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Liquid nitrogen calibrations of industry-standard LNG flow meters used in LNG custody transfer

Introduction

Liquified Natural Gas (LNG) is traded between the exporter and the importer during custody transfer. Typical applications of LNG are (at the large scale) to regassify it and inject it into the gas grid, and (at the small to midscale) as a transport fuel. LNG is an alternative to pipeline gas with strategic, and for long distances, economic benefits [1]. Further, LNG has considerable environmental benefits. Engines running on LNG will meet the (new) limits set on NO_x and CO_2 emissions and produce less noise than diesel operated engines. LNG fuelled trucks are an alternative to diesel fuelled trucks for long-distance road freight transport. LNG shipments may overtake inter-regional pipeline shipments in the 2020s [2]. Clearly, the global trade in LNG is growing and there is a need for metrological infrastructure to facilitate it. The quantity of LNG traded is based on the amount of energy transferred [3]. To determine this amount, current practice is to measure the volume of LNG which, in combination with the mass density and the measurement of LNG composition, allows the computation of the amount of energy transferred (see for example [3]).

One method to measure the volume is based on level gauges and calibration tables in the LNG carrier. Another method is to measure the flow when custody transfer takes place, such as when fuelling an LNG truck or in LNG ship bunkering. Typical instruments used in the second method are ultrasonic flow meters (USM's) and Coriolis flow meters (CFM's). Currently, USM's and CFM's are calibrated with water and correction equations are applied to compensate for temperature effects at cryogenic conditions when measuring LNG flow (see for example [4,5]). Clearly, traceable calibrations with LNG will help to establish confidence in LNG flow metering and therefore in LNG custody transfer.

Within the European Metrology Research Programme (EMRP), the European Metrology Programme for Innovation and Research (EMPIR), and the "Regeling Nationale EZK subsidies" (Dutch Ministry of Economic Affairs and Climate Policy) research and innovation projects were undertaken to establish metrological infrastructure for LNG applications. In 2019 VSL completed the construction of the Cryogenic Research and Calibration facility to enable traceable cryogenic flow meter calibrations with a target maximum flow rate of 200 m^3/h and a target measurement uncertainty of 0.15% in mass flow rate (which equates to about 0.20% in volume flow rate) [6]. An LNG roadmap is displayed in Figure 1. A primary standard was built in 2013 and documented [7]. It is now integrated into the Cryogenic Research and Calibration Facility, which was completed and put into use in 2019. It is currently used for flow meter calibrations with liquid nitrogen (LIN) for flow rates up to 100 m^3/h. It is the intention to replace the LIN with LNG in a future stage, turning the facility into the LNG research and calibration facility of Figure 1. The facility will serve the needs of small-scale to mid-scale LNG flow meter calibrations. The LNG composition primary standard allows the calibration of alternative LNG composition measurement systems as well. Thus, the facility provides the means to traceably calibrate flow meter and composition measurement systems, which in turn allows the calibration of the quantity of LNG-energy transferred in LNG trade.

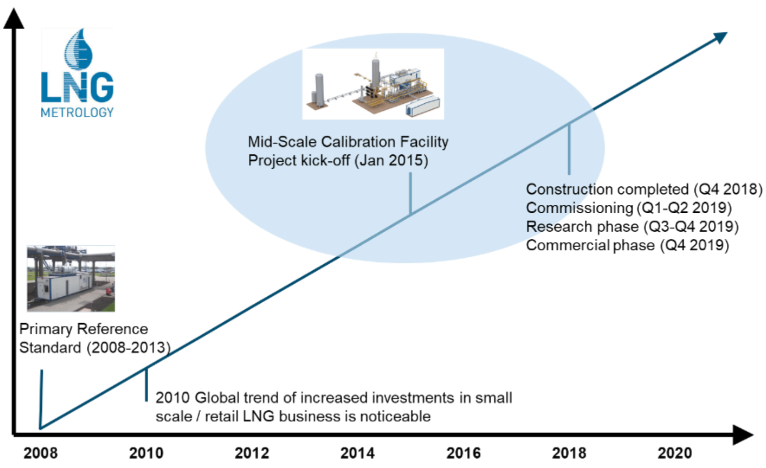

Figure 1: Roadmap for SI-traceable LNG flow meter calibrations.

SI-traceable flow calibrations with LIN are of interest to the LNG-industry because the currently employed temperature correction equations of LNG flow meters, which compensate for temperature effects when measuring LNG flow, are based on LIN literature data or calibrations with alternative cryogenic liquid(s) such as LIN. LIN-density and LIN-viscosity are of similar magnitude as for LNG, therefore the Reynolds numbers will be as well. An important difference is that the boiling line of LIN is about 30 °C – 50 °C below that of LNG. Consequently, the temperature correction equations employed by LNG flow meters can not be directly validated with direct LIN-calibrations.

This paper reports on the cryogenic flow test programme performed within the European Metrology Programme for Innovation and Research (EMPIR) (Project Numbers: ENG60 and 16ENG09) and the “Regeling Nationale EZK subsidies” (Dutch Ministry of Economic Affairs and Climate Policy, Project Numbers: TELN115006 and TELN116063). The overall LNG flow objective of the research is: “To reduce the onsite flow measurement uncertainty for small- and mid-scale cryogenic applications to the level comparable to meet the current OIML recommendations (1.5 %) [8, 9]. To include a systematic assessment of the impact of flow disturbances and the impact of flow meter insulation.” For conventional fuels, the legal requirement is 0.5 % flow measurement uncertainty for the measurement chain [8]. It is known that flow disturbances, which occur in actual on-site LNG installations, can affect LNG flow meter readings and that this depends on the meter type (e.g., Coriolis, ultrasonic). Effects of insulation are hard to assess when performing the water calibrations at ambient conditions. Therefore, within this research programme, a systematic assessment of upstream flow disturbances and the effect of meter insulation under cryogenic conditions was undertaken to determine the SI-traceable meter deviations in setups typical for those in which LNG flow meters are installed in LNG applications worldwide. Prior to the cryogenic assessment of the effect of upstream flow disturbances, a water assessment at 20 °C and 37 °C was made with the aim to quantify the uncertainty from currently used temperature correction models employed by LNG flow meters. In flow metrology there is an ongoing discussion, depending on meter type and medium of which the flow is measured, on whether so-called alternative fluid calibrations suffice to establish the flow meter uncertainty when it is used to measure flow of another fluid, at different process conditions (see e.g., 10, 11). A typical example is the widespread acceptance of calibrating a flow meter with air for use on gases other than air [see gas meter standards 12 and 13]. The quantification of the uncertainty from water calibrations for meters used to measure LNG flow will be the topic of a future publication.

This paper will start with describing the LNG research and calibration facility for calibrations with LIN, followed by a description of the upstream flow disturbances and insulation-effect test protocol. Thereafter, metrological specifications for the calibrations will be given, followed by a presentation of the results, a discussion on them and conclusions. The following flow meter manufacturers participated in the research programme: Baker Hughes, Emerson, Endress + Hauser, KROHNE, and Yokogawa. A total of six meters were tested, two of them are ultrasonic meters, and four of them are Coriolis flow meters.

Method

The LNG research and calibration facility

The completion of the LNG research and calibration facility with LIN has taken about a decade in total and some phases are yet to be implemented at the time of writing, such as the introduction of LNG to replace LIN, and the full metrological validation of the LNG composition standards. In the years 2010 – 2013, a gravimetric primary standard was realized with an estimated Calibration and Measurement Capability (CMC) in the range 0.12% to 0.15% for mass flow rate. During this time period, LNG flow meter calibrations were performed for 2”-sized meters with LIN and LNG [7]. Meter calibrations showed typical deviations from the primary stand to within 0.5%. In the years 2013 – 2018 the LNG research and calibration facility was built and commissioned with LIN in 2019. The primary flow standard was fully integrated into this facility in order to provide SI-traceability for the cryogenic research into flow meters and the calibrations of LNG flow meters. The primary flow standard had to be modified in the operational sense, and along the way, modifications were made to improve its metrological performance [14]. The facility provides the means to traceably calibrate flow meters with cryogenic liquid directly. The facility allows for systematic research into flow meter performance in varied circumstances, such as the effects of flow-meter insulation, (upstream) flow disturbances, multi-phase flow, and variable temperature and pressure conditions. Prototypes of cryogenic flow meters and different meter models can be tested and calibrated in a metrologically traceable manner.

