DP) can be used to identify the flow regimes in the venturi.
- The plots of the Venturi throat pressure and that of the Differential pressure provide an alternative for discrimination of slug flow from plug flow in the loop.
- The PDF plots of the void fractions of the horizontal wire mesh sensor (WMS) and vertical WMS could be used to identify the flow regimes and their transitions in the flow loop.
- The frequency of the wave was affected by superficial fluid velocities, with the frequency increasing versus the superficial velocities.
- For fully developed plug flow, the wave frequency remains fairly constant in the horizontal and vertical sections of the flow loop.
- Waves travel faster in slug flow compared with the plug flow regime.

These results were also used to validate the CFD modelling undertaken by PTB and CMI.

A number of CFD simulations were produced by PTB and CMI that were validated against the small-scale and full-scale experimental data; thereby, supporting the data rationalisation in the intercomparison test programme. Initially, multiphase flow in a horizontal pipe was studied to investigate and compare the flow patterns observed during the intercomparison testing in the transparent viewing section. In addition to this, the multiphase flow in the small-scale experimental loop at partner CU was modelled and compared to measurement results.

Comparison of the experimental observations and simulations was made by comparing flow pattern development in the horizontal and vertical section of the small scale flow loop. Some of the key findings were; (i) finer mesh resolution, as well as more detailed comparison with tomography data is needed for complete validation of numerical modelling, (ii) using the analysis of mean slug frequency, no fully developed flow pattern could be demonstrated until 600 pipe diameters – both simulation and experiment showed a decrease in the frequency through the pipe.

Partners NEL and DNV GL undertook the full-scale experiments to investigate the influence of pipe geometry (primarily the gas inlet position) and of the gas phase activity. In each case the aim was to assess whether or not these characteristics influence the flow regime and the reproducibility of the transfer package (objective 1). This research is vital for intercomparisons between multiphase flow laboratories as it provided important insight into the possible variations between facilities. The analysis of these tests was conducted by UofG.

The NEL facility was used to investigate variations in upstream geometry (as shown in table 3 below), with an identical comprehensive test matrix for each of the configurations,

Flow development distance (number of pipe diameters)	Gas inlet entry position
0	Side
0	Below
100	Side
100	Below
300	Below
600	Below

Table 3. flow development distances from gas inlet position at NEL.

and the closed loop at DNV GL was used to investigate variations in gas phase activity and pressure (shown in table 4 below).

Gas	Pressure
Nitrogen	8 barg
Argon	15 barg
Argon	30 barg

Table 4. Gas type and pressure combinations and DNV GL.

The analysis of these full-scale experiments at NEL and DNV GL was facilitated in part by the high-speed video footage obtained at the Perspex viewing sections and the tomography data.

To quantify the analysis of the experimental data, a comparability parameter, ζ , was defined. This was developed by considering the relative deviation of the measurement (by the MPFM) of a specific parameter from the measurand (the true value). For the measurement of flow rate, Q_i , at laboratory j , this was calculated as

$$\Delta Q_j = \frac{Q_{i,j} - Q_{i,j}^{MPFM}}{|Q_{i,j}|}.$$

The uncertainty associated with this deviation must take into the uncertainties of both the measurand and the measurement. Thus, it can be calculated as

$$\sigma(\Delta Q_j) = \sqrt{u_{ref,j}^2 + u_{MPFM,j}^2}.$$

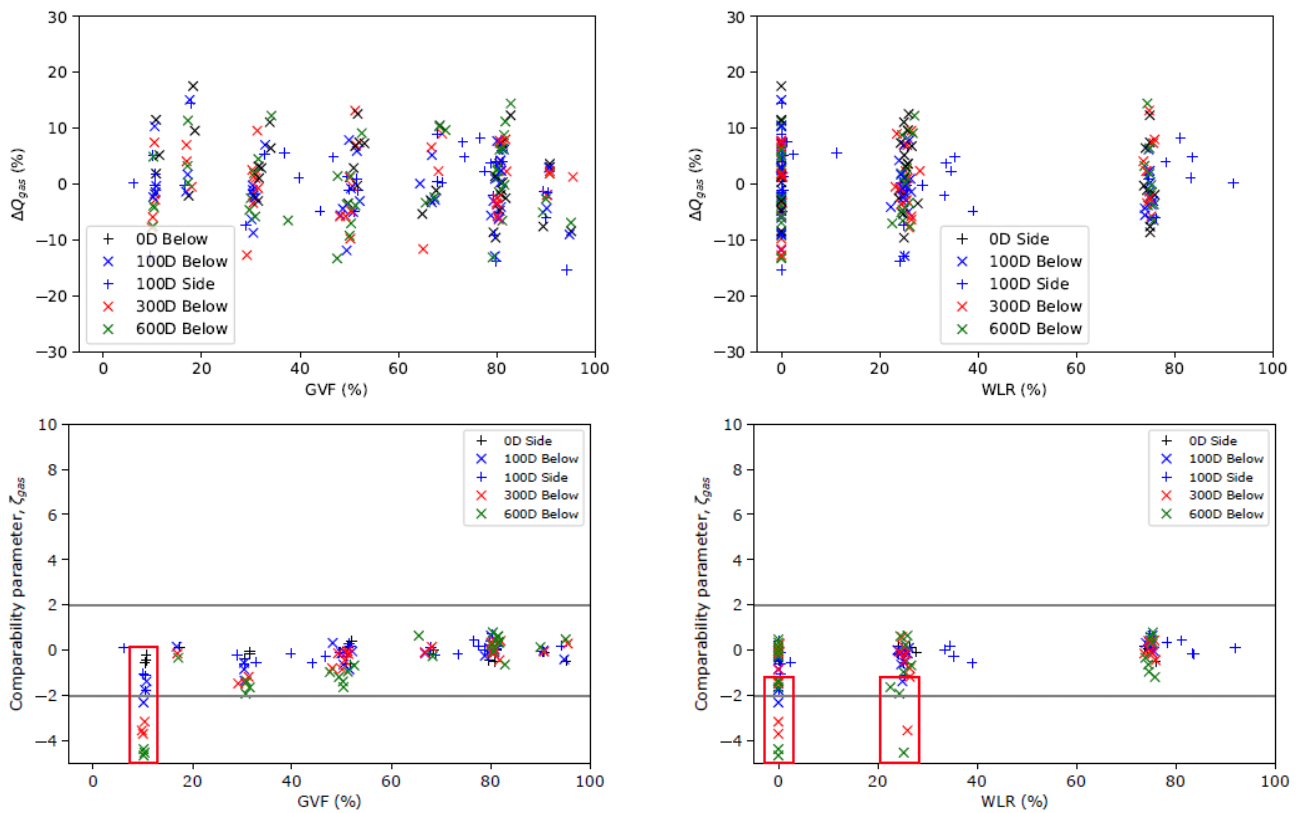
Therefore, the comparability parameter can be written as

