21GRD06 MetCCUS

D1 - Report on the development, intercomparison of new facilities, operating ranges and traceability of primary facilities for intermediate scale (below 50 m3/h and low pressure) and large scale (Qmax = up to 400 m3/h and higher pressure) flow standards for gaseous CO2 in order to enable the calibration of flow meters (target uncertainties of 1.5 % – 2.5 %)

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METROLOGY PARTNERSHIP EURAMET

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1 Summary

This report presents the outcomes of a collaborative effort under the MetCCUS project to advance traceable flow measurement for gaseous carbon dioxide (CO_2) in Carbon Capture and Storage (CCS) systems. To support accurate and harmonised CO_2 flow metering, the project upgraded calibration infrastructure and carried out coordinated inter-laboratory comparisons across major European metrology institutes.

Key activities included testing various flow meter technologies (Coriolis, turbine, Ultrasonic, rotary) at both large and intermediate flow scales, assessing calibration transferability from alternative gases such as nitrogen and natural gas.

The results confirmed agreement across facilities and demonstrated the feasibility of using substitute gases when appropriate considerations and corrections are applied. However, limitations were identified in Critical Flow Nozzles performance with CO_2 and in turbine meter accuracy at low flow rates, highlighting areas for further investigation.

2 Introduction

Flow measurement of carbon dioxide transferred across the Carbon Capture and Storage (CCS) chain is required for operational, fiscal and regulatory purposes [1], [2], [3], [4]. Carbon dioxide streams are measured at different locations across the CCS chain either in gas, liquid or supercritical phase. This report solely focusses on the measurement in gaseous phase.

Independent, traceable, flow calibration facilities capable of calibrating flow meters with carbon dioxide across the full range of CCS gaseous conditions are lacking [1]. Common limitations of existing gaseous calibration facilities include:

1. **Traceability -** lack of direct traceability to a primary carbon dioxide standard;
2. **Stream composition -** operation limited to either pure CO_2 or a narrow range of CO_2-rich mixtures; and
3. **Flow range -** restricted operational maximum flow rate.

As part of the MetCCUS project multiple activities aimed at addressing these limitations were undertaken as follow:

- **Traceability** limitation

At large-scale, FORCE technologies re-purposed and upgraded its natural gas primary piston prover to operate with gaseous pure CO_2. An intercomparison was conducted between the primary piston prover at FORCE and the secondary standard flow facilities at TÜV SÜD National Engineering Laboratory (NEL) and DNV. The intercomparison results provided confidence in the traceability of these facilities between 20 and 400 m^3/h. VSL also upgraded their primary high-pressure standard (Gas-Oil Piston Prover) to operate with CO_2.

At intermediate scale, INRIM and VSL re-purposed and upgraded their primary piston provers to operate with gaseous pure CO_2. An intercomparison was conducted between the primary piston provers at INRIM and VSL and the secondary standard flow facilities at TÜV SÜD National Engineering Laboratory (NEL). The intercomparison results provided confidence in the traceability of these facilities between 0.1 and 30 m^3/h.

- **Stream composition** and **flow range** limitations

Different technologies of flow meters were tested with nitrogen or natural gas, and with carbon dioxide to evaluate the influence of the gas type on the meter performance. The objective was to determine whether a meter can be calibrated with nitrogen or natural gas and used with carbon dioxide. Demonstrating calibration transferability provides confidence in the meter's independence from gas composition. Moreover, it enables the use of alternative calibration gases for which larger-scale facilities are available, allowing calibration at higher maximum operational flow rates.

2.1 Report outline

Given the significant differences in flow rate ranges among the partners facilities, this report distinguishes between large-scale facilities (FORCE, NEL, DNV, VSL) and intermediate-scale facilities (INRIM, VSL, NEL).

The large-scale facilities are discussed in Section 3, with their design and operating principles outlined in Section 3.1, 3.2, 3.3 and 3.4, intercomparison results presented in Section 3.5, and calibration transferability addressed in Section 3.6.

The intermediate-scale facilities are covered in Section 4, with design and operating principles in Section 4.1, 4.2 and 4.3, intercomparison results in Section 4.4, and transferability of the calibration in Section 4.6.

Section 5 provides the final conclusions and recommendations.

3 Large scale facilities

3.1 FORCE piston prover

The primary standard at FORCE Technology's gas flow test facility is a piston prover system. It is based on a closed-loop, bidirectional configuration, consisting of two parallel cylinders with a bore diameter of 0.6 m. Each piston is hydraulically driven, and its position is monitored by a linear transducer to ensure precise control of the flow. Four directional control valves maintain a consistent flow path during both forward and reverse operation.

The facility supports calibration of flowmeters with nominal pipe sizes ranging from 2 to 6 inches. It operates at a nominal temperature of 20 °C and can handle pressures from 1 to 66 bar(a). The test gases include natural gas, CO_2, nitrogen, and air. The system accommodates flow rates from 2 to 400 m^3/h, with differential pressures up to 500 mbar.

