

# Influence of Flow Disturbances on Measurement Uncertainty of Industry-Standard LNG Flow Meters

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## Abstract

In the last decade significant progress has been achieved in the development of measurement traceability for LNG inline metering technologies such as Coriolis and ultrasonic flow meters. In 2019, the world's first LNG research and calibration facility has been realised thus enabling calibration and performance testing of small and mid-scale LNG flow meters under realistic cryogenic conditions at a maximum flow rate of 200 m<sup>3</sup>/hr and provisional mass flow measurement uncertainty of 0.30% ( $k = 2$ ) using liquid nitrogen as the calibration fluid. This facility enabled the work described in this paper to be carried out to achieve three main objectives; the first is to reduce the onsite flow measurement uncertainty for small and mid-scale LNG applications to meet a target measurement uncertainty of 0.50% ( $k = 2$ ), the second is to systematically assess the impact of upstream flow disturbances and meter insulation on meter performance and the third is to assess transferability of meter calibrations with water at ambient conditions to cryogenic conditions. SI-traceable flow calibration results from testing six LNG flow meters (four Coriolis and two ultrasonic, see acknowledgement section) with water and liquid nitrogen (LIN) under various test conditions are fully described in this paper. It was observed that the influence of removing the meter insulation on mass flow rate measurement accuracy can be more significant (meter error  $> \pm 0.50\%$ ) than the influence of many typical upstream disturbances when the meter is preceded by a straight piping length equal to twenty pipe diameters (20D) with no additional flow conditioning devices, in particular for ultrasonic meters. The results indicate that the correction models used to transfer the water calibration to cryogenic conditions (using LIN) can potentially result in mass flow rate measurement errors below  $\pm 0.5\%$ ; however, the correction models are specific to the meter type and manufacturer. This work shows that the target measurement uncertainty of 0.50% can be achieved if the expanded standard error of the mean value measured by the meter is smaller than 0.40% ( $k = 2$ ). This was the case for about 85% of the LIN test results.

Keywords: LNG, liquid nitrogen, calibration, cryogenic, flow meter, flow disturbance, custody transfer

## 1 Introduction

The utilisation of liquefied natural gas (LNG) and liquefied biogas (LBG) as transport fuels constitutes one of the pillars of the European clean fuel strategy which seeks to reduce the usage of diesel and petrol [1]. The European Commission proposes that by 2020 LNG fuelling stations are installed every 400 km along the roads of Trans-European Transport Core Networks. The number of LNG fuelling stations in Europe is growing rapidly, currently there are 282 stations [2].

The current alternatives are still not yet widespread (e.g. hydrogen), but LNG and LBG are particularly suited as diesel replacements in shipping and long-distance road transport. However, this will require the development of measurement traceability for the vast applications of LNG custody transfer.

The overall aim of this work is to enable the large scale roll-out of liquefied natural gas (LNG) and liquefied biogas (LBG) as transport fuels through establishment of flow measurement metrological infrastructure [3]. An essential part of the work is the development of measurement traceability for the small-scale and mid-scale LNG custody transfer applications.

In the last decade, significant progress has been achieved in the development of measurement traceability for LNG inline flow metering technologies, in particular, the production of flow calibration standards for small and mid-scale LNG industries to enable a reduction in LNG flow measurement

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uncertainty. A new small scale primary standard based on a gravimetric system capable of handling LNG flows up to 25 m<sup>3</sup>/hr and with a mass flow measurement uncertainty of 0.12% to 0.15% ( $k = 2$ ) has been developed and validated [4] [5]. This primary standard has been modified subsequently to improve its metrological performance [6]. This standard was then used as the basis for developing a mid-scale LNG research and calibration facility capable of handling flows up to 200 m<sup>3</sup>/hr using a bank of master meters traceable to the primary standard [7]. This facility has been completed and commissioned in 2019 with a provisional mass flow measurement uncertainty of 0.30% ( $k = 2$ ) using liquid nitrogen as the calibration fluid.

Using the mid-scale LNG research and calibration facility, flow meters of different sizes (2 inch and 4 inch) and types (Coriolis and ultrasonic) have been investigated for their measurement uncertainty due to several influencing parameters under both ambient (water) and cryogenic (liquid nitrogen) flow conditions. The research programme was carried out in collaboration with five flow meter manufacturers; Panametrics a Baker Hughes company, Emerson, Endress + Hauser, KROHNE, and Yokogawa. It is important to note that this work is not aimed at direct comparison of meters from different manufacturers but rather to achieve the three main objectives of the work presented in this paper, which are indicated below. The work will be presented anonymously (i.e. only the meter type and size will be indicated).

The first objective is to reduce the flow measurement uncertainty for small and mid-scale LNG applications to meet a target measurement uncertainty of 0.50% ( $k = 2$ ) which is comparable to the flow measurement uncertainty for conventional fuels. The main focus will be on development of Coriolis and ultrasonic metering technologies which are typically used in these applications. The second objective is to systematically assess the impact of upstream flow disturbances, such as pipe fittings and valves, and meter insulation on meter performance under ambient and cryogenic test conditions. The third objective is to investigate the transferability of meter calibrations with water at ambient conditions to cryogenic conditions.

At this stage liquid nitrogen (LIN) was used as a safe fluid to commission and operate the LNG research and calibration facility and as an essential step to verify the operation and robustness of facility components and instrumentation under cryogenic conditions and to establish the stability criterion for flow, temperature, and pressure. Although LIN has different properties than LNG, the LIN boiling point temperature (typically -196 °C) is about 35 °C lower than the corresponding temperature for LNG (typically -161 °C) at ambient pressure. It is planned to repeat these tests with LNG in the future in order to compare the results with the LIN tests presented in this paper. This may reveal that testing with a safe and environmentally friendly fluid such as LIN produces representative results for testing LNG flow meters.

In section 2 of this paper, more information will be given on the background of this research programme to achieve the objectives indicated above. Section 3 describes the test setups used to investigate the influence of flow disturbances on flow meter calibrations. Section 4 describes the water and cryogenic test facilities used to carry out these calibrations and provides information on cryogenic flow calibration preparations, cryogenic flow stability, and the cryogenic flow calibration uncertainty. Section 5 presents the water and cryogenic calibration results which are discussed in section 6. The last section summarises the main conclusions of the work.

## 2 LNG measurement- current state of the art

The high energy density of LNG means that it can be transported easily by ships from areas of production to areas of need, and the practice for measuring what is delivered to or received from a ship's tanks is made in the form of energy transferred according to the GIIGNL Handbook (International Group of Liquefied Natural Gas Importers) [8].

However, the GIIGNL is only an agreed handbook of good practice, it is neither a standard nor a specification. An ISO standard (ISO 10976) [9] describing a procedure for measurement of LNG quantities on board LNG carriers was published in 2012 (and updated in 2015) but it has not overridden the GIIGNL handbook and therefore its application will be subject to agreement between involved parties.



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The calculation of LNG energy transferred requires measurement of LNG volume in the ship's tanks using level gauges and the density and gross calorific value (GCV), which are based on the average composition of the LNG obtained from sampling and subsequent analysis by gas chromatography. While some challenges with effective measurement are related to the measurement of the LNG volume, the main challenges are with the LNG composition obtained from such sampling. The GIIGNL therefore estimates an overall uncertainty in the measured LNG energy transferred of 0.74% ( $k = 2$ ) [8].

The accuracy of LNG composition obtained from sampling will have a direct influence on the accuracy of calculated density and gross calorific value, and subsequently the accuracy of LNG energy transferred. LNG shipment values are often in the range of €30 - €40 million. A small error in the determination of the gross calorific value and density of the LNG therefore has a significant financial impact on the exporter/importer. A one per cent error in energy transferred equates to €300,000 - €400,000 in misallocation during custody transfer.

The density of LNG is calculated from the measured composition, temperature and pressure using an equation of state. Important sources of uncertainty are the choice of the correct equation of state, as well as the accuracy of temperature and composition measurements.

In principal, better accuracy can be achieved by direct measurement of the LNG flow rate, rather than measuring the volume in tanks. However, the nature of LNG presents some very real challenges for flow meter technology, the biggest of which is the cryogenic temperature at which LNG exists (typically -160 °C).

Flow meters are usually calibrated using water at ambient temperatures and due to the international scarcity of cryogenic test facilities, combined with the complexities of testing under low temperature conditions, little independent research has been done to establish if flow meters remain accurate under the extremely cold condition that LNG exists at.

At present the development of cryogenic flow metering has focused on ultrasonic and Coriolis techniques. Whilst these are promising, a number of issues including lack of cryogenic calibration facilities and means for quantifying installation effects (in particular for ultrasonic meters for fiscal applications) have still to be addressed. Although the lack of calibration facilities is currently addressed by development of an alternative calibration approach based on correcting the water calibration to cryogenic conditions, the efficacy of this approach has not been fully verified. This is the main reason why LNG flow meters are currently used for allocation and control but not for custody transfer which requires accurate and traceable measurement.

Addressing these issues is one of the main drivers for the work described in this paper.

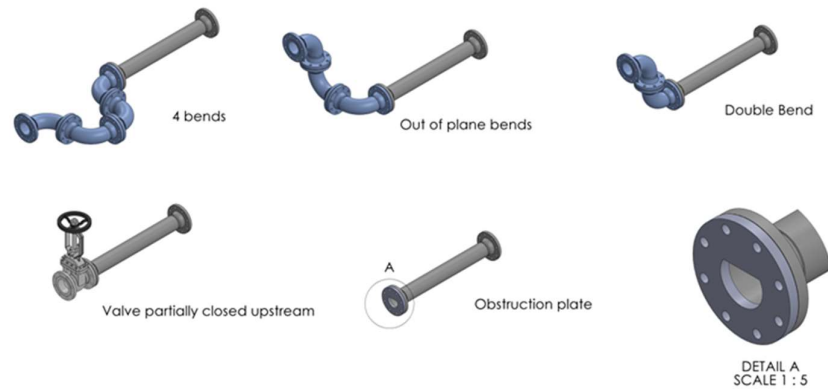
The following section describes the design of the metering setups tested in this work.

### 3 Test configurations

As indicated above, one of the main objectives of this work is to reduce the LNG flow measurement uncertainty when Coriolis and ultrasonic flow meters are used. This will be achieved by investigating the meter performance under both ambient (water) and cryogenic (liquid nitrogen) conditions when exposed to several influencing parameters such as flow disturbances and the importance of meter insulation under cryogenic conditions.