Figure 2 shows an overview of the main components of the Cryogenic Research and Calibration facility.

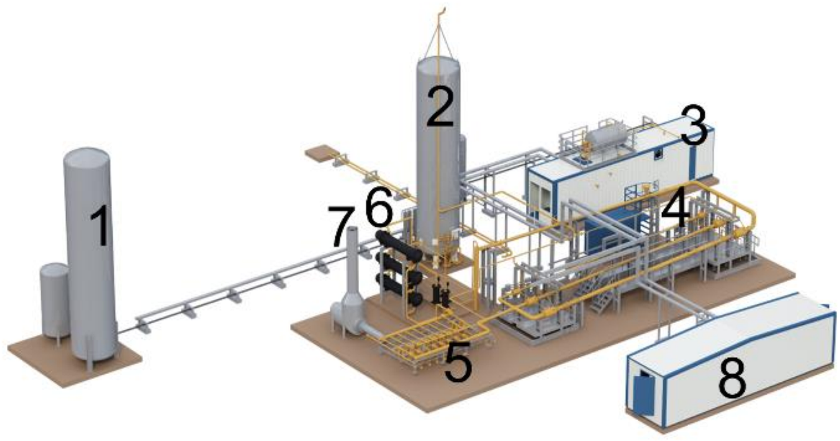

Figure 2: The Cryogenic Research and Calibration facility: 1) Liquid Nitrogen (LIN) storage tank, 2) cryogenic liquid storage tank, 3) Primary Standard (PSL) for mass flow utilizing the gravimetric method to calibrate the CFM's in the PSL, 4) Meter under Test (MuT) section, 5) working standards, a set of CFM's, 6) heat exchangers and pumps, 7) Nitrogen (N_2-)warmer and 8) control room. Not all details in the drawing reflect the actual situation at the facility. Picture taken from [6].

The Cryogenic Research and Calibration facility is based on a closed-loop system where cryogenic liquid is pumped (Figure 2, item 6) from the cryogenic vessel (Figure 2, item 2) to the working standard CFM's (Figure 2, item 5), then towards the Meter(s)-under-Test (Figure 2, item 4), and then recirculated by the pumps towards the working standards (Figure 2, item 5). This loop is termed Mid-Scale Loop (MSL). The results shown in this paper are obtained from LNG flow meters installed within the Meter(s)-under-Test section and calibrated with the working standard CFM's. An overview of LNG flow meters calibrated in the Meter(s)-under-Test section is given in Table 1. LIN (Figure 2, item 1) is used to subcool the cryogenic liquid, which occurs in the heat exchanger (Figure 2, item 6). Subcooling avoids boiling and concomitant two-phase flow of the circulated cryogenic liquid. Heating of cryogenic liquid occurs due to the heat transfer from the atmosphere at ambient temperatures towards the cryogenic liquid at cryogenic temperatures. When using the facility with LIN, the subcooling efficiency of LIN is reduced with respect to using the facility with LNG. Therefore, it is expected that flow stability will be improved when LNG is introduced to replace the LIN in the loop. A composition measurement primary standard (not shown in Figure 2) is located downstream of the Meter(s)-under-Test.

Meter manufacturer	**Meter Type**
Baker Hughes	USM
Emerson	CFM
Endress + Hauser	CFM
KROHNE	USM
KROHNE	CFM
Yokogawa	CFM

Table 1: Meter manufacturer and meter type included in the LIN calibration research programme.

The fully integrated primary flow standard is item 3 in Figure 2 and is located within a transportable container. SI-traceable calibrations of CFM's in the primary standard can be performed and used to transfer SI-traceability towards the working standards of the MSL through a bootstrapping procedure. The flow loop will then be diverted from the MSL to include the primary standard. After having (re)established the SI-traceability, the flow will be diverted back towards the MSL to perform SI-traceable calibrations of Meter(s)-under-Test in a loop from the MSL working standards towards the Meter(s)-under-Test and then back to the working standards.

Upstream flow disturbances – metering lines in MuT-section

The Meter(s)-under-Test section (Figure 2, item 4) of the Cryogenic Research and Calibration facility consists of parallel 2” and 4” lines that can be operated separately. Meters within these lines can be replaced to be calibrated against the working standards (Figure 2, item 5). It is also possible to install complete replacement metering lines within the Meter(s)-under-Test section.

Metrological institutes JV, NEL and VSL collaborated within this research to investigate the effect of typical on-site LNG installation upstream flow disturbances on LNG flow meter readings. Both water and LIN calibrations were performed in order to widen the range of study with respect to fluid properties (density, viscosity, flow-velocity, Reynolds numbers) and to be able to compare water calibrations with LIN calibrations. Figure 3 shows the metering setup of the 2”-line which contains 2 CFM’s. An open plate is installed upstream for the “ideal setup”. For the ideal setup, the metering line including the flow meters was insulated with rockwool by a professional insulation company. The following perturbations were made with respect to the ideal setup:

- Installation of 25% blockage plate instead of an open plate to study the effect of a partial upstream flow blockage (see Figure 3 - 06-DN50-LNG-SS).
- Installation of four bends (replacing Figure 3 – 01-DN50-LNG-SS). The four bends downstream exit was located at the open/blocking plate location and the bends were insulated after installation. A picture of the four bends is shown in Figure 5.
- Removal of flow meter insulation.

A repeat of the ideal setup measurements was performed in order to assess the reproducibility of the ideal setup measurements. Note that the pipe length between the flow disturbances and the first downstream meter is 20 diameters (Figures 3 and 4).

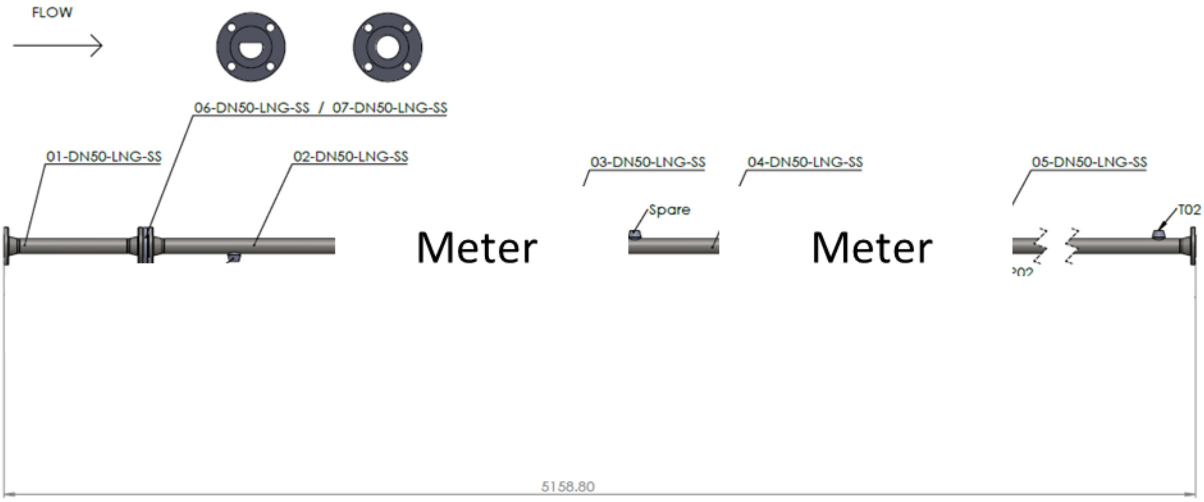

Figure 3: layout of the 2” metering setup without disturbance (ideal setup, open plate) and with the blocking plate disturbance. Number below indicates lengths in mm. Modified from picture in courtesy of NEL [15].

