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## Final Publishable JRP Summary Report for ENG58 'MultiFlowMet' Multiphase Flow Metrology in the Oil and Gas Production

### Overview

The world will be dependent for many decades to come on the production of oil and gas for its underpinning energy needs. Currently, well 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 \$3,000 bn per year for oil and \$500 bn for gas. 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 on 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 combining into shared pipelines leading to the nearest processing facility. Measuring the flow rate of each component is an underpinning metrology requirement that is key to operational resource efficiency, as well as prerequisite for custodial and fiscal measurement.

This project established and implemented methods for measurement harmonisation between multiphase flow laboratories, to enable multiphase flowmeters to be more reliably verified, enabling developers to advance the state-of-the art in flow measurement.

### Need for the project

Typical multiphase flow measurement systems can have an uncertainty on component flow rate of 20 % or greater under field conditions. These figures are cause for concern by themselves but the implication for financial exposure is staggering in the context of the global production values. Despite this, the industry has struggled to improve upon these levels of uncertainty. Part of this is due to the intrinsic complexity of the fluids but another contributing factor is the lack of a proven traceable reference network for independent evaluation of multiphase meters themselves. In order to improve measurements under field conditions, there is first a need for reliable supporting reference measurements.

This is in stark contrast to *single-phase* flow metrology, where there is a well-established metrology reference network with mutually supporting programmes of inter-comparison, harmonisation of test methods and uncertainty quantification. Thus, one of the project objectives was to develop a metrological reference network for multiphase flow measurement. Prior to this project no such network, norms or standards existed for multiphase flow metrology. This project advanced the state-of-the art in multiphase referencing by undertaking the world's first comprehensive inter-comparison study on multiphase flow measurement, the basis of a sustainable reference network.

Any reference network relies on comparability of measurements across different facilities within the network. Fundamental to being able to make such comparisons is the determination of uncertainty of measurement in a consistent way. The project therefore looked at ways of improving methodology for the calculation of uncertainty budgets for multiphase measurements. Multiphase flow patterns are one of the most indeterminate aspects of multiphase flow metrology, therefore it was important to improve upon previous methods for determining flow patterns, both experimentally, using flow visualisation technology and numerically, using computational fluid dynamics (CFD) modelling.

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**Report Status: PU** Public

## Scientific and technical objectives

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 patterns* (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

## Results

### **Objective 1: Developing a metrological reference network**

The objective was achieved by developing underpinning protocols and methodology and harmonisation between multiphase flow laboratories.

#### *Methods developed*

A transfer standard was developed and successfully deployed, incorporating a single MPFM (multiphase flow metering), standard upstream straight pipe length and optical section for observation of flow pattern. A standard testing protocol was also established.

A set of principles was established enabling uncertainty budgets from different facilities to be reviewed for comparability and for use in intercomparison data analysis. A data comparison methodology was also developed that combines facility and transfer standard uncertainties in a way that allows facilities to be compared against one another without explicit reference to the performance of any flowmeters deployed in the transfer package. Objective success criteria were proposed for intercomparison validation.

#### *Harmonisation achieved*

Based on the work carried out, a successful intercomparison was performed between NEL and DNV-GL, across a wide-range of the three parameters oil, water and gas flow rates.

In the liquid comparisons, liquid monophasic flow conditions exhibited the highest level of interlaboratory measurement variance. These variances were not worryingly high but they were significant. The important lesson learned is that, in future tests (in the project MultiFlowMet II), the differential pressure device (creates a constriction within the pipe - such as Venturi, cone) built into the MPFM should be utilised in 'stand-alone' single-phase mode, rather than rely on the MPFM as a system to undertake accurate single-phase measurements.

MPFM should be coupled with a single phase meter (such as a full-bore ultrasonic meter) to provide better insight into this anomaly.

Also borne out in the intercomparison is the desire to match line pressure between facilities, together with any other factors that may affect flow pattern/regime, such as the injection point location relative to the test location.

