North Sea Flow Measurement Workshop
22-25 October 2019

Technical Paper

Getting rid of the prover, by using a new multipath ultrasonic flow meter

Dag Flølo, Equinor
Pico Brand, KROHNE
Peter van Brakel, KROHNE
Frode Endresen, KROHNE

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1 INTRODUCTION

Metering systems with ball-provers are commonly used for loading / offloading of oil tankers. Such metering systems have significant cost, size, weight, and a considerable number of components. In this project, Equinor and KROHNE have cooperated on the testing of a new design multipath ultrasonic flow meter which is suitable for metering systems with master meter rather than ball-prover.

The aims of this technology development project was to develop a master-meter system that:

- Has an uncertainty estimate which is about the same as that of a system with ball-prover
- Has considerably lower costs, size, and weight than a system with ball-prover

To reach that goal, it was required to define a flow-metering run that would make the new ultrasonic meter independent of flow profile disturbances from upstream piping. Multiple tests were performed with different metering runs and different upstream pipe configurations. Following these flow profile disturbance tests, the flowmeter installed in the optimal metering run was calibrated and adjusted at one laboratory and verified by calibration on multiple liquids at 3 independent accredited laboratories.

This paper:

- Describes the prototype design of the new ultrasonic flow meter
- Shows results from the flow profile disturbance tests
- Shows results from calibration on different liquids in 4 independent laboratories
- Shows the design of the master-meter system
- Address Failure Modes, Effects and Consequences for the master-meter system
- Compares the estimated uncertainty of the master-meter system with that of a ball-prover system
- Concludes on the results

2 Flow meter design

2.1 Design of the new ultrasonic flow meter

This paper describes the test results done with the first prototype of an ALTOSONIC 5 X08 flow meter intended to be used in high performance applications. The ALTOSONIC 5 X08 is a multipath ultrasonic flow meter consisting of 14 measuring paths for flow calculation and one diagnostic path.

The meter is based on the proven technology of the ALTOSONIC 5 having 7 measuring paths in 7 planes. The 14 measuring paths of the X08 are located on the same 7 planes. At every plane two paths are crossed at an angle of 90 deg. The diagnostic path is vertical. The prototype meter had a nominal diameter of 8 inches. See figure 1 for measuring path layout:

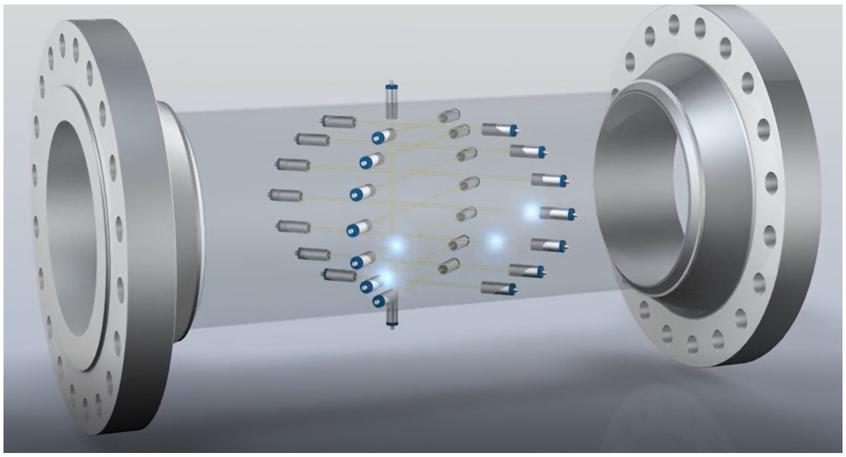

Figure 1: Ultrasonic path layout of the ALTOSONIC 5 X08 prototype

3 Flow profile disturbance tests

3.1 Introduction

Flow profile disturbance tests were performed against a piston prover at Euroloop. Euroloop is accredited in accordance with ISO17025 for the calibration. The uncertainty of the laboratory reference is stated to be 0.02 % @95% confidence level.

To maximize the impact of upstream flow profile disturbances, the tests were done with a low viscosity liquid with the following specifications:

- Medium : Paraffin oil
- Kinematic viscosity : 1.54 cSt @25 ^{o}C

Choosing the liquid lowest available viscosity at Euroloop for the flow profile disturbance testing is based on the phenomenon that the decay of flow profile disturbances is determined by viscosity.

N. Kolmogoroff, a Russian mathematician, introduced a new theory in turbulent motion in 1941, the decay of flow profile disturbances is depending of the viscosity of the liquid. The higher the viscosity of the liquid the quicker the decay of flow profile disturbances therefore the lower the viscosity the slower the decay of flow profile disturbances.

This is consistent with the finding in the thesis ‘Turbulent Pipe Flow with Swirl’ by W.Steenbergen Page 25 [1] where it is stated: “The rate of decay [in swirl intensity] appears to decrease with increasing Reynolds number”.

$$Reynolds\ number = \frac{Pipe\ diameter * Fluid\ velocity}{Kinematic\ viscosity}$$

By using a low viscous liquid, we ensure a high impact of upstream piping on the flow profile at the location of the flow meter.

The aim of the flow profile disturbance tests was to identify a metering run that makes the new ultrasonic meter independent of flow profile disturbances from upstream piping.

Based on the test results for a few metering run layouts, it was decided that an upstream metering run with 10 Diameter – Flow conditioner – 10 Diameter – flow meter, was the best performing metering run. This metering run is illustrated in Figure 2:

Figure 2: Layout of the optimal metering run configuration (10D= 10 Diameter straight pipe; FC=Flow Conditioner; MUT= Meter Under Test)

The flow profile disturbance tests were performed with the Meter Under Test installed both in normal position (Horizontal) and rotated 90 Deg (Vertical). This was done because it was easier to rotate the meter than rotating the upstream piping to test for both vertical and horizontal upstream bends.

3.2 Baseline calibration and adjustment

A baseline calibration was performed with:

- A 10 inch straight pipe reduced to a 20 diameter long 8 inch straight pipe
- Metering run with 10 diameter straight pipe – Flow conditioner – 10 diameter straight pipe – Meter Under Test.

Figure 3 shows the flow meter meter installed for baseline calibration.