Table 2 summarizes the setups in which measurements were performed and the sequence of changes to the metering lines. In the first setup calibrations were performed in the ideal setup (setup 1). Then the blocking plate was installed and insulated, and calibrations were repeated (setup 2). This was followed by calibrations with insulated 4-bend disturbance (setup 3). The first setup was restored, and calibrations were repeated (setup 1, sequence 3), and lastly, calibrations were repeated after the insulation was removed from the flow meters (setup 4).

Sequence	Setup	Description
0	1	Ideal set-up, no flow disturbance and insulated flow meters
1	2	As setup 1, but with insulated partially blocking plate
2	3	As setup 1, but with insulated 4-bend disturbance to replace 01-DN50-LNG-SS (for 2”-line) or 01-DN100-LNG-SS (for 4”-line)
3	1	Ideal set-up, no flow disturbance and insulated flow meters
4	4	Ideal setup, as setup 1 but with un-insulated flow meters

Table 2: Sequence of modification and corresponding setups of the metering lines for the investigation into upstream flow disturbances and the insulation effect.

Meters installed in two different 4”-lines (4”a and 4”b) were studied with setups analogously to those of Table 2. Figure 4 shows the metering setup of the 4”-lines. An USM was installed upstream of a CFM for each of the two 4”-lines.

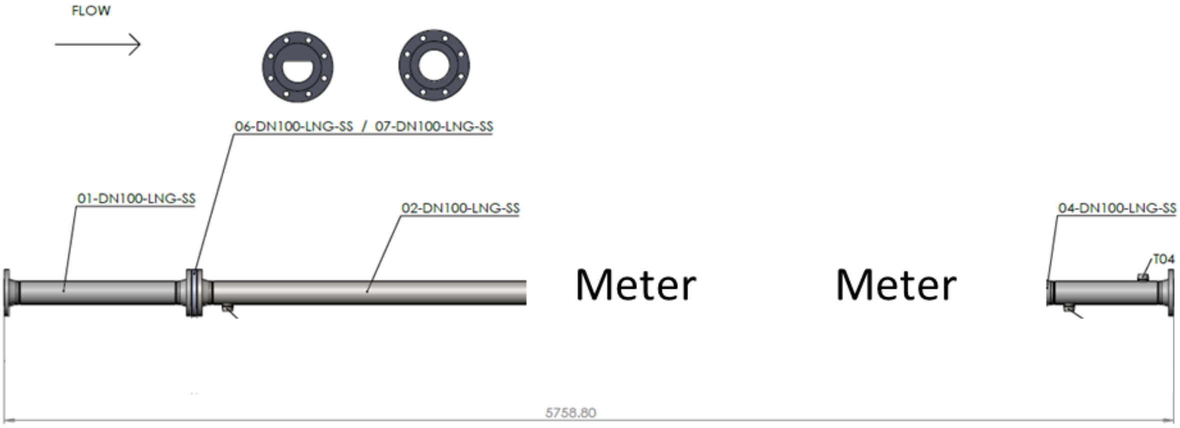

Figure 4: layout of the 4” metering setups without disturbance (ideal setup, open plate) and with the blocking plate disturbance. Number below indicates length in mm. Modified from picture in courtesy of NEL [15].

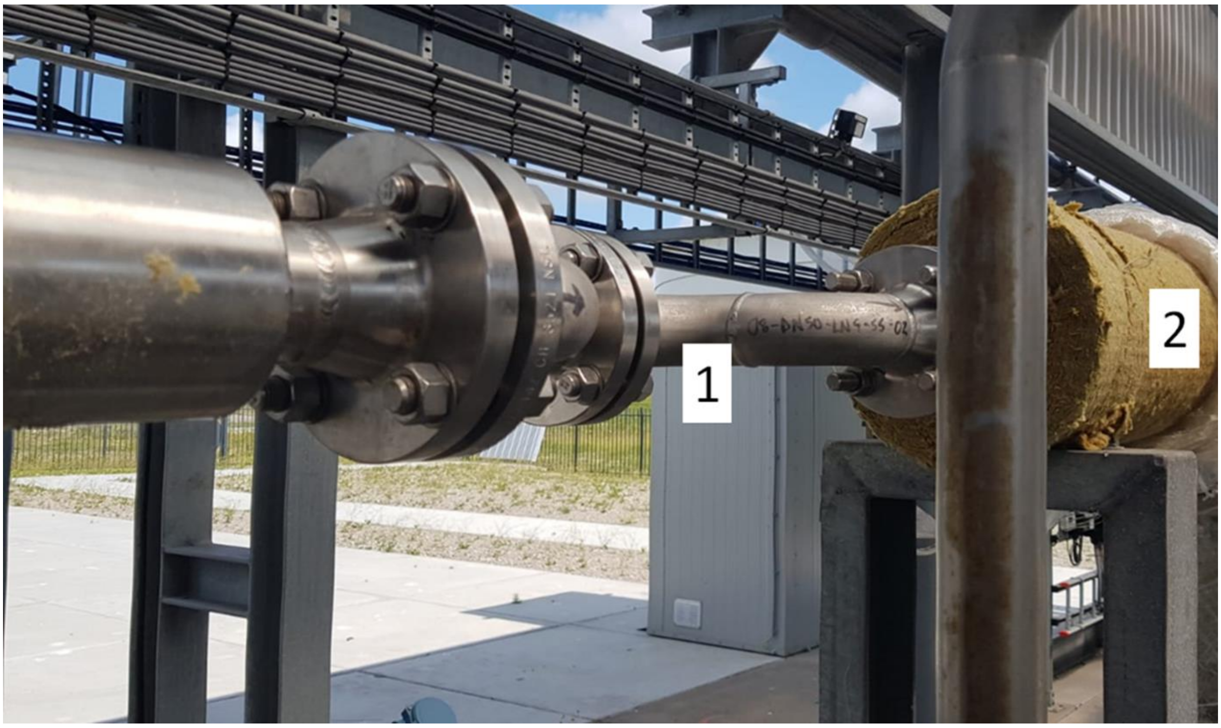

Figure 5: Picture of 2” metering line in facility showing (1) 2 bends of the four-bends prior to insulation and (2) insulation of pipe.

One of the meters was insulated with bluedec® as preferred option from the flow meter manufacturer. There was an inner diameter mismatch between the upstream & downstream spools and meter 8 (see results section) of 5.8%, while best practice is to stay within 1%. The mismatch was found just before the first calibrations (in the water calibration programme) and the manufacturer decided to continue the programme in similar fashion during the cryogenic testing to keep the geometry constant. Accurate diameter match and parallel alignment is of utmost importance for any accurate USM flow reading.

Metrological specifications – flow calibration protocol

Tables 3 and 4 show the flow calibration protocol. All repeats had a 120 s – 130 s batch run. In practice, some of the flow points could not be achieved for operational reasons (e.g., the highest ones: 50 m^3/h for the 2”-line and 100 m^3/h for the 4”-line) and pressures were dictated by the flow point.

Flow (m^3/h)	Approximate mass flow rate (kg/s)	Temperature (°C)	Pressure (barg)	Repeats (n)	Reynolds 10^6 (-)
5	1	-180	6	3	0.271
10	2	-180	6	3	0.542
20	4	-180	6	3	1.085
30	6	-180	6	3	1.627
40	8	-180	6	3	2.169
50	10	-180	6	3	2.712

Table 3: Flow points for the 2" line. The Reynolds number is computed from literature values. Table modified from [16].