To enable the testing of two different sizes of the flow meters and compare the measurement from each meter against the test facility reference measurement, it was necessary to design two separate metering setups, one to accommodate the 2 inch meters and the other to accommodate the 4 inch meters. Since the 4 inch meters differ in length, two arrangements had to be designed for the 4 inch setup, each arrangement housed one ultrasonic meter and one Coriolis meter in series.

In practical LNG installations there are various types of pipe fittings and arrangements that may cause disturbance to the flow entering the flow meter. Typical examples are shown in figure 1.



**Figure 1.** Typical pipe installations causing flow disturbance.

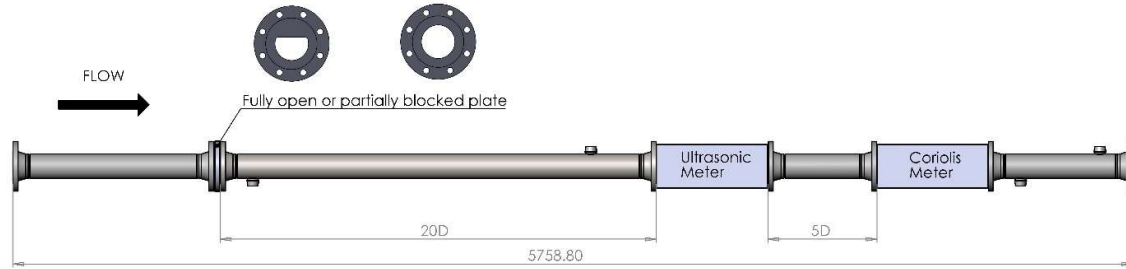
In this work, the idea was to perform testing with one moderate disturbance and one severe disturbance upstream, one at a time. After careful consideration and consulting with the meter manufacturers who participated in this work, it was decided to select the 4-bend (or double-bend) disturbance (figure 1 top left) as a moderate disturbance and the partially blocked plate (25% blockage, detail A, figure 1) as the severe disturbance.

A schematic of each metering setup with and without the selected disturbance is given in figures 2 and 3. The open plate represents the setup with no flow disturbance. In the 2 inch setup, figure 2, two Coriolis flow meters are installed in series while in the 4 inch setup, figure 3, one ultrasonic flow meter (upstream) and one Coriolis flow meter (downstream) are installed in each of the two arrangements. In all metering setups the straight pipe length between the disturbance and the first flow meter is equivalent to 20 pipe diameters (20D).

As indicated in section 1, since the data from this testing are presented anonymously, the make (manufacturer) and the location of each test meter are not shown and the meters were numbered randomly as: meter 0, meter 1, meter 3, meter 4, meter 6 and meter 8. These numbers will be referred to in the results section.



**Figure 2.** The 2-inch metering setup.



**Figure 3.** The 4-inch metering setup.

For the water testing, each metering line has been tested with the following setups. The fully open plate is used in all setups except setup 2:

- Setup 1: ideal setup, no flow disturbance and no insulation;
- Setup 2: as setup 1, but with the partially blocking plate;
- Setup 3: as setup 1, but with the double-bend disturbance.

For cryogenic testing, each metering line has been tested with the following setups. The fully open plate is used in all setups except setup 2:

- Setup 1: ideal setup, no flow disturbance and all meters are insulated;
- Setup 2: as setup 1, but with the partially blocking plate;
- Setup 3: as setup 1, but with the double-bend disturbance;
- Setup 4: as setup 1 but with meter insulation removed.

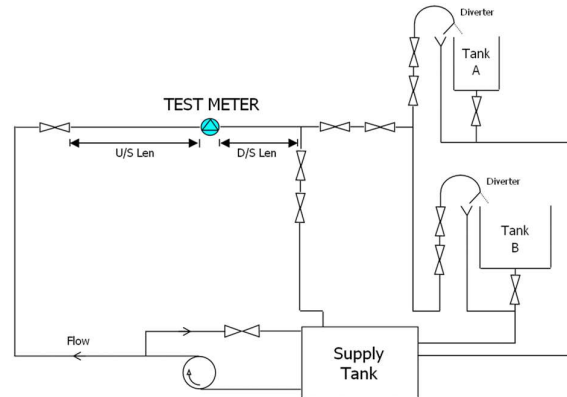
For the Cryogenic testing, five flow meters were insulated with rockwool by a professional insulation company and one meter with bluedec® insulation as this was the option preferred by the flow meter manufacturer.

An important point to note, there was an inner diameter mismatch of 5.8% between the upstream and downstream pipe spools and meter 8, however, the best practice is to stay within 1%. Accurate inner diameter match with upstream and downstream piping as well as parallel alignment are essential to achieve accurate measurements from ultrasonic flow meters. The fact that the inner diameter of this meter is 6mm larger than the inner diameter of the connecting upstream and downstream piping means the flow entering the meter slightly expands and when leaving the meter slightly contracts, which may adversely affect the shape of the velocity profile measured by the meter. It is difficult to judge how significant this effect is until the meter is tested again with the correct inner pipe diameter. The mismatch was found just before the first water calibrations test and the manufacturer decided to continue the programme in similar fashion during the cryogenic testing to keep the same geometry.

## 4 Test facilities and test conditions

### 4.1 Water test facility and test conditions

The flow metering setups described in section 3 have been installed and tested in the TUV SUD National Engineering Laboratory water flow measurement facility shown in figure 4. The facility has four separate flow lines, covering a wide range of flow rates in different line sizes. The flowmeters have been calibrated by comparison of the output value from each test meter with the value derived from a reference gravimetric weighing system. The method used is a diversion technique where the flow is continuous and diverted into the chosen weight tank for the duration of the test.



**Figure 4.** Water calibration facility.

The flow rate is calculated from the ratio of accumulated mass and time taken for the quantity of fluid to pass through the meter. All measurements are fully traceable to UK National Standards. The percentage error (or meter deviation) is calculated for the indicated totalised mass ( $M_i$ ) from the meter under test with respect to the reference totalised mass ( $M$ ):

$$\text{Percent Error} = \frac{M_i - M}{M} \cdot 100 \quad (1)$$

Using the test method outlined, the uncertainty in the measurement of the reference quantity of fluid passed through the flowmeter under test is estimated to be 0.10% for flow rates up to 200 l/s and 0.15% for flow rates 200 to 400 l/s. The uncertainty in measured density is 0.03% [10]. 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% for a normally distributed function. The uncertainties quoted form part of NEL's ISO 17025 [11] Scope of Accreditation for calibration of flow meters, issued by the United Kingdom Accreditation Service (UKAS).

The flow points for the 2-inch and 4-inch lines are given in tables 1 and 2. All setups were calibrated at 20 °C ( $T_1$ ), whereas the ideal setup (setup 1) was also calibrated at 36 °C ( $T_2$ ). Each test point was taken three times.

**Table 1.** Water flow calibration points for the 2-inch line.

Flow	Approx. Mass flow rate	Pressure	T <sub>1</sub>	T <sub>2</sub>	Repeats (N)	Reynolds No. at T <sub>1</sub>	Reynolds No. at T <sub>2</sub>
m <sup>3</sup> /h	kg/s	bar(g)	°C	°C	-	-	-
3.2	0.85	2	20	36	3	21,232	30,028
7.0	1.94	2	20	36	3	48,531	68,636
11	3.05	2	20	36	3	75,829	107,244
15	4.15	2	20	36	3	103,127	145,852
19	5.22	2	20	36	3	130,426	184,459
23	6.31	2	20	36	3	157,724	223,067
27	7.41	2	20	36	3	185,023	261,675
31	8.5	2	20	36	3	212,321	300,283

**Table 2.** Water flow calibration points for the 4-inch line.

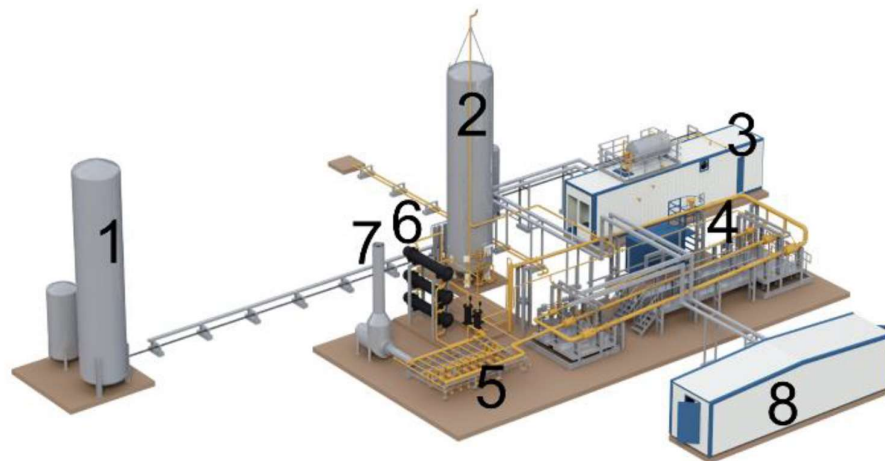
Flow	Approx.	Pressure	T <sub>1</sub>	T <sub>2</sub>	Repeats (N)	Reynolds No. at T <sub>1</sub>	Reynolds No. at T <sub>2</sub>
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m <sup>3</sup> /h	Mass flow rate		bar(g)	°C	°C	-	-	-
	kg/s							
25	7	2	20	36	3	87,426	123,646	
58	16	2	20	36	3	199,832	282,619	
90	25	2	20	36	3	312,237	441,592	
122	34	2	20	36	3	424,643	600,565	
155	43	2	20	36	3	537,048	759,538	
187	52	2	20	36	3	649,453	918,511	
220	61	2	20	36	3	761,859	1,077,485	
252	70	2	20	36	3	874,859	1,236,458	

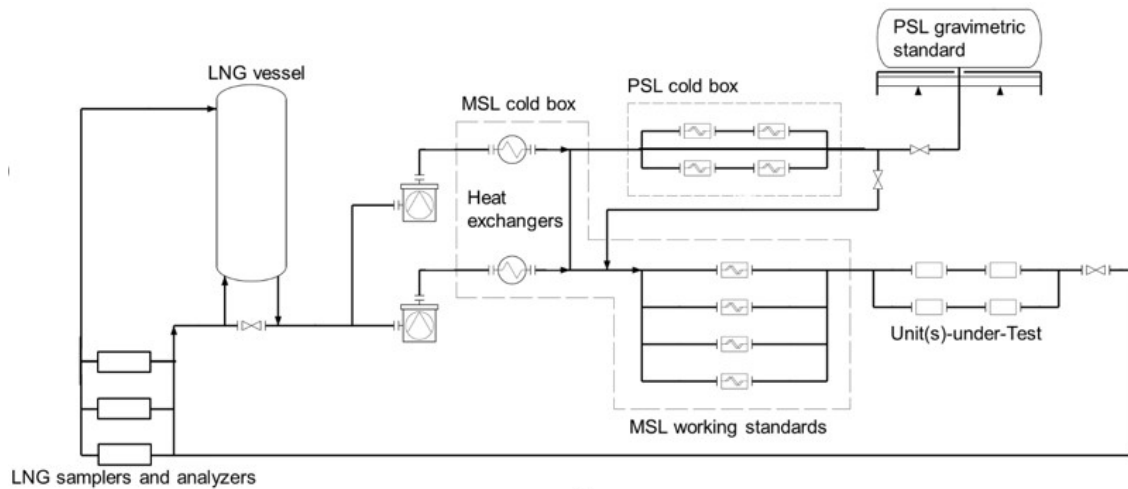
Meter settings were taken "as found". Settings were established by the manufacturer with their own uncertainty claim. For Coriolis flow meters, a standard procedure was followed in the water calibration facility for the meter zero adjustment, zero verifications and zero checks before and after testing each metering setup.

