CORIOLIS FLOW METERS - CALIBRATION APPROACH FOR CRYOGENIC APPLICATIONS
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A Report for

EMRP ENG-03 LNG Project

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1 Introduction

This report is made for the research project ‘Metrology for LNG’. This project is part of the European Metrology Research Programme (EMRP) which is jointly funded by the European commission and participating countries within Euramet and the European Union. The objective of this project is to improve the uncertainty associated with the calculation of LNG energy transfer by developing new techniques and methods.

This will be achieved by looking at the complete LNG custody transfer process including volume and composition measurements along with density and gross calorific value calculations. Detailed description of all work packages and tasks within each work package (WP) is found in the Joint Research Project (JRP) Protocol [1]. In addition to Measurements of LNG volume by tank gauging methods, measurement of volumetric and mass flow rates using ultrasonic and Coriolis flow meters are investigated in this project. These flow metering technologies have been found to be suitable for measurement of LNG [11].

This report presents results from a test programme designed to gather data from Coriolis flow meters in order to explore their application to LNG flow measurement. This will be carried out by assessing the cryogenic correction models that are used in the transfer of a standard factory calibration with water at ambient conditions to cryogenic conditions. The work was carried out in collaboration with three flow meter manufacturers.

Coriolis mass flow meters are currently used across all industries for liquid, gas and cryogenic flow and density measurement applications. The international Organization of Legal Metrology (OIML) sets the standards of performance for fiscal measurement equipment [2].

Coriolis mass flow measurement has been widely applied in the distribution and delivery of natural gas. Large sized units are used to monitor and control flows in the re-gasification processes at LNG terminals, and monitor LNG transfers around the terminals. Smaller sized units are used to monitor local deliveries to CNG-powered vehicles, from the fuel dispensers at their depots. Due to the absence of cryogenic calibration facilities, Coriolis flow meters are normally calibrated at ambient condition with a process fluid such as water and corrections are then applied to account for cryogenic conditions. There is therefore a requirement to independently check the applicability of this calibration approach.

Testing experience with cryogenic fluids showed that the Young’s modulus of elasticity of stainless steel used in the Coriolis meter tubes has a (non-linear) dependence on temperature, causing a calibration shift. It is claimed that, when the temperature-dependent calibration shift is allowed for, standard factory calibrations at ambient conditions can be transferred to operation at cryogenic temperatures [2]. Similar conclusion has also been reported in [9]. The aforementioned work has set the foundation for development of a procedure for transferring standard factory
calibrations at ambient conditions to operation at cryogenic temperature. However, a reliable and generalised procedure requires gathering test data from flow meters of different make and size in order to investigate its applicability to LNG.

Until very recently, the NIST cryogenic flowmeter calibration facility was the only independent facility of its kind in the world, and it has been used by many manufacturers to address the above issue. However, this facility allows testing with liquid nitrogen only. A new facility of similar size has been developed by VSL, the Dutch Metrology Institute, during the last three years under this EMRP-LNG project in order to overcome the limitation of NIST facility by allowing testing with LNG as well as liquid nitrogen. The other objective of this facility is to reduce the uncertainty associated with flow meter calibration. Despite size limitation, the VSL facility will set the ground for building a mid-scale facility in the near future. The knowledge and experience gained from these two facilities will aid the construction of large scale industrial facility in the future.

The work presented here adds to the previous work by providing more cryogenic test data for Coriolis flow meters from different manufacturers. This helps to meet the growing demand for building more confidence in the claimed accuracy and performance of this technology for cryogenic flow measurement.

In this EMRP project, it was intended to develop a similar calibration approach for ultrasonic flow meters; however, due to difficulty in obtaining test flow meters combined with lack of cryogenic test facilities for the size of meters used in LNG industry, it was not possible to undertake this activity under the current EMRP project for LNG. It was therefore decided to focus effort on Coriolis meters and plan work for ultrasonic meters in a future project.
2 Calibration approach for cryogenic applications

Coriolis flow meters have been used commercially since the late 1970s, although designs based on the Coriolis principle have been reported since the early 1950s [3]. They are capable of accurately measuring mass flow rate for most single phase fluids. Modern flow meters are normally claimed to have an accuracy of \( \pm 0.1\% \) or better when calibrated at reference conditions.