$$\pm \zeta_Q = \frac{\overline{\Delta Q_{j_1}} - \overline{\Delta Q_{j_2}}}{\sqrt{\sigma(\Delta Q_{j_1})^2 + \sigma(\Delta Q_{j_2})^2}},$$

where the bar notation denotes the mean of the observations, where multiple measurements are made. The two measurements are said to be *metrologically compatible* if $|\zeta| < \kappa$, for a specified threshold. In the present case, it is the standard uncertainties that are used, as opposed to the expanded uncertainties, so a value of $\kappa = 2$. The expanded interpretation of the comparability is given in Table 5 parameter.

ζ value	Interpretation
$ \zeta = 0$	Idealised case in which both laboratories achieve identical flow conditions and the MPFM exhibits perfect reproducibility.
$0 < \zeta \leq 2$	Strong statistical agreement between the measurements taken in the two test campaigns; metrological compatibility has been achieved.
$2 < \zeta \leq 3$	Poor comparability.
$ \zeta > 3$	Comparison failed.

Table 5: Interpretation of the comparability parameter values.

Figure 3: Relative deviations and comparability parameter values for Q_{gas} .

From the data analysis of the full-scale experiments under taken at NEL, although there were noticeable variations in the resulting parameters (sometimes exceeding 20 % for water flow rate), there were no apparent cases in which one configuration showed significantly smaller deviations than the others across the entire range of gas volume fractions (GVFs) and water liquid ratios (WLRs). However, $WLR \approx 0$ % and $GVF \leq 30$ %, the deviation in gas flow rate was observed to increase with mixing distance. Similar trends were observed when $WLR \approx 25$ %, but were less pronounced. The side inlet position also appeared to have some influence on the flow conditions.

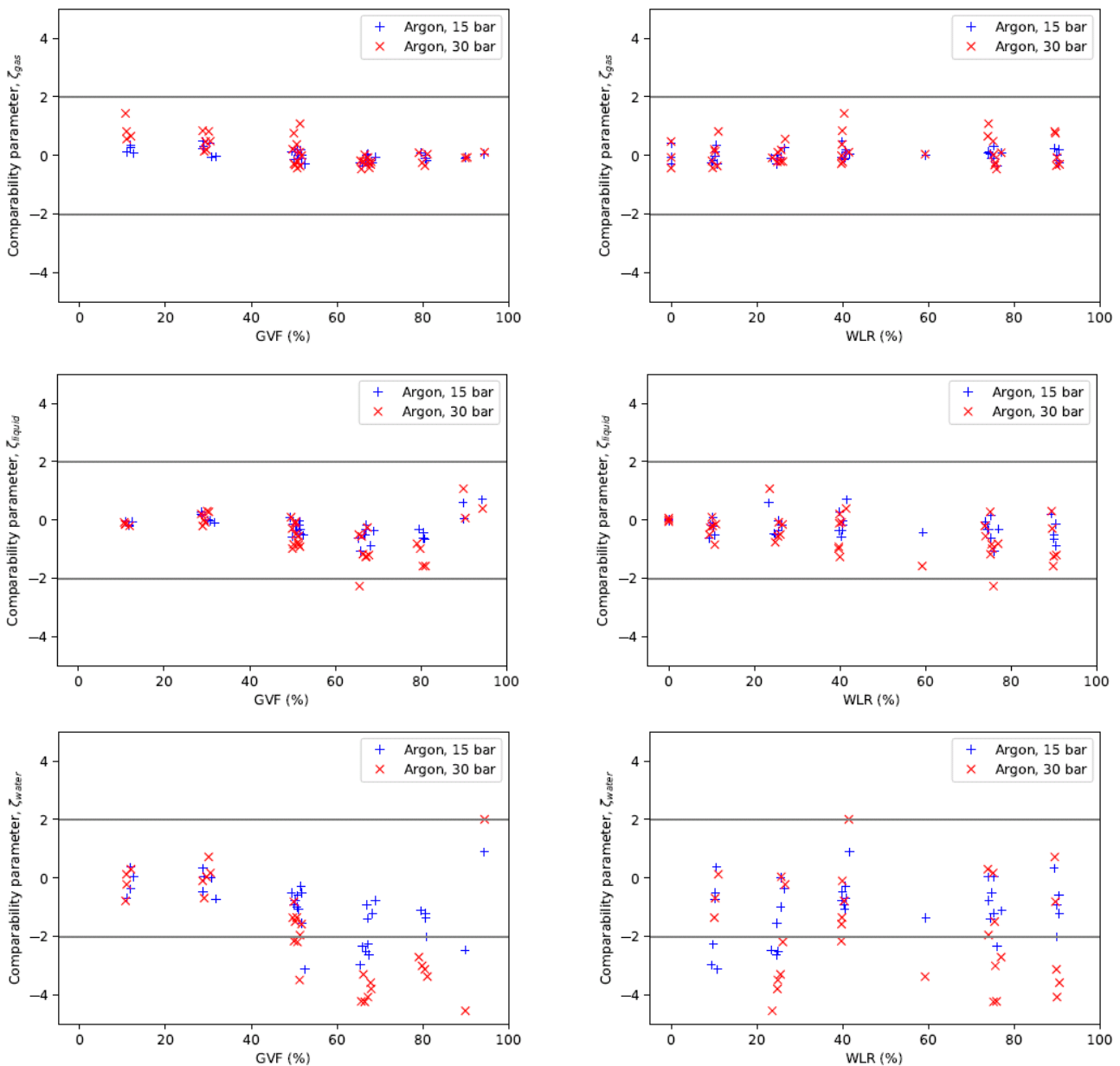
To illustrate this point further, Figure 3 presents the relative deviations and comparability parameter values for the measurement of Q_{gas} . As discussed, the deviations themselves were all below 20 %, and with no observable trends with respect to the mixing distance or inlet position.