The piston prover serves as a primary standard with metrological traceability to the metre, based on dimensional measurements of the piston and its displacement. All measurements of static pressure, differential pressure, and temperature are performed using traceable calibrated instrumentation. Gas properties are normally calculated using ProGas version 5.

In this test programme, the FORCE Technology facility was operated in direct comparison mode, with the Device Under Test (DUT) calibrated against the flow derived from the piston diameter and its measured displacement. For this programme, gas property calculations were performed using the REFPROP database developed by NIST.

3.2 NEL high pressure gas flow facility

The NEL large scale gas flow facility is based around a DN150 nominal bore flow loop as illustrated in Figure 1. Although nominally DN150 diameter, the test section can accommodate line sizes ranging from DN80 through to DN250. The gas used for testing is nitrogen or carbon dioxide. Mixtures of carbon dioxide and inert gases (*i.e.* N_2, Ar, He) can also be tested. The gas properties are calculated from NEL's implementation of REFPROP from NIST [5].

The facility operates at a nominal temperature of 20 °C, over a nominal pressure range of 10 bar(g) to 63 bar(g) for nitrogen (which corresponds to a gas density range of approximately 13 kg/m^3 to 74 kg/m^3) and 20 bar(g) to 40 bar(g) for carbon dioxide (which corresponds to a gas density range of approximately 43 kg/m^3 to 101 kg/m^3).

The gas is driven around the flow loop by a 200 kW fully encapsulated gas blower and the flowrate is controlled by varying the speed of the blower. The maximum achievable gas volumetric flow rate is dependent upon the size and type of reference/test flow meter installed. The facility is UKAS accredited for a flow range of 20 m^3/h to 1600 m^3/h, but can reach up to 2100 m^3/h.

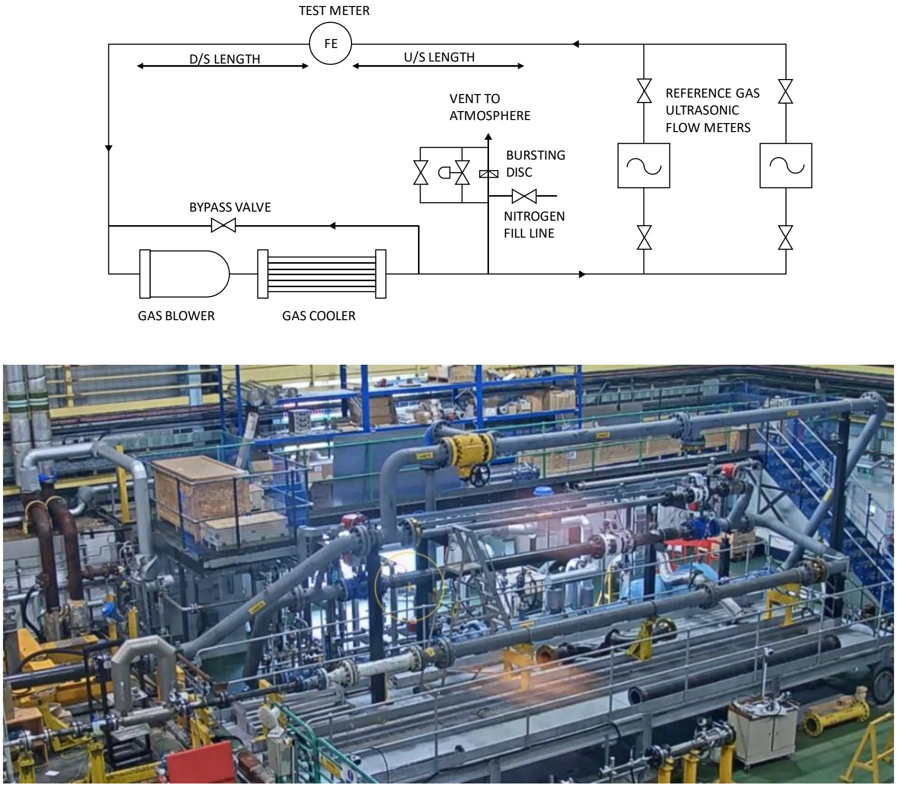

Figure 1 - Schematic (top) and picture (bottom) of the NEL large scale flow facility.

The reference master meter used for the tests described in this report is a DN200 FLOWSIC600-XT ultrasonic gas meter (serial number 22101021 and calibrated K factor 7992 for nitrogen, and 7962 for carbon dioxide).

The ultrasonic meter K factor was obtained against a 6-inch turbine meter from PTB [6], and it is checked for drift at regular interval against an in-house 8-inch orifice package.

All static pressure, differential pressure, and temperature measurements are taken using traceable calibrated instrumentation.