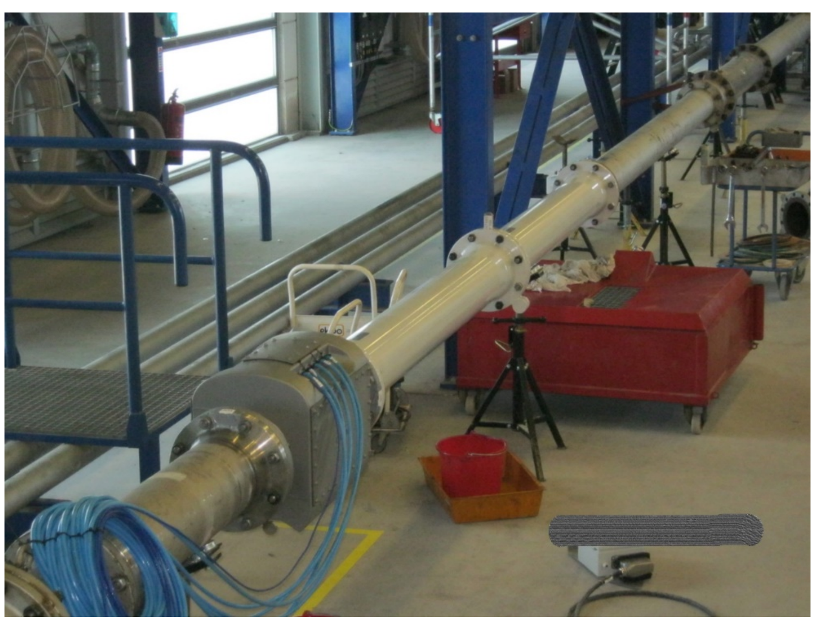

Figure 3: Flow meter (Grey with blue cables) and the optimal metering run (10D – flow conditioner – 10 D seen as white painted spools) installed in a long straight run for baseline calibration.

The meter was adjusted based on the baseline calibration. The meter was then verified at similar but not identical Reynolds numbers. Verification results are shown in Figure 6 together with the results from the flow profile disturbance tests.

3.3 Test with: Single bend - 10D – Flow conditioner – 10D – Flow Meter

Figure 4 shows the layout for the flow profile disturbance tests with a single bend upstream the metering run.

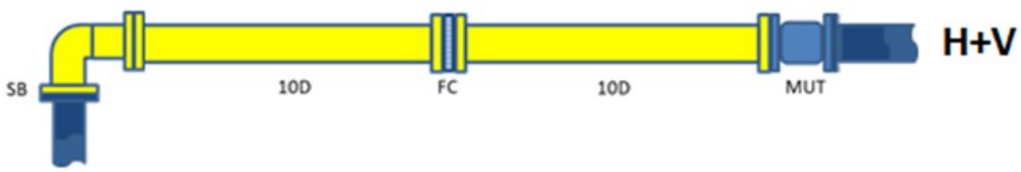

Figure 4: Layout for the flow profile disturbance tests with upstream single bend (SB= Single Bend; 10D= 10 Diameter straight pipe; FC=Flow Conditioner; MUT= Meter Under Test; H = Horizontal installation V = Vertical installation ->meter rotated 90 Deg)

3.4 Test with: Double bend -10D-Flow Conditioner-10D-Flow Meter

Figure 5 shows the layout for the flow profile disturbance tests with two bends in two different planes upstream the metering run.

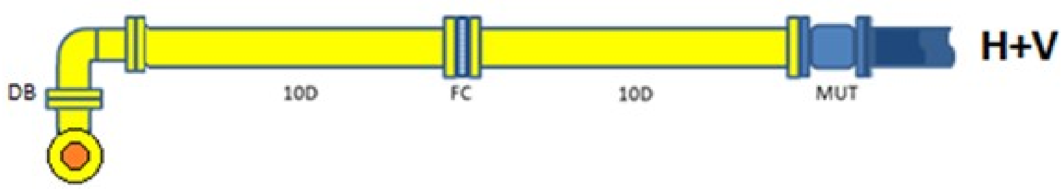

Figure 5: Layout for the flow profile disturbance tests with upstream double bend out of plane. (DB= Double Bend; 10D= 10 Diameter straight pipe; FC=Flow Conditioner; MUT= Meter Under Test; H = Horizontal installation V = Vertical installation = meter rotated 90 Deg)

3.5 Summary of flow profile disturbance tests

The results from baseline verification tests and the flow profile disturbance tests are shown in Figure 6.

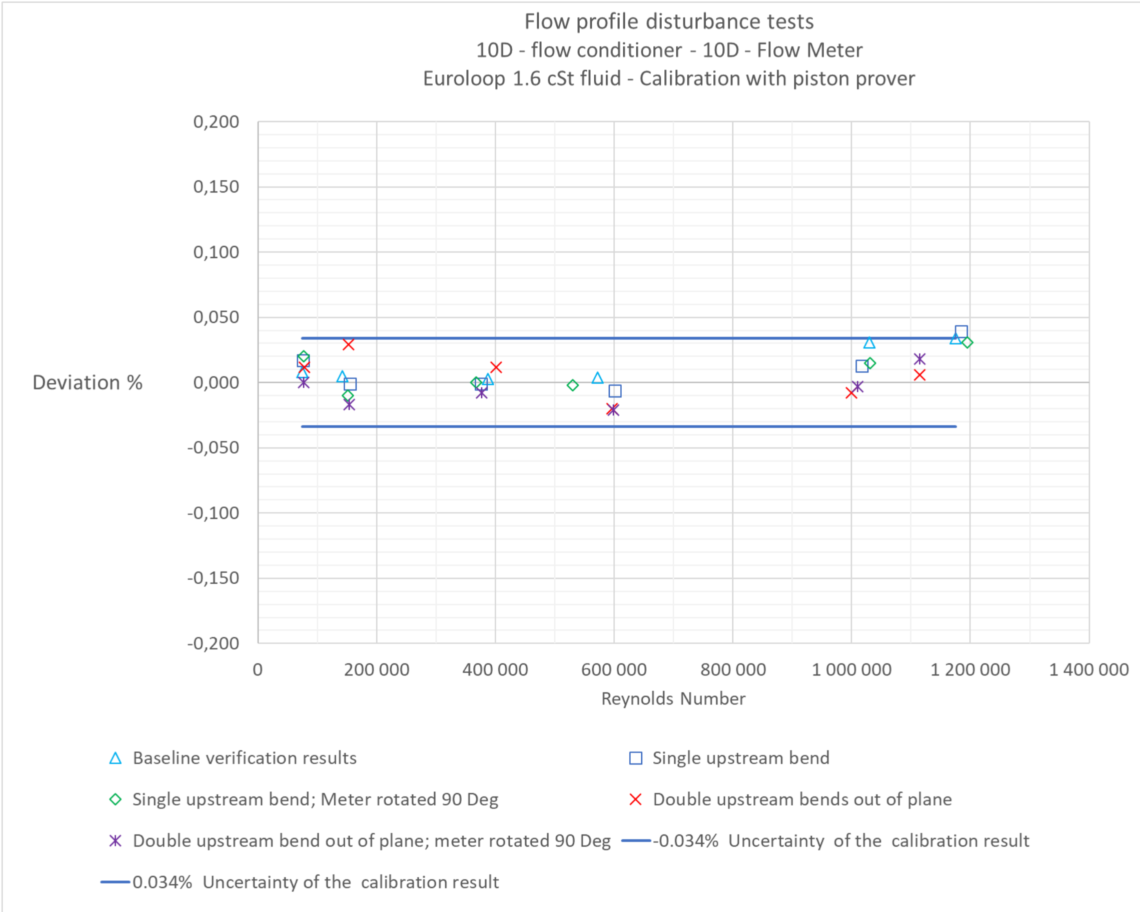

Figure 6: Results from baseline verification test and flow profile disturbance tests.