However, the red boxes in the lower panels in Figure 3 highlight a clear increase in the comparability parameter with respect to mixing distance for $WLR \approx 0$ % and $GVF \leq 30$ %. Similar trends in the deviations were observed for the liquid flow rates (not presented here), though similar observations were not made for ζ_{liquid} .

From the data analysis of the experiments undertaken at DNV GL, variations in the measured flow rates were relatively small. They were noticeably higher for the volumetric gas flow rate, although this decreased for higher GVFs. The reproducibility was strong for both gas and liquid flow rates, although this was diminished for the individual oil and water flow rates at high GVFs.

The 15 barg Argon and 30 barg natural gas cases were compared to investigate the influence of using inert gas, there was a noticeable difference in the formation of bubbles and slugs, as assessed through the use of the video footage.

In Figure 4, the variations in the comparability parameter for the different volumetric flow rates are presented; i.e. the higher pressure (15 and 30 barg) Argon tests are compared with the 8 barg Nitrogen tests. It can be seen that metrological compatibility was achieved for almost all measurements of Q_{gas} and Q_{liquid} , but this was not always the case for high GVF test points when the oil and water flow rates were measured separately. The trends for the natural vs. inert gas comparison follow similar trends but are not presented here.



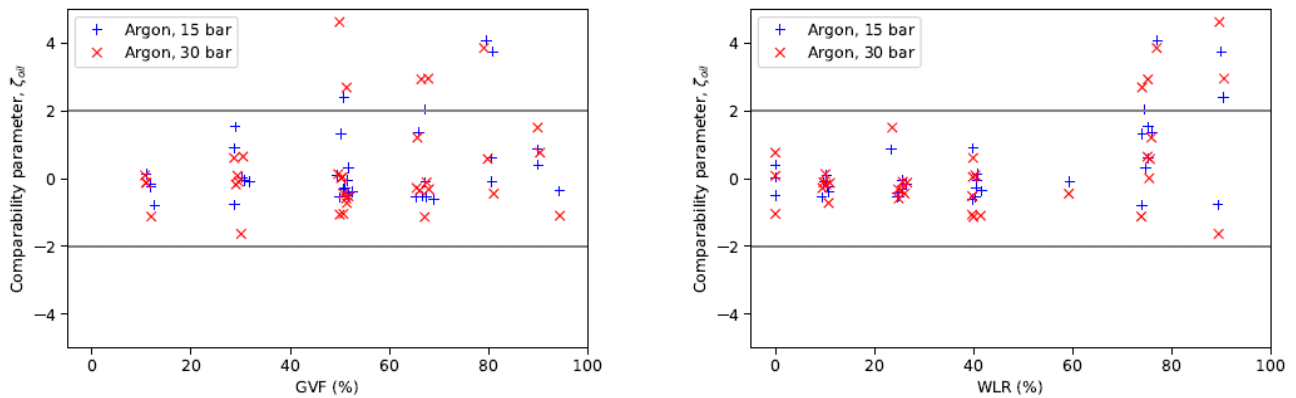


Figure 4: Comparability parameter values for pressure variation tests.

Summary

The project successfully developed modelling including CFD techniques for the significant improvement of the metrological characterisation of multiphase flows, using small and full-scale experimental testing. Improvements included the extension and creation of flow regime map(s) and additional research to understand geometrical influences and the influence of gas phase activity.

Objective 4 - To make statistical cross-comparisons between the measurements undertaken in each intercomparison laboratory with a view to establishing comparability of measurement between test laboratories. The analysis will compare findings, identify anomalies, deduce their method of investigation and state the resolutions achieved.

The project's comparison of MPFM were successfully completed at partners NEL, DNV GL and NORCE. Ideally, any comparison would be performed under exactly the same conditions at all laboratories. However, variations in operating ranges, different test fluids, and different geometrical configurations meant that this was not possible for this project. (see Tables 6 & 7 below)

To account for the differences in test fluids and facility operating ranges, optimal facility operating conditions, including temperatures, pressures and water salinity, were determined. The optimal facility conditions were determined in order to achieve the best match of important dimensionless numbers; the Froude number and oil Reynolds number. The optimal operating pressures and temperatures chosen for each laboratory to achieve the best match of Froude and Reynolds numbers are summarised in Table 8 below.

Characteristic	NEL, low press.	NEL, high press.	NORCE	DNV GL
Flow loop design	Open loop	Open loop	Closed loop	Closed loop
Injection type	Gas into liquid	Gas into liquid	Gas into liquid	Liquid into gas
Mixing distance* (m)	0	0	5-10	4
Oil viscosity (cP)	7.26 to 8.26	6.95 to 8.51	2.4 to 2.7	4.8 to 5.2
Gas density (kg/m ³)	5.54 to 6.41	9.74 to 11.21	6.26 to 7.47	8.52 to 12.03
Water density (kg/m ³)	1023.65 to 1025.49	1022.79 to 1025.89	1031.58 to 1032.07	1030.87 to 1032.03
Oil density (kg/m ³)	814.56 to 829.60	813.91 to 818.15	823.52 to 824.78	825.47 to 828.50

Table 6. Overview of the differences between multiphase flow laboratories involved in the intercomparison.

Test round	Test period
NEL, 9 barg	18 th March - 11 th April 2019
NEL, 4.5 barg	2 nd May - 7 th May 2019
NORCE, 4.5 barg	4 th - 7 th June 2019
DNV GL, 8 barg	8 th - 15 th July 2019
Intercomparison reproducibility testing at NEL, 9 barg	16 th - 22 nd August 2019
Intercomparison reproducibility testing at NEL, 4.5 barg	23 rd - 27 th August 2019

Table 7. Intercomparison Test Schedule.

