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Paper 8.3

Qualifying a Coriolis Condensate Export Metering Station for Fiscal Use for Ormen Lange Using 12” Coriolis Meters

Trond Folkestad
Norsk Hydro ASA

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Qualifying a Coriolis Condensate Export Metering Station for Fiscal Use for Ormen Lange Using 12” Coriolis Meters

Trond Folkestad, Norsk Hydro ASA

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1 INTRODUCTION

Hydro has qualified a novel liquid export metering station design based on large Coriolis mass flow meters and Coriolis master meter proving for fiscal use in Norway, with very good results.

This paper will share the experience gained during the extensive testing of the Coriolis meters, describe the metering issues that were uncovered and the subsequent improvements that were made.

2 BACKGROUND

The Ormen Lange field is Norway’s largest gas field and will be developed with seabed installations at depths between 800 and 1100 metres, and will be linked through a 120 kilometres pipeline to a processing plant on land at Nyhamna on the west coast of Norway, see Figure 1.

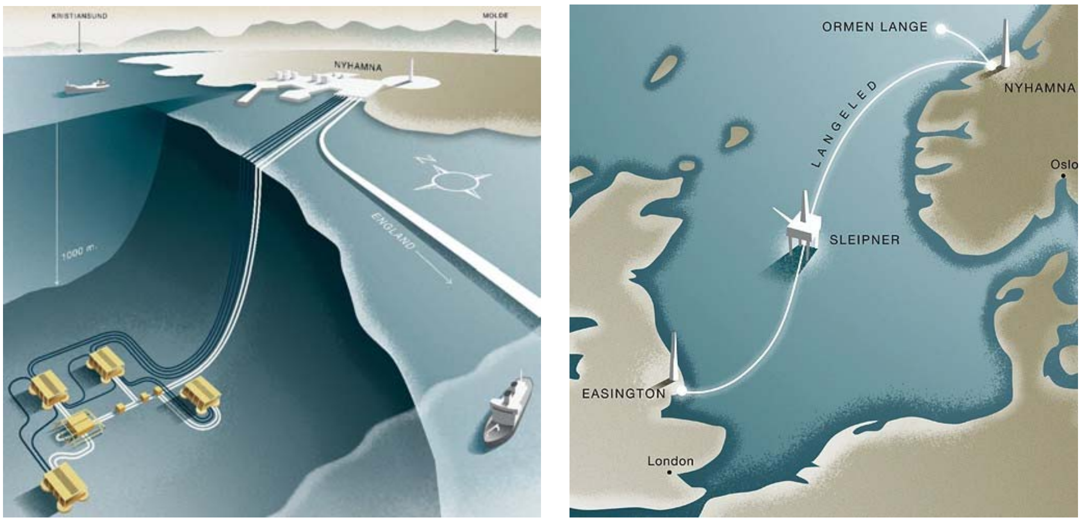

Figure 1 – Location of Ormen Lange

The gas will be exported to Easington on the east coast of England through the world's longest subsea export pipeline, a 1200 kilometre long export-pipeline called Langeled. The condensate will be stabilized and stored in a 150,000 Sm^3 cavern prior to export by tanker.

Production will start in October 2007. A total of 24 subsea wells in four seabed templates will produce 6000 to 8500 Sm^3 per day of condensate and 70 million Sm^3 per day of gas.

- Recoverable gas reserves: 397 billion Sm^3
- Recoverable condensate: 28.5 million Sm^3

For more information visit: http://www.hydro.com/ormenlange/en/

3 DESIGN SELECTION

Hydro (operator for the development phase) and Shell (future operator for operational phase) together with Aker Kværner (EPC contractor) evaluated various measurement designs during 2003. Shell was very keen on evaluating “new” measurement designs especially based on ultrasonic meters and wanted more alternatives to a conventional turbine meter with prover design. Hydro suggested evaluating designs based on Coriolis meters especially since Shell had some operating experiences with Coriolis meters and since a 12” Coriolis meter now was available. It was agreed to look at six designs and to evaluate the different designs based on these criteria.

Design criteria:
- Loading rate 8000 Sm^3/h
- On site calibration of master meters
- Portable prover capacity is maximum 800 Sm^3/h
- Volumetric flow primary meters shall have volumetric flow master meters
- Mass flow primary meters shall have mass flow master meters
- Maximum meter run line size 12” to ease maintenance

Selection criteria:
- All designs to be such that they can be considered equally suitable
- The design with lowest expected lifecycle cost is selected

Aker Kværner then prepared and evaluated the measurement design evaluation matrix in Table 1.

Table 1 – Evaluation matrix

Alternatives	Primary measurement type	Prover / Master meter type	Ranking
1	5 x 12” Turbine meters	Bi-directional prover	3
2	5 x 12” Ultrasonic meters	Bi-directional prover	5
3	5 x 12” Coriolis meters	Bi-directional prover	2
4	5 x 12” Turbine meters	3 x 8” Turbine meters	4
5	5 x 12” Ultrasonic meters	3 x 8” Turbine meters	6
6	5 x 12” Coriolis meters	3 x 8” Coriolis meters	1

Therefore, it was decided to use a novel metering station design with five parallel 12” Coriolis meter runs for exporting the condensate.

A master meter bank consisting of three parallel 8” Coriolis meters is used enabling a mass flow against mass flow proving see Figure 2. Onsite calibration of the master meter bank using a transportable reference is also part of the design.

The design capacity was later reduced to 6000 Sm^3/h (1500 Sm^3/h per meter run) to keep the velocity through the Coriolis meters below 10 m/s. The meters however, showed no sign of not operating correctly also for higher flow rates.