The uncertainty of the laboratory reference is stated to be 0.02 % @95% confidence level. Taking into account an uncertainty 0.027% @95% confidence for each calibration point due to repeatability, the combined uncertainty of each calibration result is estimated to be: 0,034 % @95% confidence level.

As can be seen in figure 6, the influence of the flow disturbances was not detectable as the effects of the disturbances were within the uncertainty of the calibration result.

For an upstream metering run consisting of 10 Diameter straight pipe – flow conditioner – 10 Diameter straight pipe - flow meter, it was concluded that neither an upstream single bend nor two bends in different planes had a detectable influence on the flow measurement.

3.6 Test with partly blocked flow conditioner in KROHNE water tower

To see the effect of a partly blocked flow conditioner, the flow conditioner was partly blocked as shown in Figure 7. The flow meter was then tested at 2 different flow rates in the KROHNE water tower.

To avoid cavitation caused by the blocked flow conditioner, the maximum velocity was limited to 2.09 m/s.

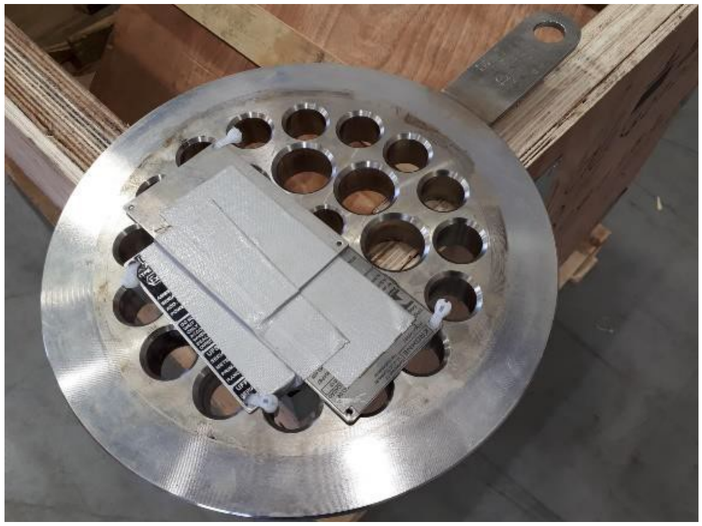

Figure 7: Picture showing the partially blocked flow conditioner.

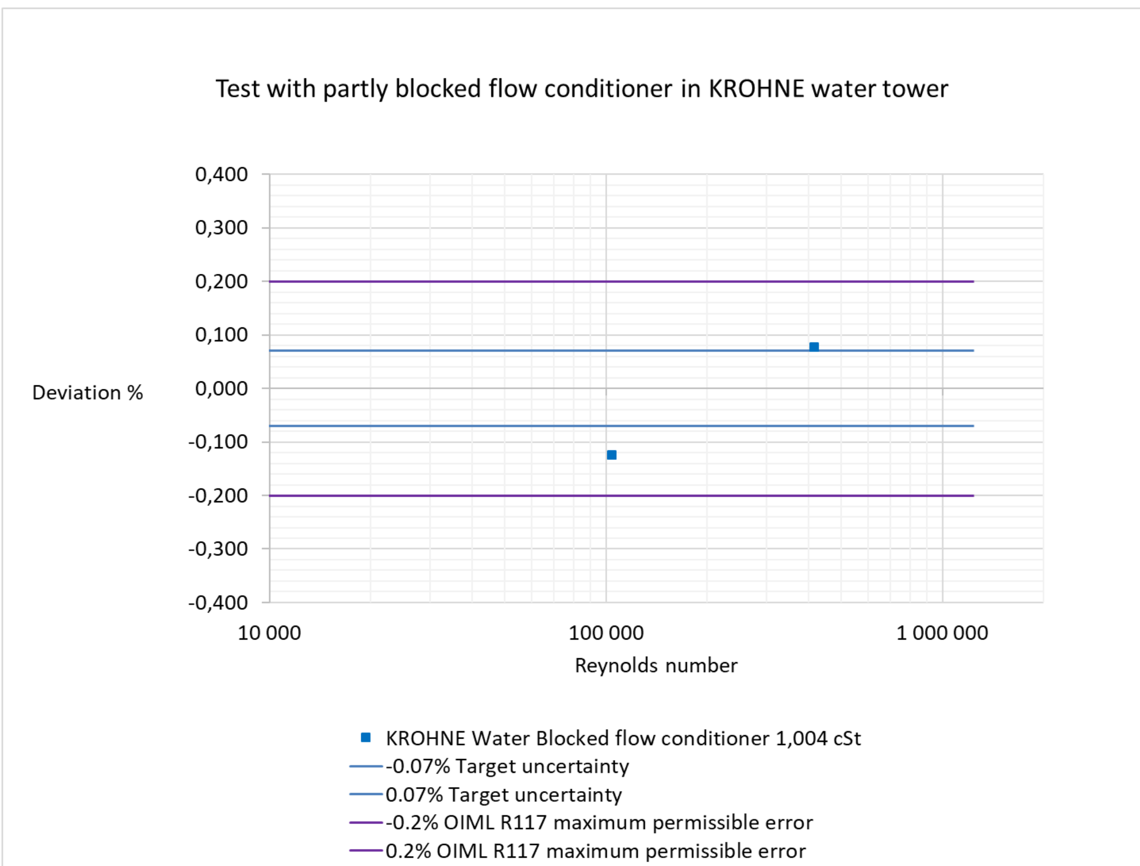

Figure 8: Test results from KROHNE water tower with a partially blocked flow conditioner.

As can be seen in Figure 8, a blocked flow conditioner had a significant influence on the measurements. The meter performance was outside the target uncertainty of 0,07% at 95% confidence level. Still, the performance was well within the OIML R 117-1 [2] class 0,3 requirements for a Maximum Permissible Error of the measuring device of +/- 0,2 %.

4 Flow tests with various liquids in various laboratories

4.1 Verification results at Euroloop

The flow meter was characterized by calibration, adjusted, and verified against a piston prover at Euroloop. Characterization was performed by typically 10 calibration points on 3 different liquids. Verification was performed at the flow rates defined by OIML R117-2 [3]. There was no attempt to match verification flow rates with calibration and adjustment flow rates.

Figure 9 shows the verification results. Liquid densities and viscosities are identified in the legends. The uncertainty of the reference value was stated to be 0.02 % @95%confidence level. The meter was verified on liquid velocities from 0,9 m/s to 9 m/s.