Flow (m^3/h)	Approximate mass flow rate (kg/s)	Temperature (°C)	Pressure (barg)	Repeats (n)	Reynolds 10^6 (-)
20	4	-180	6	3	0.542
40	8	-180	6	3	1.085
60	12	-180	6	3	1.627
80	16	-180	6	3	2.169
100	20	-180	6	3	2.712

Table 4: Flow points for the 4" lines. The Reynolds number is computed from literature values. Table modified from [16].

Metrological specifications – flow stability

The density changed over the course of the measurements. Due to the design, subcooling capability of the facility is more limited using LIN than when using LNG. It was checked by SI-traceable temperature and pressure measurements that the (computed) LIN-density corresponded to that of single-phase liquid. This was done systematically both during the measurements and in the data-analysis. The test protocol volumetric flow points where converted to the corresponding mass flow rate reference during the measurements given the variable density. Density was computed from the NIST REFPROP database [17].

The stability criterion objectives for flow measurements were:

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

Achieved stability criteria for all setups and all calibration runs for repeat duration of 120 s – 130 s were:

- Pressure variability.
  - Mean pressure standard deviation for individual batch runs < 0.03 bar, thereby meeting the pressure variability criterion.
  - For 2"-line. Mean change < 0.10 bar and standard deviation of this change < 0.10 bar (amount of rejected samples after filtering – see start of **Results** section for description of filtering criteria – is less than 2% of the filtered results).
  - For 4"-line. Mean change < 0.05 bar and standard deviation of this change < 0.05 bar.
- Temperature variability.
  - Mean temperature standard deviation for individual batch runs < 0.10 °C, thereby meeting the temperature variability criterion.
  - For 2"-line. Mean change < 0.20 °C and standard deviation of this change < 0.20 °C.
  - For 4"-line. Mean change < 0.10 °C and standard deviation of this change < 0.20 °C.
- Density variability.
  - For 2"-line. Mean change < 1.0 kg/m^3 and standard deviation of this change < 1.0 kg/m^3.
  - For 4"-line. Mean change < 1.0 kg/m^3 and standard deviation of this change < 1.0 kg/m^3.

- Flow rate variability.
    - For 2”-line. Mass flow rate standard deviation < ±1.5% of flow rate, thereby meeting the flow rate variability criterion. Maximum mass flow rate standard deviation at ±2.0 % of flow rate (based on unfiltered data).
    - For 4”-line. Mass flow rate standard deviation < ±0.5% of flow rate, thereby meeting the flow rate variability criterion. Maximum mass flow rate standard deviation at ±1.0 % of flow rate (±1.5% of outliers in unfiltered data rejected).

Metrological specifications – calibration preparations

Zero adjustment procedures, zero verifications and zero checks were performed by VSL personnel, to the best available knowledge, for all CFM’s. Guidelines from the applicable draft ISO standard [18], such as to assure that stable process conditions of fluid temperature, pressure, and density are achieved, and adhering to the typical zero monitoring time of about 30 s were followed. It must be noted that the implementation of zeroing under process conditions is not exactly performed the same for all meter models of the test programme. 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 and therefore any significant zero error will exhibit as a meter error with inverse dependence on mass flow rate.

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. 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^3/h), which is < 0.02% at 5 kg/s (or approximately 25 m^3/h). The working standards are comprised of a set of four CFM’s which are used in parallel when going to higher flow rates. Typically, when the flow rate through one meter exceeded 4 kg/s another CFM was added for the reference mass flow rate in the working standard. Obviously, as the flow rate is much higher than 2 kg/s, the zero-stability uncertainty from using an additional meter will be insignificant with respect to the total uncertainty (see next paragraph) of the calibrations.

The setups of the test protocol (Table 2) imply modifications to the metering line. In cryogenic flow, a large leak will show as icing on the piping, flanges, appendages, bolts, pressure relief valves etc. (prior to insulation). To assure proper metrological calibrations, smaller leaks were quantified based on pressure decay with time after pressurizing several parts of the loop with gas. Estimated maximum leak rate magnitudes were < 0.05% of the lowest flow rate considered (2 kg/s or approximately 10 m^3/h), which is < 0.02% at 5 kg/s (or approximately 25 m^3/h). At the start of the programme, for the 2”-line and the 4”a-line setups 1 and 2 in Table 2, the estimated maximum leak rate was < 0.10% of the lowest flow rate considered (2 kg/s or approximately 10 m^3/h), which is < 0.04% at 5 kg/s (or approximately 25 m^3/h).

Metrological specifications – estimated SI-traceable calibration uncertainty

The uncertainty statement that follows makes use of the formulation made in the Technical note 606 from the United States Department of Commerce [19]. 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 [17]. 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). Repeatability uncertainty (Type A) of the calibrations shown in this paper is not included.

The SI-traceable uncertainty comprises:

- Uncertainty of PSL gravimetric standard. An example uncertainty budget for a cryogenic mass flow rate gravimetric standard is given in [7].
- Uncertainty of calibration and correction of the MSL CFM working standards against which the calibrations shown in this paper are performed.
- Uncertainties of MSL-to-MuT calibrations: MSL zero variability uncertainty, linepack correction uncertainty, and maximum leak rate uncertainty.

Results

All graphs shown in this section are against SI-traceable LIN mass flow rate along the *x*-axis (see above for uncertainty of calibration statements). Results shown in this section have been filtered based on: large meter deviations (i.e., >10%) from the working standard, large linepack effects (i.e., with an estimated maximum contribution to the magnitude of the calibration deviation > 0.10%), spurious effects in the data acquisition (e.g., dropped pulses from meters/acquisition system), or obvious outliers manifested in two meters along the same metering line (these outliers can be on the order of > 0.10% in meter deviations relative to the repeats at the same flow rates). Data was acquired traceably to underlying raw data which is an effective means for outlier identification.

Figures 6 - 8 show the meter deviations for the 2”-line, meter 1 and meter 6 (randomized numbers) respectively. Meter 6 was replaced from modification 2 to 3 in Table 2. Therefore, its display of results is split up in Figure 7 (initial meter) and Figure 8 (replacement meter) separately.
Figures 9 - 12 show the meter deviations for the 4”-lines, meters 0, 3, 4, and 8 (randomized numbers) respectively.