#### 4.2 Cryogenic research and calibration facility and test conditions

The flow metering setups described in section 3 have been installed and tested in VSL's cryogenic research and calibration facility shown in figure 5. This facility combines a Primary Standard Loop (PSL), a Mid-Scale Loop (MSL) and primary composition measurement system. This facility is fully described in [7] and briefly described below.



a. 3-D layout



b. Flow diagram

**Figure 5.** The cryogenic research and calibration facility.

The elements numbered in figure 5 (a) are described below:

- 1) Liquid nitrogen (LIN) storage tank, used for various purposes such as a cooling fluid and as a source of purging gas. Since the tank is a cryostat, the cryogenic liquid is maintained by the process of auto refrigeration. This storage tank is equipped with a pressure control system.
- 2) Cryogenic liquid storage tank, same as the above tank but used to store the cryogenic liquid (e.g. LIN or LNG).
- 3) The Primary Standard Loop (PSL) [4], a gravimetric primary standard for mass flow which is used to provide metrological traceability to SI-units for the mass flow measured by the working standards (5 below) of the Mid-Scale loop (MSL). The MSL is used for calibrating cryogenic flow meters in the Meter-under-Test (MuT) section (4 below) against the working standards.
- 4) Meter-under-Test section where cryogenic flow meters can be installed and calibrated. The test section has two parallel lines, 2" and 4" lines, that can be operated separately.
- 5) The working standards of the MSL, a skid housing four Coriolis flow meters. The working standards are kept in a cold box refrigerated by the cold nitrogen gas leaving the heat exchangers.
- 6) Cryogenic circulation pumps, are used to pump the cryogenic liquid at various flow rates, from storage tank through the working standards skid then through the meter under test before it finally returns back to the pumps. The heat exchangers keep the cryogenic liquid below its boiling point by creating a sub-cooling margin using liquid nitrogen as the cooling fluid. The cryogenic liquid should have a higher boiling point (e.g. LNG) so that it can be cooled efficiently by LIN.
- 7) Nitrogen gas-warmer, heats the relatively cold waste nitrogen gas leaving the working standards cold box and guides the heated gas towards a safe point into the atmosphere.
- 8) Control room, used for the operation and control of the test facility.

The flow facility can be operated in three different modes. The first mode is to use the PSL gravimetric system on its own to calibrate the master Coriolis flow meters installed in the PSL. Once calibrated, the PSL master meters are then used in combination (using the boot strapping method) to calibrate each of the working standard Coriolis meters in the MSL in the second mode of operation. Once the working standards are all calibrated, the facility can be operated in the third mode as described below.

In the third mode of operation, the PSL is fully isolated. The cryogenic operating fluid (liquid nitrogen used in these tests) is drawn from the storage tank (2 above) by the cryogenic pumps and flows through the heat exchangers to remove the heat generated by the pumps and any ambient heat gain to the facility and to create a sub-cooled condition, i.e., at a temperature below the boiling temperature of the liquid. It is possible to create a sub-cooled condition of a calibration liquid that is of the same type as the

cooling liquid when the calibration liquid is at a higher pressure than the cooling liquid. Therefore, the sub-cooling is created by pressuring the test facility to raise the boiling temperature of the calibration liquid while maintaining the cooling liquid at lower pressure using the pressure control systems in the storage tanks. After leaving the heat exchangers, the liquid enters the working standards skid where the reference flow rate of the liquid is measured before it enters the MuT-section. After leaving the test section the liquid returns back to the pumps where one cycle of the flow is completed. The flow rate of the liquid can be varied over the desired calibration range using the variable speed pumps.

The calculation of the percentage error in the mass flow rate measured by the test meter follows the same approach described in section 4.1, equation 1. The next section provides information on preparations for cryogenic calibration, flow stability, and the cryogenic calibration uncertainty.

The flow points for the 2-inch and 4-inch test lines are given in tables 3 and 4.

**Table 3.** LIN flow calibration points for the 2-inch line.

Flow	Approx. Mass flow rate	Pressure	Temperature	Repeats (N)	Reynolds No.
m <sup>3</sup> /h	kg/s	bar(g)	°C	-	-
10	2	6	-180	3	542,000
20	4	6	-180	3	1,058,000
30	6	6	-180	3	1,627,000
40	8	6	-180	3	2,169,000
50	10	6	-180	3	2,712,000

**Table 4.** LIN flow calibration points for the 4-inch line.

Flow	Approx. Mass flow rate	Pressure	Temperature	Repeats (N)	Reynolds No.
m <sup>3</sup> /h	kg/s	bar(g)	°C	-	-
20	4	6	-180	3	542,000
40	8	6	-180	3	1,058,000
60	12	6	-180	3	1,627,000
80	16	6	-180	3	2,169,000
100	20	6	-180	3	2,712,000

Due to operational limitations, some of the cryogenic flow points could not be achieved, e.g., the highest flow rates of the 2-inch and 4-inch lines, 50 m<sup>3</sup>/hr and 100 m<sup>3</sup>/hr respectively.

In this test programme, an attempt was made to create a test matrix that matches the Reynolds number for water and LIN testing. However, due to the lower viscosity and density of LIN it was not possible to achieve this match for most test flow rates despite raising the water temperature up to 36 °C which is the highest temperature that can be achieved in the water facility over the test flow range. This can be seen by comparing table 1 with table 3 and table 2 with table 4. However, there is a good overlap in the mass flow rate. Therefore, the results presented in section 5 will be shown against the reference mass flow rate.



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### 4.3 Cryogenic calibration- preparations, flow stability and calibration uncertainty

For Coriolis flow meters, the zeroing procedure followed during water testing was generally also followed during the cryogenic testing. Zero adjustment procedures and visual zero verifications were performed, to the best available knowledge, for all Coriolis meters. Guidelines from the applicable ISO standard [12] were followed to assure that stable process conditions of fluid temperature, pressure, and density were achieved, and adhering to the typical zero monitoring time of about 30 s. It must be noted that zeroing times longer than 30 seconds can be allowed for if the no flow process conditions remain stable [12]. It must be also noted that the implementation of zeroing under process conditions is not exactly performed the same way for all meter models tested. Zero checks were performed prior to and/or after the calibrations for each of the setups. The zero mass flow rate reading (ideally) corresponds to the mass flow rate at zero flow, therefore any significant zero error will exhibit as a meter error with inverse dependence on mass flow rate [13].

Zero stability of the reference mass flow standard against which the calibrations were performed was checked and recorded prior to the calibrations under cryogenic conditions. Leak tests were performed based on qualitative visual inspection (icing) and quantitative assessment of maximum leak rate based on gas pressure decay with time. It was assured that the magnitude of zero variability uncertainty due to the working standards was  $< 0.0010$  kg/s ( $k = 2$ ) or below 0.05% of the lowest flow rate considered (2 kg/s or approximately 10 m<sup>3</sup>/h), and that the estimated maximum leak rate was  $< 0.10\%$  of the lowest flow rate considered (2 kg/s or approximately 10 m<sup>3</sup>/h) [13].

The calibration stability for flow, temperature, and pressure was established as follows (for LIN calibration runs of 120 s – 130 s) [13]:

- Mean pressure standard deviation for individual batch runs  $< 0.03$  bar.
- Mean temperature standard deviation for individual batch runs  $< 0.10$  °C.
- Flow rate:
  - For 2"-line. Mass flow rate standard deviation  $< \pm 1.5\%$  of flow rate, thereby meeting the flow rate variability criterion given below. Maximum mass flow rate standard deviation at  $\pm 2.0\%$  of flow rate (based on unfiltered data).
  - For 4"-line. Mass flow rate standard deviation  $< \pm 0.5\%$  of flow rate, thereby meeting the flow rate variability criterion given below. Maximum mass flow rate standard deviation at  $\pm 1.0\%$  of flow rate ( $\pm 1.5\%$  of outliers in unfiltered data rejected).

These match the criteria which were defined prior to the establishment of the cryogenic research and calibration facility, which are:

- Pressure variability: 0.2 bar/minute.
- Temperature variability: 0.2 °C/minute.
- Flow rate variability: 1% – 2% of flow rate.

Prior to the cryogenic calibrations, the cryogenic research and calibration facility was commissioned with LIN and its SI-traceable calibration uncertainty was estimated as follows [13]:

“The uncertainty statement should be considered provisional based on our current knowledge of being able to determine the SI-traceable calibration uncertainty of the facility, and is currently restricted to LIN flow rates between 2 kg/s and 20 kg/s, pressures between 3 barg and 10 barg, and temperatures between -190 °C and -172 °C, and for conditions where operational or equipment malfunctions are not present. The estimated SI-traceable calibration uncertainty is 0.30% ( $k = 2$ ) of reference mass flow rate. As more validation tests are done, it is the intention to improve on the uncertainty statement (with LIN or LNG). For the USM’s the volume-to-mass added uncertainty is estimated at  $< 0.15\%$ , which stems from the temperature and pressure measurement uncertainties and the LIN-density equation-of-state [14]. Therefore, for the USM’s, the estimated SI-traceable calibration uncertainty is  $< 0.35\%$  ( $k = 2$ ). It was checked with the LIN supplier (based on product specification sheet) that the LIN was of 99.999% purity rendering any composition uncertainty negligible. The LIN-density uncertainty is dominated by temperature uncertainty for the applicable pressure range (1 – 10 barg).”



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Repeatability (Type A) calibration uncertainty is not included in this uncertainty statement. See section 6 for a discussion on the total measurement uncertainty.

## 5 Test results

### 5.1 Introduction

In this section results are presented for the mass flow rate measurement from each meter tested under the setups described in section 3 at ambient (water) and cryogenic (LIN) test conditions. All water tests were carried out without meter insulation while the LIN tests were carried out with and without insulation as indicated in the next tables.