Flow Lab	Pressure (barg)	Temperature (°C)	Water				Oil		
			Type	Salinity (wt.%)	Density (kg/m ³)	Viscosity (cP)	Type	Density (kg/m ³)	Viscosity (cP)
DNV GL	8	18	NaCl	4.8	1031.69	1.04	Exxsol D120	827.55	5.10
NEL	9	45	NaCl	4.8	1024.19	0.65	Paraflex HT9	815.10	7.32
NEL	4.5	45	NaCl	4.8	1024.19	0.65	Paraflex HT9	814.81	7.32
NORCE	4.5	25	NaCl	4.8	1031.99	0.99	Diesel	824.05	2.52

Table 8. Selected operating parameters and nominal fluid properties to best match dimensionless numbers between facilities.

A full analysis of the intercomparison was undertaken in order to compare findings, identified anomalies and investigate them and finally deduce their method of resolution. To ensure a fair and accurate comparison, the statistical methodology applied to the data was performed in accordance with ISO 5275- 2:2019 Accuracy (trueness and precision) of measurement methods and results — Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method.

Mandel's h statistics was also used to determine or confirm which test points were usable for the analysis, and whether or not any needed to be discarded. In the end, no test points were discarded, as shown in Figure 5.

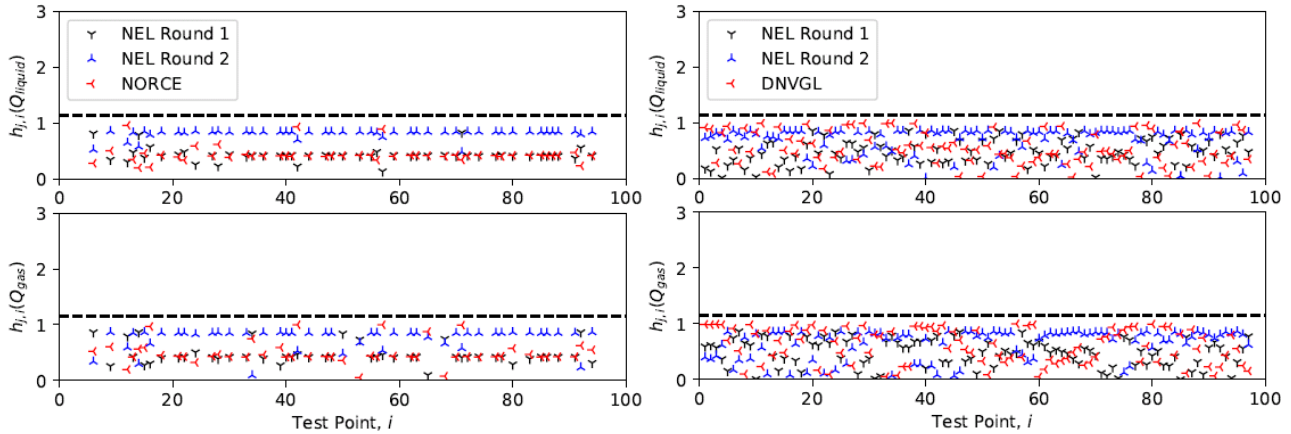


Figure 5: Values for Mandel's h statistic for the lower (left panel) and higher (right panel) intercomparison test points.

It must also be noted that there were differences in the uncertainty of the measurements made at each laboratory. This is important for analysis of comparisons between differences in the measured flow rates and the uncertainty of the measurements that were used to investigate metrological compatibility. The quoted uncertainties for each lab and whether or not they took into account phase transitions in their respective uncertainty budgets are shown in table 9.

Parameter	NEL/Lab. 1	NORCE/Lab. 2	DNV GL/Lab. 3
Phase transitions included?	No	Yes	Yes
$\bar{u}(Q_{\text{liquid}})$	0.40%	0.21%	0.75%
$\bar{u}(\text{WLR})$	0.18 abs-%	0.53 abs-%	1.24%*
$\bar{u}(\text{GVF})$	0.12 abs-%	0.38 abs-%	0.75%*

Table 9. Physical and statistical characteristics achieved at each facility; these values were taken from the in-house measurements of each facility. Uncertainties with an (*) indicate no direct calculation, but from a combination of single phase flow rate uncertainties.

The reproducibility uncertainty of the transfer package plus the facility was calculated using data from NEL rounds 1 and 2. The results of the expanded reproducibility uncertainty are shown in table 10 below.

Quantity measured, M	U_{repro} , low pressure	U_{repro} , high pressure
Total volume flow rate, Q_{total}	6.3%	9.8%
Gas volume flow rate, Q_{gas}	5.7%	8.7%
Liquid volume flow rate, Q_{liquid}	1.9%	2.5%
Water volume flow rate, Q_{water}	1.4%	1.6%
Oil volume flow rate, Q_{oil}	1.4%	2.0%
Gas volume fraction, GVF	2.1 abs-%	2.3 abs-%
Water liquid ratio, WLR	5.1 abs-%	4.0 abs-%