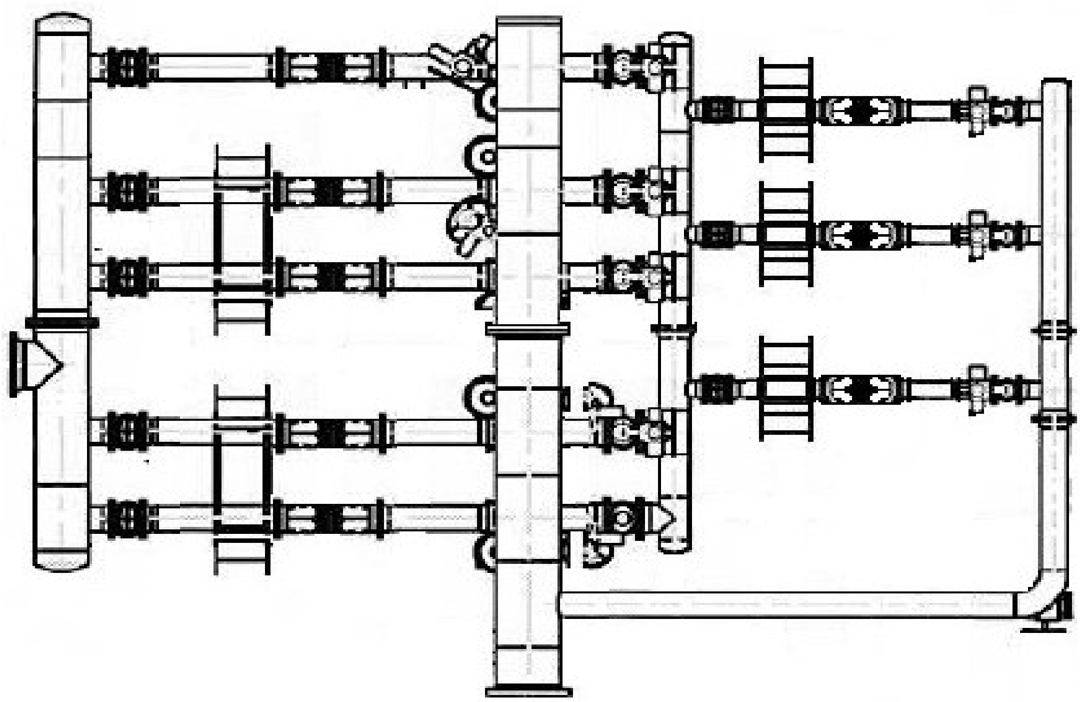

Figure 2 – Design of the condensate export metering station for Ormen Lange

4 QUALIFYING ACTIVITY

The selected design is not among the recommended solutions in the Norwegian Petroleum Directorate's (NPD) Regulations [1] although the Coriolis meter is covered by several international standards [2], [3].

In December 2003 in the approval for the metering station in the Plan for development and operation of a petroleum deposit (PDO) the NPD included additional conditions:

> *"The operator must well in advance of deciding the final measurement design for fiscal condensate metering demonstrate to the NPD that the suggested solution is suitable."*

The NPD viewed the proposed design as an unusual measurement solution although described in international standards. Due to lack of references to similar installations, the NPD considered the design as an alternative to more established metering solutions. This, together with an unfamiliar supplier of Coriolis meters led the NPD to set additional conditions.

To gain final approval for the design from the NPD a qualifying activity was agreed. Starting in January 2004 the qualifying team (Hydro, Shell and NPD) together with the Norwegian meter supplier Håland Instrumentering witnessed the calibration of a large 12" Coriolis meter on water at a calibration facility accredited by NMI, at ODS in Barendrecht in the Netherlands. One calibration run was performed by filling a 10 000 litre calibration tank, starting from zero flow, up to test flow rate and back to zero flow. Totalising was performed internally in the meter and manually read out, and compared to the level measured in the tank. Considering the test conditions the meter demonstrated impressive performance, achieving a linearity of 0.14% band and repeatability of 0.05% band, see Figure 3.

This was followed by a site visit to Shell Chemie in the Netherlands where similar sized Rheonik meters were in use and a visit to the manufacturer Rheonik in Odelzhausen in Germany.

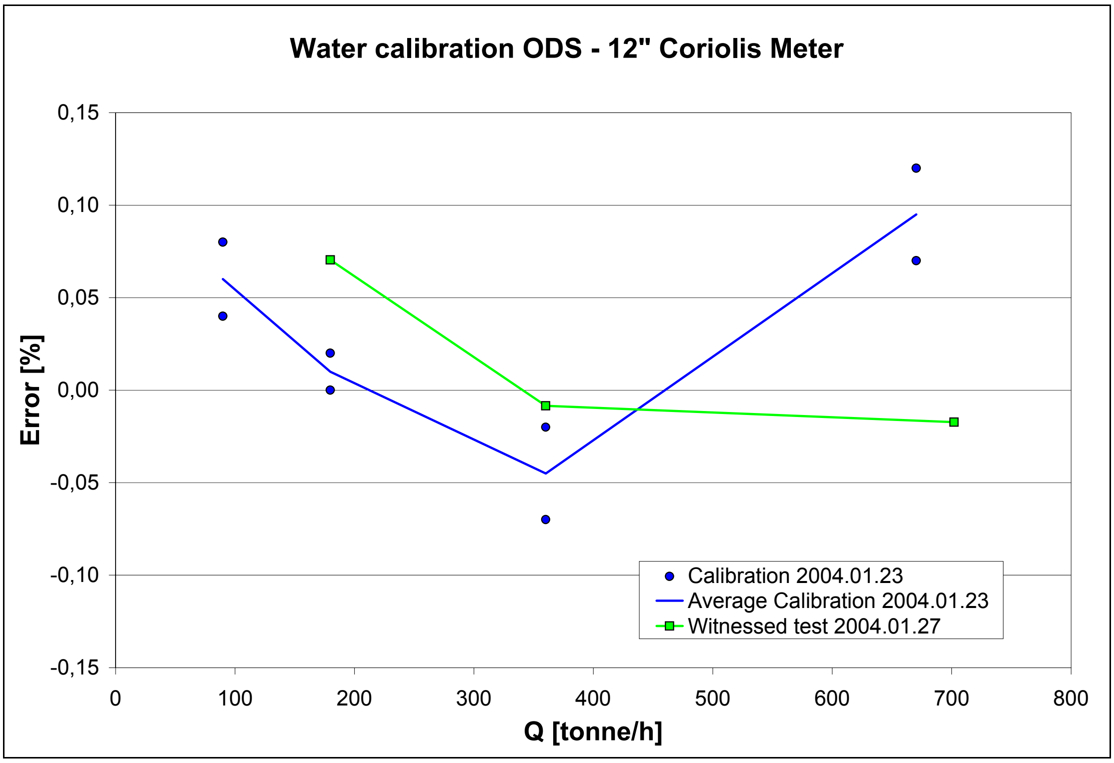

Figure 3 – Water Calibration at ODS of Rheonik 12” Coriolis meter

An acceptance to go ahead with the building of the metering station was then obtained from the NPD. The Coriolis meters would be put through normal FAT to demonstrate linearity (0.30% band) and repeatability (0.07% band) according to NPD requirements followed by a flow test of the metering skid.