In a Coriolis flowmeter, the primary part is a (flow) sensor consisting of one or more measuring tubes and a supporting structure. The measuring tube is normally driven at one of its resonant frequencies with minimum energy consumption. The amplitude of the vibration is very small, typically a fraction of a millimetre. On both the inlet and outlet sides of the measuring tube, there are also motion sensing devices, for example electromagnetic coil and magnet devices, to detect vibration signals. When the fluid is passing through the sensor, it is accelerated by the measuring tube through the Coriolis effect which is perpendicular to both the flow and rotating directions. Coriolis accelerations on the inlet and outlet sides are opposite to each other, which can create phase difference between the vibration signals. In the sensor, there are also other temperature and strain sensing devices.

Within a certain limit of the fluid velocity, the time delay between vibration signals can be regarded as linearly proportional to mass flow rate. In practice, because it is impossible to obtain a perfectly symmetric structure in terms of its dynamic properties (mass, stiffness and damping), a small time delay between inlet and outlet motion sensing devices usually occurs even when there is no flow. Thus a zeroing procedure is normally required, preferably under a condition similar to the measurement condition. The final signal used for measuring mass flow rate is, therefore, the time delay with flow subtracting the zero value when there is no flow. In addition to flow rate measurement, fluid density can also be measured using the driving frequency.

As one of the major traditional commercial designs, twin tubes bent into a ‘U’ or other shapes are used for the sensor. The fluid coming from the inlet process pipe splits equally between the two parallel measuring tubes. The tubes are caused to vibrate perpendicular to the plane of the bent shape like a tuning fork. There are also other commercial designs, such as single or twin straight tube flow sensors [4, 5], which have their intrinsic advantages, such as compactness, low pressure drop, self-draining, etc. For cryogenic applications, bent tube designs are suitable because thermal stresses created from temperature changes are low and within the material limit. However, straight tube designs have also been tested with success in cryogenic applications.

To measure mass flow rate, the flowmeter is normally calibrated in the factory against a weigh standard at the reference condition, for example using water at ambient conditions. This provides a single flow calibration factor which relates time delay to mass flow rate. It is known that the Young’s modulus of the measuring tube can affect this flow calibration factor, since the Young’s modulus of a material changes with
temperature. It is, therefore, necessary to provide another flow correction factor to compensate the change of fluid temperature. This can be done through individual calibration or default material data.

In a flow meter design with straight measuring tubes and mechanical oscillating system arranged in a support tube, a temperature gradient between the support tube and oscillating system (dynamic temperature changes and different thermal coefficients of expansion) may exist. These temperature induced influences affect the behaviour of the mechanical oscillating system and result in temperature induced error to the measured mass flow rate. These errors are compensated for by measuring the temperature of the support tube and the temperature of the mechanical oscillating system and these temperatures are fed into a special correction circuit to correct the measured signal and thus the mass flow rate.

To measure density, two density calibration factors are determined in the factory using air and water data. Similar to flow measurement, density correction factor is also needed to compensate the change of fluid temperature.

Current industry practice is to calibrate the flow meter with water at both room and elevated temperatures to ensure the best accuracy for a wider temperature application. Temperature correction factors for both mass flow and density measurements are stored in the flow meter. These correction factors are typically based on the well known relationship of Young’s modulus versus temperature as shown in Figure 2-1. Therefore, these correction factors typically are based on some polynomial of the temperature reading. Note that the Young’s modulus is fairly linear to temperatures down to, say, 150 K. For lower temperatures the Young’s modulus is clearly nonlinear.

![Figure 2-1 Young Modulus of three types of stainless steel](Source: J.Appl.Phys., Vol. 52, No. 3, March 1981).
3 Test flow meters

Details of flowmeters tested in this work are listed in table 1. Three meters have twin bent tube configuration and one meter has twin straight tube configuration.

Since the purpose of this project is to review, validate and improve the calibration approach currently adopted by industry, the performance of these flow meters is not directly compared and their identities are therefore kept anonymous.