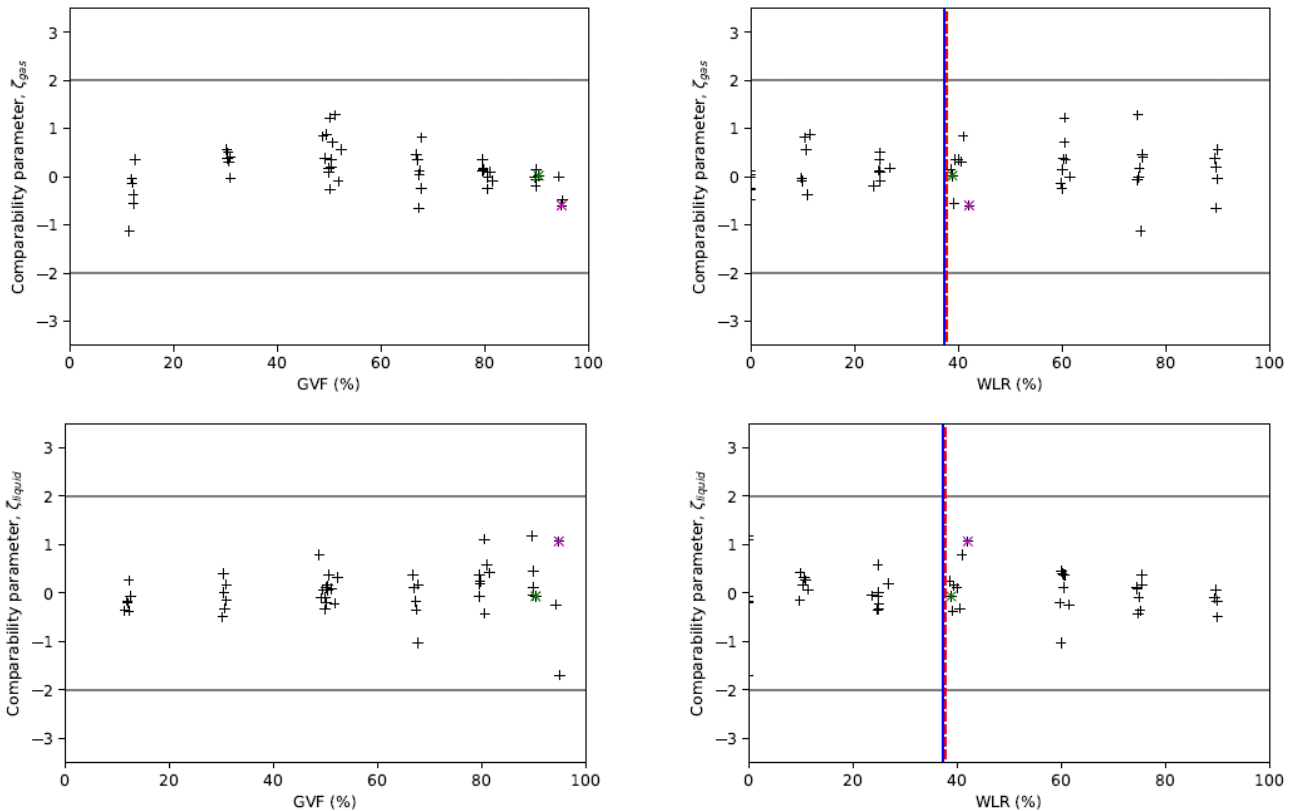
Table 10. Expanded reproducibility results.

In order to assess the reproducibility more thoroughly the same comparability parameter used in objective 3 above, ζ , and from the previous ENG58 MultiFlowMet project was used to compare flow conditions for each test point.

The results from using the ENG58 comparability parameter showed that the reproducibility of the transfer package (objective 1) was adequate for making direct comparisons between laboratories. Subsequently a set of conclusions was produced, summarising where good measurement agreement was obtained between laboratories.

A case-by-case summary was written on the intercomparison. The summary covers areas where good measurement agreement was not obtained, and details the analysis carried out that rationalised any measurement variances.

The results from the lower pressure reproducibility test, (both data sets were generated at NEL and at a pressure of 4.5 barg), are presented in Figure 6. It can be observed that metrological compatibility was achieved for all test points. The corresponding tests at higher pressure (9 barg) showed similar results. In particular, strong reproducibility was observed for almost all points, although there were two tests points for which this was not the case (close to the phase inversion point and shown as vertical lines in Figure 6).



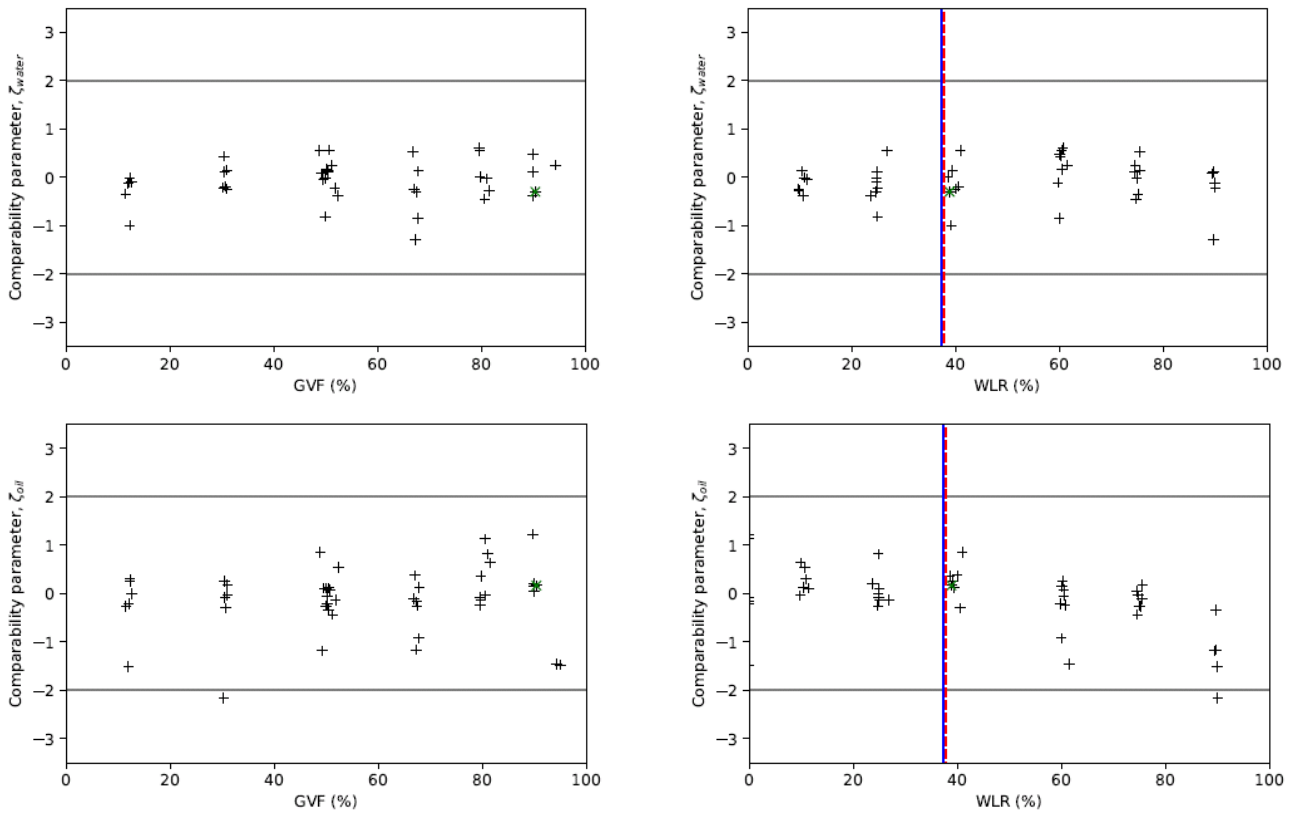
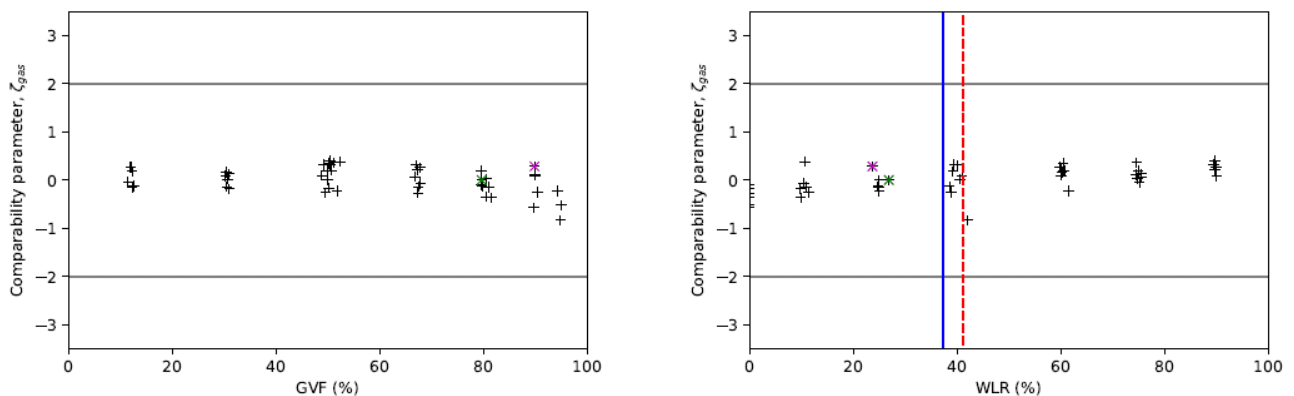