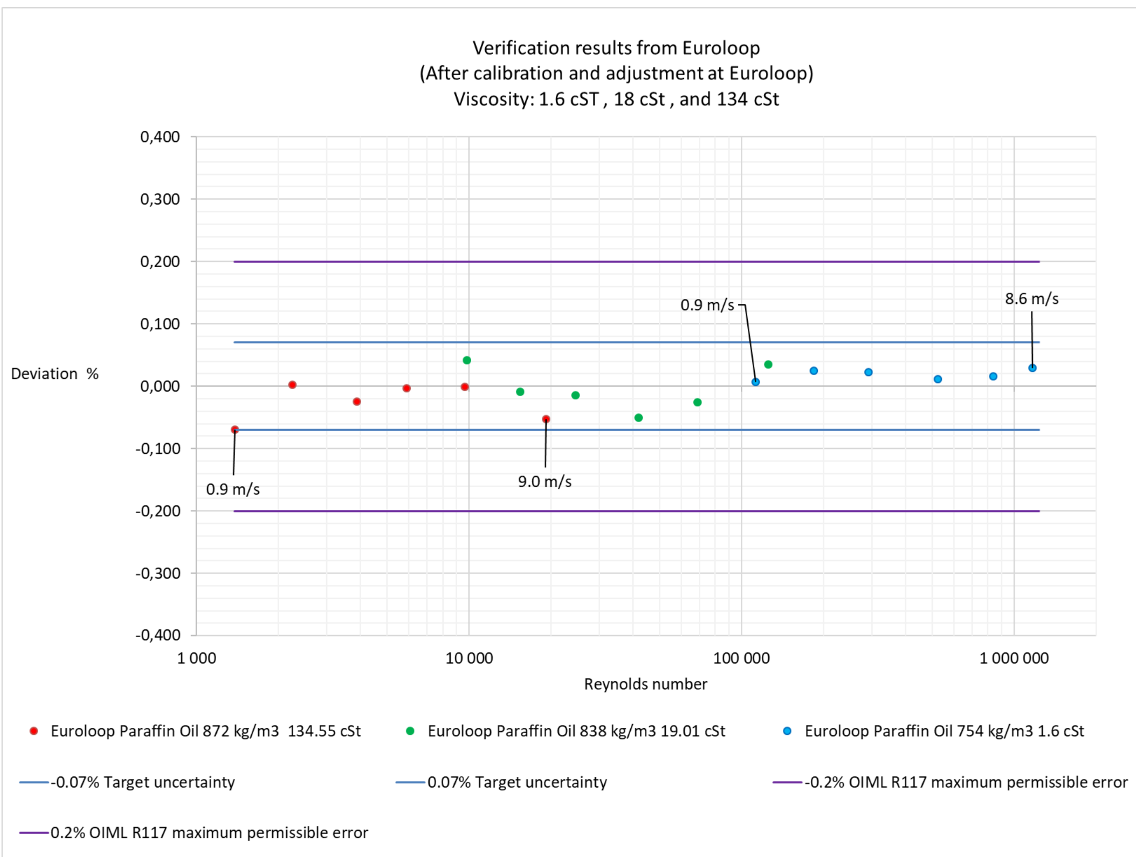

Figure 9: Verification results from calibration on 3 different liquids at Euroloop.

The viscosity values indicated in the legends in figure 9 are the average viscosities for each liquid. The viscosity at the highest flow rates was a bit lower because the temperature increased. However, the exact viscosity value is not regarded essential.

All verification results for the 8 inch meter were within the target uncertainty of 0.07 % @95%confidence level for:

- Velocity range 0.9 to 9 m/s (100 m3/h to 1000 m3/h)
- Reynolds number range from about 1 000 to 1 000 000
- Viscosities 1.5, 19, and 134 cSt

The test results indicate that the uncertainty for a flow-meter that is used for the same liquids that are used for calibration can be expected to be well within 0.07 % @95%confidence level.

4.2 Test on liquids that the meter was not calibrated and adjusted for

A common requirement in international standard is to calibrate, adjust and verify flow meters on liquids that are as similar as possible to the liquids that will be seen in operations.

To test the effect of using the meter on different liquids than used for calibration and adjustment, the flow meter was tested on different liquids at KROHNE water tower, Trapil and SPSE.

No adjustment of the meter was performed after the initial calibration, characterization, and adjustment at Euroloop. The meter was identical for all tests.

Figure 10 shows that there was a large difference in density and viscosity between the liquids used for testing and the liquids used for calibration, characterization and adjustment of the flow meter. So these tests can be characterized as severe tests.

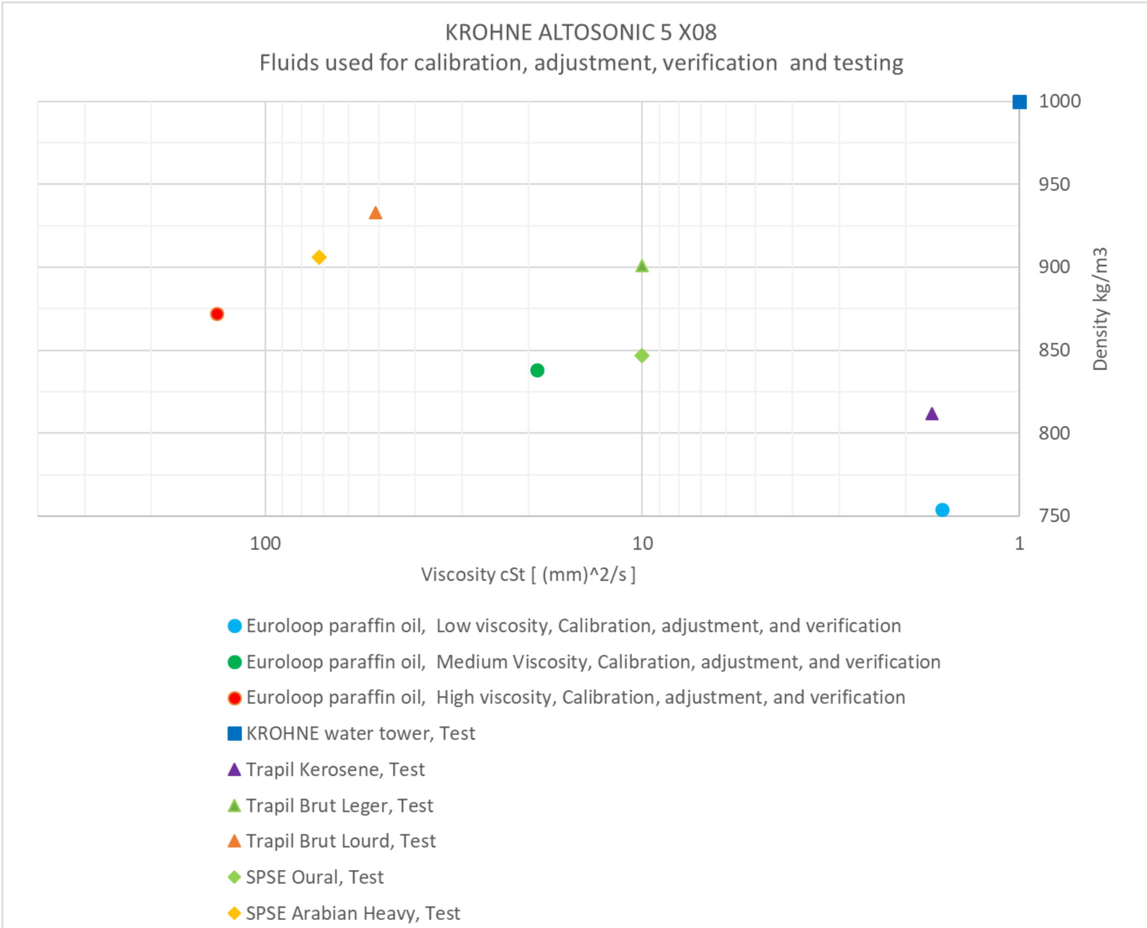

Figure 10: Density and viscosity for liquids used for calibration, adjustment, verification, and testing.