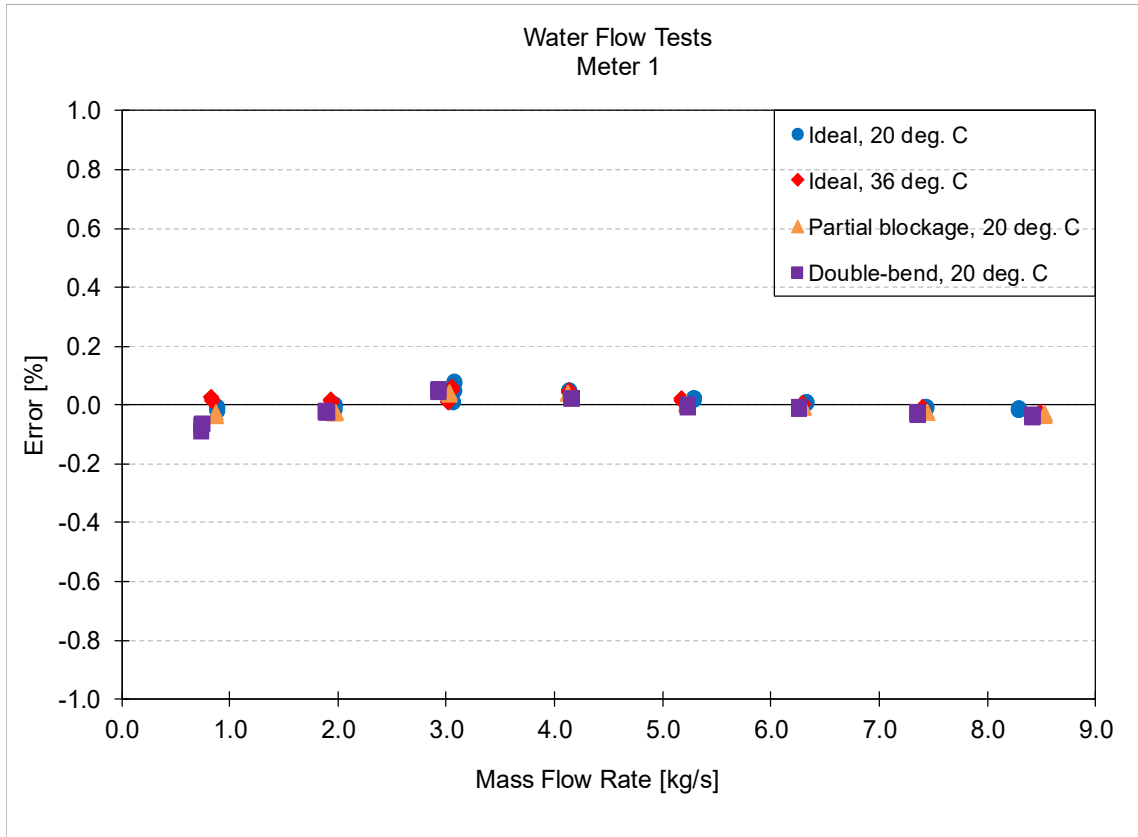
Any test data that falls outside the metrological uncertainty and facility stability criterion has been rejected and therefore not shown. The cryogenic test data was also filtered to remove outliers as described in reference [13].

The results are presented as percentage error (equation 1) in the measured mass flow rate (y-axis) from the reference mass flow rate (x-axis). The scale of the y-axis for the water and LIN results was dictated by the meter giving the largest error. The scale for the x-axis was chosen so that the test flow rate range matches as closely as possible for both water and LIN. For clarity, the test data collected from each meter will also be presented in tabulated form showing the average error for each test point.

The typical flow meter measurement accuracy given by the meter manufacturer is discussed in section 6 and can be referred to when looking at the results presented in section 5.

### 5.2 The 2-inch test line

Figures 6 and 7 show the water and LIN test results for meter 1. The meter error results are also given in tables 5 and 6 respectively. Each table shows the meter average mass flow rate error for the ideal setup with respect to (wrt) the reference mass flow rate as a percentage (table a) and the averaged mass flow rate error of each disturbance case with respect to the ideal case as a percentage (table b). In table 5 (b) the greyed out cells are zero by definition for the ideal case as the errors are computed with respect to this case. The other greyed out cells in table (b) represent non-existing cryogenic calibration points.



**Figure 6.** Meter 1, mass flow rate error, 2-inch line, water flow tests.

**Table 5.** Meter 1, average mass flow rate errors for water tests.

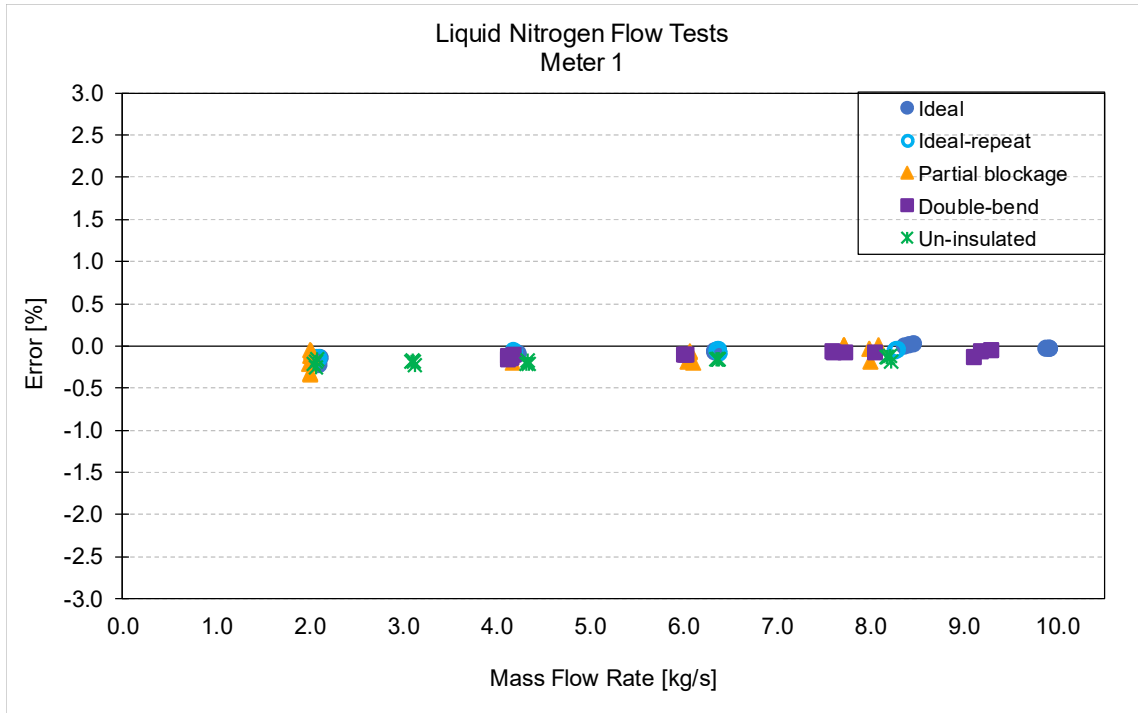
Nominal Rate (kg/s)	Ideal, 20 °C		Un-insulated			
		Nominal Rate (kg/s)	Ideal, 20 °C	Ideal, 36 °C	Partial Blockage	Double Bends
1	-0.018			0.04	-0.01	-0.06
2	-0.010			0.02	-0.02	-0.02
3	0.048			-0.03	-0.01	0.00
4	0.044			0.00	0.00	-0.03
5	0.017			0.00	-0.01	-0.03
6	0.004			0.00	-0.01	-0.02
7	-0.013			0.00	-0.01	-0.02
8.5	-0.018			-0.01	-0.01	-0.02

Average mass flow rate error wrt to reference (%)

(a)

Mass flow rate error wrt ideal (%)

(b)



**Figure 7.** Meter 1, mass flow rate error, 2-inch line, LIN flow tests

**Table 6.** Meter 1, average mass flow rate errors for LIN tests.

Nominal Rate (kg/s)	Ideal	Insulated				Un-insulated
		Ideal	Partial Blockage	Double Bends	Ideal Repeat	
2	-0.19		0.03	0.19	0.03	-0.01
4	-0.10		-0.04	-0.03	0.02	-0.10
6	-0.07		-0.06	-0.03	0.00	-0.09
8	0.00		-0.04	-0.07	-0.06	-0.15
10	-0.04			-0.04		

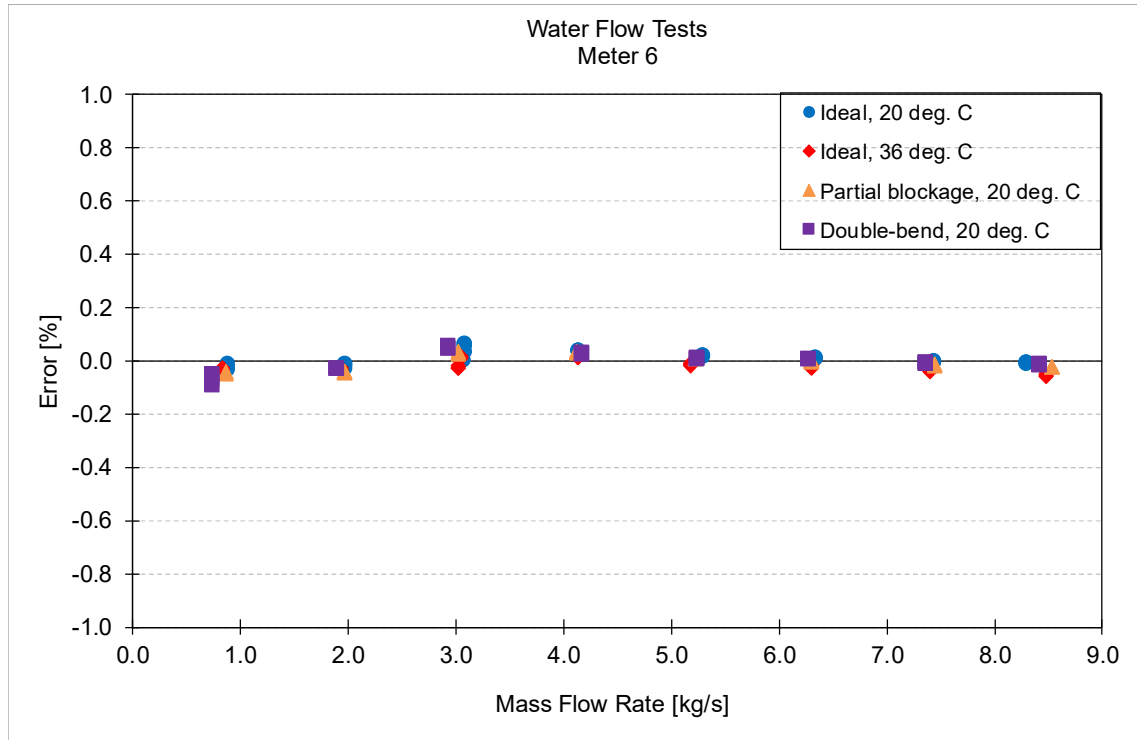
Average mass flow rate error wrt reference (%)

(a)

Mass flow rate error wrt ideal (%)

(b)

The results for meter 6 are given in figures 8 and 9 with a summary of the averaged errors listed in tables 7 and 8 respectively.



