

Results from an intercomparison between multiphase flow test facilities

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Abstract

Multiphase flow meters are measurement instruments that simultaneously measure the flow rates of oil, natural gas and water flowing through a pipe line. Their traceability and the comparability of test results stemming from different multiphase test facilities is much less well established than that of single phase flow meters and single phase calibration facilities. In the (first) EMRP MultiFlowMet project an intercomparison for multiphase test facilities was organised to investigate the comparability of multiphase flow test facilities. Three facilities participated: NEL, DNV GL and OneSubsea-Schlumberger (OSS). VSL acted as independent partner auditing the uncertainty budgets, witnessing the tests and analysing the data. The outcome of this analysis was pairwise consistencies in the order of 80 %, taking into account the claimed uncertainties of the test facilities and the estimated meter reproducibility. This value was also found for the comparison with OSS, where a different inlet geometry was used. Open access to data and more extensive testing could provide means to get a better understanding of the reasons behind the inconsistency of a small part of the points.

1. Introduction

The traceability of single-phase flow meters is well managed by means of accredited calibration facilities performing calibrations for clients, with quality assured by means of audits on test methods and uncertainty quantification, and supplemented by the organisation of intercomparisons between the facilities. This is not the case for multiphase flow meters and multiphase test facilities.

To improve this situation an intercomparison for multiphase test facilities was organised as part of (the first) EMRP project MultiFlowMet [1]. Three facilities participated: NEL, DNV GL and OneSubsea (OSS), a Schlumberger Company. VSL acted as independent partner during the tests, arranging the tests and test protocol in close collaboration with the partners, auditing the uncertainty budgets, witnessing the tests and analysing the data.

In the next section the test protocol will be shortly presented. The paper will then focus on the analysis method and the test results. As the complete set of comparison partners could not agree on a common publication of the results, this paper is mainly based

on the project's Final Publishable JRP Report with Associated Annex [2].

2. Test protocol

In an earlier paper [3] at Flomeko 2016 the test protocol including flow meter package and test matrix was extensively presented. In this paper only the main points of interest will be repeated.

2.1 Test protocol

The test protocol defined the flow meter package (see section 2.2), the procedure of installation and configuration, and the test points (flow rates) to be used (see section 2.3). The finally performed test schedule was as indicated in Table 1 with test rounds subsequently at NEL, DNV GL, NEL and OneSubsea (owner of the meter, for practical reasons placed at the end of the schedule).

Table 1: Performed test schedule.

Test round	Test period
NEL Round 1	27 July 2015 – 7 August 2015
DNV GL	13 July 2016 – 19 July 2016
NEL Round 2	29 August 2016 – 12 September 2016
OneSubsea	22 November 2016 – 12 December 2016

The test protocol specified pressures and temperatures to be used in order to get flow conditions as similar as possible, see [3] for a more detailed discussion. However, due to the design of the facilities, differences remained, as illustrated by Table 2. The large range in water density at NEL is due to a different salinity in NEL Round 1 and NEL Round 2. In NEL's open loop design the nitrogen gas is vented at the separator. DNV GL tested at a higher temperature than initially specified for reasons of available testing time.

Table 2: Some characteristics per facility with a focus on the differences. 'Dist of mix' denotes the distance of the mixing point of the pure fluids upstream of the flow meter, '*U*' the expanded relative uncertainty, '*q*-single-phase' the single phase flow rates (oil, water, gas), and 'o&w' means 'oil & water'.

Characteristic	NEL	DNV GL	OneSubsea
Pressure at MUT / barg	2.1 to 9.5	7.3 to 8.3	15.9 to 17.1
Temperature at MUT / °C	38 to 45	19 to 21	11 to 17
Oil viscosity / cP	7.5 to 9.1	4.6 to 5.0	1.7 to 1.9
Water density / kg/m ³	1015 to 1029	1029 to 1030	999 to 1000
Flow loop design	Open loop	Closed loop	Closed loop
Dist. of mix / m	11	20	3
<i>U</i> (<i>q</i> -single-phase)	< 0.9 %	< 1.0 %	o&w: 1.5 % gas: 5 %
<i>U</i> (WLR)	< 0.23 %	< 0.17 %	< 0.6 %
<i>U</i> (GVF)	< 0.14 %	< 0.24 %	< 1.3 %

2.2 Flow meter package

The multiphase flow meter to be tested by each of the laboratories (MUT, Meter Under Test) was a Schlumberger PhaseTester Vx52. The meter has a pipe diameter of 4" and is based on Venturi tube with throat diameter is 52 mm. Pressure, temperature, differential pressure and gamma-ray attenuation measurements allow for determination of the oil, water and gas flow rates separately.