4.3 Uncertainty of the reference values

When evaluating the test results from a laboratory, the uncertainty of the reference and the repeatability of the test must be taken into account.

The repeatability requirement used under the tests was the common repeatability requirement in fiscal metering systems of 0.027% @95%confidence. A minimum of 3 repeats was performed at each point.

The uncertainty of the calibration result is here considered to be:

	Stated uncertainty for the laboratory	Uncertainty due to repeatability	Combined uncertainty
Uncertainty at 95% confidence level	%	%	%
Euroloop	0.02	0.027	0.034
KROHNE water tower	0.028	0.027	0.039
Trapil	0.043	0.027	0.051
SPSE	0.10	0.027	0.104

Table 1: Uncertainty of the calibration result at various laboratories.

When the deviation is within the combined uncertainty value provided in Table 1, it can not be concluded that the flow meter measurement deviates from the true value.

4.4 Criteria for concluding if meter performance is outside specification

When evaluating if the performance of the meter is outside uncertainty specification, the uncertainty specification of the meter will have to be taken into account in addition to the uncertainty of the reference value. For uncorrelated uncertainty contributions:

$$Criteria\ @\ 95\ \%\ confidence\ level = \sqrt{\sum (uncertainty\ contribution)^2}$$

	Uncertainty specification for the meter	Uncertainty of the laboratory	Repeatability at each test point	Criteria for concluding if the meter is outside specification
Uncertainty at 95% confidence level	%	%	%	%
Euroloop	0.07	0.02	0.027	0.08
KROHNE water tower	0.07	0.028	0.027	0.08
Trapil	0.07	0.043	0.027	0.08
SPSE	0.07	0.10	0.027	0.13

Table 2: Criteria for concluding if the performance of the meter is outside its uncertainty specification at different flow laboratories.

If the meter performs outside the criteria in Table 2 in a particular laboratory, it can be concluded at a 95% confidence level that the measurement is outside the uncertainty specification.

4.5 Tests for low viscosity liquids

To test the assumed independence from liquid and flow laboratory for low viscosity liquids, the flow meter was calibrated at KROHNE water tower and at Trapil. Test results for low viscosity liquids are shown in figure 11.

The verification results from Euroloop are also included in this figure. As the meter was calibrated, characterized, and adjusted by using the same liquid at Eurooloop, the test results from Euroloop are are termed 'verification' results rather than test results.

To avoid cavitation caused by the flow conditioner, the maximum velocity was limited to 4.79 m/s in the KROHNE water tower.

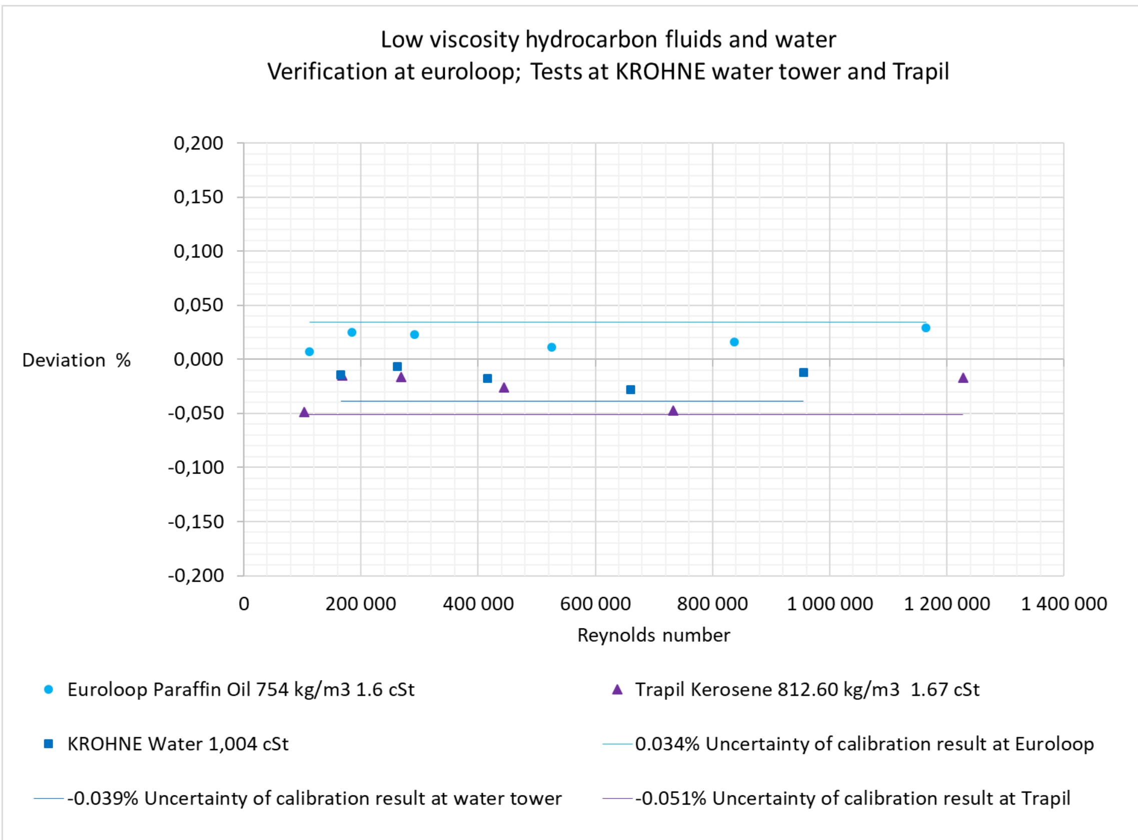

Figure 11: Test results from verification at Euroloop, test on water at KROHNE water tower, and test at Trapil. The relevant positive or negative uncertainty limit of the calibration result is also indicated in the figure.

It is noteworthy that the meter was calibrated on a 1.6 cSt hydrocarbon liquid in Euroloop and the largest deviation found on water in KROHNE water tower was only 0.028 %.

All test results were within the combined uncertainty of the stated laboratory uncertainty and the repeatability of each calibration point as established in section 4.3 and indicated in the figure above. (To avoid too much lines in Figure 11, only the relevant positive or negative uncertainty is indicated in the figure).

As can be seen in Figure 11, all deviations were less than the combined uncertainty of the laboratory reference and the repeatability at each calibration point.

The performance of the meter was well within the target uncertainty of 0.07% @95%confidence level.

