Publishable Summary for 16ENG07 MultiFlowMet II
Multiphase flow reference metrology

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.

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.

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 m^3/hr for liquid and 3 to 300 m^3/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.

Progress beyond the state of the art

Reference infrastructure (Objectives 1, 2 and 4)

In the preceding EMRP project, ENG58 MultiFlowMet, a small reference network (of two laboratories) was established based on a single multiphase metering technology. This project expanded the reference network itself by one additional laboratory and used a different mode of MPFM from the previous project. The enduring measurement capability was achieved by completion of an uncertainty method protocol, which is a fundamental basis of harmonisation for intercomparison testing between labs. The uncertainty method protocol is publicly available on the project website (https://www.tuvsud.com/en-gb/industries/chemical-and-process/flow-measurement/research-and-development/multiflowmet---multiphase-flow-reference-metrology) in order to share best practice with industry. The project also incorporated a wider range of industry relevant flow conditions that were proven across a more representative range of field deployed MPFM technologies.

Flow Pattern Visualisation by Tomography (Objectives 1 and 2)

In the preceding ENG58 project, an experimental, multiphase visualisation and characterisation platform was developed with realistic and necessary spatial and temporal resolutions for multiphase flow metrology. This project migrated software implementations of the appropriate advancements from an offline to an online (real-time) platform. Also, in this project the tomography platform was deployed for the first time in live intercomparison testing, which greatly enhanced the experimental capability and direct comparison to the CFD modelling.

CFD Modelling (Objective 3)

Multiphase flow modelling using CFD is extremely challenging. In the preceding ENG58project, key advancements in techniques were made and a number of insightful simulations performed in both OpenFOAM and ANSYS Fluent software. Further advancements were made in this project, by the definition and application of more exact inflow (boundary) conditions, which had a big influence on the resulting flow pattern, and by direct comparison of test points with the aforementioned tomography data.

Data analysis & conclusions (Objective 4)

The proven methods from the preceding ENG58 project were adapted and extended to cope with the much greater number of test laboratory variants and metering technologies. The analysis in this project drew upon the theoretical background of multiphase flow in terms of dimensionless numbers.

Results

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.

Specification of the transfer package - This consisted of common instrumentation and other physical elements to be used alongside the MPFM. The transfer package included flow pattern observation sections and was supplemented with tomographic visualisation technology. Assembly of the bespoke transfer package to be used in this project was completed early in 2019. 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 also incorporated four types of state-of-the-art tomography sensors that, could be used to successfully provide measured evidence of multiphase flow phenomenon and hence in turn provide quantitative evidence of the test points of interest.

Test matrix and protocols - A test matrix defining the test points, in terms of laboratory flow conditions, for optimally selected permutations of test laboratories and MPFMs was developed for the transfer package. To ensure the intercomparison in objective 4 was as relevant as possible to end users, input from the project's end user advisory group was used. Following this input 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).

Logistics plan - The logistics plan was completed in early 2019 and included all necessary aspects for successfully setting up and managing the intercomparsion. The logistics plan included (i) the testing schedules, (ii) shipping details, order and responsibilities, (iii) details of customs requirements for shipping, and (iv) special licensing and/or certification requirements for shipping and the means of obtaining them.

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.

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 and the MPFM) from the NEL facility were obtained under identical conditions, at the start and end of the test programme. The data was used to rule-out (or detect) drift in any of the instrumentation (including the transfer package form objective 1). 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 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.

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.

Full-scale experimental research - was carried out at NEL and DNV GL to assist with intercomparison data rationalisation and to provide additional verification data for the project's modelling processes. At NEL, the influence of upstream geometrical variances on developing flow patterns was studied and the measurements were completed by varying the upstream gas injection point and position. The most notable new results were that test points with low Water-in-Liquid ration (WLR) and low Gas Volume Fraction (GVF) at gas injections points 300 D and 600 D upstream of the transfer package (objective 1) exhibited reduced reproducibility compared to test points with higher WLR and GVF and closer injection point locations. In addition, the transfer package (objective 1) reproducibility generally decreased with increased mixing distance (gas injection point). Further analysis also provided useful insight on the equations of state (EOS) currently used to correct for phase transitions in flow loops. In general, EOS assume that phase equilibrium has occurred and thus they can be used to correct for differences between the MPFM and reference flow meters. However, if this phase equilibrium has not occurred, then the use of an EOS could produce inaccurate results.