**Figure 8.** Meter 6, mass flow rate error, 2-inch line, water flow tests

**Table 7.** Meter 6, average mass flow rate errors for water tests.

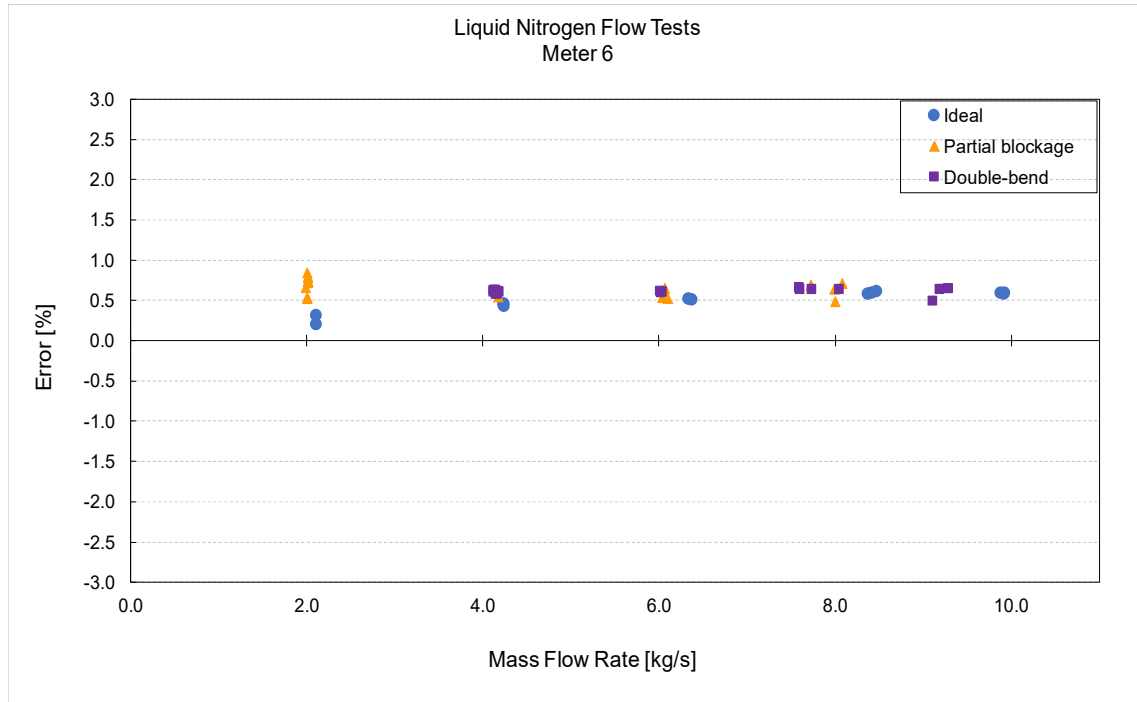
Nominal Rate (kg/s)	Ideal, 20 °C	Un-insulated			
		Ideal, 20 °C	Ideal, 36 °C	Partial Blockage	Double Bends
1	-0.026		0.00	-0.02	-0.05
2	-0.020		-0.01	-0.02	-0.01
3	0.036		-0.02	-0.01	0.01
4	0.036		-0.02	0.00	-0.01
5	0.016		-0.03	-0.01	-0.01
6	0.007		-0.03	-0.01	0.00
7	-0.006		-0.03	-0.01	-0.01
8.5	-0.010		-0.04	-0.01	-0.01

Average mass flow rate error wrt reference (%)

(a)

Mass flow rate error wrt ideal (%)

(b)



**Figure 9.** Meter 6, mass flow rate error, 2-inch line, LIN flow tests

**Table 8.** Meter 6, average mass flow rate errors for LIN tests.

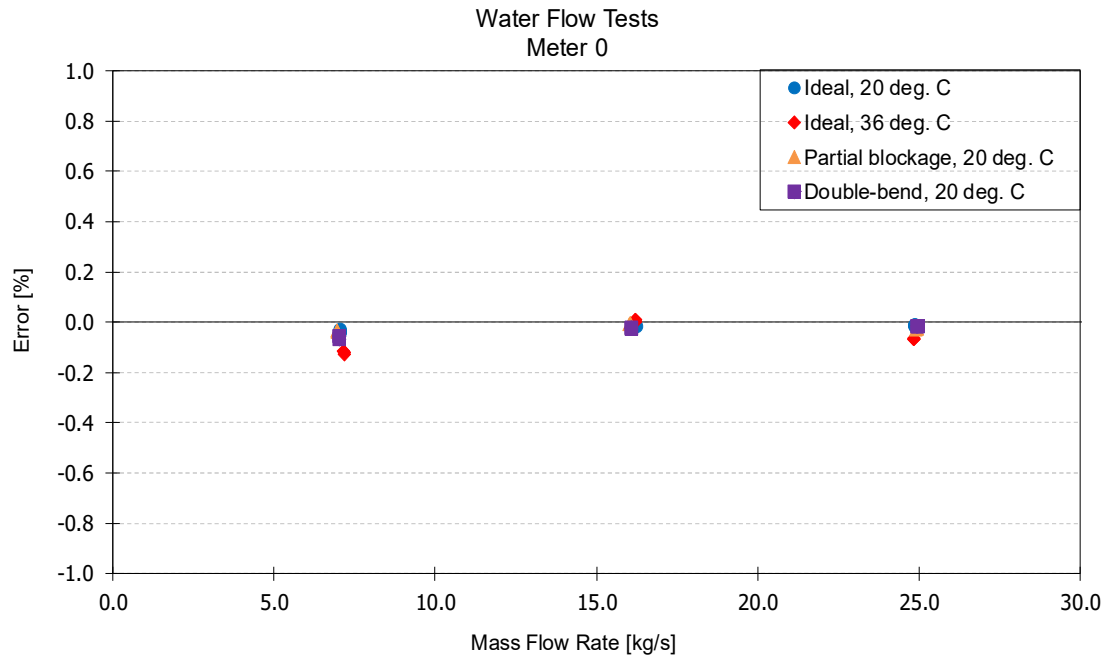
Nominal Rate (kg/s)	Ideal	Insulated		
Nominal Rate (kg/s)	Ideal	Partial Blockage	Double Bends	
2	0.26	0.44		
4	0.44	0.16	0.16	
6	0.52	0.07	0.09	
8	0.60	0.05	0.05	
10	0.59		0.02	

Average mass flow rate error wrt reference (%)  
(a)

Mass flow rate error wrt ideal (%)  
Note: The un-insulated test has not been carried out for this meter.  
(b)

### 5.3 The 4-inch test line

Figure 10 and table 9 show the water test results for meter 0.



**Figure 10.** Meter 0, mass flow rate error, 4-inch line, water flow tests

**Table 9.** Meter 0, average mass flow rate errors for water tests.

Nominal Rate (kg/s)	Ideal, 20 °C	Un-insulated			
Nominal Rate (kg/s)	Ideal, 20 °C	Ideal, 36 °C	Partial Blockage	Double Bends	
7	-0.041	-0.080	0.006	-0.019	
16	-0.017	0.023	0.010	-0.007	
25	-0.018	-0.048	-0.008	0.002	
35	-0.012	-0.045	-0.009	0.005	

Average mass flow rate error wrt reference (%)

(a)

Mass flow rate error wrt ideal (%)

(b)

Figure 11 and table 10 show the LIN test results for meter 0.

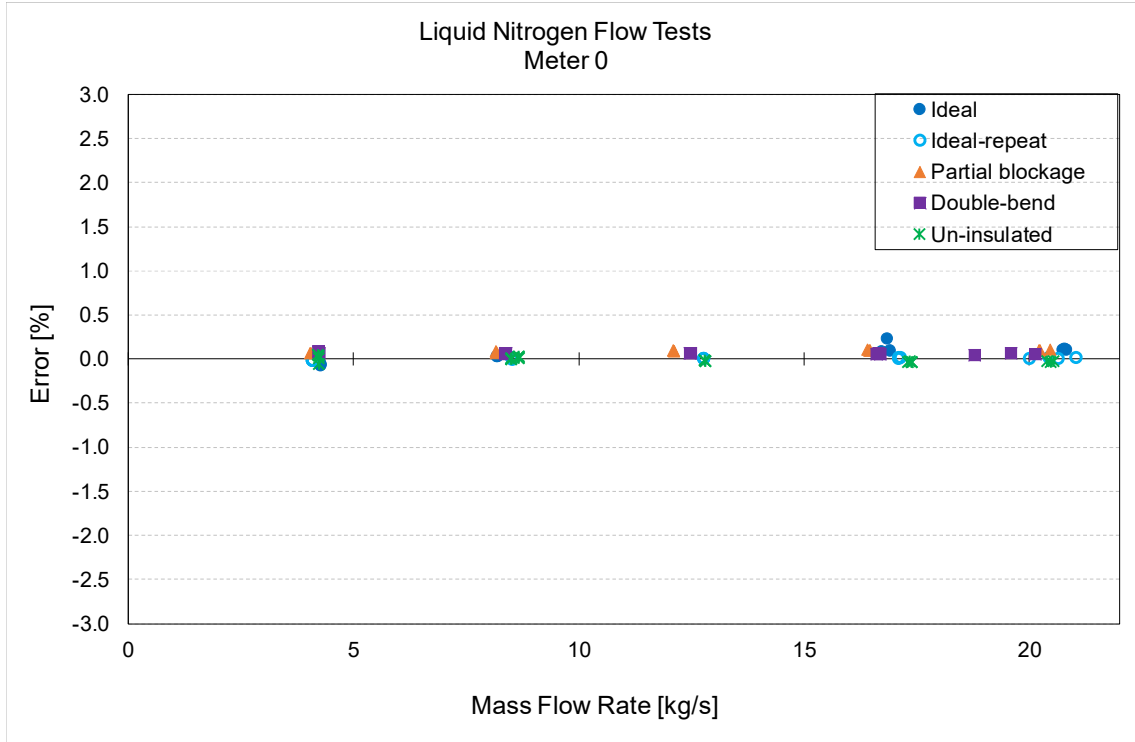


Figure 11. Meter 0, mass flow rate error, 4-inch line, LIN flow tests

Table 10. Meter 0, average mass flow rate errors for LIN tests.