FMC Kongsberg Metering was selected as system supplier in competitive bidding with several other qualified European suppliers. The Rheonik Coriolis meters were supplied by Håland Instrumentering in Stavanger see Figure 4.

Figure 4 – Rheonik 12” Coriolis meter without casing and 8” with casing

Technical information can be found at: www.rheonik.com/c.php/englisch/rheonik.rsys

5 FAT TESTS AT TRAPIL

Factory acceptance test (FAT) for the eight Coriolis mass flow meters from Rheonik was performed in January 2005 at Trapil in Paris in France, witnessed by the qualifying team (Hydro, Shell, Aker Kværner and NPD), the Norwegian meter supplier Håland Instrumentering, the system supplier FMC Kongsberg Metering and the manufacturer Rheonik. At Trapil the mass flow meters were calibrated against a volumetric reference, a uni-directional ball prover, see Figures 5 and 6. Using calculated volume flow and calculated density at meter conditions, reference mass flow was calculated.

Figure 5 – The test loop at Trapil with uni-directional prover

Figure 6 – Test setup for 12" and 8" Coriolis mass flow meters at Trapil

During this FAT only 3 meters out of 8 met the requirements – only just. The repeatability was good but most meters had very poor linearity.

As many as five tests of the Coriolis mass flow meters from Rheonik had to be performed at TRAPIL between January 2005 and February 2006, before all meters achieved acceptable linearity. A number of metering issues had to be addressed and a lot of additional testing performed before acceptable solutions were found.

A brief summary of the five tests at Trapil is given in Table 2. Detailed descriptions of the test results and metering issues are given in the next section.

Table 2 – Summary of five test periods at Trapil

Test 1	FAT. Only 3 meters out of 8 met the requirements. Questions asked about density correction and temperature effects. Corrective actions: Mechanical adjustment of 5 failed meters.
Test 2	Effect of adjustment verified on one 12" meter. Pressure effect documented. Corrective actions: Rheonik perform independent tests to determine pressure correction method.
Test 3	Retest of all 8 meters. 6 of 8 meters with linearity and repeatability within requirements. 1 meter needs further mechanical adjustment. 1 meter not tested, damaged during transportation. Flow dependant density effect verified. Test results and theoretical calculations demonstrates that significant improvement in linearity is possible by modifying internal algorithms in meter with respect to mass flow and density Corrective actions: Technical clarification meeting with Rheonik. Rheonik decided to implement improved algorithm for mass flow in their flow computer. Rheonik performed pressure testing at PTB. Rheonik established pressure correction equation and coefficient. FMC implements pressure correction in metering station control system. Pressure transmitters are added to metering station design. Rheonik looks into improving density correction. Improved density correction is expected to have less effect on linearity than improved algorithm.
Test 4	Retest of 2 remaining meters. Two meters tested with improved algorithm for mass flow. Considerable improvement in linearity at high flow rates. 1 meter still outside linearity requirement. Corrective actions: Upgrade the remaining 6 meters before flow test. All 8 meters to be retested after flow test.
Test 5a	Retest of all 8 meters. All 8 meters within linearity and repeatability requirements.
Test 5b	One 8" and one 12" meter tested with new density correction. Large improvement in linearity. Corrective actions: Upgrade all meters with new density correction before commissioning and start-up.

The extensive effort from all parties involved paid off. During the final test (5b) at Trapil extraordinary results like a linearity of 0.025% band was achieved for one 8" Coriolis master meter. Repeatability was never a problem and had been excellent during all the tests; usually well within the requirement of 0.07%. See Tables 3 and 4, and Figures 7 and 8 to see the step by step improvement in performance from test to test for both 8" master meters and 12" meters.

Table 3 – Improved linearity for an 8" Coriolis master meter during the tests at Trapil

Linearity band (Working range 5:1)					
Test 1	Test 2	Test 3	Test 4	Test 5a	Test 5b
0.690%	Not tested	0.238%	Not tested	0.109%	0.025%

Table 4 – Improved linearity for a 12" Coriolis master meter during the tests at Trapil

Linearity band (Working range 5:1)					
Test 1	Test 2	Test 3	Test 4	Test 5a	Test 5b
0.411%	Not tested	Damaged	0.125%	0.208%	0.113%