Figure 6: Comparability parameter values for the volumetric gas, total liquid, oil, and water flow rates in the NEL reproducibility tests.

The trends for the inter-laboratory compatibility were separated into lower pressure (Figure 7) and higher pressure (Figure 8) investigations. In both cases, the influence of GVF and WLR were observed to be of greater significance than for the reproducibility tests. In general, metrological compatibility was achieved for most test points. However, there were distinct regions in which the reproducibility was not as strong. An important observation across all of these cases was the challenge faced in taking measurements close to the phase transition point.



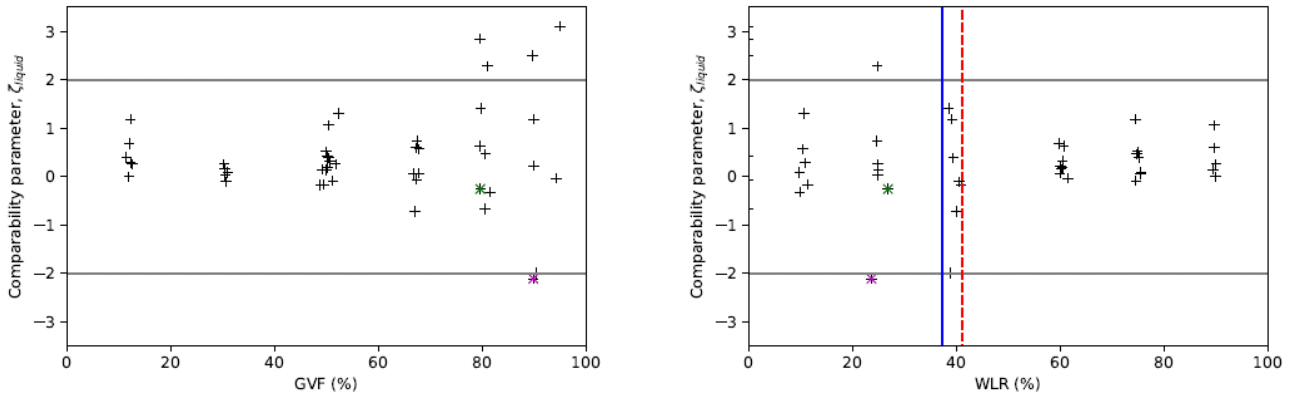


Figure 7: Comparability parameter values for the volumetric gas and liquid flow rates in the NEL vs. NORCE (lower pressure) comparability tests.