4.6 Independent tests on 10 cST and 82 cSt liquids at SPSE

The meter that was calibrated and adjusted on paraffin oils at Euroloop was then tested on 10 cST and 82 cSt liquids at SPSE. This was a severe test, where the meter was tested on liquids that were very different from the liquids that were used for calibration and adjustment of the flow meter. Se figure 10 for an overview of viscosity and density for the various liquids. Figure 12 shows the test results.

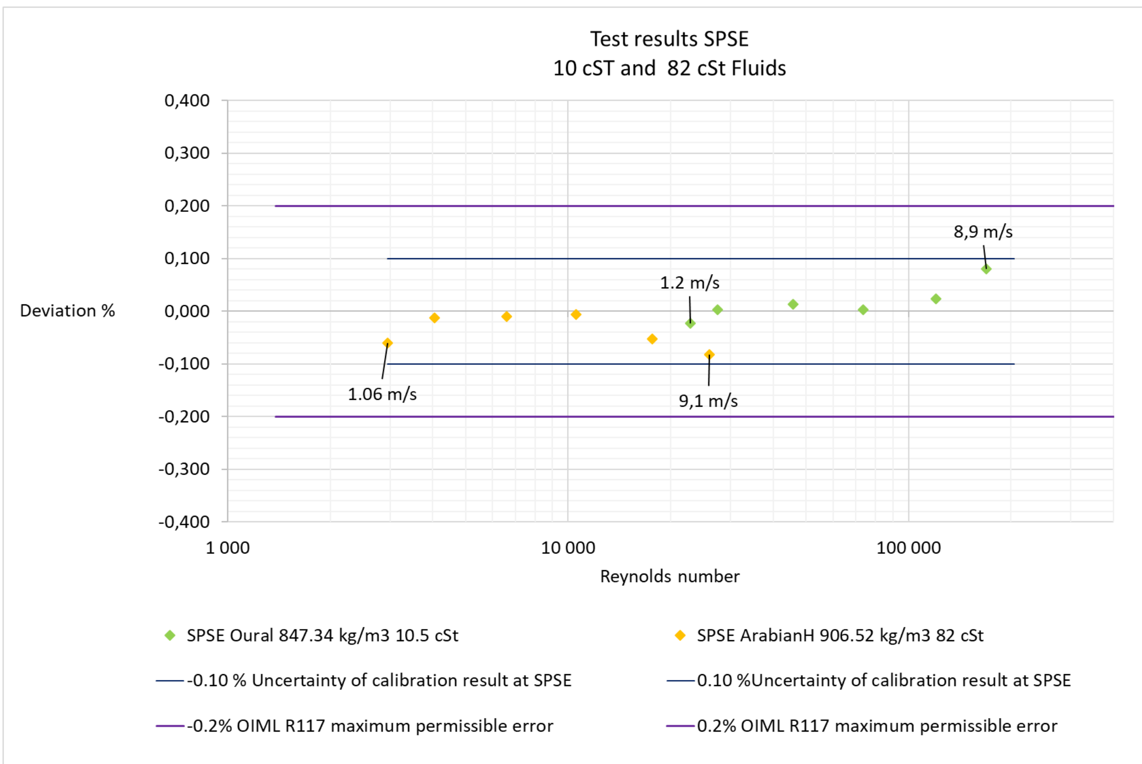

Figure 12: Test results from test with 10cSt and 82 cSt liquids at SPSE.

The uncertainty of the SPCE laboratory was stated to be 0.10 % @95% confidence level while the target uncertainty of the meter was 0.07 % @95% confidence level. Hence the uncertainty of the laboratory was too high to conclude if the performance of the meter was within the target uncertainty of 0.07 % @95%confidence level.

The test liquids were very different from the liquids that were used for calibration and adjustment of the flow meter. When taking into account the uncertainty of the laboratory, none of the test results identified a detectable deviation.

4.7 Independent tests on 10 cST and 45 cSt liquids at TRAPIL

The meter that was calibrated and adjusted on paraffin oils at Euroloop was then tested on 10 cST and 45 cSt liquids at Trapil. The liquids used at Trapil differed even more from the calibration liquids than the liquids that were used at SPSE. The densities and viscosities of the various liquids are shown in See figure 10. Figure 13 shows the test results.

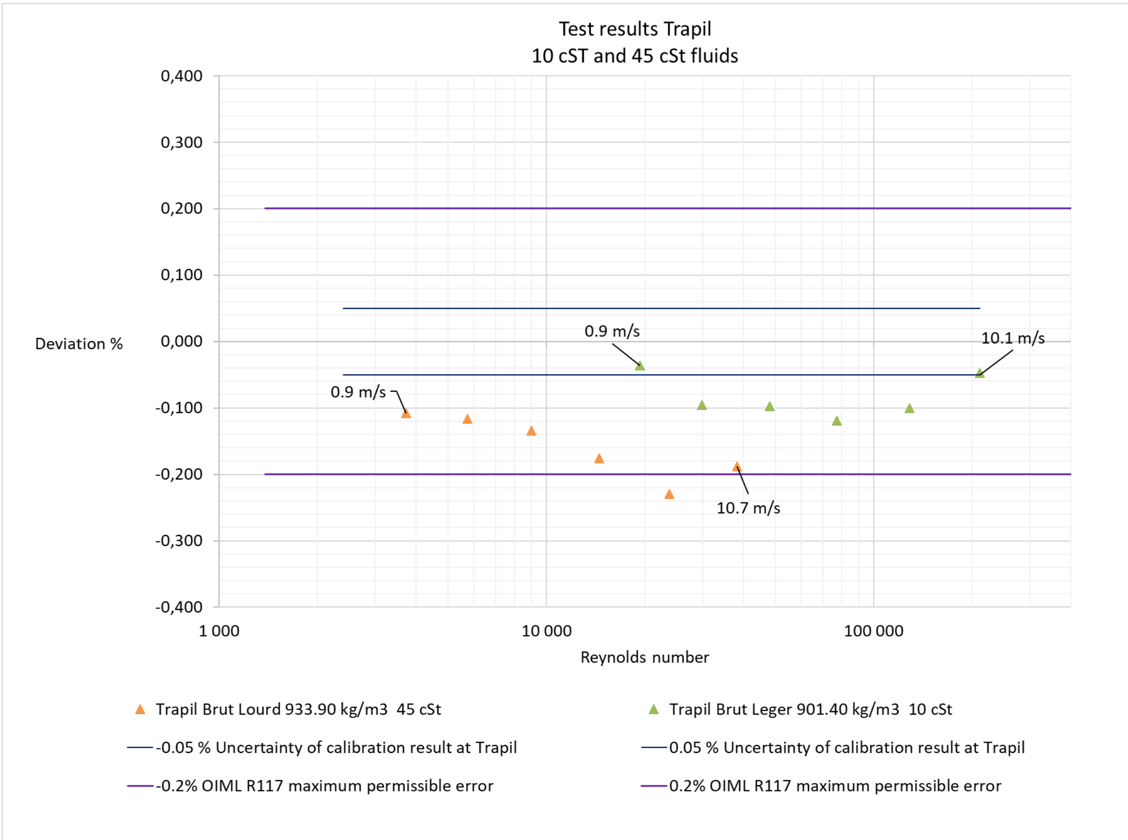

Figure 13: Test results from test on 10cSt and 45cST liquids at Trapil

The test results showed deviations that were larger than the uncertainty of the reference value. The reasons for this deviation is not known.