In order to make the flow conditions as similar as possible, it was agreed to install a 10 meter (100 D) straight inlet pipe section followed by a transparent pipe section to be used for flow regime recording by a video camera, and finally a 90° elbow connected to the inlet of the flow meter. This configuration was used at both DNV GL and NEL. At the Horsøy test facility of OneSubsea this turned out not to be possible for practical reasons and a different inlet configuration was used, which is the standard way of testing flow meters at OneSubsea. A picture of the flow meter while being tested at OneSubsea's test facility is shown in Figure 1.

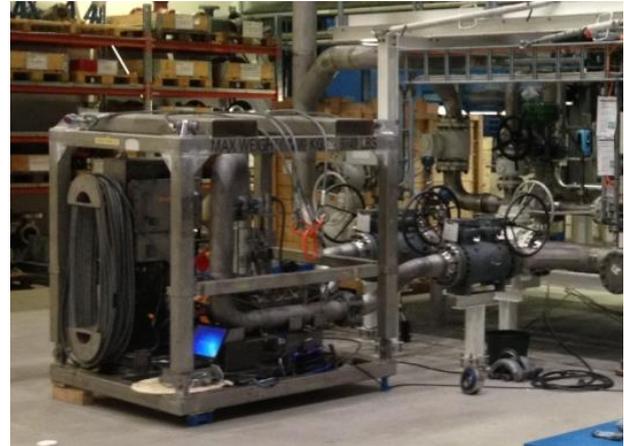


Figure 2: Vx multiphase flow meter being tested at OneSubsea's test facility Horsøy.

2.3 Test matrix

It was agreed to perform both single and multiphase test points. The agreed multiphase test points ranged from liquid flow rates 9 to 90 m³/h, gas volume fractions (GVF) 25 to 96 % and water liquid ratios (WLR) 0 to 100 %. More details can be found in Table 3. Due to a limited amount of available testing time at DNV GL no tests were performed at WLR = 70 % at this facility. At both NEL and OneSubsea additional tests were carried out in order to analyse specific research questions, which are not presented in this short paper.

Table 3: Test matrix for multiphase points defining liquid flow rates and gas volume fractions to be tested, together with the following water cut specification: test points marked 'O' were to be carried out at water liquid ratios 0%, 25%, 45%, 70%, 90% and 100%; test points marked 'X' were to be carried out at 25%, 45%, 70% and 90% water liquid ratios.

Liquid Flow m ³ /h	Gas Volume Fraction / %					
	25	55	70	84	92	96
9					X	O
18				X	O	X
35		O	X	O	X	
50	O	X	O	X		
70	X	O	X			
90	O					

3. Analysis method

3.1 Validation of measurement points

The flow meter was installed and configured by an operator of OneSubsea. VSL witnessed all tests. After the data had been collected various sanity checks were performed. This included following checks: correspondence of measured time period by MUT and facility, differential pressure in throat of Venturi of MUT above 50 mbar, physical conservation laws in the reported data, correspondence of measured density with theoretical density, consistency of the noise levels

and standard deviations in the data, correspondence of actual flow rates, WLR and GVF with the nominal values prescribed by the test protocol. Points not respecting the quality criteria were removed.

Data from NEL was reprocessed by the flow meter manufacturer in order to compensate for changing fluid properties (due to the open loop design) that could have affected the flow meter performance. This resulted in only small changes.

3.2 Consistency assessment

An important goal of the comparisons is to assess if the claimed uncertainties by the test facilities can be validated or not. The measurand is the absolute or relative deviation d of the MUT for various multiphase quantities like water oil and gas volume flow rates, total mass flow rate, GVF (Gas Volume Fraction) and WLR (Water Liquid Ratio).

For example, let d be the relative deviation of the average MUT oil flow rate q_{MUT} with respect to the average reference oil flow rate q_{ref} provided by the test facility recorded during a test point, i.e. $d = (q_{MUT} - q_{ref}) / q_{ref}$. If the testing time was long enough the recorded average q_{MUT} has very small uncertainty, as the natural variability of the flow rate will be averaged out.