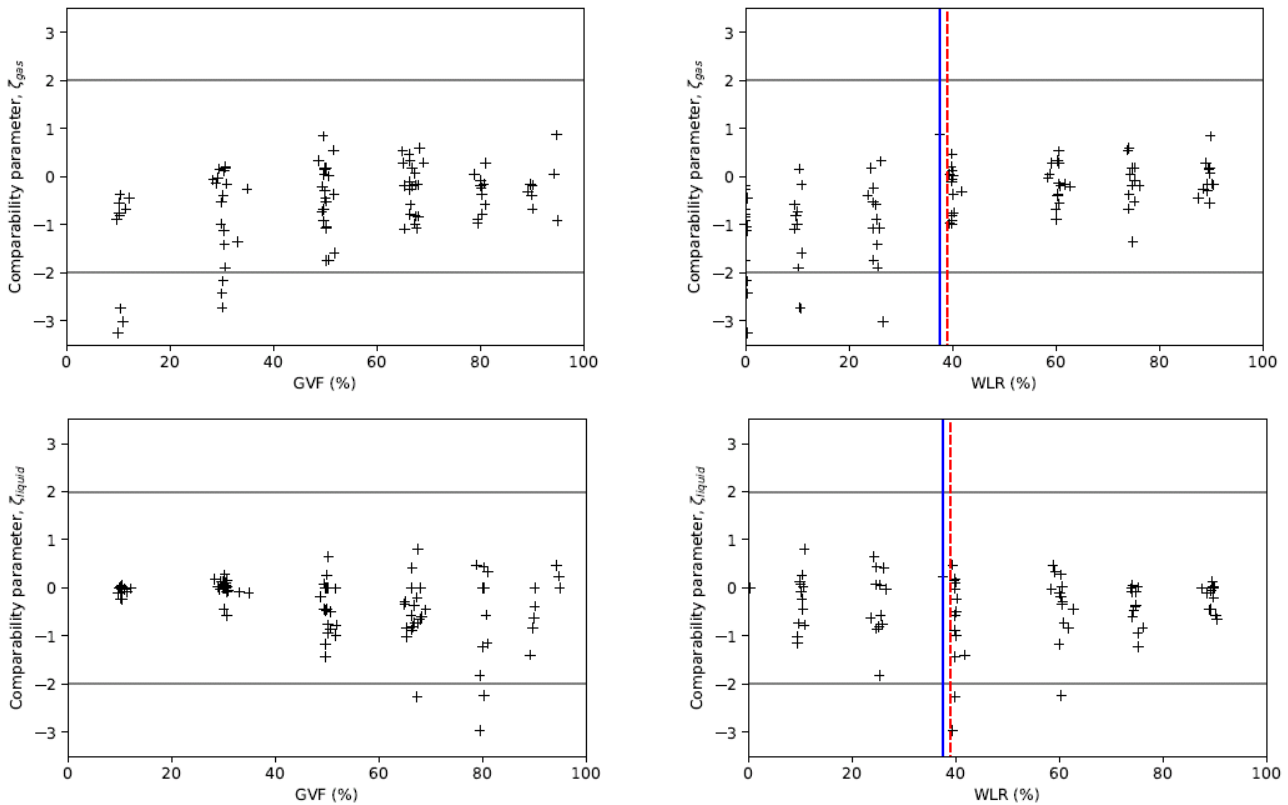


Figure 8: Comparability parameter values for the volumetric gas and liquid flow rates in the NEL vs. DNV GL (higher pressure) comparability tests.

Summary

The project has successfully made statistical cross-comparisons between the measurements undertaken in each intercomparison laboratory and established the comparability of measurement between test laboratories. The analysis compared findings, identified anomalies, deduced their method of investigation and stated the resolutions achieved.

The conclusions from the project's intercomparison were that very good measurement agreement was successfully obtained between laboratories across a range of MPFM technologies. Metrological comparability ($\zeta < 1$) was achieved for 94 % of all test points for gas volume flow and 87.5 % of all test points for liquid volume flow. In addition, the project also concluded that upstream geometrical variances, phase transitions and

pressure were identified as the most important influence parameters that need to be controlled in order to achieve good measurement comparability for future studies.

The overall goal of this project was to establish an enduring multiphase flow measurement capability to end users. The project has achieved this by creating an enlarged, comparable network of 3 multiphase flow measurement reference facilities with an enduring measurement capability (objectives 1-4). Partners NEL, DNV GL and NORCE can now provide oil and gas operators (the instrumentation end-users) and instrumentation developers with improved confidence in the testing and reference measurement infrastructure.

5 Impact

The project has produced 11 open-access peer reviewed publications with a further publication in submission. The project has also been presented as either a presentation or a poster, at 15 conferences e.g. the 9th World Congress in Industrial Process Tomography, the International Measurement Confederation (IMEKO) and the International Flow Measurement Conference (FLOMEKO).

Further to this, 5 internal training courses have been provided for the consortium on topics such as 'Multiphase laboratory appreciation' and 'Multiphase measurement familiarisation'. In addition, 2 international online workshops for Multiphase Flow Reference Metrology were hosted for end users in order to promote the dissemination of the project's results.

Finally, 2 good practice guides, 3 technical reports and a webinar on: Improving Multiphase Flow Metrology through Harmonisation have been produced and are now available for end users.

Impact on industrial and other user communities

The results of this project impact the oil and gas community a group that has become increasingly reliant on multiphase metrology. The project has done so by creating an enlarged, comparable network of 3 multiphase flow measurement reference facilities with an enduring measurement capability (objectives 1-4). Partners NEL, DNV GL and NORCE can now provide oil and gas operators (the instrumentation end-users) and instrumentation developers with improved confidence in the testing and reference measurement infrastructure. In turn, this leads to lower uncertainty of measurement and greater confidence in the deployment of multiphase metering technology.

Increased confidence and lower uncertainties of measurement associated with multiphase metering reduces both financial exposure and risk, as well as enabling better operational efficiency. This occurs at two levels;

1. Operational decision-making – multiphase flow measurement data are key to deciding if (at the assessment stage), when and how a field will be exploited, balancing capital investment against revenue potential at set-up, then optimising conditions when the well is in production.
2. Allocation (and fiscal) exposure – arising from uncertainty regarding how much of operators production is being commingled into common networked flowlines. There is also significant financial exposure related to uncertainty of measurement for the application of taxation.

The project engaged with industrial and end user communities through its end user advisory group, which included members from the UK Oil & Gas Authority, Apache and the Norwegian Petroleum Directorate. The end user advisory group provided advice and feedback to the project to help ensure its results remained relevant to end users. The end user advisory group also helped with the promotion and dissemination of the project's results.

The project also promoted itself and its results to the end user community via a webinar on: Improving Multiphase Flow Metrology through Harmonisation and through 6 press releases in Subsea UK News Archive, Scandinavian Oil. Gas Magazine, Diesel Gasoil News, World Oil Magazine, AWE International and Offshore Magazine.

Finally, NEL has already begun to exploit some of the findings of this project (e.g. the importance of phase transitions in flow loop uncertainty budgets) and applied it to their new Advanced Multiphase Facility (AMF) uncertainty budget. There have already been two multiphase factory acceptance tests carried out with this upgraded AMF uncertainty budget with end users being Saipem, Kuwait Oil Company and ExxonMobile.

Impact on the metrology and scientific communities

A key benefit from this project for the European flow metrology community is that it is the first step in establishing a long-term Key Comparisons programme for NMIs and other laboratories. Key elements such as harmonised uncertainty budgets, intercomparisons, auditing and accreditation, have existed for single phase flow metrology activity for decades, but not for multiphase flow metrology. The preceding ENG58 project made significant progress towards this but this project has expanded and improved on this work i.e. with a

metrological comparability of 94 % of all test points for gas volume flow and 87.5 % of all test points for liquid volume flow, for three different multiphase flow measurement reference facilities.