In this evaluation programme, the NEL gas flow facility was operated in ‘recirculation’ mode with the transfer package compared against the reference master meter system. For this mode, the overall uncertainty in the volumetric quantity of gas passed through the DUT, is ±0.35 % (k = 2).

3.3 DNV flow facility

Note: This Section 3.3 is adapted from [7]

The All Gas Flow Loop Groningen (AGFLG) test facility at DNV is a closed loop system based on DNV’s existing multiphase test facility, extended with a dedicated gas reference system. The facility can handle large differential pressure, 25 bar, which makes it suitable for testing several meters in series and allows for the use of Critical Venturi Flow Nozzles (CVFNs) as reference meters. The operational range of the facility is summarised in Table 1.

Table 1 - Specifications of the All Gas Flow Loop Groningen (AGFLG) test facility at DNV

Test Fluids:	Nitrogen, hydrogen (up to 30% in natural gas, and 100% in future), methane, carbon dioxide
Flow Range:	16 am^3/h to 1000 am^3/h
Test Sections:	2-inch to 8-inch
Operating Pressure:	5 bar(g) to 33 bar(g)
Test section differential pressure:	25 bar
Temperature Range:	-45 °C to 35 °C
Reference meters:	Sonic nozzles, turbine meters, Coriolis meters
Claimed reference uncertainty:	±0.12% to ±0.15% (k=2)

The AGFLG reference system consists of a sonic nozzle skid (containing 5 parallel CVFNs) in series with 4-inch and 6-inch dual lines containing a turbine and Coriolis reference meter, as outlined in Figure 2. A 4-inch turbine meter (FMG MT400, 40 to 400 m^3/h) and a 2-inch Coriolis meter (Emerson Micromotion CMF200) are installed in the 4-inch line, while a 6-inch turbine meter (FMG MT1000, 100 to 1000 m^3/h) and an 3-inch Coriolis meter (Emerson Micromotion CMF300) are installed in the 6-inch line, see Figure 2 and reference [8].

Each reference meter has its own traceability chain [8]. The CFVNs are traceable via dimensional measurements (throat diameter and curvature) [9], [10] and air calibration tests at Physikalisch-Technische Bundesanstalt (PTB) [8], the German national metrology institute. The Coriolis meters were calibrated at the manufacturer's calibration facility with water (Emerson's test facility in Ede, NL). The turbine gas meters are traceable via DNV and FORCE, the Danish Designated Institute for flow measurement. The turbine meters are corrected by means of the PTB turbine meter model [11], [12] and the Coriolis meters are corrected for pressure and compressibility effects [13], [14], [15]. The reference system is installed downstream of the test section as shown in Figure 2.

The metrological evaluation and facility uncertainty estimation was performed independently by PTB, detailed information is provided in [8]. The facility uncertainty is estimated between ±0.12% and ±0.15% (k=2).

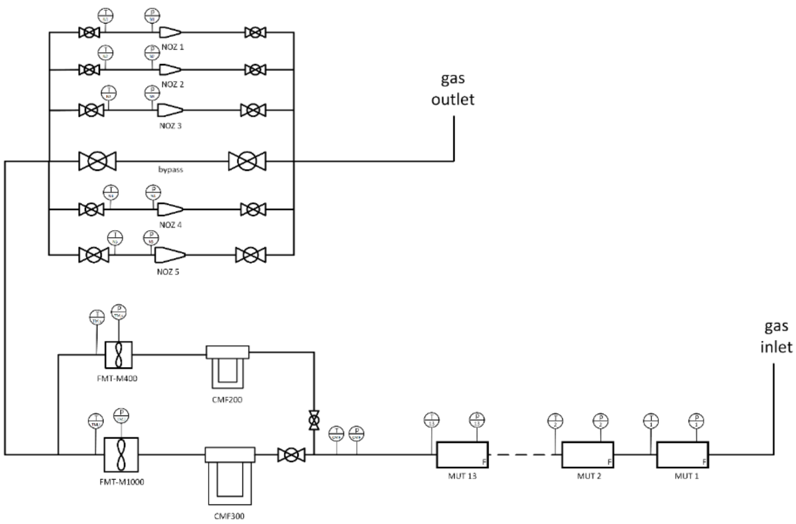

Figure 2 - Schematic (top) and picture (bottom) of the reference section of the All Gas Flow Loop Groningen (AGFLG) test facility at DNV. From the right, the gas flows first through the Meters Under Test (MUT), then through the reference Coriolis meters, the reference turbine meters, and the reference Critical Flow Venturi Nozzles.

3.4 VSL Gas-Oil Piston Prover (GOPP)

The GOPP is the primary standard of high-pressure natural gas flow measurement in the Netherlands. Its working principle is based on the displacement of a piston acting as a Gas-Oil separator. A speed-controlled centrifugal pump generates an oil flow rate that moves the piston with a uniform velocity inside the measuring cylinder, passing sensors indicating discrete volumes. The oil & gas container at the top-side of the configuration also works like a displacement system and the gas is forced towards the open outlet of the top container and flows back into the measuring cylinder. Figure 3 show a diagram of the GOPP.