Through the use of the closed DNV GL multiphase loop, it was possible to investigate the effects of changing the type and pressure of the gas phase. Four gas phase cases were considered: (i) Nitrogen at 8 barg; (ii) Argon at 15 (iii) Argon at 30 barg; and (iv) natural gas at 30 barg. To investigate the influence of pressure, the 8 barg Nitrogen, and 15 and 30 barg Argon configurations were compared. Variations in the measured flow rates detected were relatively small. But they were noticeably higher for the volumetric gas flow rate, though this decreased for higher GVFs. The reproducibility was strong for both gas flow rates and liquid flow rates. although this reproducibility in measurements was diminished for 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, and the trends observed were relatively small and similar to those of pressure. However, there was a noticeable difference in the formation of bubbles and slugs (i.e. types of flow pattern).

Inter-laboratory analysis - An analysis of the intercomparison (objective 4) measurement differences was carried out, including the geometrical variances. 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).

Small-scale modelling - small-scale experimental modelling was performed in order to better quantify the key measurement influence factors in the intercomparison. Void fractions were directly measured in a small scale set up using a wire mesh sensor directly upstream of the Venturi. The results showed that the existence of the

Venturi to predict upward flow regimes at the entrance and throat of the Venturi section should be taken into consideration in existing typical vertical upward gas-liquid flow regime maps, irrespective of the distance between the Venturi and the blind tee. The small-scale modelling also provided helpful insight into the flow structures and their transitions in horizontal and vertical sections in a multiphase flow loop.

Tomographic sensors – the tomographic sensors in the intercomparison (objective 4) and full-scale testing were used to evaluate flow patterns in the horizontal direction. Based on the experimental and numerical studies performed in two 2” flow loops with a variety of geometries and configurations, (i.e. different horizontal entrance lengths (100 D, 290 D, and 660 D), different gas injector designs, and different upstream geometries (with or without horizontal 90° bend), the project was able to conclude that the entrance length has a significant influence on the horizontal flow pattern. In addition, the flow could not be fully established in the horizontal section with an entrance length up to 290 D; however the impact of the gas injection design can be significantly mitigated by a blind tee; Further to this, the horizontal 90°D bend had less influence on the downstream flow pattern for low fluid mixture velocities than that of high mixture velocities; i.e. an increase of gas and liquid velocity where a transition to annular flow was present.

CFD simulations - The project’s CFD modelling agreed with these tomographic sensors results and the correct flow regime was predicted in the horizontal section. However, the flow regime predicted via CFD modelling did not match experimental results in the vertical section. It was also concluded that additional experimental and numerical tests for gas and liquid superficial velocities would be necessary to fully determine the effects of the geometry, mixing and scale on the two-phase flow development in both the horizontal, vertical, and contract sections. The project’s CFD simulations were validated against small-scale and full-scale experimental data, thereby, supporting data rationalisation in the intercomparison. The CFD simulations perfomed by PTB and CMI demonstrated that multiphase flow patterns are not fully developed until the mixing point is at 600D. Good comparibility between experimental observations and CFD simulations were shown between flow pattern development in the horizonatal and vertical sections of the small scale flow loop. However further work is needed for detailed CFD comparisons with the project’s tomography data.

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 and a full analysis of the meausrement data obtained has been undertaken. This analysis was done in order to compare findings, identify anomalies and investigate them and finally deduce their method of resolution. The first step in the analysis was to assess the reproducibility of the transfer package (objective 1) using the same methods developed in the previous ENG58 project.

The results were very positive and showed that with the except of two test points which were at the transition point from oil continuous to water continuous, the transfer package was well within the prescribed range of the comparability parameter (ζ): $0 < |\zeta| \leq 2$.

Once the transfer package (objective 1) was shown to be sufficiently reproducible for the intercomparison, the data from the intercomparison was then assessed for its comparability.

There were differences in the uncertainty of the measurements made at each laboratory making a direct comparison challenging, especially as the uncertainty of the measurements is used to investigate metrological compatibility. One of the key differences was whether or not phase transitions were included in the uncertainty budgets. Another difference was that WLR and GVF were not directly calculated directly in some cases but calculated from the single-phase flow rate uncertainties. The comparability parameter used in the preceding ENG58 MultiFlowMet project was used for the analysis in this project. The same comparability parameter that was used to determine the reproducibility of the transfer package was also used to investigate the comparability between the test campaigns undertaken at the different laboratories.

Intercomparison conclusions – 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.

The results of the full-scale, small-scale and modelling experiments conducted in objective 3 helped with the project’s understanding of the reason for any outliers in the intercomparison results i.e. where metrological comparability was not achieved (e.g. low GVF points). Such outliers/topics 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).

From the intercomparison results 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. This is important information for other users and a case-by-case summary of the intercomparsion has been produced by the project. The summary covers any areas where good measurement agreement was not obtained, and the analysis carried out to rationalise any measurement variances. This summary is available for end users on the project's website.

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 the 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.

List of publications

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This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	01 June 2017, 36 months	
Coordinator: Anna Pieper, NEL Tel: +44 1355 593818 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: -		