<table>
<thead>
<tr>
<th>Test Flow meter</th>
<th>Size [“]</th>
<th>Meter Flow range, [kg/s]</th>
<th>Temperature range [°C]</th>
<th>Pressure range [bar]</th>
<th>Claimed Accuracy (full scale) [%]</th>
<th>Zero point stability, [kg/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2</td>
<td>1 to 24</td>
<td>-240 to 204</td>
<td>up to 108</td>
<td>within ±0.35</td>
<td>&lt;0.002</td>
</tr>
<tr>
<td>B</td>
<td>2</td>
<td>1 to 13</td>
<td>-240 to 200</td>
<td>up to 100</td>
<td>within ±0.30</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>C</td>
<td>2</td>
<td>1 to 24</td>
<td>-240 to 204</td>
<td>up to 108</td>
<td>within ±0.35</td>
<td>&lt;0.002</td>
</tr>
<tr>
<td>D</td>
<td>2</td>
<td>1 to 9</td>
<td>-180 to 230</td>
<td>up to 200</td>
<td>within ±0.20</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Flow meter D was tested previously in another project [9] and the data was made available to this project. A successor of this flow meter (same make and model but with newer electronics) was made available to the EMRP project. Hence, actually two different meters have been used for the measurements indicated for meter D.

It can be seen that all test flow meters were 2” in size as the cryogenic test facilities employed in this work are limited to this flow meters size and the flow range that can be covered.
4 Test programme

The main objective of the test programme is to assess the transfer of a standard factory calibration with water at ambient conditions to operation at cryogenic conditions.

An ideal test programme was planned as given below. However, depending on prevailing circumstances during the project, this sequence was not necessarily followed for all flow meters:

1. Calibrate the flow meter with water at ambient temperatures (e.g. 20°C)
2. Calibrate the flow meter with liquid nitrogen, typically at temperatures around -193°C.
3. Calibrate the flow meter with LNG, typically at temperatures around -161°C.
4. Repeat the testing with water in order to establish reproducibility of measurements and check that the exposure of the flow meter to very low temperatures has not affected the performance of its sensor.

The following table gives an overview of tests performed for each flow meter and the institute carried out the test.

<table>
<thead>
<tr>
<th>Test Flowmeter</th>
<th>Water flow range, kg/s &amp; (Institute)</th>
<th>Liquid Nitrogen flow range, kg/s &amp; (Institute)</th>
<th>LNG flow range, kg/s &amp; (Institute)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1 to 12 (VSL)</td>
<td>1 to 9 (NIST)</td>
<td>1 to 4.7 (VSL)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 to 5 (VSL)</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>1 to 4 (third party)</td>
<td>Not tested</td>
<td>1 to 4.7 (VSL)</td>
</tr>
<tr>
<td>C</td>
<td>1 to 16.4 (JV)</td>
<td>Not tested</td>
<td>4.3 (JV)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1 to 4 (VSL)</td>
</tr>
<tr>
<td>D(^1)</td>
<td>1 to 9 (NEL)</td>
<td>1 to 9 (NEL/NIST)</td>
<td>1 to 4 (VSL)</td>
</tr>
</tbody>
</table>

Because the calibrations have been performed at various labs, the calibration procedures have not been completely the same. However, the following approach has typically been followed.

The flow meter zero was set for the current testing conditions (ambient or cryogenic). This was achieved by closing the two valves upstream and downstream of the flow meter.

\(^1\) Actually two different meters have been used for the measurements indicated for meter D; the meter used for the tests for LNG is of the same make and model, however a successor of the meter that has been used for the calibrations with water and LIN.
For a short time to avoid any liquid boiling. No further change was made to its value during subsequent tests. However, for flow meter D, the zero was set for ambient conditions. At cryogenic conditions, the zero value was monitored and recorded before and after each test in order to monitor its shift from the stored value. Note, the various procedures for zeroing the meter together with the zero stability may attribute to a small discrepancy for low flow rates (worst case scenario is 0.1% for 1 kg/s). It was observed that the zero stability was much better for LNG than for LIN.

For water, the flow meters have been calibrated between 10% and 50% of full scale (100% for flow meter D). For LIN, flow meter A has been calibrated up to 40% and flow meter D up to 100% of full scale. For LNG, flow meters A and C have been calibrated up to 20% and for flow meter B and D up to 36% and 44% respectively. In the table of Section 3 the range of the various meters is shown, in the table of Section 4 the tested flow rate range is shown.