The project has produced 2 Good Practice Guides on: 1) the acquisition of experimental data for the determination of multiphase flow patterns and 2) minimising uncertainty of laboratory flow reference measurement. In addition, the project produced 3 technical reports on 1) Enduring Measurement Capability, 2) Small Scale experimental and 3) Full Scale experimental research. The Good Practice Guides and Technical Reports are available for end-users on the project webpage.

Further to this, the findings of the intercomparison analysis (objective 4) with regard to the importance of taking into account phase transitions has been exploited by NEL in the uncertainty budget of their new advanced multiphase facility.

Impact on relevant standards

The project has engaged and provided input to relevant standardisation bodies such as ISO TC28 (Petroleum and related products, fuels and lubricants from natural or synthetic sources), where partner NEL supported the publication of ISO/TS 21354 Multiphase Flow Measurement. The publication of the updated ISO/TS 21354 version 6 is now imminent and will represent the first ISO Technical Standard in this area for over 40 years of developments in the use of MPFMs.

In addition, the project has been presented at the EURAMET Technical Committee Flow annual meeting to over 60 delegates and at the Energy Institute HMC-1 (Hydrocarbon Management Committee) to members from oil and gas operators and service providers such as BP, Shell, Premier Oil and Emerson.

Longer-term economic, social and environmental impacts

In the longer term, the potential economic impact of reduced uncertainty of flow measurement is significant for both industry and government. In allocation and fiscal metering, certainty of measurement is an enabler of 'fair-trade' – which in turn underpins economic prosperity in Europe. It has been shown that the development of multiphase flow measurement over the last few decades has facilitated the exploitation of marginal oil and gas fields previously considered uneconomic to produce. As future field development becomes more technically and economically challenging, the ability to squeeze those additional few percentages out of the available resource will be paramount to energy resource efficiency.

Industries, hence, employment and economic prosperity, are dependent on an optimised energy mix, not only in terms of cost, but in terms of adequacy and continuity of supply. Measurement of production is key for better optimisation of Europe's energy supply.

Currently no other, more environmentally friendly, sources of energy are ready in sufficient volume to replace fossil fuels - nor will they be for decades to come. If we therefore accept our oil and gas dependency for the time being we must focus on what can be done to minimise its environmental impact. Reduced uncertainty of measurement of multiphase flow is one possible area that can support this, as it should lead to optimal operational decisions, hence more efficient resource exploitation, which in turn, should help to underpin environmental sustainability.

6 List of publications

- [1]. Qiang Wang, Xiaodong Jia, Mi Wang, Bubble Mapping: three-dimensional visualisation for gas-liquid flow regimes using electrical tomography, Measurement Science and Technology, Volume 30, Number 4, <https://doi.org/10.1088/1361-6501/ab06a9>
- [2]. Qiang Wang, Xiaodong Jia, Mi Wang, Fuzzy Logic Based Multi-Dimensional Image Fusion for Gas-Oil-Water Flows with Dual-Modality Electrical Tomography, IEEE Transactions on Instrumentation and Measurement, <http://eprints.whiterose.ac.uk/149072>
- [3]. Wang, Q., Wang, M, Thresholding Values and Fuzzy Logic Fusion in Visualisation of Gas-Oil-Water Horizontal Flow using Dual-Modality Electrical Tomography. Proceedings of 9th World Congress on Industrial Process Tomography. WC-IPT-9, 02-06 Sep 2018 <http://eprints.whiterose.ac.uk/140300/>

- [4]. M. Olbrich, E. Schmeyer, L. Riazzy, K. Oberleithner, M. Bär and S. Schmelter, Validation of simulations in multiphase flow metrology by comparison with experimental video observations, *Journal of Physics: Conference Series*, Volume 1065, Flow Measurement, <http://iopscience.iop.org/article/10.1088/1742-6596/1065/9/092015>
- [5]. Kun Li, Qiang Wang, Mi Wang, Three-dimensional visualisation of gas-water two-phase flow based on bubble mapping method and size projection algorithm, *Flow Measurement and Instrumentation*, Volume 69, October 2019, 101590, <https://doi.org/10.1016/j.flowmeasinst.2019.101590>
- [6]. Sonja Schmelter, M. Olbrich, E. Schmeyer, M. Bär, Numerical simulation, validation, and analysis of two-phase slug flow in large horizontal pipes, *Flow measurement and instrumentation*, Volume 73, June 2020, 101722, <https://doi.org/10.1016/j.flowmeasinst.2020.101722>
- [7]. M. Olbrich, E. Schmeyer, M. Bär, M. Sieber, K. Oberleithner, S. Schmelter, Identification of coherent structures in horizontal slug flow, *Flow Measurement and Instrumentation*, Volume 76, December 2020, 101814, <https://doi.org/10.1016/j.flowmeasinst.2020.101814>
- [8]. S. Schmelter, M. Olbrich, M. Bär, K. Oberleithner, Statistical characterization of horizontal slug flow using snapshot proper orthogonal decomposition, *International Journal of Multiphase Flow*, Volume 134, January 2021, 103453, <https://doi.org/10.1016/j.ijmultiphaseflow.2020.103453>
- [9]. L. Xiaolei, Liyun Lao, Gioia Falcome, A comprehensive assessment of correlations for two-phase flow through Venturi tubes, *Journal of Natural Gas Science and Engineering*, 78 (June) Article No. 103323, <https://doi.org/10.1016/j.jngse.2020.103323>
- [10]. S. Iacovides, M. Wang, Q. Wang, Bubble Mapping Method for Transient Taylor Bubble Flows, *Proceedings of 9th World Congress on Industrial Process Tomography*, March 2019, <http://eprints.whiterose.ac.uk/140303/>
- [11]. Schmelter, S, Knotek, S., Olbrich, M., Fiebach, A. and Baer, M., On the influence of inlet perturbations on slug dynamics in horizontal multiphase flow – a computational study, *Metrologia*, Volume 58 (1) January 2021, <https://iopscience.iop.org/article/10.1088/1681-7575/abd1c9>

7 Contact details

For more details, please contact Anna Pieper (NEL) at anna.pieper@tuvsud.com