#### *Recommendations*

. It is recommended that, to cover a wide range of conditions, MPFMs are deployed that have characteristics that are complementary to one another. Combining mass-flow and volumetric flowmeters, for example, could extend the range of gas volume fractions over which a high level of harmonisation may be achieved between laboratories. MPFMs of different sizes (pipe diameters) should also be considered, to extend the range of flow conditions as widely as possible, smaller MPFMs being more suited to accurate measurements at lower flow rates. Finally, the rolling-out of the intercomparison testing method to an increasing number of participating multiphase flow laboratories will lend greater confidence to its robustness and relevance.

#### **Objective 2: Improving on theoretical and experimental determination of flow patterns**

The objective was achieved with regard to both contribution to theory and the expansion of flow pattern map data. This was aided by the successful deployment of optical (Objective 1) and electrical tomographic (Objective 4) methods of flow pattern experimental observation.

A number of well-established flow-pattern maps from the open literature were compared against the experimental observations at industry-scale for water, oil and gas multiphase flow. The predictive accuracy of the flow pattern maps tested was generally good. In some cases, predictive accuracy was greater than 80 %.

In facility testing at NEL, the influences of water-liquid ratio, oil viscosity and upstream straight length were all investigated. It was found that when the liquid phase was changed from oil to water, the only significant change observed was for the transition between annular flow (with a liquid film on the pipe wall, and gas flowing in the core) and slug flow (where the gas phase exists as large bubbles separated by liquid 'slugs'), which occurred at higher gas velocities as water-liquid ratio was increased. Change in liquid viscosity over the range 8 to 16 cP did not have a noticeable influence on any of the flow pattern transitions. The length of the upstream straight length was found to have an influence on slugging, the proportion of which increased with the former, as did the average slug length. Flow pattern maps generated for testing at NEL and DNV GL were almost identical with regard to the predominant flow pattern (bubble, slug etc.).

#### **Objective 3: Improving the numerical modelling of multiphase flow in pipes and Venturi tubes**

The objective was achieved by developing CFD methods for multiphase flow in horizontal pipes and vertical Venturi tubes, validated in both cases by experimental observation.

##### *Flow in horizontal pipes*

CFD models were developed that allowed close comparison of predicted flow patterns between simulation and experimental results. The CFD models were validated by comparison with test cases both from the open literature and from experimental observation, using both transparent sight tube and electrical capacitance tomography. The results showed a good qualitative agreement. The structure of the slugs were particularly well matched between experiment and simulation, including slug length.

##### *Flow in a vertical Venturi tube*

In order to investigate the influence of several operational parameters on Venturi pressure drop, the whole transfer package geometry was modelled for CFD simulation. The corresponding CFD models gave useful insight into parametric influences that cannot be easily varied in isolation in experiments. For comparison with experimental data from the intercomparison, the pressure difference over the Venturi was calculated from the

simulation results, good agreement being obtained in terms of mean values. This was achieved using two independent CFD platforms, OpenFoam and Fluent. 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 also made in the intercomparison testing and experimental flow pattern observations.

#### **Objective 4: Evaluating and improving experimental methods of flow visualisation**

The objective was achieved for the two types of electrical tomography system that were explored in the work – dual-modality (combining electrical resistance tomography (ERT) with electrical capacitance tomography (ECT)) and high-speed single-modality (based on ECT alone). Complimentary optical methods that were deployed in pursuit of Objective 1 were also used for correlation with the tomographic methods.

Each of the electrical tomographic systems deployed has strengths and weaknesses for different areas of application. Two significant findings 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 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 used was that the raw data acquired from the existing sensor arrays is very rich in information. Whilst considerable advances were made in the course of the work in the interpretation of sensor outputs from both types of system, there would appear to be significant potential for further developments in data processing before the limits of the existing hardware systems are reached.

#### **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.

## List of Publications

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](http://www.tuvnel.com/EMRP1/emrp1_project_home)
10. Andre Fiebach, Sonja Schmelter, Ellen Schmeyer, Stanislav Knotec, Good Practice Guide, Numerical modelling of multiphase flow, JRP website [http://www.tuvnel.com/EMRP1/emrp1\\_project\\_home](http://www.tuvnel.com/EMRP1/emrp1_project_home)
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](http://www.tuvnel.com/EMRP1/emrp1_project_home)

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