The medium can be air, natural gas, hydrogen-enriched-natural-gas (up to 50%), other nontoxic and non explosive gas (mixtures) under various pressure conditions and ambient temperatures. The maximum pressure amounts to 6.4 MPa(a). The facility has been successfully used at temperatures between 4 °C and 26 °C.

GOPP has a flow range of 5 m^3/h till 230 m^3/h at actual gas flow conditions with uncertainties from 0.06 % to 0.29 % (k = 2). The system is designed for calibrations of Travelling Reference Meters (TRMs), which are then used to calibrate field meters. The TRMs are typically rotary gas meters of the size G250.

The traceability of the GOPP is through the determination of the discrete volumes between the sensors along the length of its tube. The volume is determined through the calibration of the length between each sensor and the diameter of the tube. The length and diameter calibrations are directly traceable to the “meter”, and combined with calibrated timers, also traceable to the “second”, the GOPP has a direct relation to the SI-units the "meter" and the "second". Consequently, "GOPP"-calibrated gas-meters are calibrated with reference values at various pressures to disseminate traceability to SI units.

Additionally, since the calibration of the internal volume is independent of the fluid, it is possible to calibrate gas flow meters at high pressure with any gas, with direct traceability to SI units.

For this project, the GOPP was upgraded to be compatible with CO_2 by conducting a material compatibility study, obtaining new PED certification, modifying operational procedures and supply gas line to the standard [16].

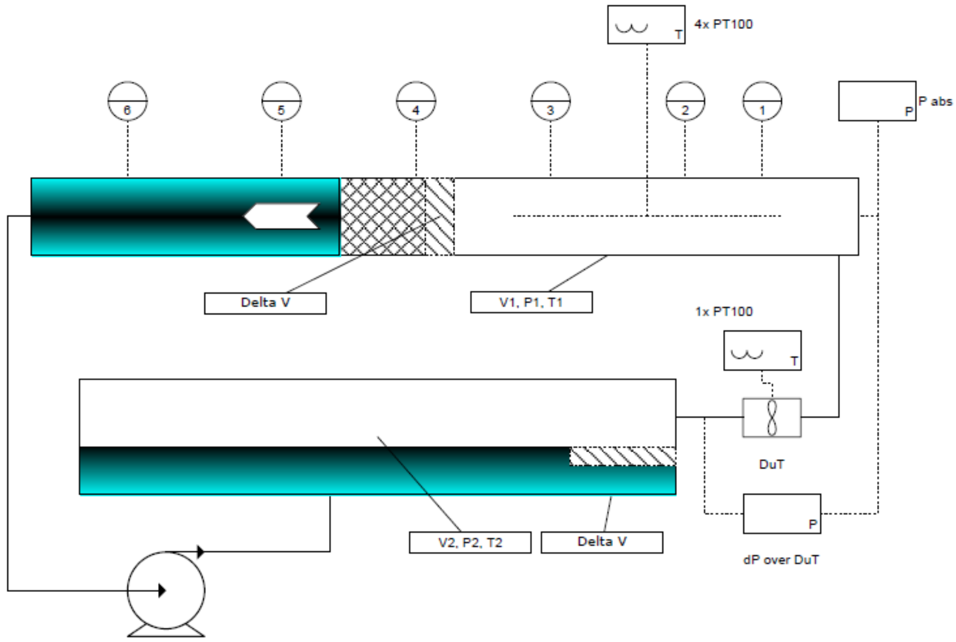

Figure 3 - Diagram of the VSL Gas-Oil Piston Prover (GOPP)

3.5 Intercomparison results

Test meters

Two meters were selected as the transfer package for the intercomparison. The first is an Emerson 3-inch Coriolis meter (CMF300M serial number 21046486) provided by NEL. The second flow meter is a DN100 Honeywell turbine gas meter provided by FORCE (SM-RI-X G250 serial number 10533326). Employing two different types of transfer standards allows evaluation of whether the intercomparison results vary using different meter types.

The 3-inch Coriolis meter was previously calibrated at NEL in the Elevated Pressure and Temperature (EPAT) oil facility up to 90 barg. The EPAT facility has an uncertainty in mass of ±0.08 % at 95 % confidence level. This calibration provided a reference baseline of the meter’s response and allowed the derivation of an experimental pressure correction factor. The resulting oil flow error was within ±0.05 % after pressure correction was applied.

Figure 4 – Picture of the 4-inch turbine and Coriolis meter installed at NEL. The meters are installed in series with the turbine upstream of the Coriolis meter. The flow is from right to left.

Figure 5 - Pictures of the 4-inch turbine and Coriolis meter installed at DNV. The meters are installed in series with the turbine upstream of the Coriolis meter. The flow is from right to left.

Figure 6 - Pictures of the 4-inch turbine (bottom) and Coriolis meter (top) installed at FORCE. The meters are not tested in series like in the other facilities due to length constraint.