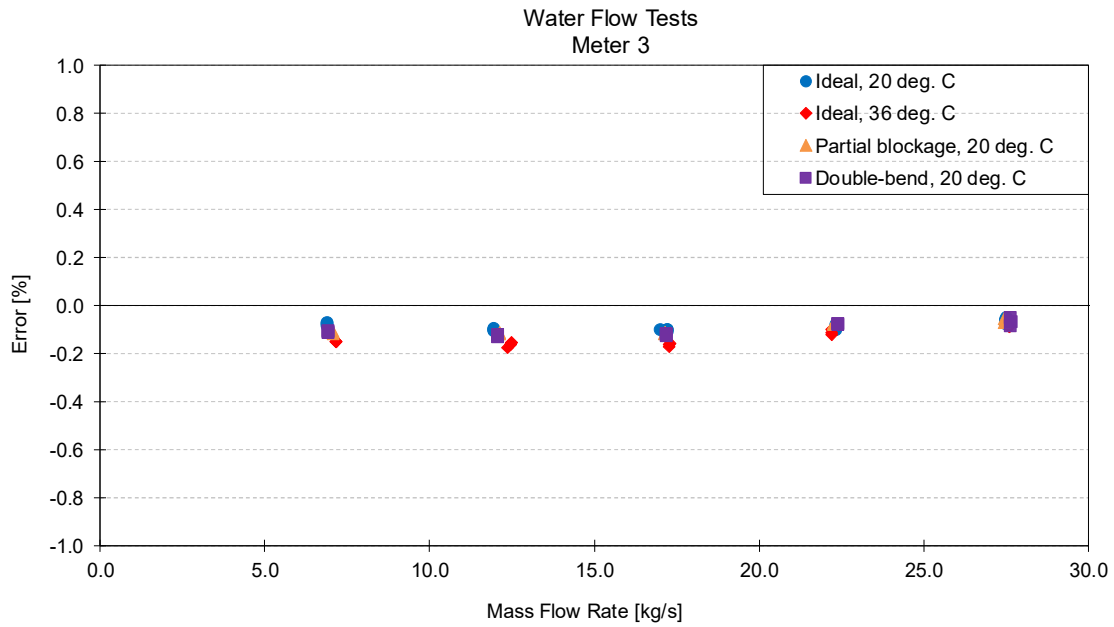
Nominal Rate (kg/s)	Ideal	Insulated				Un-insulated
		Ideal	Partial Blockage	Double Bends	Ideal Repeat	
4	-0.07		0.14	0.15	0.05	0.08
8	0.02		0.06	0.04	-0.01	-0.02
12			0.09	0.06		-0.02
16	0.13		-0.03	-0.07	-0.12	-0.17
20	0.10		0.00	-0.05	-0.10	-0.13

Average mass flow rate error wrt reference (%) (a)

Mass flow rate error wrt ideal (%) (b)

Note: At 12 kg/s the ideal repeat was taken as the reference because the ideal calibrations were not performed at this flow rate.

Figure 12 and table 11 show the water test results for meter 3.



**Figure 12.** Meter 3, mass flow rate error, 4-inch line, water flow tests

**Table 11.** Meter 3, average mass flow rate errors for water tests.

Nominal Rate (kg/s)	Ideal, 20 °C	Un-insulated			
		Ideal, 20 °C	Ideal, 36 °C	Partial Blockage	Double Bends
7	-0.107		-0.021	-0.012	-0.005
12	-0.115		-0.007	-0.009	-0.013
17	-0.123		-0.006	-0.002	-0.001
22	-0.145		0.001	0.017	0.066
28	-0.137		-0.006	0.000	0.067

Average mass flow rate error wrt reference (%)

(a)

Mass flow rate error wrt ideal (%)

(b)

Figure 13 and table 12 shows the LIN test results for meter 3.

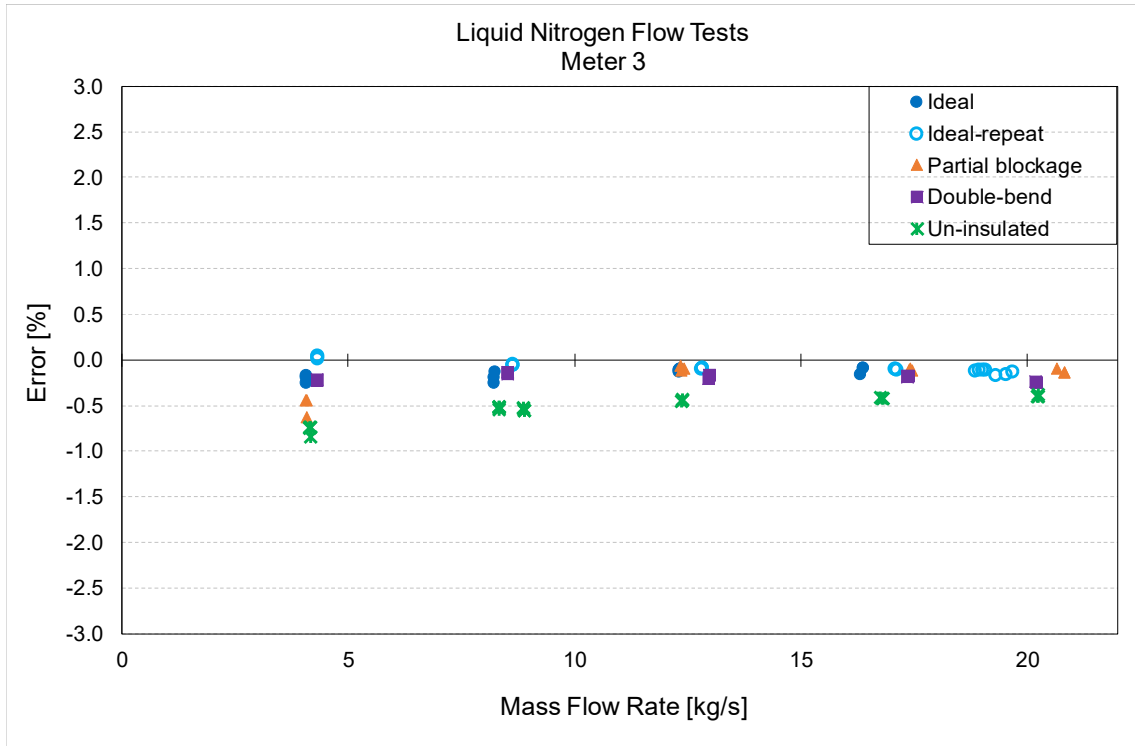


Figure 13. Meter 3, mass flow rate error, 4-inch line, LIN flow tests

Table 12. Meter 3, average mass flow rate errors for LIN tests.

Nominal Rate (kg/s)	Ideal	Insulated				Un-insulated
		Ideal	Partial Blockage	Double Bends	Ideal Repeat	
4	-0.21		-0.29	-0.01	0.24	-0.56
8	-0.20			0.06	0.14	-0.33
12	-0.12		0.03	-0.06	0.01	-0.33
16	-0.12		0.01	-0.06	0.01	-0.30
20			0.02	-0.10		-0.26

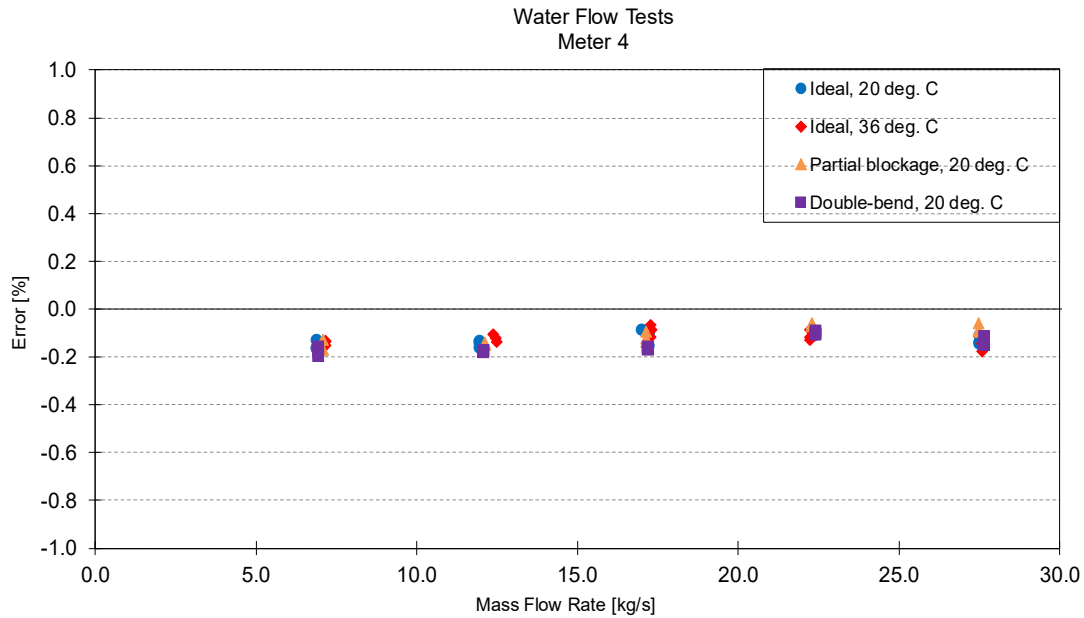
Average mass flow rate error wrt reference (%)

(a)

Mass flow rate error wrt ideal (%)

(b)

Figure 14 and table 13 show the water test results for meter 4.



**Figure 14.** Meter 4, mass flow rate error, 4-inch line, water flow tests

**Table 13.** Meter 4, average mass flow rate errors for water tests.

Nominal Rate (kg/s)	Ideal, 20 °C	Un-insulated			
		Ideal, 20 °C	Ideal, 36 °C	Partial Blockage	Double Bends
7	-0.155		0.014	0.001	-0.025
12	-0.148		0.027	0.001	-0.031
17	-0.118		0.028	0.001	-0.049
22	-0.111		0.001	0.047	0.009
28	-0.135		-0.018	0.054	-0.003

Average mass flow rate error wrt reference (%)

(a)

Mass flow rate error wrt ideal (%)

(b)

Figure 15 and table 14 show the LIN test results for meter 4.