The results from Trapil seem to indicate that the recommendation in international standards to calibrate the meter on similar viscosity to the operating conditions still has to be taken into consideration for a target uncertainty of 0.07 % @95% confidence level.

Regarding calibration liquids, ISO 12242:2012(E) states:
"To minimize the uncertainty of the calibration, the calibration shall be conducted:
…..
h) Where possible, at similar viscosity to meter operating conditions This ensures that not only Reynolds number but also flowrate are matched. If a wide range of

viscosity is encountered in the field, then calibration at more than one viscosity may be required, so that the whole Reynolds number range is covered.”

However, all results except one were within the OIML R 117-1 [2] class 0,3 requirements of a Maximum Permissible Error of the measuring device of +/- 0,2 %.

The results indicate that this meter can be calibrated on paraffin Oils at Euroloop and still largely provide measurements within the OIML R 117-1 [2] class 0,3 requirements for very different liquids.

5 Metering system design

5.1 Planned design of the metering system

The following system diagram illustrates the planned oil export metering system consisting of two metering runs and and master meter:

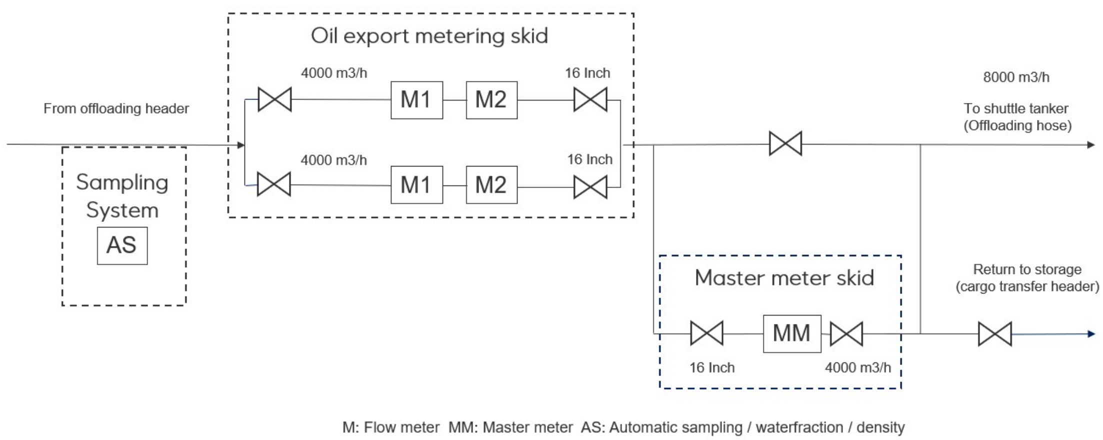

Figure 14 – System diagram of the master meter system considered in this study

The system consists of:

- Two parallel metering runs
  (to ensure that each metering run can be calibrated at full flow rates within maximum capacity of an onshore accredited flow laboratory.)
- Two high accuracy meters in series in each metering run
  (for redundancy and continuous condition monitoring.)
- A high accuracy meter used as a master meter
  (for verification / proving)

Calibration of a metering run will be performed by closing the metering run that is not being calibrated. Calibration during offloading will be performed at 50% of the full offloading rate. It is expected that calibration will take less than 10 minutes per metering run. The calibration rate will be taken into account when planning the offloading operation.

Calibration can also be performed in-between offloading operations by returing the liquid to the FPSO storage.

If the calibration facility has less capacity than the 4000 m3/h required to calibrate at full flow velocity, the Master meter skid shown in figure 14 can be designed with two (or more) parallel metering runs. As illustrated in Figure 15:

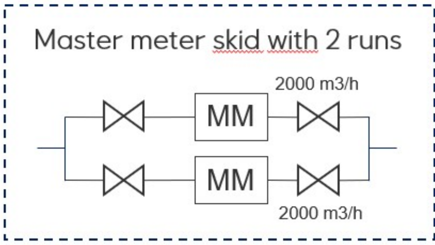

Figure 15: A master meter skid with 2 parallel metering runs

5.2 Failure mode and effect analysis

The potential failures and the consequences of these failures are summarized in the table below:

Failure mode	Consequence
Failure of one flow computer	Use the back-up meter which has its own flow computer
Failure of one duty meter	Use the back-up meter
Failure of one temperature transmitter	Use the back-up transmitter
Failure of on pressure transmitter	Use the back-up transmitter
Failure of leakage detection system or leakage detected on the dual expanding plug valve at the inlet of a metering run.	Close the flow regulation valve on the outlet. By specification, the flow regulation valve provides tight shut-off. Bleed off pressure in the line. If there is no significant pressure build-up, the dual expanding plug valve at the inlet still keeps tight.
Failure in the flow regulation valve	Use the other valve to balance the flow; or keep both valves fully open and operate with unbalanced flow within maximum flow rate.
Failure of master meter	Operate without calibration as long as the two meters in each line shows corresponding values within an operational limit (decided from experience).
Failure of inlet valve to the master meter run	No problem, this valve is mainly for maintenance purposes. Maintenance can be performed on a pressure less system inbetween offloading

	operations.
Failure of the back pressure valve downstream the master meter	This will only be a problem if there is cavitation in the master meter at maximum flow rate during calibration by return of oil to storage.
Wax in metering run	All metering runs are heated above wax appearance temperature and can be heated to above wax dissolution temperature. If heating fails, significant amount of wax will be detected during by calibration. If not detrimental, the effect of wax can be calibrated away. If detrimental, the wax will have to be removed by circulating warm oil through the metering runs and back to storage.
Wax in master meter run	The master meter will be less exposed to wax than the metering run. If wax is detected by calibration, heated oil will be circulated and dissolve the wax both in the metering runs and the master meter run.
Need for maintenance during operation	The main function of the metering system will be maintaned for all single failures and for most simultaneous failures. Maintenance can be performed in the (minimum) 4-5 day window between offloading operations.

Table 3: Failure Mode Effect and Consequence Analysis (FMECA) for the suggested master meter system

As the number of components in the master meter system is less than 50% of the number of components in a conventional metering system with 4 parallel metering runs and a ball prover, the number of potential failures is reduced proportionally. A component that is not in the design cannot fail.

5.3 Uncertainty analysis

Before the development was started, an uncertainty evaluation was performed to determine a target uncertainty for the flow meter. From documentation of existing systems, it was found that conventional metering system with bi-directional prover applied on similar applications as the planned application had an uncertainty estimate of 0.11 % @95%confidence.

The freely available uncertainty tool, available at www.nfogm.no was used for the uncertainty evaluation of the planned system.