Sequence of testing

The 3-inch Coriolis meter was initially tested at NEL in November 2023 as part of a separate previous project [6]. Upon receiving the turbine meter from the manufacturer, FORCE conducted preliminary tests using air and natural gas.

The first test of the complete intercomparison package took place at NEL in July 2024. The package was subsequently tested by DNV in January 2025, followed by the final set of intercomparison tests conducted by FORCE between March and May 2025. To assess for any potential drift, the Coriolis meter was returned to NEL and re-tested in July 2025. And the turbine meter was returned to FORCE and re-tested using air.

Test conditions

The intercomparison was performed between NEL, DNV and FORCE for carbon dioxide. Intercomparison test conditions are reported in Table 2. Three consecutive repeats were taken for each test point.

Table 2 – Large scale facilities intercomparison test conditions

Test Fluid	Pressure (bar.a)	Temperature (°C)	Density (kg/m^3)	Flow Rate Range (kg/s)	Flow Rate Range (m^3/h)	NEL	DNV	FORCE Coriolis	FORCE Turbine
CO_2	31	20	70	0.4 to 7.8	20 to 400	Yes	Yes	Only 80, 160 and 280 m^3/h	From 40 m^3/h
CO_2	21	20	44	0.25 to 4.9	20 to 400	Yes	Yes	Up to 280 m^3/h	Yes

Measured values and meter corrections

Each facility used its own pressure and temperature measurement devices. For the turbine meter, the pressure was measured at the turbine body, temperature was measured downstream of the turbine. For the Coriolis meter the pressure was measured upstream and the temperature downstream.

Pulse output was collected for the turbine and Coriolis meter. In addition, the Modbus output was logged for the Coriolis meter by NEL.

It should be noted that the Coriolis meter output was corrected for pressure and compressibility effects according to the following formula:

$$\dot{m}_{corrected} = \dot{m}_{out}\,(1 - E_c - E_p) \tag{0}$$

$$f_c = a_c\, 0.5 \left(\frac{2\,\pi\, f_{tube}\, r}{c}\right)^2 \tag{1}$$

$$f_p = a_p\,(p - p_{cal}) \tag{2}$$

where a_p = - 0.0077 (%/bar) was obtained empirically from NEL test with oil at high pressure, p is the test pressure, p_{cal} is the factory water calibration pressure (equal to 2.06843 bar g for this Coriolis meter), a_c = 1 (-) is a meter specific compressibility factor, c is the fluid speed of sound, r is the Coriolis tube inner radius (in this case 0.02235 m), and f_{tube} is the Coriolis tube frequency (in this case a constant value of 93.53 Hz was used for all the tests).

Intercomparison calculations

Each flow measurement facility conducted the tests and processed the recorded data in accordance with their respective internal procedures. The comparison calculations were based on standardised methods as found in [17], [18], [19], [20].

It should be noted that the comparison was done for mass flow rate for the Coriolis and for volumetric flow rate for the turbine.

The inter-comparison of the test facilities was undertaken at each flow condition by using the mean value of the flow measurement from the three repeats. Expanded uncertainty of the mean value for each test point, U_r was determined using the expression in Equation (3).

$$U_r = \frac{t^*\sigma}{\sqrt{n}} \tag{3}$$

where ; t^* is Students t value at 95 % confidence, σ is the sample standard deviation of the results and n is the number of repeats (i.e. 3).

In the case of this inter-comparison tests, the degrees of freedom for each test point, $v = n - 1 = 2$

Hence, for a t-distribution with 2 degrees of freedom at 95 % confidence, t (4,95%) ; t^* =4.303

Thus Equation (3) becomes:

$$U_r = \frac{4.303\ \sigma}{\sqrt{3}} \tag{4}$$

The overall expanded uncertainty for each test facility, U_i was calculated by combining the reference lab expanded uncertainty, U_{lab} quoted by the test facility and the repeatability uncertainty of the mean, U_r [20], as follow:

$$U_i = \sqrt{{U_{lab}}^2 + {U_r}^2} \tag{5}$$

Calibration and Measurement Capability (CMC) values for each test facility were used as the reference uncertainty, U_{lab}. Table 3 summarises the CMC values applied in this inter-comparison, which vary depending on the test conditions. It is worth noting that Equation (5) is rearranged from the equation included in the "WGFF Guideline for CMC Uncertainty and Calibration Report Uncertainty" [19] as follows:

$$U_i = \ 2\ \sqrt{\left(\frac{U_{lab}}{2}\right)^2 + \left(\frac{t_{95}}{2}\ \frac{\sigma}{\sqrt{n}}\right)^2} = \sqrt{{U_{lab}}^2 + \left(t_{95}\ \frac{\sigma}{\sqrt{n}}\right)^2} = \sqrt{{U_{lab}}^2 + {U_r}^2}$$

Table 3 – Calibration and Measurement Capabilities (CMC) for each facility

Transfer Meter	Calibration and Measurement Capability (%) (k = 2)		
	NEL	DNV	FORCE
Coriolis meter (mass flow)	0.35	0.22 to 0.29	0.27
Turbine meter (volumetric flow)	0.35	0.22 to 0.27	0.15

The Degree of Equivalence, E_n between each laboratory's results and the Comparison Reference Value, CRV were calculated following the procedure outlined by Cox [18] and is summarised as follows.