In the case of relative small deviations between MUT and test facility, it can be verified that $u(d) \approx u^*(q_{ref})$, where $u^*(q_{ref})$ denotes the relative standard uncertainty of the reference flow rate provided by the test facility. For each facility k , and for each test point i and for each quantity of interest j a deviation d_{ij}^k with uncertainty $u(d_{ij}^k)$ can be calculated. The results of two facilities A and B are consistent if

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

The term $u(r_j^{MUT})$ denotes the reproducibility uncertainty of the MUT for quantity j , which is assumed to be independent of the actual test point i (e.g. the overall reproducibility of the MUT for measured oil flow rates, as a number independent of the actual flow rate). Note that a dependence on GVF was observed (see **Fout! Verwijzingsbron niet gevonden.**4), but in the overall consistency calculations the overall value has been used. The reproducibility uncertainty accounts for the fact that the MUT itself produces slightly different measurement results, when a measurement is

repeated under the same measurement conditions. It is present at both facilities A and B , which is the reason for the factor 2 before $u^2(r_j^{MUT})$ in equation (1).

This uncertainty contribution has been assessed by analysing the data measured at NEL in two different rounds of measurement, which were separated by approximately one year in time. The fact that the MUT may produce different results in different operating conditions (see Table 2 for the differences) is not accounted for in this consistency assessment, as it is difficult to quantify.

Thus, if results are inconsistent, either an uncertainty provided by (at least) one test facility is too low, or the flow meter has a higher reproducibility uncertainty between different facilities than the calculated value $u(r_j^{MUT})$.

Also note that it is impossible to thoroughly validate facility uncertainties $u(d_{ij}^k)$ which are smaller than $u(r_j^{MUT})$, as in that case potential inconsistencies are obfuscated by the flow meter reproducibility. It is therefore important that the flow meter reproducibility is as low as possible, and a priori assuming a high value for $u(r_j^{MUT})$ makes the comparison a priori of little significance. The factor 2 before the square root in equation (1) is linked to the fact that the target is 'consistency with a 95 % coverage probability (assuming a normal distribution for the uncertainties)'.

Multiphase flow patterns have a natural variability. Flow rates of oil, water and gas fluctuate over time. The reported mean values measured over a sufficient long time have been compared in this analysis. The standard deviation of the flow rates is seen as irrelevant as long as the averaging time is long enough, or, alternatively, if its effect on the uncertainty is incorporated in the uncertainty statements by the test facilities. If one would include these standard deviations in the analysis, a facility can claim any uncertainty and get consistent results as long as the natural variability in time of the multiphase flow pattern is high¹.

1.4 Flow meter reproducibility

In this section the results for the flow meter reproducibility $u(r_j^{MUT})$ are presented. This has been done by comparing the results of 56 multiphase test points measured at NEL in August

¹ This approach was followed in an alternative analysis not presented in this paper.

2015 and September 2016. The batch of single phase test points was not used in this analysis, nor some points with questionable quality (low dP values or timing error). The expanded reproducibility uncertainties U_{repro} , where $U_{repro} = 2\sqrt{2} u(r_j^{MUT})$, are presented in Table 4 split out to GVF range. These values are both affected both by flow meter and test facility reproducibility. The factor $2\sqrt{2}$ has been included in order to present an expanded uncertainty (factor 2) covering the uncertainty of both measurement rounds (factor $\sqrt{2}$).

Table 4: Results of the reproducibility analysis, split out for different GVFs. The value U_{repro} corresponds to $2\sqrt{2} u(r_j^{MUT})$ in Equation (1).

Quantity	U_{repro} (all GVFs)	U_{repro} (GVF ≤ 90 %)	U_{repro} (GVF = 92 %)	U_{repro} (GVF = 96 %)
Total mass flow rate, $q_{m, total}$	2.2 %	2.0 %	2.3 %	3.5 %
Total volume flow rate, q_{total}	2.2 %	2.1 %	2.1 %	3.0 %
Gas volume flow rate, q_{gas}	3.2 %	3.3 %	2.1 %	2.9 %
Liquid volume flow rate, q_{liquid}	2.4 %	2.0 %	2.4 %	4.2 %
Water liquid ratio, WLR	1.9 %-abs	1.2 %-abs	1.6 %-abs	4.4 %-abs
Gas volume fraction, GVF	0.7 %-abs	0.8 %-abs	0.2 %-abs	0.2 %-abs
Oil volume flow rate ² , q_{oil}	5.6 %	4.3 %	8.7 %	8.5 %
Water volume flow rate, q_{water}	3.4 %	3.0 %	3.0 %	5.7 %