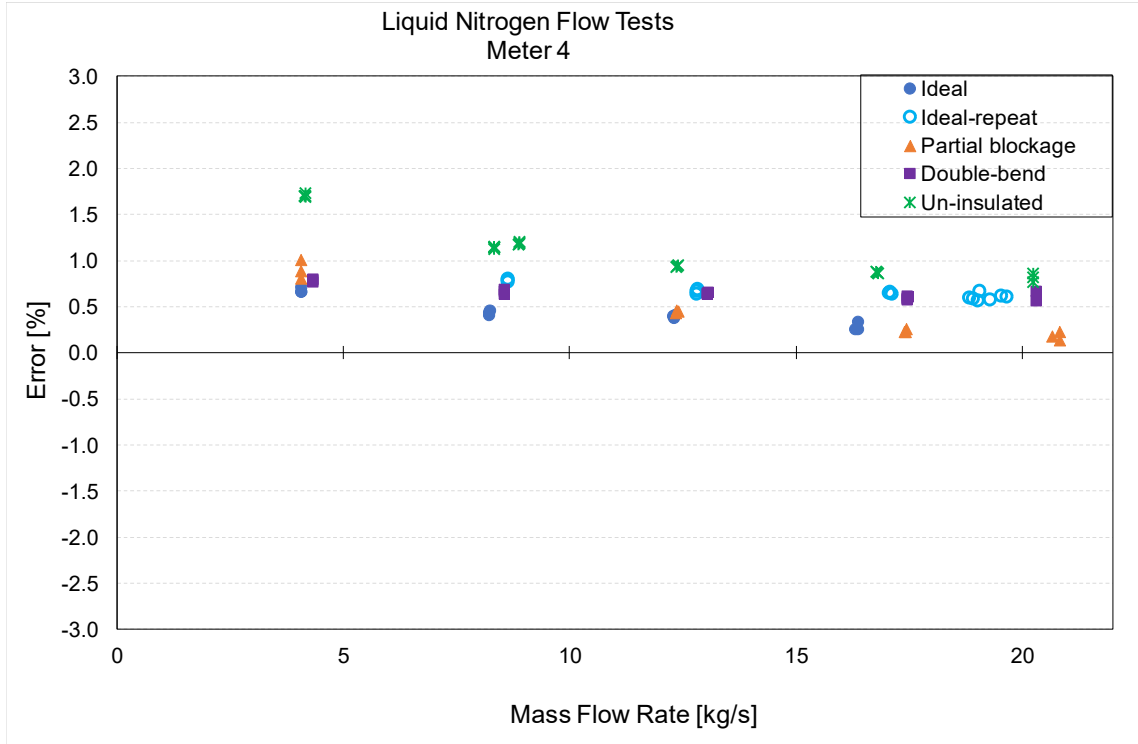


Figure 15. Meter 4, mass flow rate error, 4-inch line, LIN flow tests

Table 14. Meter 4, average mass flow rate errors for LIN tests.

Nominal Rate (kg/s)	Ideal	Insulated				Un-insulated
		Ideal	Partial Blockage	Double Bends	Ideal Repeat	
4	0.67		0.23	0.11	0.16	1.04
8	0.43			0.23	0.14	0.73
12	0.38		0.06	0.26	0.15	0.56
16	0.27		-0.04	0.32	0.27	0.60
20						

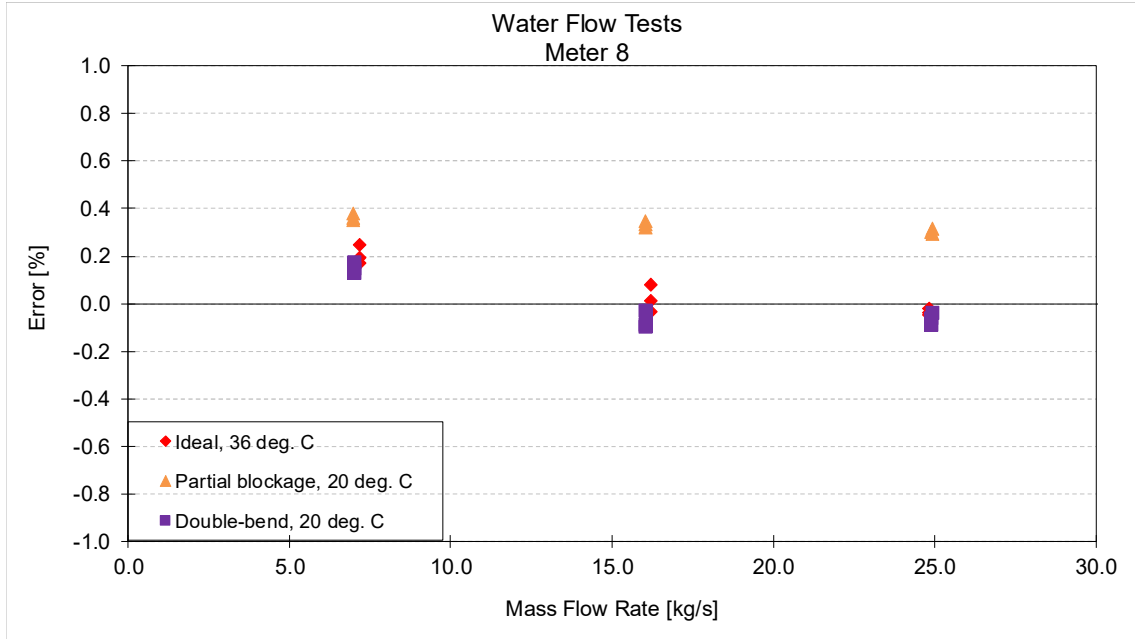
Average mass flow rate error wrt reference (%)

(a)

Mass flow rate error wrt ideal (%)

(b)

Figure 16 and table 15 show the water test results for meter 8.



**Figure 16.** Meter 8, mass flow rate error, 4-inch line, water flow tests.

Note: The ideal 20 °C curve is not displayed as it was not possible to verify if the meter was configured properly when installed and tested.

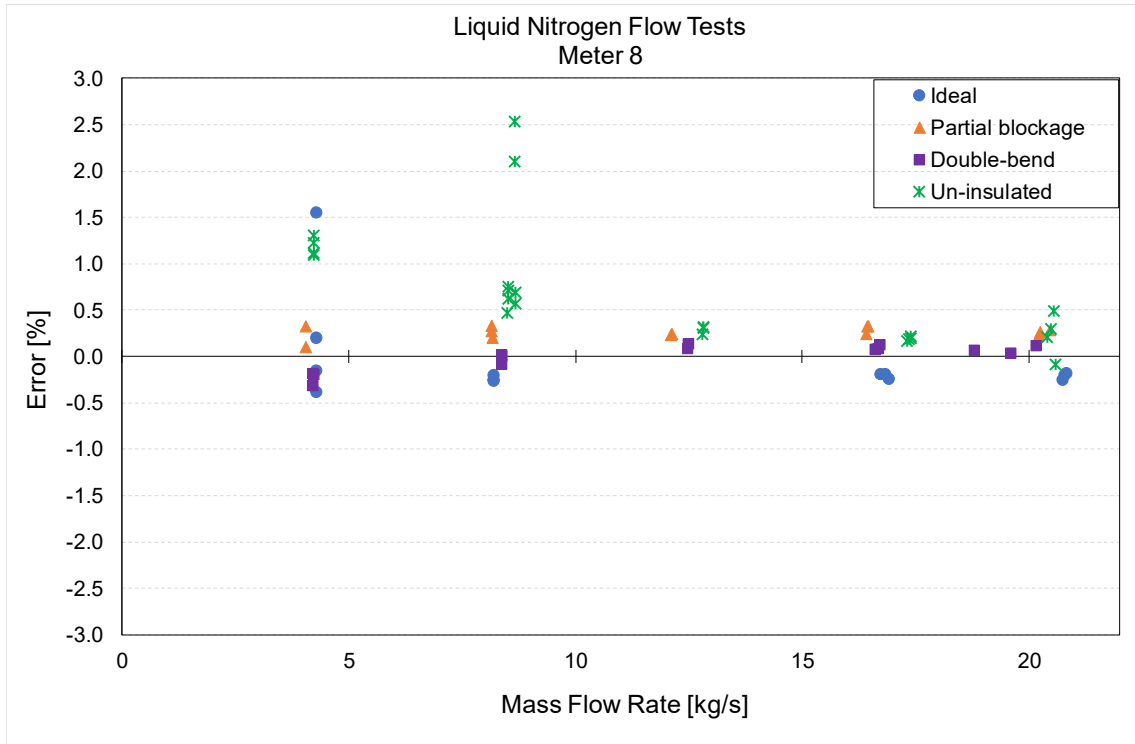
**Table 15.** Meter 8, average mass flow rate errors for water tests.

Nominal Rate (kg/s)	Ideal, 36 °C	Un-insulated		
		Ideal, 36 °C	Partial Blockage	Double Bends
7	0.204		0.160	-0.058
16	0.021		0.314	-0.096
25	-0.035		0.339	-0.031

Average mass flow rate error wrt reference (%)  
(a)

Mass flow rate error wrt ideal (%).  
Note: For this meter the 36 °C calibration results are taken as the reference.  
(b)

Figure 17 and table 16 show the LIN test results for meter 8.



**Figure 17.** Meter 8, mass flow rate error, 4-inch line, LIN flow tests.

Note: The ideal repeat curve is not displayed because changes to the metering line were made with respect to the initial ideal calibration while proper parallel alignment of the meter was not verified after these changes.

**Table 16.** Meter 8, average mass flow rate errors for LIN tests.

Nominal Rate (kg/s)	Ideal	Insulated			Un-insulated
		Ideal	Partial Blockage	Double Bends	
4	0.29		-0.08	-0.53	0.89
8	-0.25		0.51	0.22	0.88
12					
16	-0.22		0.52	0.31	0.42
20	-0.22		0.48	0.29	0.45

Average mass flow rate error wrt reference (%)  
(a)

Mass flow rate error wrt ideal (%)  
Note: For the un-insulated setup, at 8 kg/s, two measurement batches, each with 4 repeats, were recorded, however, the numbers displayed in the table are calculated from the first batch only and hence these numbers do not reflect what is shown in figure 17.  
(b)

## 6 Discussion

In this section the test results presented above are discussed in the context of the three objectives of this work indicated in section 1. It will be seen from this section and the next section that the outcomes from these objectives are interrelated.