The CRV and its associated uncertainty are determined using the weighted mean formula, as expressed in equations (6) and (7), respectively.

$$CRV = \frac{\sum_{i=0}^{n} \frac{e_i}{U_i^2}}{\sum_{i=0}^{n} \frac{1}{U_i^2}} \tag{6}$$

$$U^2(CRV) = \frac{1}{\sum_{i=0}^{n} \frac{1}{U_i^2}} \tag{7}$$

Where, e_i is the mean relative error of the transfer meter for each test facility and U_i is the overall uncertainty of the test facility as defined by Equation (5).

The difference between mean relative error for each test facility, d_i and the CRV was calculated by using Equation (8).

$$d_i = e_i - CRV \tag{8}$$

And the expanded uncertainty $U(d_i)$ was calculated using Equation (9).

$$U^2(d_i) = U_i^2 - U^2(CRV) \tag{9}$$

Since the test facilities operated independently and contribute to the CRV, the Degrees of Equivalence, E_n was calculated for each test facility according to Equation (10).

$$E_n = \frac{d_i}{U(d_i)} \tag{10}$$

The Degrees of Equivalence, E_n provides a measure of the equivalence of each the test facility's results relative to the CRV. The interpretation of the absolute value of E_n is as follows:

- $|E_n| < 1$: the result of the test facility is consistent with CRV (passed).
- $1 < |E_n| < 1.2$: the result of the test facility might indicate a possible warning in the measurement process. For this particular situation the particular facility is recommended to check the procedures and methodology.
- $|E_n| > 1.2$: the result of the laboratory is not consistent with CRV (failed).

Test results

The comparison results for the Coriolis meter and turbine gas meter at each test facility along with the average uncertainties associated with each facility are presented in Figure 8 and Figure 7 respectively. Figure 9 presents the calibration results of the turbine meter as a function of Reynolds number. Each plotted test result is the averaged value of 3 consecutive repeats. It should be noted that the average uncertainties plotted in the figures also include the repeatability associated to the three repeats.

The results indicate that the average relative error in the flow measurements with both meters by the different test facilities generally fall within the uncertainty range of these test facilities other than at the bottom of the flow range.

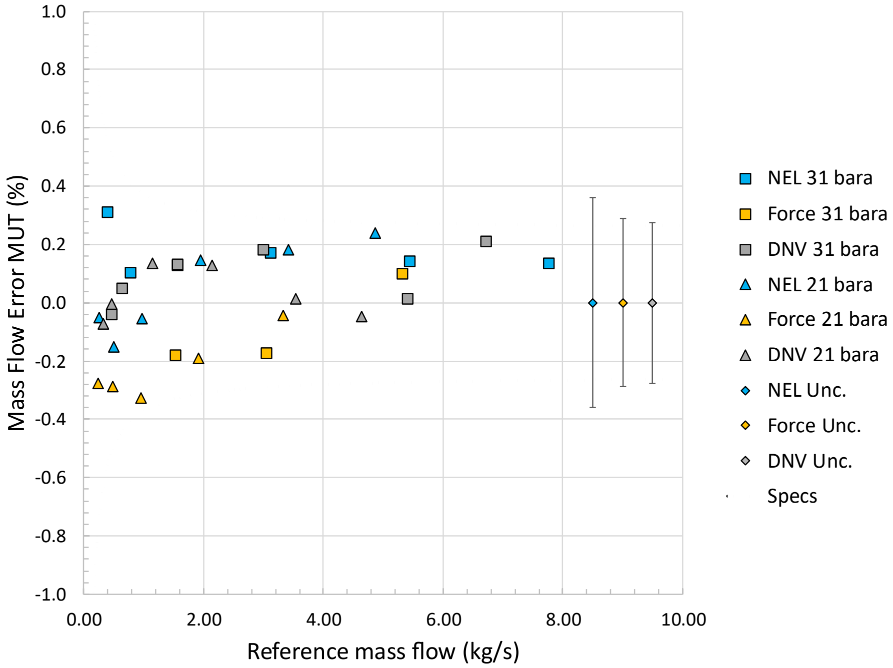

Figure 7 - Coriolis meter relative error in gas mass flow rate at each facility as a function of the reference mass flow rate.