4. Pairwise comparisons

In this paper the results of NEL and DNV GL, and the results of DNV GL and OneSubsea are pairwise compared. NEL does not wish its results to be compared with OSS for reasons of the different inlet geometry used at OSS. NEL and DNV GL claim a similarly low uncertainty whereas OneSubsea claims a higher uncertainty. DNV GL and OneSubsea have tested at different operating pressure. These two facilities represent the extremes regarding the location of the mixing point of the three phase points with DNV GL having a mixing point far upstream and OneSubsea relatively close to the MUT.

4.1 Measurement results

As a first step an overview of some of the main measurement results is given. Figure 3 shows the measured MUT deviations for gas volume flow rate (relative deviation in %) and Figure 4 for Water

Liquid Ratio (WLR, absolute deviation in %). The results for 100 % gas have been excluded from the plots and analysis.

Although the specifications regarding absolute accuracy of the manufacturer are strictly speaking not relevant in a comparison context, they have nevertheless been included, as it is still interesting to see how they compare with the results of the test facilities, and it can serve as a quality check of the MUT. It is seen that most points for WLR fall within specifications. For gas volume flow rate more points fall outside. For high GVF measurements at NEL this is not a complete surprise due to the low operating pressure at these points. It is not surprising that the MUT deviations as measured at OneSubsea's multiphase facility all lie within specifications, as OneSubsea is the manufacturer of the MUT. At high GVFs the various test results for the gas volume rate start to differ. This is probably due to the difference in operating pressure at the test facilities. Note that it is known that the meter uncertainty specification increases at lower pressure for high GVF.

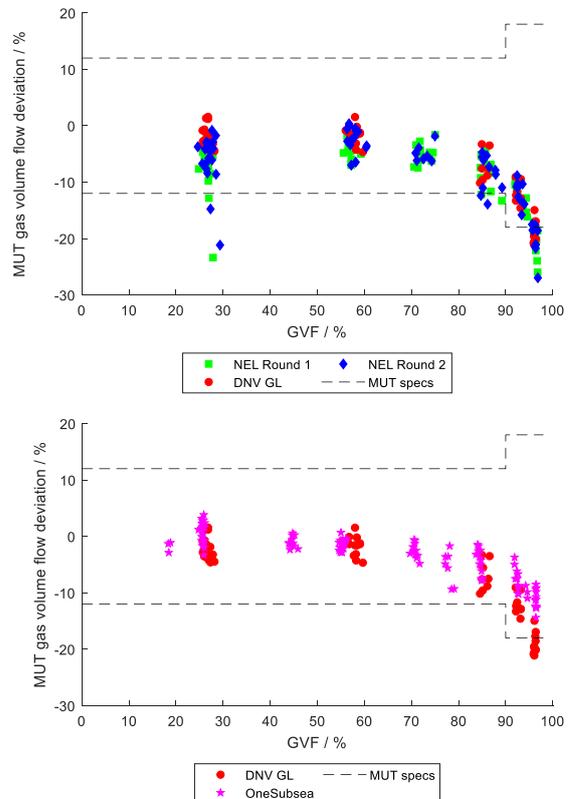


Figure 3: Pairwise comparison of measurement results for MUT relative gas volume flow deviation as function of GVF. Top: NEL and DNV GL. Bottom: DNV GL and OneSubsea.

² One value with a difference of 36 % in measured flow meter oil volume flow rate deviation between the two test rounds was removed in this calculation.