Each flow rate was taken multiple times to assess the repeatability of the measurements. The whole test was then repeated 4 times. Tests were typically performed over multiple days. For flow meter D, an additional set of data was taken at cryogenic conditions to check the flow meter performance when its insulation jacket is removed. This test is essential to explore the influence of ambient heat gain on the performance of the meter and importance of using thermal insulation.

The measured values of mass flow rate, density and temperature from the flow meter were collected in addition to the reference flow rates and physical property data from the calibration rigs. There were no statistical evaluations done to observe any pressure, temperature or thermal cycling dependencies.
5 Test facilities and calibration procedures

5.1 Water Calibration Facilities (VSL, NEL, JV)

In this section the water calibration facilities are described. However, because water calibration facilities are relatively straightforward, only one facility is shown here (NEL facility, see Figure 5-1).

![Diagram of NEL gravimetric test facility](image)

Figure 5-1 Schematic diagram of NEL gravimetric test facility.

For all labs, the flow meter was calibrated by comparison of the output value with the value derived from a reference gravimetric weighing system. The method used was a diversion technique where the flow was continuous and diverted into the chosen weight tank for the duration of the test.

The flowrate was calculated using the time taken for the quantity of fluid to pass through the meter. All measurements are fully traceable to Dutch, Norwegian or UK National Standards.

The percentage error or meter deviation was calculated for the indicated totalised mass ($M_i$) from the device under test with respect to the reference totalised mass ($M$):

$$\text{Percent Deviation} = \frac{M_i - M}{M} \times 100$$  \hspace{1cm} (1)

The same approach was used to calculate the percentage error in measured density.
The uncertainty estimates quoted are expanded uncertainties based on a standard uncertainty multiplied by a coverage factor $k=2$. This provides a level of confidence of approximately 95%.

Using the test method outlined, the uncertainty in the measurement of the reference quantity of fluid passed through the flow meter under test is estimated to be 0.1 percent or better for mass flow rate and 0.02 percent or better for density.

### 5.2 LNG/Liquid Nitrogen Test Facility at VSL

A schematic picture of the measurement set-up of VSL for cryogenic liquids is displayed in Figure 5-2. It consists of a 1 m$^3$ storage tank, a cryogenic pump, the flow meter under test and a 0.5 m$^3$ tank placed on a mass balance. The pump drives the cryogenic liquid from the 1 m$^3$ storage tank through the meter under test (MuT) to the weighing tank. In order to obtain stable flow conditions at the MuT position (temperature, pressure and flow rate), the flow is initially circulated from the 1 m$^3$ storage tank through the MuT back into the storage tank. When the conditions are considered stable, the flow is diverted to the weighing tank using a set of fast valves. When the weighing tank is nearly full, the flow is diverted back to the storage tank.

The cryogenic liquid is kept under subcooled conditions to prevent two-phase flows. This is accomplished by pressurizing the system up to 3 bar(g) to raise the boiling point. After some time of operation, the liquid temperature will have increased and be in equilibrium with the elevated pressure. When this happens the liquid is cooled down again by depressing the system to ambient pressure. Thereafter the cycle starts all over again.

The totalized flow over the period between the start and stop time stamps is compared with the weight accumulation in the weighing tank. As vapor is replaced while filling the weighing tank, the accumulated mass needs to be corrected for this loss in mass. This mass is measured using a specially designed gas flow meter in the vapor return line. The uncertainty in the total (corrected) mass is estimated to be better than 0.2% [10]. The deviation is computed with Eq. (1).

Typically, the flow meters are calibrated at different flow rates; namely; 1, 2, 3 and 4 kg/s. At each flow rate, two successive calibrations (batches of roughly 100 kg of LNG) are performed. The LNG is then pumped back to the main tank by pressure difference between the weigh tank and the main storage tank. This process is repeated until at least five reliable measurements of current test flow rate is achieved. This allows assessment of flow meter repeatability at each test flow rate. The whole process is repeated for the next test flow rate until all flow rates are competed. The reproducibility of the whole calibration is then tested by repeating the calibration at a different day.
Although the principle and measurement procedure are the same for the calibrations for LIN and LNG, there are two substantial differences between these calibrations. First, because of a poor pump performance, the pump has been replaced with an improved model after the LIN calibrations where finished. Second, pressure control for the LNG calibrations was much more effective than for the LIN calibrations. This is because both LNG and LIN have been pressurized with Nitrogen. Because of the different boiling temperatures, the Nitrogen will condense at the LIN interface, however not at the LNG interface. Because of these two effects, pressure and flow rate stability were much better for the LNG compared to the LIN calibrations. This may be reflected in a better reproducibility for the LNG flow meter calibrations.