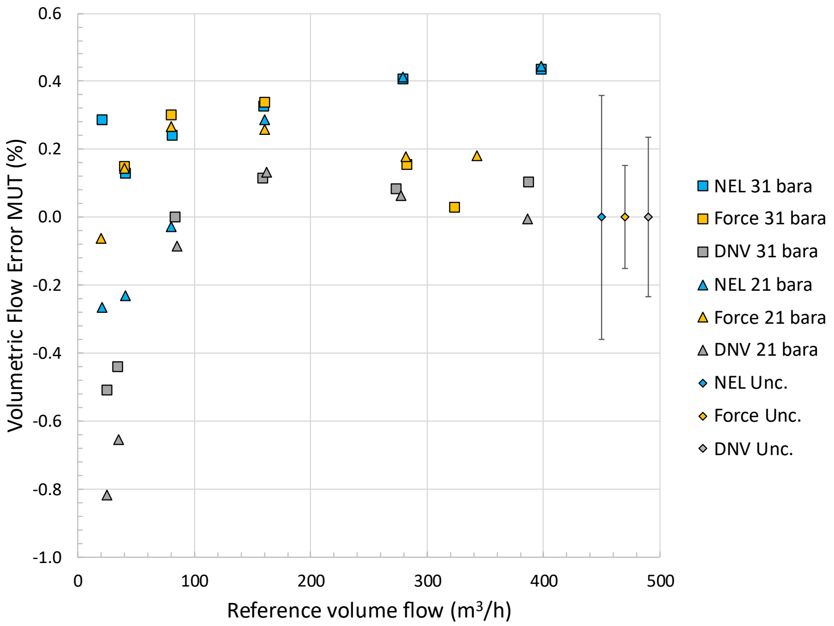

Figure 8 – Turbine meter relative error in gas volumetric flow rate at each facility as a function of the reference volumetric flow rate

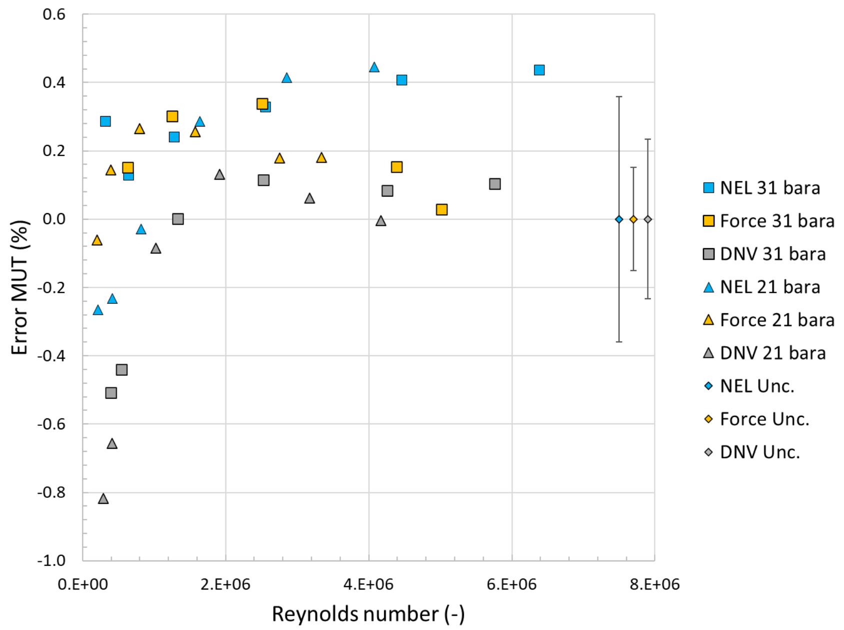

Figure 9 - Turbine meter relative error in gas volumetric flow rate at each facility as a function of the Reynolds number.

Degree of equivalence

Figure 10 presents the Degrees of Equivalence, E_n values for each test facility based on the Coriolis meter measurements. Approximately 91% of the test points shown in this graph have $|E_n| < 1$, demonstrating that the three test facilities - NEL, DNV and FORCE - are consistent with the CRV, and therefore have successfully passed the equivalency test for the specific flow conditions maintained during these test runs.