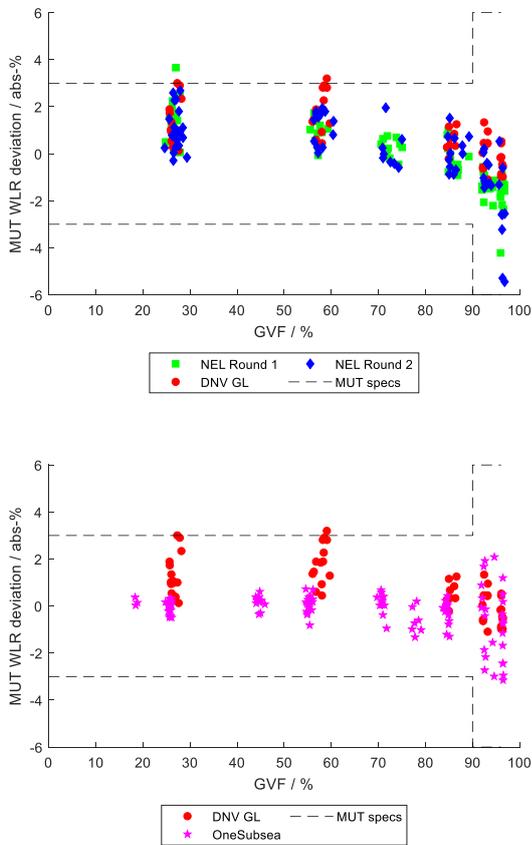


Figure 4: Pairwise comparison of measurement results for MUT WLR deviation as function of GVF. Top: NEL and DNV GL. Bottom: DNV GL and OneSubsea.

4.2 Point-wise comparison

As a next step the test points have been compared point-wise, after checking that the actual flow rates corresponded sufficiently (and not only the nominal values). Some points were removed for this reason. It was observed that for WLR = 0 % the water volume flow rate reported by the MUT became sometimes slightly negative (down to $-0.3 \text{ m}^3/\text{h}$), and for WLR = 100 % the oil flow reading became sometimes negative (down to about $-3 \text{ m}^3/\text{h}$), together with an indicated WLR of almost 104 %. This deviation is possibly related to inconsistency between fluid properties as measured during the MUT setup vs. fluids properties during actual flow testing.

The results for the test points at a total liquid flow rate $q_{\text{liquid}} = 90 \text{ m}^3/\text{h}$ and GVF = 25 % for various WLRs are shown in Figure 4 for MUT gas volume flow deviation and in Figure 5 for MUT WLR deviation. This is an interesting set of points as it contains some of the highest deviations between the facilities. The error bars indicate the expanded

uncertainty reported by the test facilities. In order to judge consistency of the results the meter reproducibility (as estimated in Table 3) has to be included as well, and equation (1) has to be applied.

For gas volume flow rate ($U_{\text{repro}}(q_{\text{gas}}) = 3.3 \%$) the results of NEL and DNV GL are consistent for high WLRs, but inconsistent for low WLRs, especially for an oil-gas mixture. The results of DNV GL and OSS are consistent.

For WLR the results of NEL and DNV GL are consistent for this set of points (as $U_{\text{repro}}(\text{WLR}) = 1.2 \%$), whereas this is not the case for DNV GL and OSS.

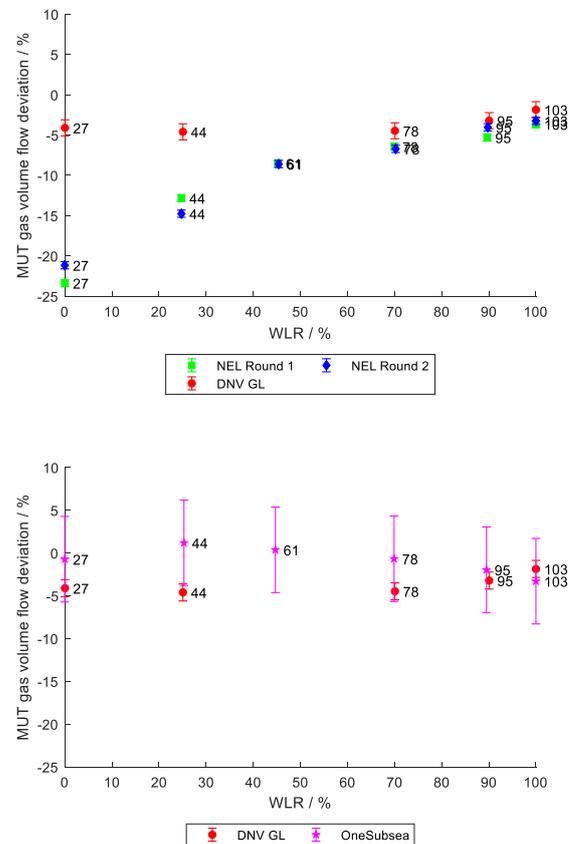


Figure 4: Examples of pairwise point-wise comparison of test point results for relative gas volume flow rate deviation ($U_{\text{repro}} = 3.3 \%$) for GVF = 25 % and $q_{\text{liquid}} = 90 \text{ m}^3/\text{h}$. Error bars indicate facility uncertainties only. Top: NEL and DNV GL. Bottom: DNV GL and OneSubsea.