Finally, there is an important difference to the set-up of VSL compared to set-ups of NIST (Section 5.3) and JV (Section 5.4) regarding the insulation of the flow meters. In the VSL facility, the flow meters are additionally insulated by placing them in a so-called cold-box that is filled with Perlite. The test set-ups of JV and NIST do not make use of this additional insulation. Therefore, it is anticipated that the ambient heat gain is less for the VSL calibrations than for the NIST and JV calibrations.

5.3 Liquid Nitrogen Test Facility at NIST

The NIST Liquid Nitrogen Flow Calibration Facility is shown schematically in Figure 5-3. Liquid nitrogen is circulated throughout the closed loop by a variable-speed centrifugal pump. The liquid flows through the subcooler, which is a heat exchanger consisting of a finned tubes submerged in a nitrogen bath. The subcooler removes the thermal energy added to the system due to pumping and ambient heat leak. The temperature
of the liquid nitrogen in the flow loop is controlled by adjusting the liquid level and the vapour pressure in the subcooler tank. Some of the test fluid can be diverted around the subcooler, if necessary. The fluid then passes through a loop with vacuum-jacketed piping, through the test section, and into the weigh/catch tank system which constitutes the reference measurement system.

![Schematic of the Liquid Nitrogen Flow Calibration Facility at NIST](image)

The flow system is pressurised with helium to prevent the liquid nitrogen from boiling. The nitrogen is always subcooled by 10 to 15 K. Helium absorbed in the liquid nitrogen is claimed not to exceed 0.5 mole percent, according to data by DeVaney, Dalton, and Meeks [6]. No test points are taken if evidence of bubbles is detected visually through a sapphire inspection window located downstream of the flow meter being tested.

The overall uncertainty in the measurement of totalized mass is estimated by NIST to be 0.17% (k=2) [7] and [8]. This uncertainty statement applies to the measurements made within a flow range of 0.95 to 9.5 kg/s which covers the flow range of the test flow meters described above.

During the tests, the temperature is typically controlled at about 80 K whereas pressure can be controlled between about 5.6 and 7.4 bar. The flow meter mass and density errors were calculated using equation 1 above.
5.4 LNG Road Tanker Setup at JV

The LNG road tanker set-up is described in this section. The key element is that the unloading of an LNG road tanker occurs through the meter under test. The difference in mass of the road tanker before and after unloading is the reference to calibrate the meter under test. The weighbridge is traceable to Norwegian National Standards. The uncertainty is estimated to be better than 0.2%.

![LNG production facility at Kollsnes, weighbridge at Laksevågneset and refuelling station at Haukås. Kollsnes – Haukås is about 70 km.](image)

The LNG production facility where the road tanker is filled is located at Kollsnes, close to Bergen on the west coast of Norway. The receiving terminal where the LNG is transferred from the road tanker to a storage tank is located at Haukås approximately 70 km by road east of the production facility location. The weighbridge is located on the route between the LNG production facility and the LNG receiving terminal. A total of 5 reproduced tests were completed.

For the tests the road tanker is first filled at the production location at Kollsnes after which the complete mass of road tanker and LNG is measured using the weighbridge at Stena Recycling. After weighing the road tanker, the LNG cargo is transferred to the storage tank at Haukås LNG terminal. The flow meter under test is mounted in the transfer line between the road tanker and the terminal storage tank. The flow rate is approximately constant throughout the transfer at 4.3 kg/s. When the LNG transfer is complete the mass of the road tanker is measured again using the same weighbridge at Stena Recycling. The mass difference before and after unloading is compared to the totalized mass indicated by the flow meter.

A step by step description of the test procedure is:

- Mass of road tanker with LNG is measured using weighbridge at Stena Recycling.
– LNG is transferred from the road tanker to the storage tank at the Haukås terminal through meter and the indicated mass from the flow meter is noted.

– The empty mass of the road tanker is measured with the weighbridge at Stena Recycling.