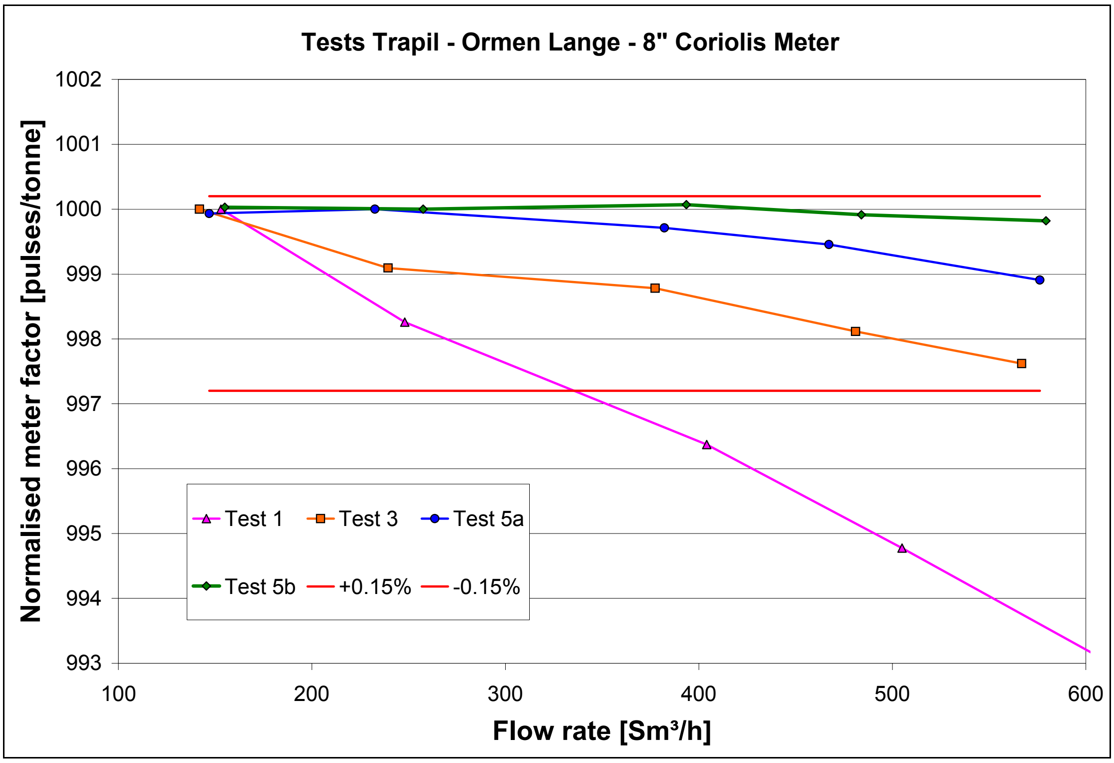

Figure 7 – Improved linearity for a 8" Coriolis master meter during the tests at Trapil

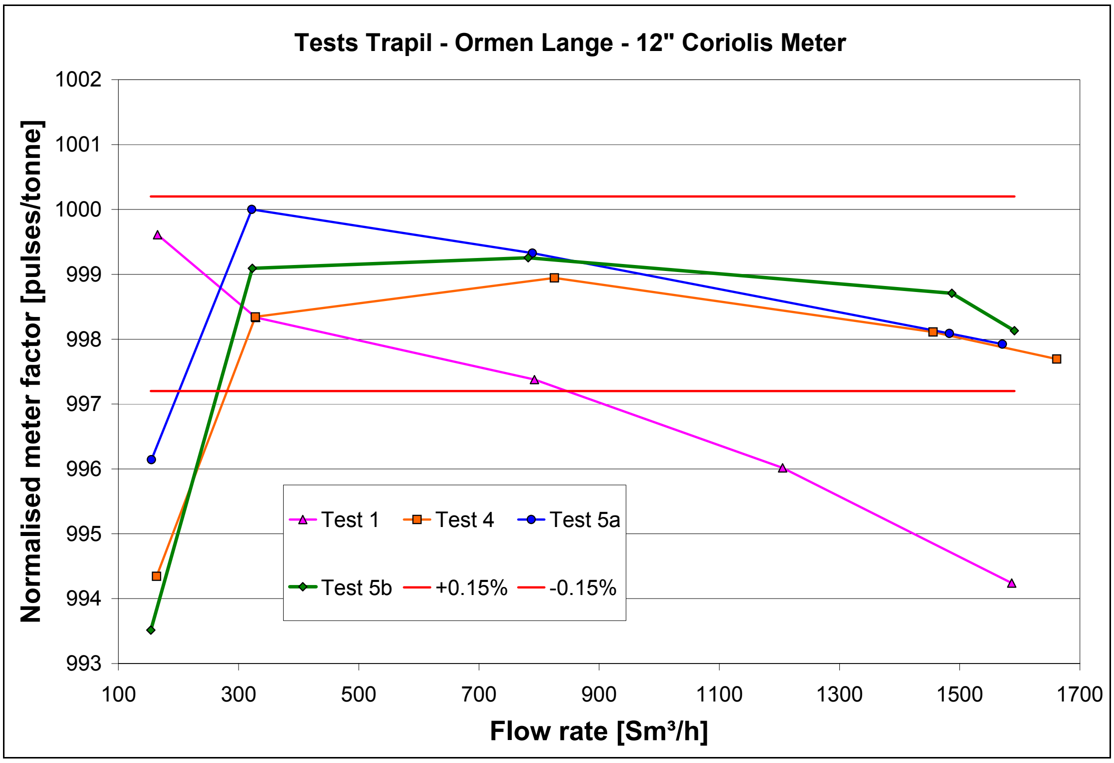

Figure 8 – Improved linearity for a 12" Coriolis meter during the tests at Trapil

6 METERING ISSUES AND IMPROVEMENTS

A number of metering issues were uncovered during the tests at Trapil in our search for improved linearity. Hydro and the rest of the qualifying team wanted as linear meters as possible especially the master meters. Therefore, we tried to identify all significant systematic effects and find satisfactory solutions for dealing with these effects.

This section describes the metering issues and the subsequent improvements that were made. The various additional tests performed by Rheonik to characterise the performance of the Coriolis meters with respect to pressure and density will be briefly covered. Most of the metering issues covered here will affect any design of Coriolis mass flow meter since everyone has to compensate for these effects.

6.1 Mechanical adjustments

During Test 1, only 3 meters met the requirements. To avoid cross talk the meters had been adjusted to different resonant frequencies. The nonlinearity seen was never before detected by Rheonik in this kind of meters and was not expected see Figure 9.