It was found that in an uncertainty budget for a total uncertainty of 0.11 % @95%confidence level there would be room for an uncertainty of 0.07 % @95%confidence for the uncertainty contribution from 'Flow profile and fluid effects on master meter'.

An uncertainty of 0.07 % @95%confidence was chosen as target uncertainty for the flow-meter tested in this project.

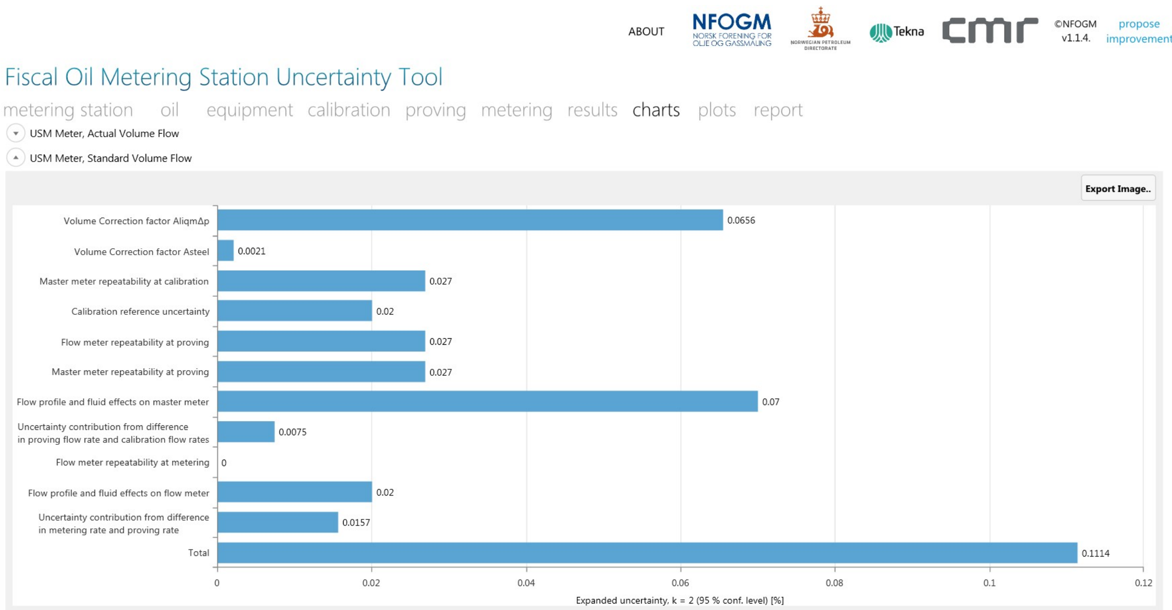

Figure 16: Chart showing the estimated uncertainty contributions and the total uncertainty for the master meter system evaluated in this study.

Figure 16 shows the uncertainty elements in the planned master meter system. The low uncertainty contributions from 'Flow profile and liquid effects' and 'difference in metering flow rate and proving flow rate' on flow meter stems from the assumption that the flow meter will be calibrated on the same liquid at the same flow rates that it will be used. Flow profile and liquid effects are therefore included on the master meter and not on the flow meter.

It was concluded that a master meter system using a master meter having an estimated uncertainty within 0.07% @95%confidence level will have about the same uncertainty as a conventional metering system with a bi-directional ball prover.

6. Conclusions

A prototype ultrasonic meter, KROHNE Altosonic 5 X08 was tested in this project.

A master meter system based on the tested meter will provide significant cost savings compared to a conventional metering system with bi-directional prover.

A system with a master meter having an uncertainty within 0.07% @95%confidence level, has been estimated to have about the same uncertainty

(0.11 % @95%confidence level) as a conventional metering system with a bi-directional ball prover.

The metering run was tested with flow disturbances induced by both 1 upstream bend and 2 upstream bends in different planes. The uncertainty of the calibration result was estimated to 0.034% in these tests. For a metering run with: 10 D – Flow conditioner – 10 D – Flow meter, neither a single bend nor a double bend had detectable influences on the performance of the meter.

The meter was calibrated, adjusted, and verified at Euroloop and then tested at KROHNE water tower, SPSE, and Trapil.

The meter was calibrated and adjusted on 3 paraffin oils at Euroloop (754 kg/m3 1.6 cSt ; 838 kg/m3 19 cSt ; 872 kg/m3 134 cSt) and then verified using the same liquids. The verification results from Euroloop indicate that the uncertainty of a flow-meter that is calibrated and adjusted at an accurate laboratory and used on liquids that are similar to the fluids used for calibration can be expected to be well within 0.07 % @95%confidence level.

For low viscosity fluids, the verification results from Euroloop (Paraffin oil: 754 kg/m3 1.6 cSt), test results from KROHNE water tower (Water: 1000 kg/m3 1.0 cSt), and test results from Trapil (Kerosene: 812 kg/m3 1.7cSt) were all within the combined uncertainty of the laboratory and the repeatability of the calibration point. The results indicate that for low viscosity liquids (Reynolds numbers above approximately 100 000), the meter can be expected to perform well within 0.07% @95% confidence level even when calibrated on one liquid and used on very different liquids.

The meter was tested on two liquids at SPSE (Oural: 847 kg/m3 10 cSt ; Arabian heavy: 906 kg/m3 82 cSt). These fluids were wery different from the fluids used for adjustment of the meter. The uncertainty of the laboratory reference at SPSE was 0.10% @95% confidence level. Hence, SPSE was not a sufficiently accurate laboratory to conclude if the meter was performing within an uncertainty of 0.07% @95% confidence level. However, all results were within the 0.10% uncertainty of the laboratory and even within a maximum deviation of 0.08% from the laboratory reference.

The meter was tested on 2 liquids at Trapil (Brut Lourd: 933 kg/m3 45 cSt ; Brut leger: 901 kg/m3 10 cST). Compared to the fluids used at SPSE, viscosity and density of these fluids differed even more from the fluids at Euroloop. The results were outside the target uncertainty of 0.07% @95% confidence level. However, except from one calibration point, all results were within the OIML R 117-1 [2] class 0,3 requirements for a Maximum Permissible Error of the measuring device of +/- 0,2 %.

The aim of this technology development project was to develop a master-meter system that:

- Has an uncertainty estimate which is about the same as that of a system with a bi-directional ball-prover
- Has considerably lower costs, size, and weight than a system with ball-prover

On basis of the test results, it was concluded that these goals were met for Reynolds numbers above approximately 100 000.

The results indicate that the goals of having a master meter within an uncertainty of 0.07% @95% confidence level can also be met for higher viscosity liquids and lower Reynolds number than approximately 100 000. However, calibration liquids, uncertainty, and flow rate capacity of the calibration laboratory needs to be taken into consideration.

For many applications a master meter system utilizing the tested master meter can be a low cost alternative with similar low uncertainty as a conventional metering system with a bi-directional ball prover.

7 REFERENCES

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[3] INTERNATIONAL RECOMMENDATION; OIML R 117-2; Edition 2014 (E); Dynamic measuring systems for liquids other than water. Part 2: Metrological controls and performance tests

Tekna

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