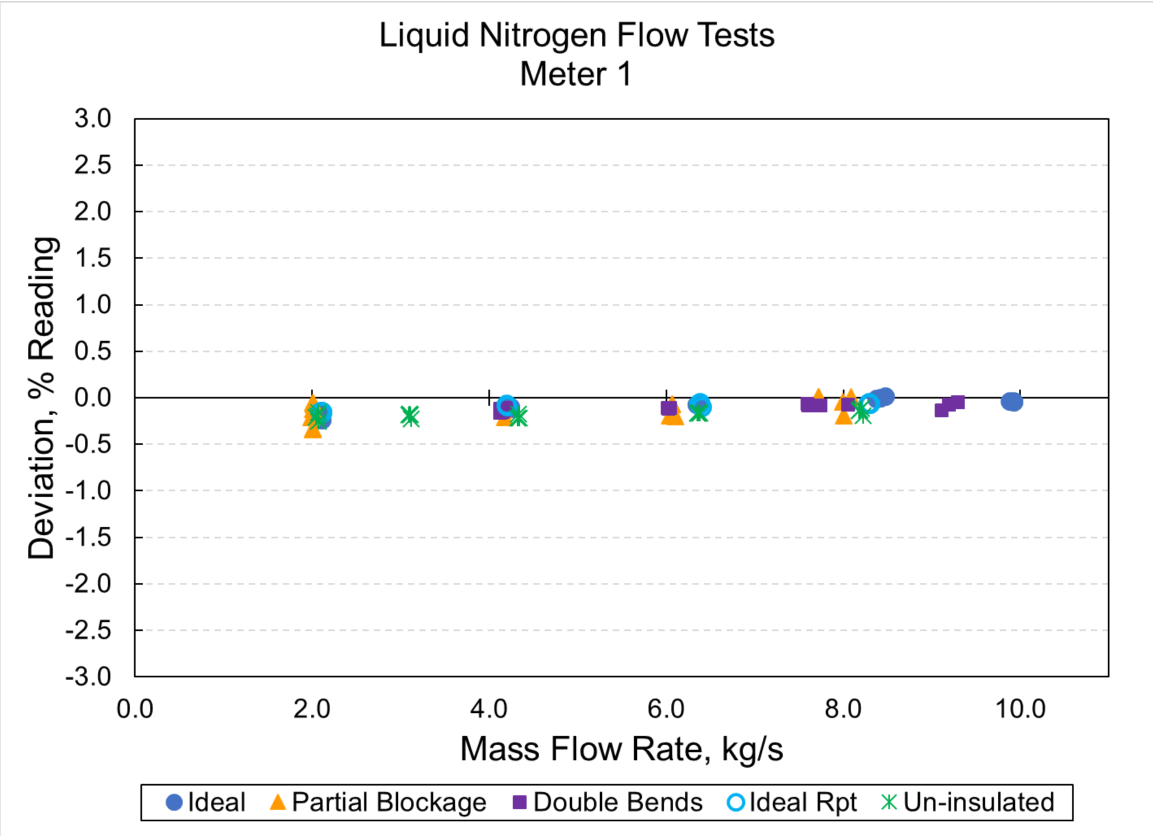

Figure 6: Graphs of meter 1 deviation versus mass flow rate for setups of Table 2.

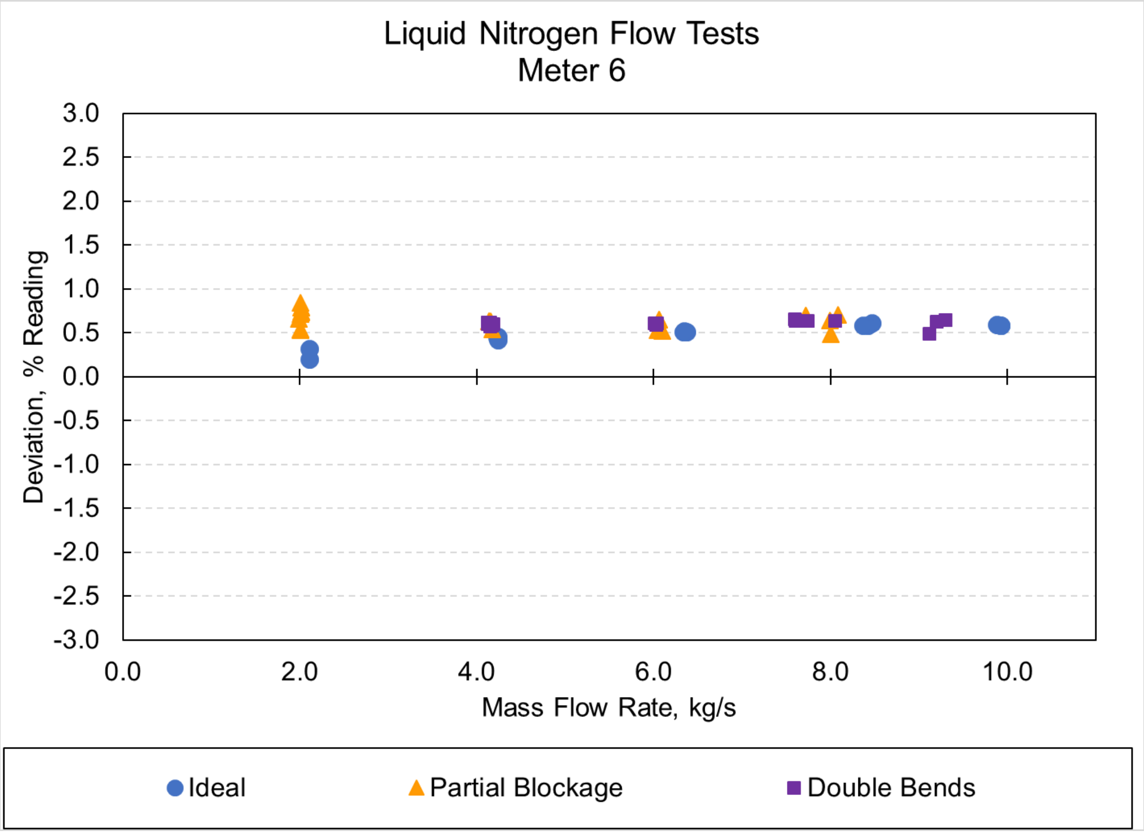

Figure 7: Graphs of meter 6 deviation versus mass flow rate for setups of Table 2. This meter was replaced from modification 2 to 3 in Table 2. Consequently, only results for setups 1 – 3 are shown.

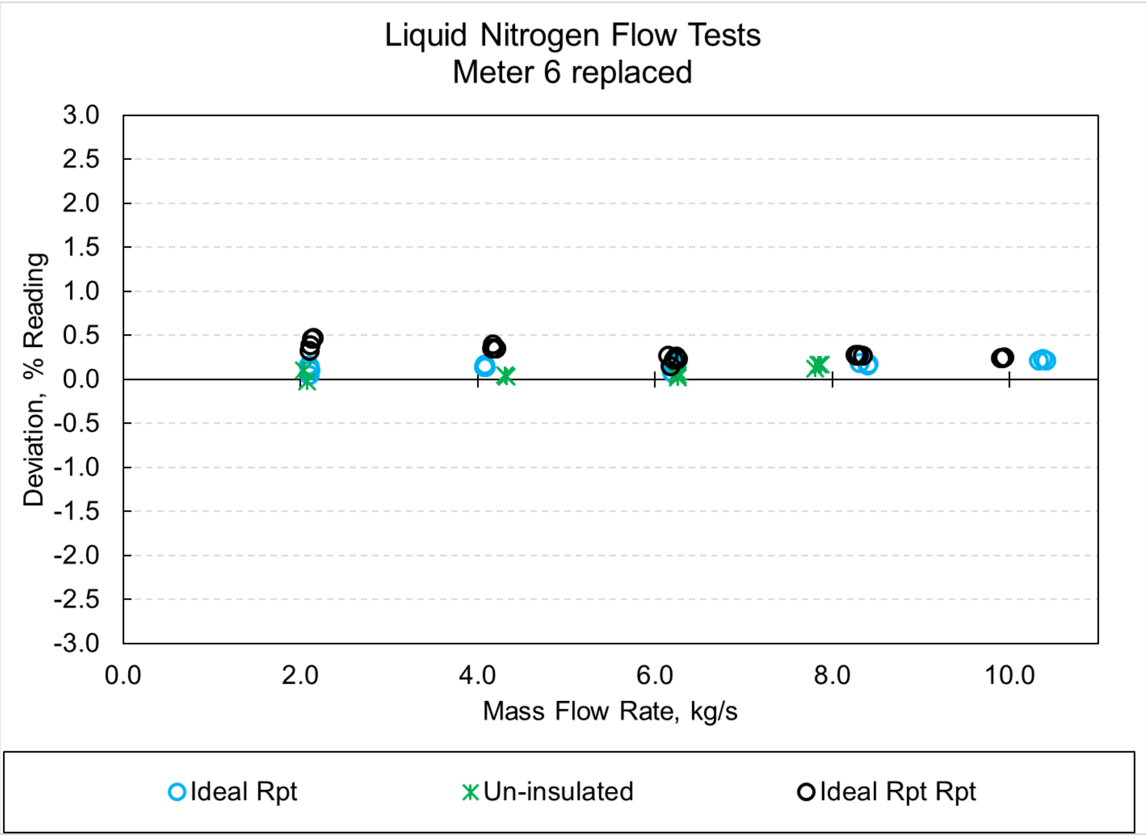

Figure 8: Graphs of meter 6 deviation versus mass flow rate for setups of Table 2. This meter was replaced from modification 2 to 3 in Table 2. Consequently, only results for setups 1 and 4 are shown. During the initial “Un-insulated” calibration (setup 4) it was not ascertained that the meter diagnostic data corresponded to manufacturers recommendations. The results from a second “Un-insulated” calibration (setup 4) are displayed here. In addition, an additional repeat of setup 1 is indicated with black symbols.