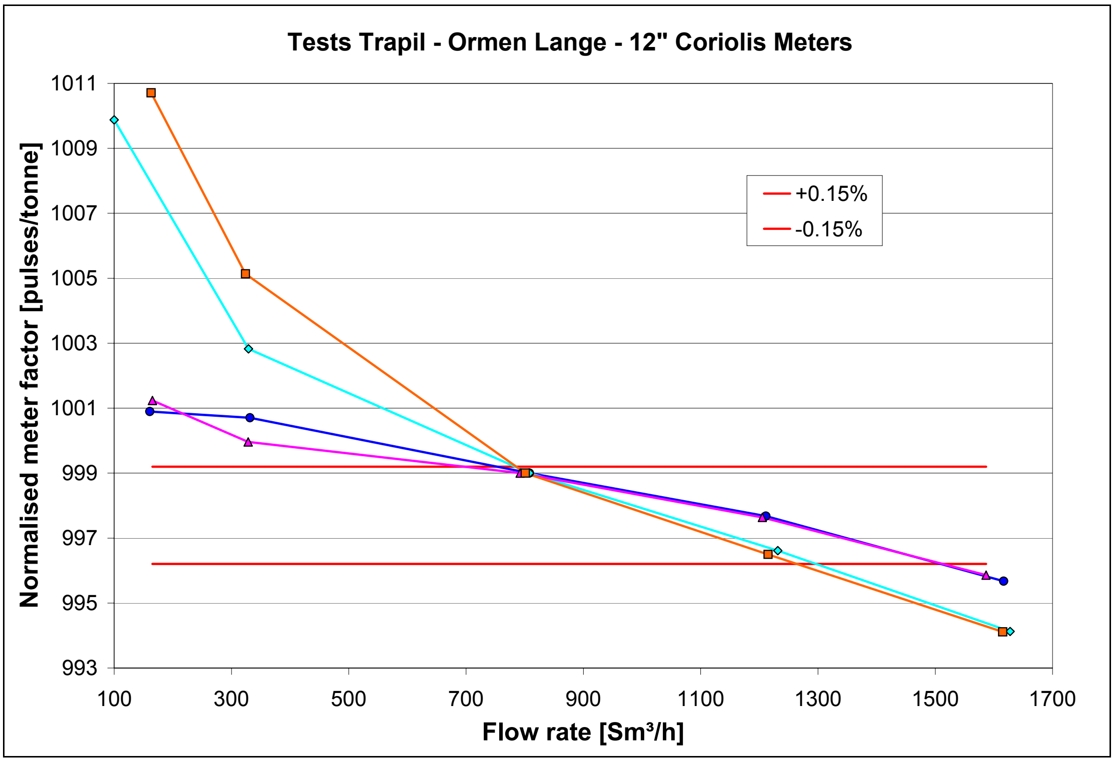

Figure 9 – 12" meters with poor linearity during Test 1

The resonant frequencies of the 5 meters that failed were mechanically adjusted by Rheonik to reduce the difference from a standard resonant frequency meter.

Test 2 at Trapil was then performed to verify the improvement on one meter see Figure 10. The results looked promising and Test 3 at Trapil was then performed to test the rest of the meters. However, this improvement alone had not solved all the linearity issues.

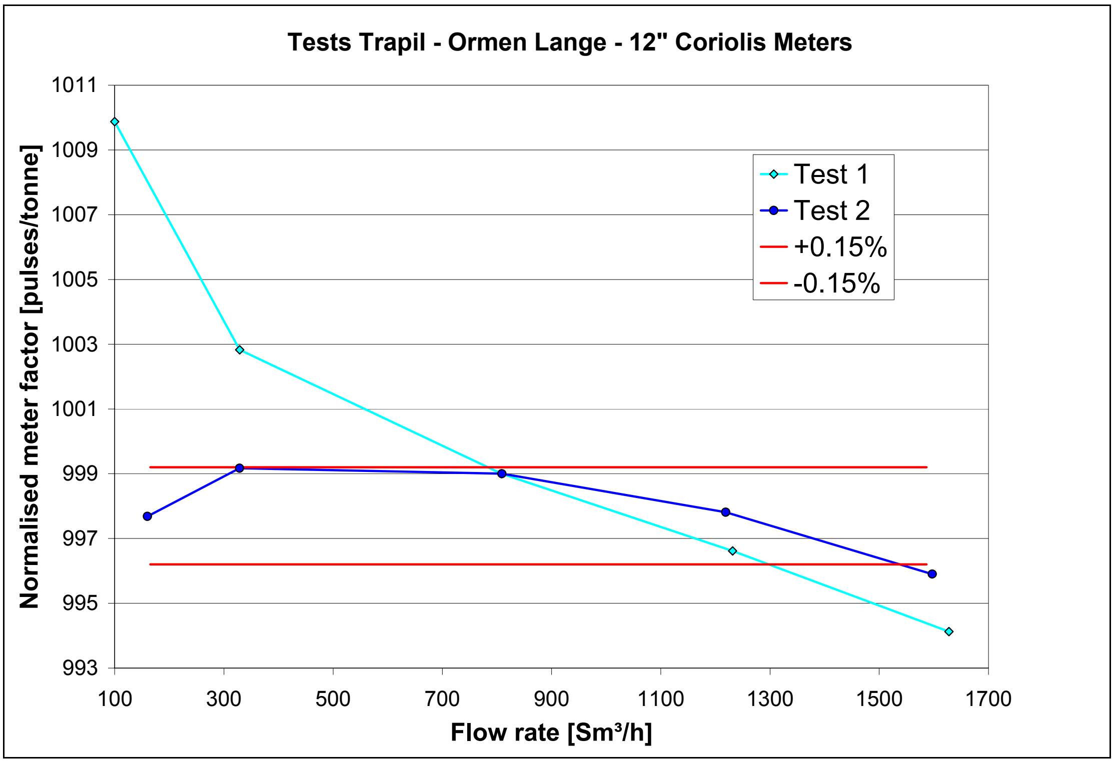

Figure 10 – 12" meter with improved linearity after adjustment

6.2 The effect of using an approximation for tan(X)

After testing several meters during Test 1 the meters appeared to have a systematic downward slope at high flow rates leading to poor linearity or linearity just barely within the requirement see Figure 11.

After Test 1 this effect was attributed to mechanical adjustments but the typical downward slope was still present during Test 3.