– The meter deviation is calculated with Eq. (1).
6 Results and discussion

In this chapter the results for the water, LIN and LNG calibrations are shown and discussed. In Sections 6.1 to 6.4 the results for flow meters A to D are shown, whereas in Section 6.5 these results are further discussed.

6.1 Results for flow meter A

6.1.1 Calibration with water at VSL
Meter A was calibrated in the VSL calibration facility described in Section 5.1. The results of this calibration test are shown in Figure 6-1. All test data show measurement accuracy well within the claimed accuracy of the meter and most data fall within accuracy of ±0.05%.

![Figure 6-1 Flow meter A Mass Error, water (VSL).](image)

6.1.2 Calibration with liquid nitrogen at NIST
Flow meter A was also calibrated in the NIST facility described in Section 5.3. Two tests were performed at two different days to check reproducibility of results. These results are shown in Figure 6-2. The mean meter deviation falls within the claimed accuracy for cryogenic application, except for the lowest flow rate. However, note that the meter under reads for flow rates tested.
6.1.3 Calibration with liquid nitrogen at VSL

Flow meter A was also calibrated for LIN in the VSL facility described in Section 5.2. Tests were performed at various days to check reproducibility of results. These results are shown in Figure 6-3.

![Figure 6-2 Flow meter A Mass Error, liquid Nitrogen (NIST).](image1)

![Figure 6-3 Flow meter A Mass Error, liquid Nitrogen (VSL).](image2)
In contrast to the calibrations performed at NIST, the flow meter does not perform within its specifications. Further, there is a significant spread in the calibration results. These two effects could be attributed to either the flow meter or the calibration standard. As will be discussed in the next section, this flow meter shows a huge deviation for LNG, indicating a very strong dependency on the temperature. However, as discussed in Section 5.2, the pressure and flow rate stability is significantly less when working with LIN than working with LNG. Therefore, the LIN calibration results for flow meter A are discarded and not discussed further.

6.1.4 Calibration with liquid natural gas at VSL
Flow meter A was also calibrated for LNG in the VSL facility described in Section 5.2. The tests were performed at various days to check reproducibility of results. These results are shown in Figure 6-4. The mean meter deviation is much greater than its claimed accuracy. These results have been discussed with the manufacturer; however there was no satisfactory explanation found that could cause this significant deviation². The calibrations for water for this meter were repeated after the LIN calibrations, however there was no significant difference found compared to the first calibration with water.

² Remark, the meter tested was somewhat older than the other meters. However, this should not be an explanation for the large deviation found.
6.2 Results for flow meter B

6.2.1 Calibration with water (third party)
Meter B was calibrated for water by a third party (no direct traceability to SI standards). The results of this calibration test are shown in Figure 6-5. All test data show measurement accuracy well within the claimed accuracy of the meter and most data fall within accuracy of ±0.05%.

![Figure 6-5 Flow meter B Mass Error, water (third party).](image)

6.2.2 Calibration with liquid natural gas at VSL
Flow meter B was also calibrated for LNG in the VSL facility described in Section 5.2. Tests were performed at various days to check reproducibility of results. These results are shown in Figure 6-6. These results show that the flow meter measures LNG flow rate somewhat outside the specified accuracy of ±0.3%, i.e. the maximum deviation is -0.5%. Further, the flow meter under reads for all flow rates.
6.3 Results for flow meter C

6.3.1 Calibration with water at JV
Meter C was calibrated in the National Standards Water Flow Measurement Facility at JV described in section 5.1. The result of this calibration test is shown in Figure 6-7. All test data show measurement accuracy within the claimed accuracy of the meter (0.1%).
6.3.2 Calibration with liquid natural gas at JV
Flow meter C was also calibrated for LNG by JV with the road tanker set-up described in section 5.3. A total of 5 reproduced measurements were carried out. The test results for a flow rate of approximately 4.3 kg/s are presented in Figure 6-8.

From Figure 6-8 it can be seen that also flow meter B under reads for this flow rate. However, the deviation of this meter is well within the claimed accuracy specifications (0.35%). The average error is -0.16% and the reproducibility is 0.06%.

![Figure 6-8 Flow meter C Mass Error, liquid natural gas (JV). Flow rate 4.3 kg/s.](image)

6.3.3 Calibration with liquid natural gas at VSL
Finally, flow meter C was also calibrated for LNG by VSL with the set-up described in Section 5.2. The results for these calibrations are shown in Figure 6-9. Similarly as for the other LNG calibrations, the flow meter under reads for all flow rates. However, again the meter (nearly) performs within the claimed accuracy specifications.