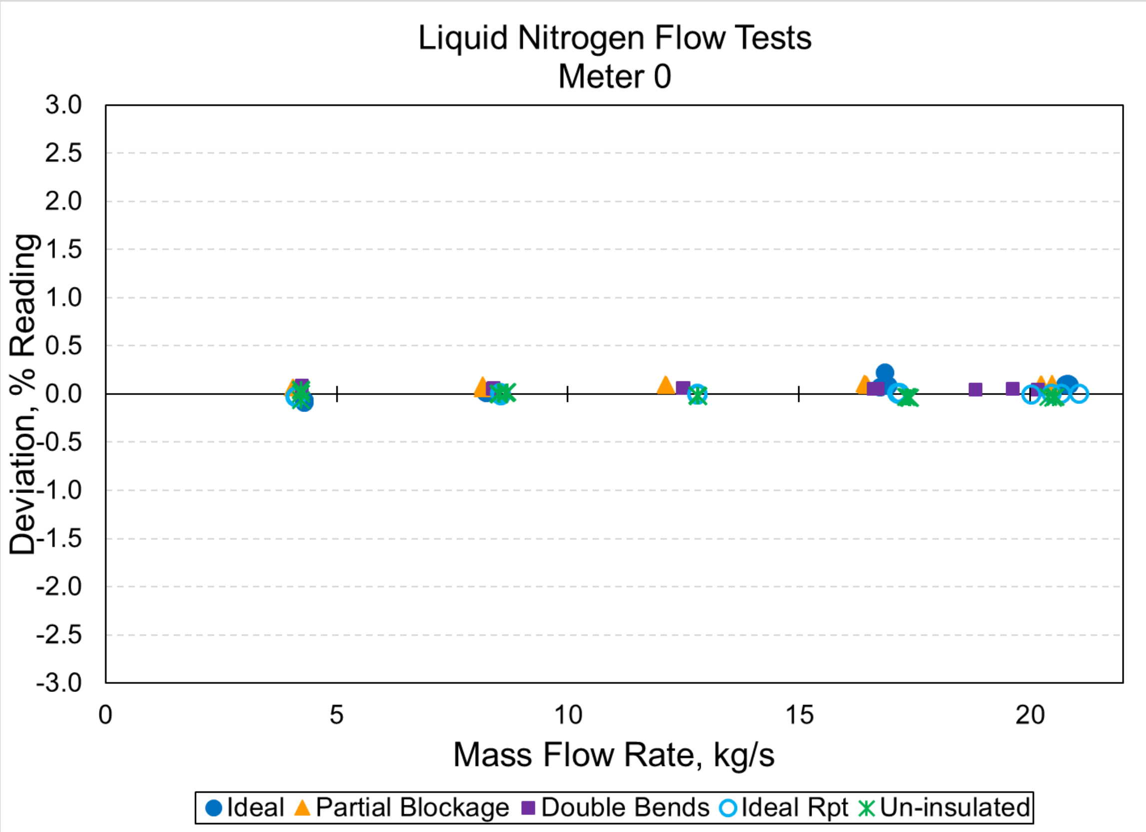

Figure 9: Graphs of meter 0 deviation versus mass flow rate for setups of Table 2.

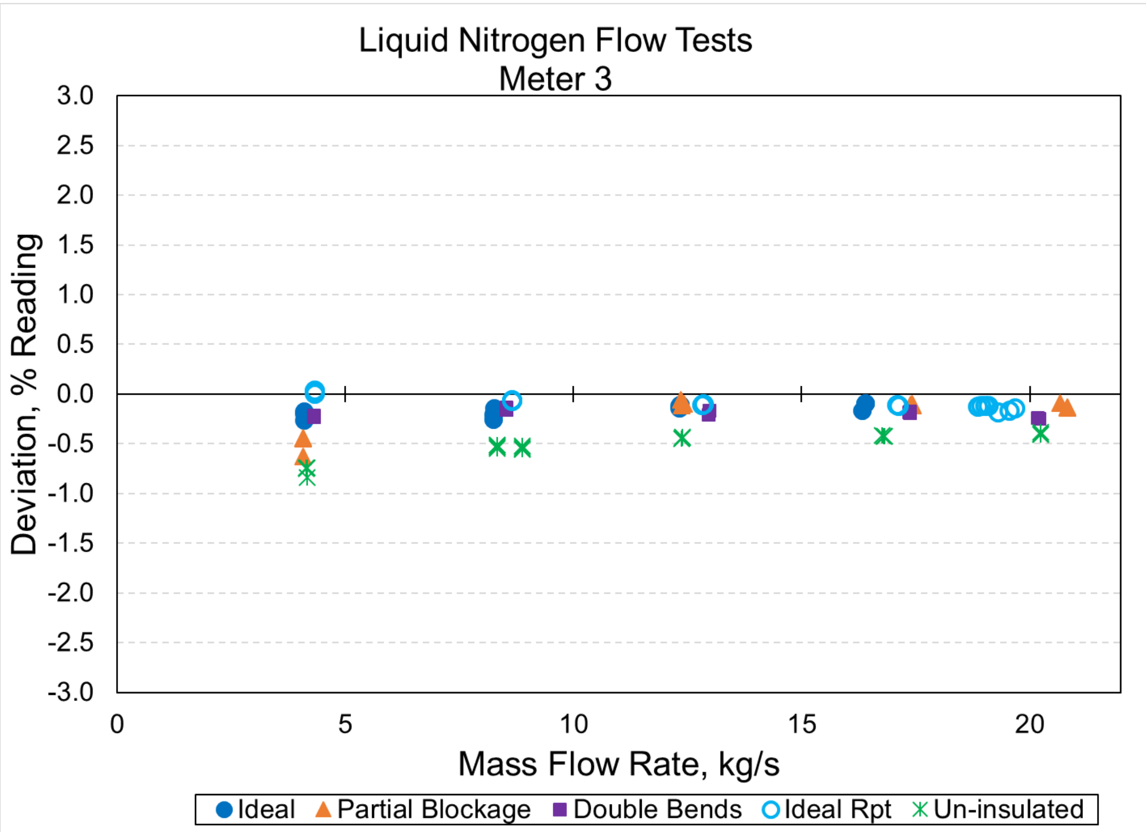

Figure 10: Graphs of meter 3 deviation versus mass flow rate for setups of Table 2.