Together with NPD, Hydro looked into this effect during Test 3 and wondered if this might have anything to do with how the equations in the Rheonik flow computer had been implemented.

The mass flow, **Q**, of a Rheonik Coriolis meter is given by Equation 1.

$$Q = f(\omega) \cdot \tan(\frac{\varphi}{2}) \quad (1)$$

Where **φ** is the Coriolis phase shift in the Rheonik meter and **ω** is angular velocity.

The shape of the curves looked very much like an **X / tan(X)** curve see Figure 12.

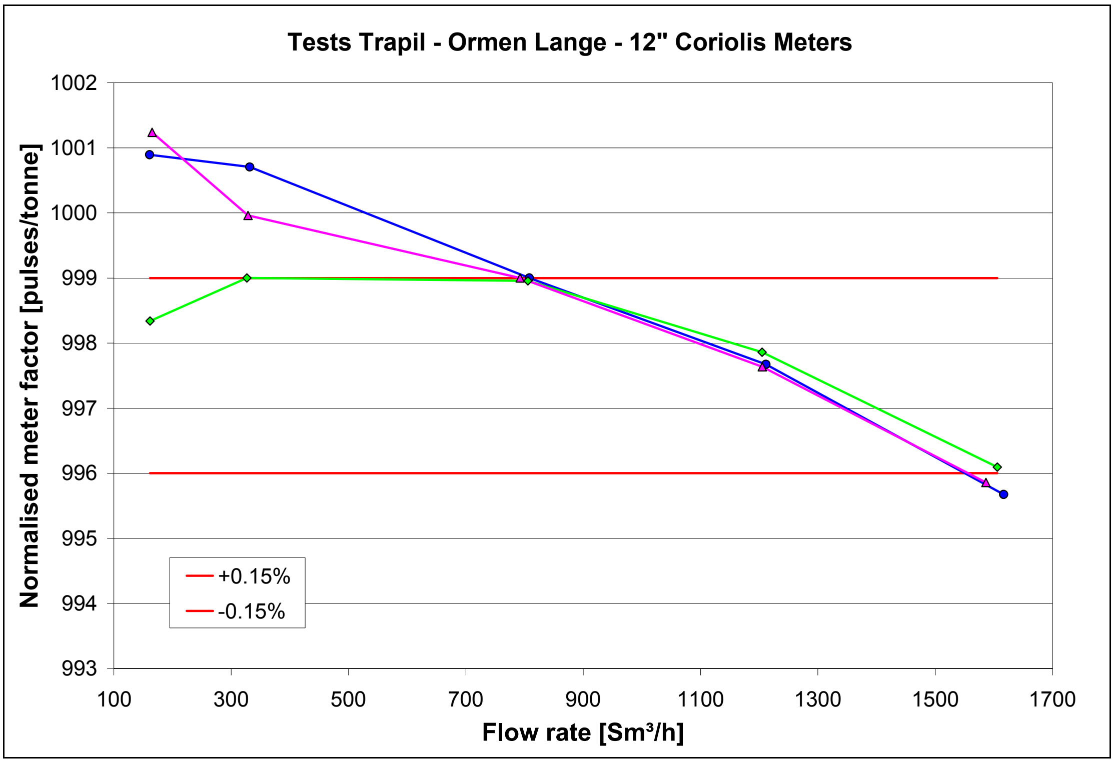

Figure 11 – Typical test results for 12" meters during Test 1

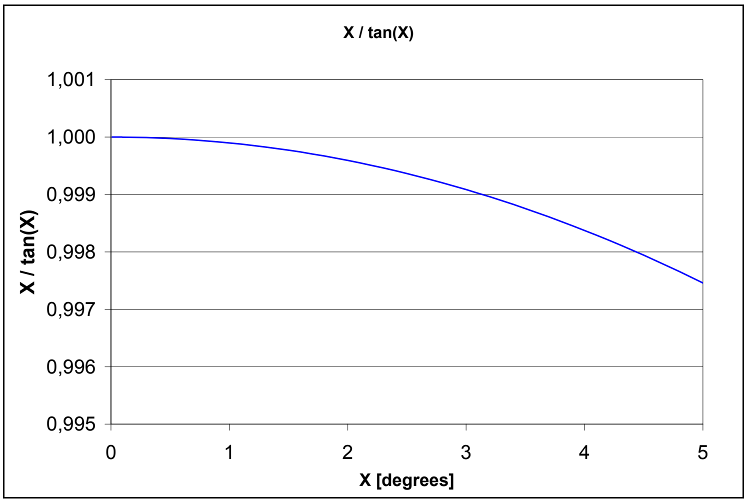

Figure 12 – X / tan(X)

Rheonik confirmed that the equation for phase shift was indeed implemented as a 1. order approximation **tan(X) ≈ X** but that in their experience this was a more than adequate approximation.

Rheonik was naturally cautious of these inquisitive Norwegians wanting details on how their meter worked in detail. We got Rheonik to estimate the Coriolis phase shift at maximum flow for both sizes meters to 7 degrees for 8" and 8.5 degrees for 12". We then simulated the effect by correcting the linearity curve using the exact values for **tan(X)** see Figure 13.