The first objective is to reduce the flow measurement uncertainty for small and mid-scale LNG applications to meet a target measurement uncertainty of 0.50% ( $k = 2$ ). It should be noted that the test fluid is liquid nitrogen (not LNG), as explained in section 1. This means that these results are not directly applicable to LNG. Therefore, the objective in this paper is to assess if this target measurement uncertainty can be achieved for LIN as a cryogenic fluid. To enable this assessment, a combined measurement uncertainty following the requirements of ISO 17025 [11] has been calculated for each measurement point presented in section 5 by combining the uncertainty in measurement repeatability of the test meter with the facility measurement uncertainty.

For the water test results the combined measurement uncertainty varied between 0.10% and 0.14% over the test flow range for all test meters and test cases.

For the LIN test results the combined measurement uncertainty varied between 0.30% and 0.37% over test flow range for 85% of the calibrations.

When the standard error of the mean, computed from the individual calibration points per set flow rate, is of a similar or larger magnitude to the calibration uncertainty (provisionally at 0.30% ( $k = 2$ ) of reference mass flow rate, or  $< 0.35%$  ( $k = 2$ ) for volumetric flow rate, see [13]), the combined measurement uncertainty will be larger than 0.37% ( $k = 2$ ).

When the standard error of the mean is below 0.025%, the combined measurement uncertainty is the same as the calibration uncertainty of 0.30% ( $k = 2$ ) or  $< 0.35%$  ( $k = 2$ ) for volumetric flow rate (up to 2 decimal percentage points).

Flow meter manufacturers provide technical data in product specification sheets on mass or volume flow measurement accuracy. Focusing on the flow meters tested in this work and the flow rates considered, the measurement accuracy, typically stated at ambient conditions, is between 0.10% and 0.15% depending on the type and size of the flow meter. Since these accuracy figures are not quoted with a coverage factor (or a confidence level) they are not treated as uncertainty figures. Therefore, in this work they will be treated as percentage errors from the reference measurement. When used under cryogenic conditions less accuracy is expected and corrections are normally applied automatically to transfer meter calibration at ambient condition to cryogenic conditions. However, apart from one manufacturer, no accuracy figures are given for cryogenic conditions due to lack of cryogenic calibration facilities. Recommendations are normally given by the meter manufacturer to adjust some of the meter parameters to suit the test fluid and test conditions, and, for Coriolis flow meters by performing a zeroing procedure at process (cryogenic) conditions. These recommendations have been followed in this work.

Taking the above into consideration, and focusing on the meter measurement error, the results presented in section 5 indicate that the measurement accuracy range of 0.10% to 0.15% is generally met with the water testing (excluding meter 8 which had an inner diameter mismatch) since almost all measurements errors were within this accuracy band and the water calibration uncertainty varied between 0.10% and 0.14%.

For cryogenic testing, the results indicate that the measurement can be achieved within  $\pm 0.50%$  errors with respect to the reference measurement system taking into consideration the combined measurement uncertainty stated above. However, since the reference uncertainty is provisional, it is difficult at this stage to draw general and firm conclusions on all the tested meters with respect to measurement uncertainty under cryogenic conditions. Further research is required in which meter-under-test diagnostic data and facility process data are acquired simultaneously. This will help to explain fully and more accurately the larger errors seen in some of the calibrations. It is planned to carry out this research when the testing is repeated with LNG in the future.

Regarding the second objective, investigating the impact of upstream flow disturbances and meter insulation on the meter performance, it can be generally said that the influence of removing the meter insulation on mass flow rate measurement accuracy can be more significant (absolute meter error  $> 0.50%$ ) than the influence of many typical upstream disturbances. This also indicates that meter errors

within  $\pm 0.50\%$  can be achieved for the cryogenic testing with LIN, even with the presence of the disturbances tested in this work and no additional flow conditioning devices installed, in particular, for ultrasonic meters. However, these results should be viewed with the proviso that these disturbances are installed, 20D upstream. This upstream length helps to condition the flow leaving the disturbance before it enters the flow meter. For applications where high measurement accuracy is required it may be necessary to take other measures such as increasing the upstream length or installing suitable flow conditioning devices to minimise the influence of disturbances on the flow meter. Unless tested, it is difficult to say which measure is more effective than the other.

When the meter insulation was removed, an ice build-up was observed on the body of the meter and during cold and less windy days this ice build is thick and acts as a layer of insulation which helps to reduce the ambient heat ingress to the meter. However, when testing during windy days and comparatively higher outside temperature, it was observed that the ice layer is thinner and completely disappeared on the side of the meter facing the wind. In this case, it is expected that the heat ingress to meter is more significant and may have contributed to the differences in results shown in section 5 when the meter insulation is removed. It is important to note that the influence of ice build-up scenarios on the flow meter body were not explored in this work. However, this kind of study is not necessary if the meter is properly insulated when used in cryogenic applications.

The third and last objective of this work is to assess transferability of meter calibrations with water at ambient conditions to cryogenic conditions. As indicated in section 2, current LNG flow meters are usually calibrated using water at ambient temperatures and then corrected to cryogenic conditions using correction models specific to the type (Coriolis or ultrasonic) and make (manufacturer) of the flow meter. The significance of this correction on the measurement from a Coriolis meter has been demonstrated in a previous work [15]. When these corrections are not applied to the water calibration, a relatively large meter error (error in mass flow rate of 2.0%) was observed when tested in LIN. After applying the corrections, the error was reduced to about 0.20%. This example is given to highlight the significance of these corrections since these corrections are specific to meter type and make.

The corrections are normally applied automatically depending on the type of the fluid and its temperature and pressure and this was the case for all meters tested in this work.

From the results presented in this work and focusing on the test results from the ideal setup, it can be said that the correction models used to transfer the water calibration to cryogenic conditions (using LIN) can potentially result in mass flow rate measurement errors below  $\pm 0.50\%$ . Taking into consideration the combined measurement uncertainty of the cryogenic facility of 0.30% ( $k = 2$ ), the target measurement uncertainty of 0.50% ( $k = 2$ ) can be achieved provided that the expanded standard deviation of the mean value, computed from the individual calibration points per set flow rate, is smaller than 0.40% ( $k = 2$ ). Metrological institutes, meter manufacturers, and LNG custody transfer end-users will continue efforts to (I) make this statement firmer and applicable to LNG, and (II) to reduce the transferability and onsite flow measurement uncertainty to a smaller figure. The present work (water calibration and LIN calibration) is a first important step to assess transferability of meter calibrations with water at ambient conditions to cryogenic conditions. As improvements will be implemented to the system and more industrial experience is gained, the measurement uncertainty will improve to a smaller figure. At this stage, based on the present work, no exact numbers can be stated. This will require more efforts from metrological institutes, meter manufacturers and LNG custody transfer end-users. The end-users will have different uncertainty requirements depending on the application of the flow meter(s), this will dictate whether an ambient calibration (e.g. using water) or a cryogenic calibration (e.g. using LIN or LNG) of the flow meter(s) to be carried out. This is often referred to as “uncertainty tiering”.

The next section summarises the general conclusions from this work.

## 7 Conclusions

This paper presents new data on testing six industry standard Coriolis and ultrasonic flow meters under ambient and cryogenic conditions using SI traceable test facilities. These meters were provided by five well known flow meter manufacturers. To study the practical installation effects on these flow meters, the meters were arranged in different setups to check the influence of different upstream disturbances on the meter reading. The meters were also tested with and without insulation under cryogenic conditions. The ultimate objectives of these tests are firstly to recommend meter installations that results

in reduced measurement uncertainty below 0.50% in LNG flow applications and secondly to examine the effectiveness of the current corrections used to transfer meter calibrations with water at ambient conditions to cryogenic conditions.

From this work the following conclusions can be drawn:

1. The results show that the measurement accuracy of 0.10% to 0.15% specified by meter manufacturers are generally met when the meters were tested with water at 20 °C and 36 °C (excluding meter 8 which had an inner diameter mismatch) since the error was within this accuracy band and the water calibration uncertainty varied between 0.10% and 0.14% over the test flow range for all test cases.
2. The results indicate that the corrections used to transfer the water calibration to LIN conditions resulted in meter errors, for the ideal case, within  $\pm 0.50\%$  for about 85% of the results. Taking into consideration the combined measurement uncertainty of the cryogenic facility of 0.30% ( $k = 2$ ) the target measurement uncertainty of 0.50% ( $k = 2$ ) can be achieved provided that the standard error of the mean value, computed from the individual calibration points per set flow rate, is smaller than 0.40%. However, systematic research would be needed to investigate if these corrections can be generalised to other meter sizes from different manufacturers, or to the same meter type from a differently produced batch. The current research with LIN provides so far new and meaningful information concerning the estimated error (and associated uncertainties) of a water-based calibrated flowmeter used in cryogenic applications, such as LNG. However, if a more concluding error and uncertainty statement are needed, then the same systematic research should be conducted with the fluid of particular interest. This work directly benefits the update of ISO 21903:2020 standard on LNG dynamic flow measurements [12].
3. From the above conclusion, it can be said that meter errors within  $\pm 0.50\%$  can be achieved for the cryogenic testing with LIN at approximately -180 °C, even with the presence of the disturbances tested in this work and no additional flow conditioning devices installed, in particular, for ultrasonic meters. This also means that the influence of these flow disturbances on meter error is limited (i.e., contribution to meter error below  $\pm 0.50\%$ ), however it should be remembered that these disturbances are followed by straight piping equivalent to 20 pipe diameters. This conclusion will be substantiated further when these meters are tested with LNG in the next programme of work.
4. The results show that the effect of removing the meter insulation on measurement accuracy can be significant (i.e. error  $> \pm 0.50\%$ ). The difference in the meter error between the insulated and un-insulated cases varied between a minimum value of -0.01% and a maximum value of 1.04%. Therefore, meter insulation is recommended when used in cryogenic service. It is important to note that the influence of ice build-up scenarios on the flow meter body, when the meter is not insulated, are not explored in this work.
5. In this work, liquid nitrogen (LIN) was used as a safe fluid to commission and operate the LNG research and calibration facility and as an essential step to verify the operation and robustness of facility components and instrumentation under cryogenic conditions and to establish the stability criterion for flow, temperature and pressure with LIN. Although LIN has different properties than LNG, the LIN boiling point temperature at ambient pressure is about 35 °C lower than the corresponding LNG boiling point. It is planned to repeat these tests with LNG in order to compare the results with the LIN tests presented in this paper. This may reveal that testing with an explosion safe and environmentally friendly fluid such as LIN produces representative results for testing LNG flow meters.
6. The results presented in this paper cannot be extrapolated, with meaningfully low uncertainty, to flow meters of different type, size, model and make (manufacturer) than those tested.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.



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## Note

Results in this publication reflect the author's view. EURAMET is not responsible for any use that may be made of the information it contains.



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