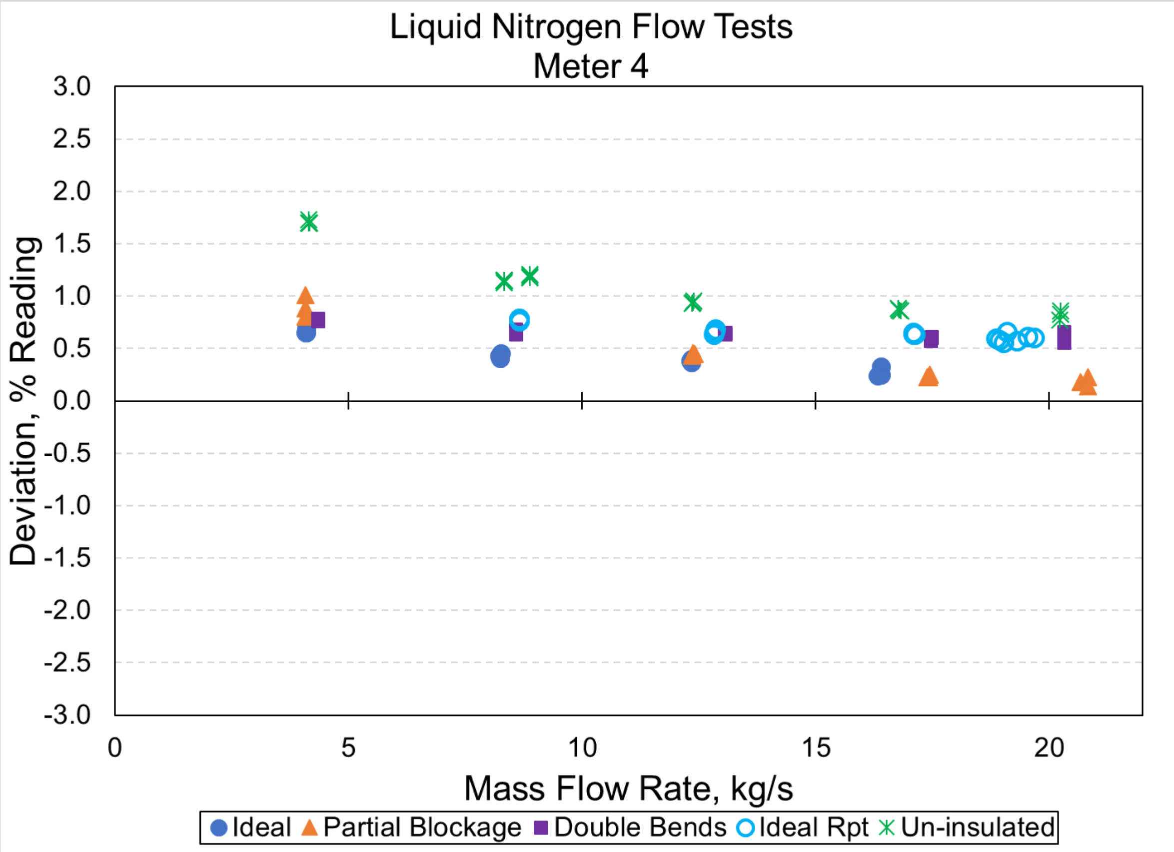

Figure 11: Graphs of meter 4 deviation versus mass flow rate for setups of Table 2.

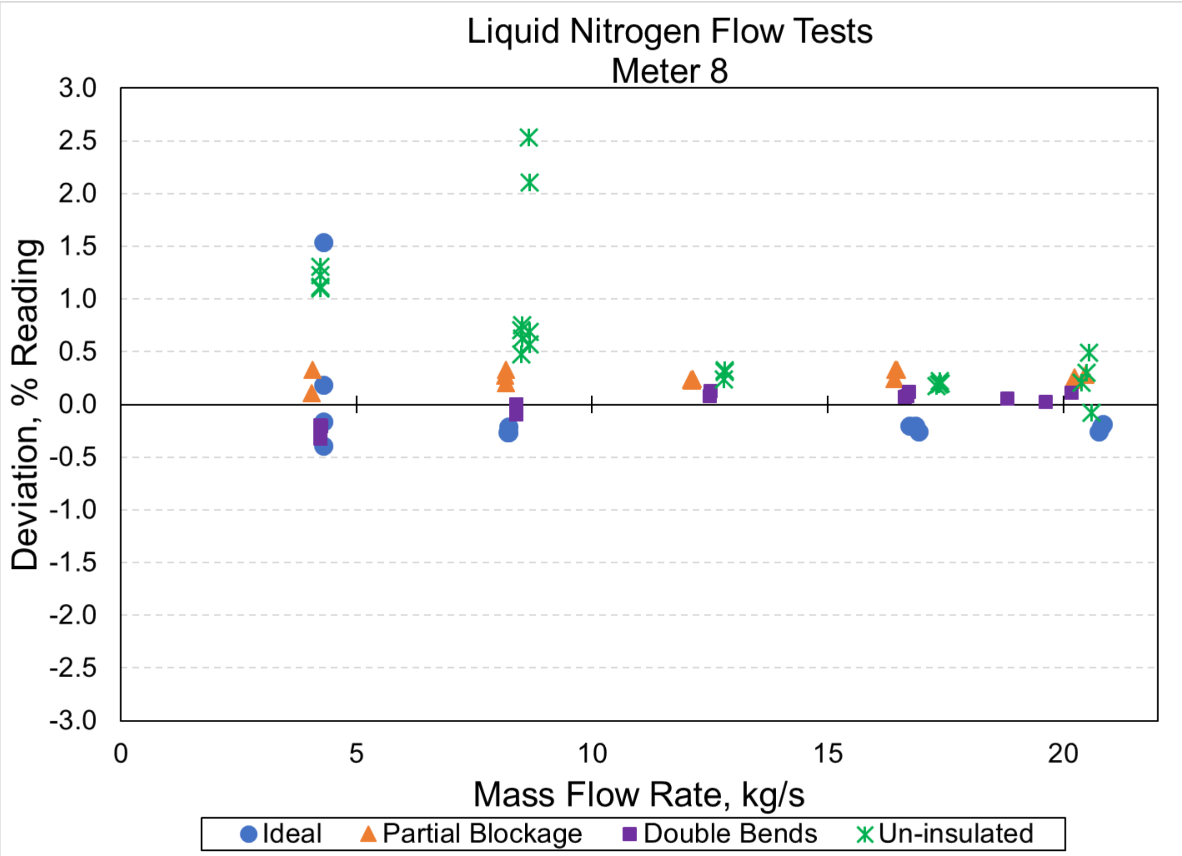

Figure 12: Graphs of meter 8 deviation versus mass flow rate for setups of Table 2. The ideal repeat curve is not displayed because changes to the metering line were made with respect to the initial ideal calibration while proper parallel alignment of the meter was not verified after this modification.

The following observations are made:

- Mean deviations for the ideal case (see Table 2) of all flow meters are approximately within ±0.5%, however they can be exceeded for individual flow/calibration points.
- The removal of insulation of LNG meters can result in significant (i.e., larger than several tenths of a percent, say larger than 0.5% in mass flow rate) measurement error, both in overreading as in underreading.
- The effect of flow disturbances is either of similar size or smaller than the insulation effects.
- Comparing “Ideal” with “Ideal Rpt” results, measurements are reproducible to within 0.10% for meters 0, 1, and 3 (≥ 8 kg/s for meter 3).

One of the meters had a typical zero-error in the initial deviation curve. Results shown for this meter had a zero-correction applied to them within the ±0.3 kg/s range. This correction was variable with setup.

Tables 6 – 12 show the average mass flow rate deviations from the ideal setup (see Table 2) for meters 1, 6, 0, 3, 4, and 8, respectively. This follows the order of Figures 6 – 12.

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

Table 6: Meter 1 average mass flow rate deviations from the ideal setup (%). Grayed out cells are zero (for Ideal column) or coincide with non-existing calibration points.

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

Table 7: Meter 6 average mass flow rate deviations from the ideal setup (%). Grayed out cells are zero (for Ideal column) or coincide with non-existing calibration points. This meter was replaced from modification 2 to 3 in Table 2. Consequently, only results for setups 1 – 3 are shown.

Nominal Rate (kg/s)	Ideal Rpt(R)	Un-insulated(R)	Ideal Rpt Repeat(R)
10			0.03
8		-0.03	0.09
6		-0.09	0.09
4		-0.11	0.21
2		-0.08	0.30

Table 8: Meter 6 average mass flow rate deviations from the ideal setup (%). Grayed out cells are zero (for Ideal(R) column, where “R” denotes replacement meter) or coincide with non-existing calibration points. This meter was replaced from modification 2 to 3 in Table 2. Consequently, only results for setups 1 and 4 are shown.