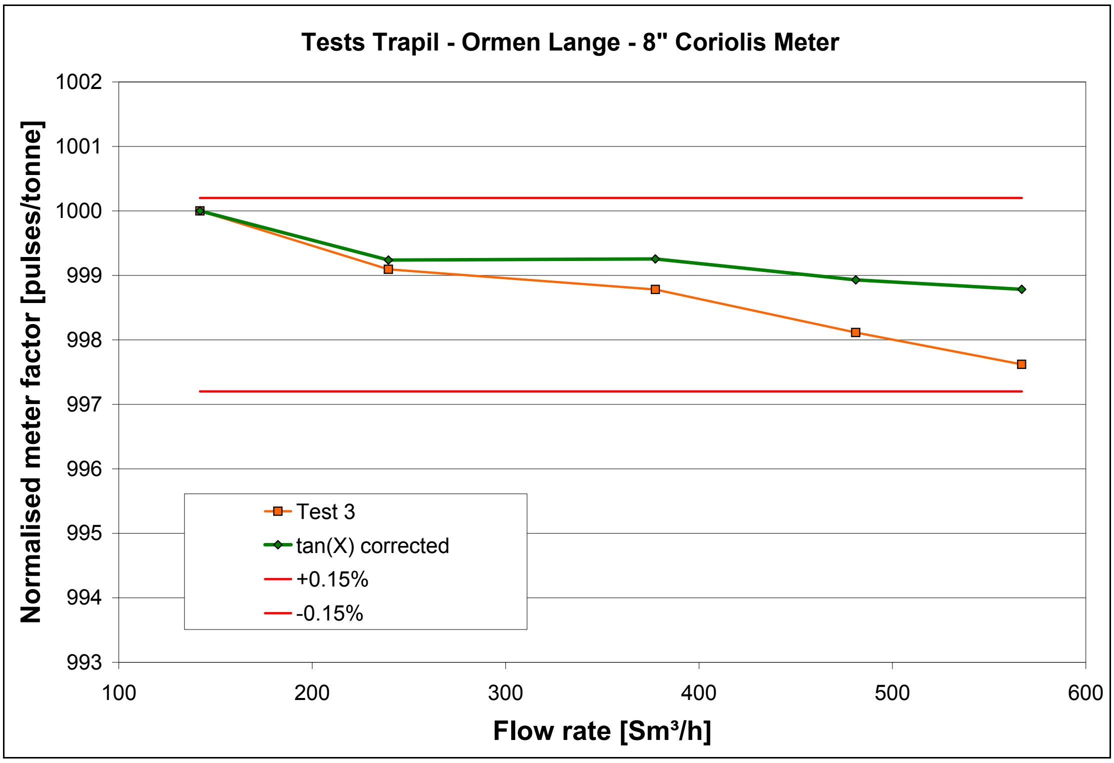

Figure 13 – Potential improvement to an 8" meter using tan(X) instead of approximation

This lifted the curve significantly and improved the linearity. There seemed to be a significant systematic error introduced by this 1. order approximation, more than 0.18% at maximum flow for a 12" meter and more than 0.12% at maximum flow for an 8" meter see Figure 14.

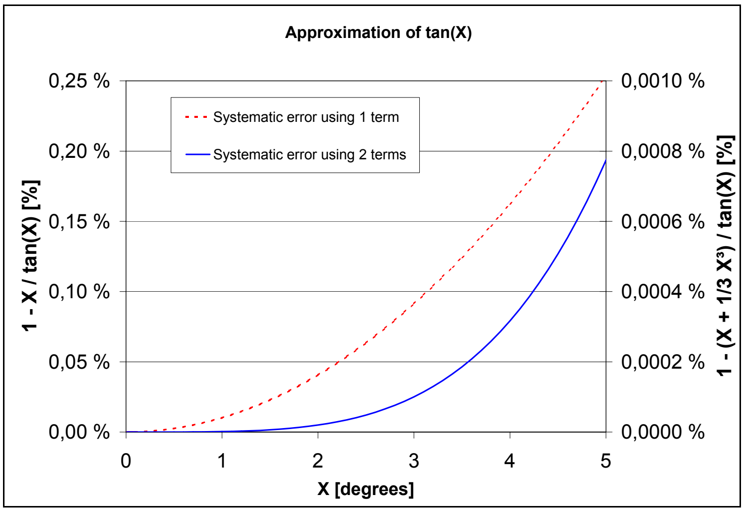

Figure 14 – Systematic error using approximation for tan(X)

At first Rheonik seemed surprised by this effect but seeing the large phase shifts at high flow rates (larger than normal / expected) they accepted that this could be a significant effect. The large phase shifts are due to the low density of the liquid increasing the resonant frequency and the Coriolis effect compared to water, combined with large size meters and large mass flow.

Since linearity requirements was not met during the first 3 tests we decided to have a technical meeting with Rheonik to discuss possible improvements to the linearity and among those changing how they implemented equations in their flow computer. Rheonik agreed to implement a more accurate approximation for **tan(X)** using the first 2 terms in the Maclaurin series for **tan(X)** see Equation 2.

$$\tan(X) = X + \frac{1}{3}X^3 + \frac{2}{15}X^5 + \frac{17}{315}X^7 + ... \qquad (2)$$

This is sufficient to eliminate the major part of the systematic error see Figure 14. The systematic error is now less than 0.0004% at maximum flow for a 12" meter (**X** = 4.25 degrees).

The mass flow of a Rheonik Coriolis meter is now implemented as indicated in Equation 3.

$$Q = f(\omega)\cdot\left[\frac{\varphi}{2} + \frac{1}{3}\cdot(\frac{\varphi}{2})^3\right] \qquad (3)$$

6.3 Pressure correction

A pressure dependency was detected and examined at Trapil during the first two tests. It was very difficult to determine the pressure effect during testing against a ball prover so the results were clear on effect but not on size. Between 5 and 12 bar the 12" meter showed a pressure dependency of approximately 0.14 %/bar compared to 0.03 %/bar for the 8" meter.

In order to eliminate the pressure sensitivity of the Coriolis meters external pressure compensation should be done in the flow computers according to Equation 4.

$$Q_{\mathrm{Corr}} = Q\cdot\left[1 - (P_{\mathrm{Cal}} - P_{Line})\cdot\frac{C_P}{100}\right] \qquad (4)$$

Where C_P is the pressure compensation factor [%/bar] for the Rheonik meter.

To further evaluate the pressure effect and to quantify C_P Rheonik performed tests in their own flow loop and at PTB. C_P was determined between 2 and 6 bar and is 0.0816 %/bar for an 8" Coriolis meter and 0.1617 %/bar for a 12" meter.

According to Rheonik the higher pressure sensitivity of the 12" meter is generated by the straight pipe section, which is implement in the top of the typical Rheonik Omega shape, in order to get the meter fabricated. Look closely at Figure 4.

The pressure correction is implemented in the metering stations flow computers and a pressure transmitter is added to each meter run.