Note there is a small discrepancy between the calibrations performed by VSL and JV. For a flow rate of 4.3 kg/s, JV finds an average deviation of -0.16%, whereas for a flow rate of 4.0 kg/s, VSL finds an average deviation of -0.37%. However, in [10] it is shown that these results are actually consistent within the claimed uncertainties of the Dutch and Norwegian test rigs (both better than 0.2%).
6.4 Results for flow meter D

Flow meter D has been investigated by NEL in a previous project and has been included in this project. The flow meter was calibrated with water at NEL and liquid nitrogen at NIST. A successor of this flow meter was made available to VSL during this EMRP project for calibration with LNG at VSL.

6.4.1 Calibration with water at NEL

Data gathered from the NEL test facility are shown in Figure 6-10 for the deviation of flow meter D measured totalised mass. The results shown in Figure 6-10 indicate that the flow meter is performing within its specified accuracy. The mass error varies between -0.04% and +0.12% for the whole measurement range of 1 to 9 kg/s. This also shows good measurement repeatability and reproducibility as these tests were conducted over a few days.

Test results for density are shown in Figure 6-11. The results show that the flow meter measures the density of water well within its specified accuracy, i.e. the maximum deviation observed was -0.09%.
6.4.2 Calibration with liquid nitrogen at NIST
Flow meter D was initially tested in the in the NIST cryogenic test facility with no change to its configuration parameters or calibration coefficients which were set for the water testing described above. This means that no adjustment was made to allow for the temperature dependence of the Young’s modulus of the stainless steel at the very low temperatures. The test results showed a consistent deviation of about 2% in measured mass as shown in Figure 6-12. This observation was also reported in reference [2] for a different meter make.
Before conducting subsequent tests, an adjustment was made to one of the calibration coefficients to allow for the non linear behaviour of the Young's modulus. The test results are shown in Figure 6-13 and were conducted over a period of 2 days. Figure 6-13 shows that, when the adjustment needed for the Young's modulus of stainless steel was made, the flow meter produced measurement very close to its claimed accuracy. Note for flow meter D the cryogenic correction makes the deviation less positive. It was found that for some other flow meter(s) the cryogenic correction works exactly the opposite, i.e. the correction factors make the deviation more positive.

In order to investigate whether the heat gain through the flow meter could have a significant effect, the calibrations shown in Figure 6-13 where repeated for the same flow meter, however with the insulation jacket removed. This situation (subcooled fluid with no meter insulation jacket) may be considered to resemble the practical case of running the flow meter with its insulation jacket but with the fluid close to its boiling point. The results for the flow meter without its insulation are shown in Figure 6-14. From this figure it follows that the flow meter is still performing rather close to its accuracy specifications. However, note that the average values over the whole flow rate range when the insulation jacket was removed makes the deviation less positive.

The good result shown in Figure 6-14 is probably partly due to the significant subcooling of liquid nitrogen of 10 to 15K. Only a small number of tiny bubbles were observed through the inspection window, which indicates that the subcooling is sufficient to prevent large-scale boiling. Hence, Figure 6-14 also shows that the flow meter is not sensitive to the presence of the tiny bubbles in the flow.

When the insulation jacket was removed there was no frosting on the body of the flow meter. Frosting on the flow meter body eventually started to build up with time. Finally,
it was found that the flow meter measured temperature was consistently about 3k lower than the rig measured temperature downstream of the flow meter.

![Figure 6-13](image1.png) Flow meter D mass error, liquid Nitrogen (NIST). Allowance was made for Young's modulus non linearity at low temperature (-193 C).