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

Table 9: Meter 0 average mass flow rate deviations from the ideal setup (%). Grayed out cells are zero (for Ideal column) or coincide with non-existing calibration points. At 12 kg/s the Ideal Repeat was taken as the reference because the Ideal calibrations were not performed at this rate.

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

Table 10: Meter 3 average mass flow rate deviations from the ideal setup (%). Grayed out cells are zero (for Ideal column) or coincide with non-existing calibration points. At 20 kg/s the Ideal Repeat was taken as the reference because the Ideal calibrations were not performed at this rate.

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

Table 11: Meter 4 average mass flow rate deviations from the ideal setup (%). Grayed out cells are zero (for Ideal column) or coincide with non-existing calibration points. At 20 kg/s results are grayed out because the Ideal calibration was not performed at this flow point, while the Ideal Repeat graph is shifted by about 0.2%.

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

Table 12: Meter 8 average mass flow rate deviations from the ideal setup (%). Grayed out cells are zero (for Ideal column) or coincide with non-existing calibration points.

Discussion

The estimated SI-traceable calibration uncertainty of the calibrations (see **Method** section, paragraph *Metrological specifications – estimated SI-traceable calibration uncertainty*) is 0.30%. This number can be improved by gathering more data in validating the facility and characterizing some of the uncertainty components better. The Cryogenic Research and Calibration Facility was designed to maintain a subcooling margin of the LNG over the course of the calibrations. With LIN, the subcooling capability is more limited (albeit the heat exchanger does provide cooling even when using LIN in the facility). The Cryogenic Research and Calibration facility is designed for controlled temperature and pressure conditions with LNG, to yield very stable flow.

Results shown in this paper were filtered by line-pack correction. When the line-pack correction criterion is exceeded the pressure, temperature, and flow conditions can result in outliers which affects the repeatability significantly. The line-pack criterion is easily implementable and has shown to be an effective means of identifying outlier calibration points. It was observed that the smaller repeatability at low flow rate (i.e. 2 kg/s along the 2”-line) coincides with the (relative) size of the line-pack effect of the calibration. Calibrations with large estimated line-pack effects (i.e., with an estimated maximum contribution to the magnitude of the calibration deviation > 0.10%) were filtered out for this reason. The line-pack correction arises from variable temperature and pressure conditions and can be formulated in terms of density change as:

$$\Delta m_l = -\big(\rho(t_1) - \rho(t_0)\big)V_c, \qquad \text{(Equation 1)}$$

where Δm_l is the correction of the batch mass due to the line-pack effect, $\rho(t_0), \rho(t_1)$ the LIN-density at the start and stop of the calibration, respectively, and V_c is the connecting volume between the working standard and the meter-under-test. The correlation of the line-pack correction with the observed smaller repeatability at low flow rates indicates that variable temperature and pressure conditions are related to the relatively small repeatability at low flow rates. At the same time, the line-pack effect does not explain the poorer repeatability of the low flow rates completely. Computed LIN-density from SI-traceable pressure and temperature measurements corresponds to 100% liquid nitrogen. From observations with sight glasses at other cryogenic facilities it is known that even when maintaining a subcooling margin, small bubbles can be formed in the LIN. More research is needed to fully explain the poorer repeatability at low flow rates.

Flow meter manufacturers provide technical data in product specification sheets specifying the zero-stability and mass or volume flow measurement accuracy. For the flow rates considered in this paper, the accuracy stated is typically at around 0.10% or above, and it is typically stated for ambient conditions. In addition, temperature and pressure sensitivities on the measurement accuracy are specified. Manufacturers recommend mitigating the temperature and pressure effects on measurement uncertainty by zeroing at process (cryogenic) conditions. The results shown in Figures 6 - 12 indicate that the calibration results can be within manufacturers specifications as given by product data sheets and user’s manuals, however, some of the calibrations deviate beyond typical specifications (0.10%-0.15%) typically stated for ambient conditions. The estimated uncertainty of the calibrations of 0.30% on mass flow rate (see **Method** section, paragraph *Metrological specifications – estimated SI-traceable calibration uncertainty*), and < 0.35% when converting to volume flow, and the relatively poorer repeatability at the lower mass flow rate calibration points (i.e., 2 kg/s for the 2”-line and 4 kg/s for the 4”-line, cf. Figures 6 - 12), limit the possibilities to draw definite conclusions on the meters in the test programme matching manufacturer specifications. Further research is required to explain fully and more accurately the deviations of the calibrations. The results do provide indications of effects of flow disturbances and meter insulation on LIN-flow measurement accuracy of LNG meters:

- Indication that removal of insulation of LNG meters can result in significant (i.e., larger than several tenths of a percent, say larger than 0.5% in mass flow rate) measurement deviation.
- Indication that a zero-error can be significant across the full range of flow rates considered (i.e., larger than several tenths of a percent). Proper zeroing in cryogenic conditions can be challenging even if carefully following manufacturer’s instructions and/or following the applicable draft ISO standard [18] as one depends on the insulation capability of a cryogenic installation. When the zero-error is significant, a zero correction can be applied posteriorly, however, this adds to the overall calibration uncertainty.

- Indication that the effect of the 20D upstream flow disturbances is more limited than that of insulation. This is expected for CFM’s. This is also expected for USM’s as the upstream disturbances are located 20D upstream of the flow meter, which is typically taken as sufficient upstream length to properly condition the flow.

Results do further indicate that calibrations are repeatable to well within < 0.10% and reproducible to within < 0.10%. It is not possible to draw definite conclusions on these numbers, because the test programme did not combine meter diagnostics with calibration data recorded at the same time. This would be a topic for further research to separate the effects of the meter from effects of the installation. It was observed that some of the larger deviations (> 0.5%) for measurements performed in the same setup of Table 2 coincide with line pressure differences of about 1 bar.

A total of six meters were calibrated from five prevalent LNG flow meter manufacturers, two meters are USM’s, and four of them are CFM’s. USM’s and CFM’s are the typical meters to use in the small to midscale < 1000 m^3/h LNG custody transfer. The results shown in this paper therefore constitute an impressive effort to calibrate a representative set of LNG flow meters with LIN in varied relevant circumstances comprising typical LNG industrial site flow disturbances and representative in-field insulation (or absent insulation) of LNG flow meters. Yet, from industry wisdom, it is known that results of this paper can not necessarily be extrapolated with meaningfully low uncertainty to: (1) larger or smaller sizes of LNG flow meters, (2) calibrations of LNG flow meters directly with LNG, (3) LNG flow meters of other flow meter manufacturers that did not participate in the research programme, (4) LNG flow meters of a different make and/or model of the same manufacturer, (5) LNG flow meters based on a different measuring principle, (6) the same flow meter defined by its unique serial number after having serviced in an installation for a particular amount of time.

Conclusions and summary

A total of six LNG flow meters from five prevalent LNG flow meter manufacturers were calibrated with LIN in the Cryogenic Research and Calibration facility. The results provide indications of the magnitude of effects of upstream flow disturbances and insulation on LIN flow measurement accuracy of LNG meters. There is an indication that improper insulation of the LNG flow meter can result in significant (i.e., larger than several tenths of a percent, say larger than 0.5% in mass flow rate) deviations from the SI-traceable reference mass flow rate. There is a further indication that the effect of the 20D upstream flow disturbances studied is more limited than that of insulation. Further research is required to explain fully and more accurately the deviations of the calibrations, and to separate deviation effects of the LNG flow meter from installation effects of the Cryogenic Research and Calibration facility. The successful execution of the cryogenic flow test programme, given its results in varied setups, shows that the Cryogenic Research and Calibration facility is the place to perform impactful SI-traceable calibrations in which flow meter manufacturers can prove their meters for the industry requirements.

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