6.4 Density correction

During Test 1 it was found that the density measured by the Rheonik Coriolis meter depended on the flow rate. At higher flow rates, the measured line density was increasingly higher than the calculated line density.

The error in density reading was +2 kg/m³ for an 8" meter and +4 kg/m³ for a 12" meter or +0.3% and +0.5% at maximum flow rates. Since the mass flow calculations in the Coriolis meters are internally density compensated, see Equation 5, the meters slightly underestimated mass flow at higher flow rates. This gave an estimated error in density compensation of -0.09% for an 8" meter and -0.12% for a 12" meter at maximum flow rates.

$$Q_{\mathrm{Corr}} = Q \cdot \left[1 + (\rho_{\mathrm{Cal}} - \rho_{Line}) \cdot \frac{C_D}{100} \right] \tag{5}$$

Where $\mathbf{C_D}$ is the density compensation factor [%/kg/m^3] for the Rheonik meter and $\boldsymbol{\rho}$ is the density.

In subsequent tests, the internal density compensation was turned "off". Rheonik decided to look into ways of correcting the density measurement in the internal algorithms of the meter.

The density effect is probably due to the "garden hose" effect. Being relatively thin walled meters the increasing flow rate "stiffens" the meters omega shape thus slightly shifting its resonant frequency.

During Test 5 Rheonik implemented a new additional internal density algorithm with a "Coriolis phase shift dependent density correction" in one 8" and one 12" meter in the form of Equation 6.

$$\rho_{\mathrm{Corr}} = \rho \cdot (a \cdot \varphi + b) \tag{6}$$

Where $\boldsymbol{\varphi}$ is the Coriolis phase shift in the Rheonik meter, $\boldsymbol{\rho}$ is the density and **a** and **b** are meter size dependant constants.

This improved linearity just as expected see curves "Test 5b" in Figures 7 and 8, giving the larger size Rheonik Coriolis mass flow meters a very good linearity.

6.5 Temperature conditioning

During testing at Trapil we noticed that the calibration curves for a newly installed cold meter would read high at low flow rates. When the low flow rate points were repeated at the end of the calibration test, when the flow had circulated through the meter for hours, they tended to drop down. We assumed this might be due to a large temperature gradient in the steal inside the meter and that this effect vanished as the steel inside the meter heated up.

Rheonik was asked for a recommendation on how the meters should be conditioned before starting a loading operation and came up with the following advice:

> *"For accurate measurement the system (sensor and transmitter) must be temperature stabilized. That means the difference between meter temperature and fluid temperature must be less than 4°C. That can be done by an external heat treatment or by circulating with the original fluid. The transmitter should be power raised for at least 60 min. All gas content should be removed. A "zero-point" recording should be done only under these stabilized conditions."*

The Ormen Lange metering station will consequently have both heat traced meters and the possibility to circulate the condensate through the metering station and back to the storage cavern prior to loading.

7 FLOW TEST IN ATHENS

The flow test of the metering station was performed in the skid manufacturer Metron's new fabrication plant in Magoula outside Athens in Greece, in November 2005. This was primarily a functional test of the metering skid to verify control system operations of valves, proving sequence etc. In addition, we wanted to verify the feasibility of on-site calibration of the master meters using transportable reference.

Con-Tech provided the transportable reference consisting of a turbine master meter, compact prover and a calibrated water can.

As expected, the flow test did have its hiccups. First, the transportable reference got lost for several days somewhere in Italy, finally arriving just in time for the test. Then, some pipe work in the flow loop was welded in *after* the skid had been thoroughly flushed. This introduced large amounts of impurities into the flow loop that caused a lot of trouble and delays during the flow test. Of course, we knew nothing about this at the start of the flow test.

The flow test started with "calibration" of the master meters on water. Unfortunately, master meter calibration results were not reproducible. After days of testing and a lot of detective work, this was found to be caused by particles in the flow loop. Con-Tech's turbine meter when removed was literally covered with paint scraps, welding beads, rust etc. A filter basket was provided by Metron and fitted in front of the transportable reference. See Figure 15 showing the inside of the filter basket filled with particles.

Figure 15 – Things that should not be inside you pipes during a flow test

While cleaning up the flow loop, the proving tests of the five 12" mass flow meters against the three 8" master meters were performed.

All proving tests were successful; achieving accepted new meter factors in 5 trials for all 5 meter runs, again demonstrating good repeatability. Everything functioned as planned and in the end, even on-site calibration of master meters was demonstrated with good results. Although not part of the flow test, the master meters achieved linearity of 0.196%, 0.275% and 0.330% band on water (with particles).

See Figure 16 for some photos of the Coriolis skid and test setup.

(a)

(b)

(c)

(d)

(e)

(f)

Figure 16 – Photos from flow test in Athens
a) Condensate skid with flow loop connected
b) A very compact skid
c) Meter runs with 12" Coriolis meters
d) Meter runs with 12" Coriolis meters seen from the side
e) 8" Coriolis master meters seen from the side
f) Master meter calibration using a transportable reference

8 CONCLUSIONS

Hydro has qualified a novel liquid export metering station design based on large Coriolis mass flow meters and Coriolis master meter proving for fiscal use in Norway, with very good results.

The extensive testing activity resulted in significant improvements to the internal measurement and compensation algorithms in the Rheonik Coriolis mass flow meters and some changes in the metering station design and in the flow computers.

The larger size Rheonik Coriolis mass flow meters now have a very good linearity. Extraordinary results like a linearity of 0.025% band was achieved for one 8" Coriolis master meter. Repeatability was excellent during all the tests; usually well within the requirement of 0.07%.

Hydro considers the compact simplified metering station design to be a large improvement and believe this is how numerous liquid fiscal metering stations will be designed in the future. Hydro also expects the design to significantly reduce operating costs.

9 ACKNOWLEDGMENT

I wish to thank the qualifying team, the metering system supplier, the Norwegian Coriolis meter supplier and the Coriolis meter manufacturer for the collective effort in making this qualification successful.

9 REFERENCES

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