![Figure 6-14](image2.png) Flow meter D mass error, liquid Nitrogen (NIST). Allowance was made for Young's modulus non linearity at low temperature (-193 C). Removed flow meter insulation.
Finally, in Figure 6-15 and Figure 6-16 the deviation in the measured density is shown, respectively with and without insulation. This indicates that the flow meter can measure the density of liquid Nitrogen to about 0.5% accuracy. Note, for the reference density the temperature is required, which may be subject to a significant uncertainty.
6.4.3 Calibration with liquid natural gas at VSL
Finally, flow meter D\(^3\) was also calibrated for LNG by VSL with the set-up described in Section 5.2. The results of these calibrations are shown in Figure 6-17. These results show that the flow meter over the whole flow rate performs within its accuracy specifications. In fact, the average deviation for this meter is lowest compared to other flow meters tested. Further, notice that this deviation is consistent with the deviation found for LIN (see Section 6.4.2).

\[\text{Figure 6-17 Flow meter D Mass Error, liquid natural gas (VSL).}\]

6.5 Discussion
This section gives an overview of all tests and common trends observed regarding the various calibrations. In Sections 6.1 to Section 6.4 flow meters A to D have been calibrated with water, liquid Nitrogen and liquid natural gas; see Figure 6-18 for the LIN calibrations and Figure 6-19 for the LNG calibrations. The goal of these tests is to investigate the suitability of the cryogenic correction factors. All selected meters perform as expected for standard water calibrations, i.e. all deviations are equal or less than 0.1%.

\[\text{3 The successor of flow meter D that was calibrated for water and LIN.}\]
The results shown in Sections 6.1.2 and 6.4.2 and Figure 6-18 reveal that measurements of liquid Nitrogen flow can be achieved within the manufactures accuracy claims. Figure 6-18 show the results obtained for all meters that have been calibrated with LIN (as discussed the results for meter C are discarded). Although the accuracy claims in general was met for the meters tested, note that these claims are quite a bit relaxed compared to accuracy claims for water calibrations; i.e. for water the specified accuracy
is typically around 0.1%, whereas the specified accuracy for cryogenic calibrations is typically around 0.3%.

The deviations found for the measurements of liquid natural gas (Sections 6.1.4, 6.2.2, 6.3.3, 6.4.30) are somewhat larger than found for liquid Nitrogen, especially for flow meter A. In Figure 6-19 the results for all meters calibrated for LNG are shown. The deviations found for flow meter A and B are outside the accuracy specifications. An explanation could be that the cryogenic correction models have so far been tuned for water and liquid Nitrogen. Nevertheless, the cryogenic correction models decrease the deviation to (almost) acceptable levels. However, note that all flow meter deviations are negative, i.e. all flow meters under read (without the cryogenic correction factor the flow meters can under or over read). Because flow meters A to D use different correction models (different polynomials in temperature), the varying deviation may be attributed to the various models used.

For flow meter D it was shown that the ambient heat gain plays a significant effect in the flow meter accuracy (Section 6.4.2). Because all meters are of the Coriolis type, it is expected that all flow meter readings will be influenced by the ambient heat gain. Further research would be required to determine the sign and magnitude of the impact of the ambient heat gain on the flow meter accuracy. This may be especially relevant as different facilities use different levels of insulation (see Section 5.2).

Finally, the results presented in this report are all for 2” flow meters. It is well-known that larger Coriolis flow meters can exhibit a different behaviour. Hence, further research is required to investigate the suitability of the correction models for larger flow rates.
7 Summary and conclusions

The Coriolis flow meters under test in this project were calibrated with three fluids; water at ambient conditions, liquid nitrogen at about -193°C and LNG at about -161°C. Depending on prevailing circumstances during the project, not all flow meters were tested with the three fluids, however, each meter was tested with water and one or both cryogenic fluids. The main objective of the test programme is to assess the cryogenic correction models that are used in the transfer of a standard factory calibration with water at ambient conditions to cryogenic conditions.

The water testing results show that all flowmeter performed well within their specified accuracy. The measurements have also shown good measurement repeatability and reproducibility.

Within certain limits, water calibrations of Coriolis flow meters can be transferred to cryogenic flow measurements taking into account the non-linear temperature dependence of the Young’s Modulus. However, even with this correction, the flowmeter deviation remains in the order of 0.2 to 0.5%, which is considerably more than for water applications (within 0.1%). These results are based on testing 2” flow meters and in this stage it cannot be assumed that these results apply to larger flowmeters until larger units are tested in the same way.

Only one flow meter showed a very large deviation for LNG flow measurements, while the flow measurements for water and LIN where (almost) within the accuracy specifications.

Ambient heat gain may play a significant role in the flow meter deviation, however further research is required to determine this effect quantitatively.
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References