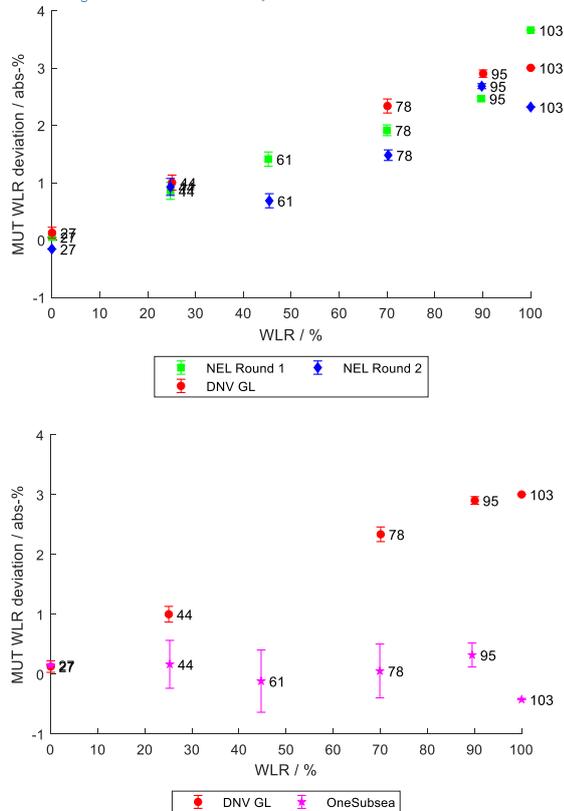


Figure 5: Examples of pairwise point-wise comparison of test point results for WLR deviation ($U_{repro} = 1.2\%$) for GVF = 25 % and $q_{liquid} = 90\text{ m}^3/\text{h}$. Error bars indicate facility uncertainties only. Top: NEL and DNV GL. Bottom: DNV GL and OneSubsea.

4.3 Overall numerical consistency

To summarize all results with a few numbers, the %-fraction of the cases that consistency was achieved has been calculated for different quantities, as listed in the first row of Table 5.

The large batch of single phase points has been excluded from this calculation. The row comparing NEL-R1 with NEL-R2 has a mean consistency of 95 %. This is as expected by the definition of U_{repro} and also confirms that the assumption of a normal distribution for the uncertainty is not so bad (i.e. 2 standard deviations corresponds to 95 %). The consistency between NEL and DNV GL, and between DNV GL and OSS is close to 80 %, where (at least) 95 % would be expected for complete consistency. Without more information it is unclear if the fraction of inconsistent results is mainly due to a larger reproducibility uncertainty of the flow meter installed in different facilities (see Table 3), or to one or more facilities underestimating their uncertainty of measurement (or anything else being overlooked in this analysis). Nevertheless, in view of all the differences between the facilities as listed in Table 2 and not explicitly addressed by increased

uncertainties, a consistency of 80 % is seen as a good result.

Table 5: Pairwise consistency of test results expressed as percentage of the number of test points. N1: NEL-Round 1, N2: NEL-Round 2, DG: DNV-GL, OS: OneSubsea. See Table 4 for the meaning of the symbols in the column headings.

Tests	$q_{m, total}$	q_{total}	q_{gas}	q_{liquid}	WLR	GVF	q_{oil}	q_{water}	Mean
N1 – N2	91%	95%	98%	93%	96%	96%	92%	96%	95%
N1 – DG	89%	78%	69%	87%	95%	71%	88%	90%	83%
N2 – DG	85%	75%	75%	90%	93%	79%	84%	86%	78%
DG – OS	82%	74%	78%	74%	80%	100%	58%	80%	78%

6. Conclusion

Pairwise comparison of test results of NEL and DNV GL, and DNV GL and OneSubsea resulted in an overall consistency of about 80 %. This is less than the desired 95 %, but still a good result in view of all the differences in e.g. fluid viscosities, operating pressures and inlet geometries, which were not explicitly incorporated in the uncertainty analysis. To get a better understanding of the results, following advices are given:

- make publicly available all measurement data of the ENG58 for further research
- organize a more extensive comparison including various types of flow meters and more partners, with open data access.

Acknowledgment

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References

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