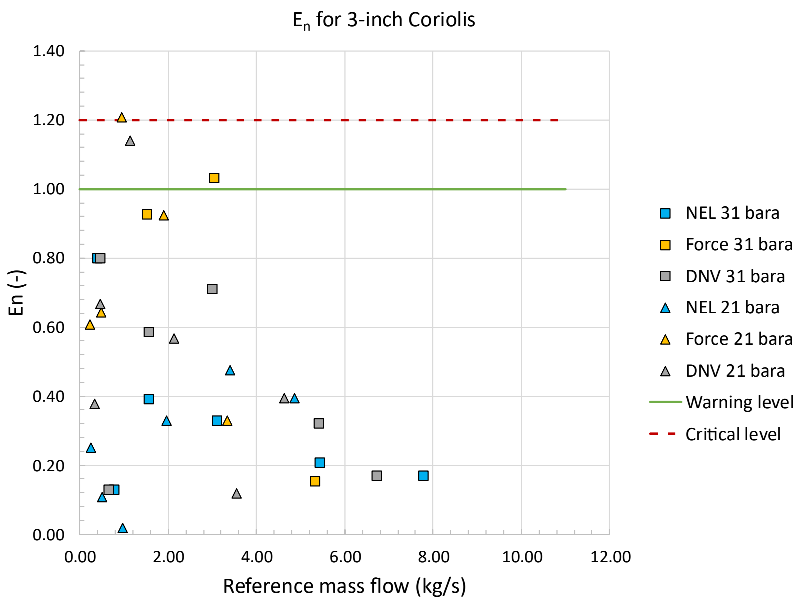

Figure 10 - Each test facility's Degrees of Equivalence when using the Coriolis meter

The figure also highlights 3 test points where $|E_n|$ exceeded 1, which are listed below in Table 4. All of these points had $|E_n|$ values between 1 and 1.2, suggesting a potential warning regarding the measurement processes at these facilities under the respective test conditions.

Table 4 – Coriolis meter points with $|E_n| > 1$

Test Facility	Pressure [bar(a)]	Flow rate [kg/s]	Flow rate [m³/h]	$\|E_n\|$	Equivalency Test
FORCE	21	0.96	80	1.21	Warning level
	31	3.05	160	1.03	Warning level
DNV	21	1.14	86	1.14	Warning level

Figure 11 presents the Degrees of Equivalence, E_n values for each test facility based on the turbine gas meter measurements. Over 68% of the test points shown in this graph have $|E_n| < 1$. The figure also highlights eleven test points where $|E_n|$ exceeded 1, which are listed in Table 5 below. Two of these points had $|E_n|$ values between 1 and 1.2, suggesting a potential warning regarding the measurement processes at these facilities under the respective test conditions. However, nine results had $|E_n| > 1.2$, indicating that the test facility failed the equivalency test under these specific low-flow conditions.

The failed test points all occurred at flow rates below 85 m³/h; a range where turbine meter performance typically deteriorates due to increased bearing friction. Additionally, measurement reliability tends to decrease in this region due to limitations of the test facility itself. Furthermore, for a given nominal test flow rate, the actual flow rates achieved at each facility can differ significantly. This discrepancy can have a considerable impact in low-flow regions, where the turbine meter's response is highly sensitive to small changes in flow rate.

Nevertheless, the discrepancies are believed to be primarily attributable to the turbine meter's performance at low flow rates. This is supported by the fact that the facilities showed better agreement at low flow rates when using the Coriolis flow meter, see Figure 7 and Figure 10.

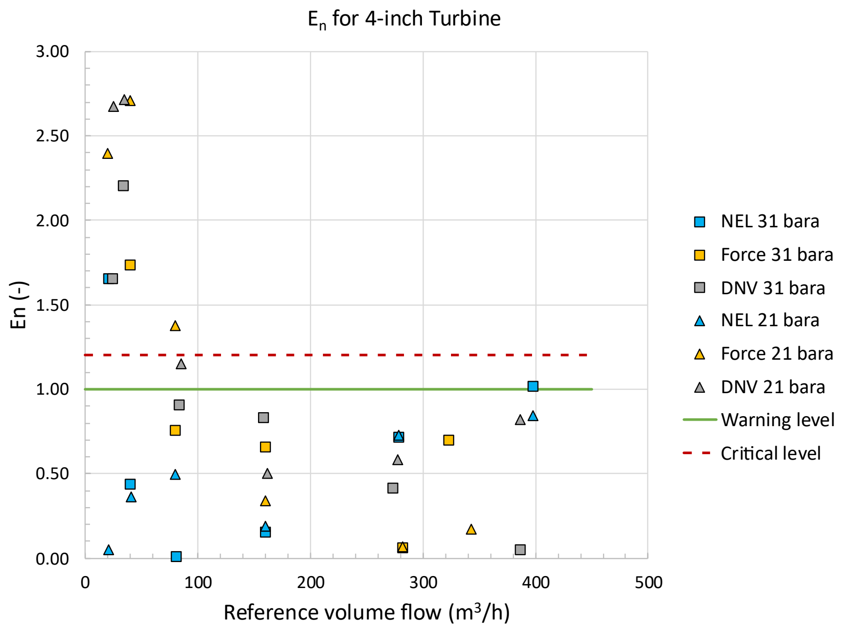

Figure 11 - Degrees of Equivalence for each test facility's measurements with the turbine gas meter

Table 5 – Turbine meter points with $|E_n| > 1$

Test Facility	Pressure [bar(a)]	Flow rate [m³/h]	$\lvert E_n \rvert$	Equivalency Test
FORCE	21	80	1.37	Failed
	21	35	2.4	Failed
	21	20	2.4	Failed
	31	40	1.73	Failed
DNV	21	85	1.15	Warning level
	21	35	2.72	Failed
	21	25	2.68	Failed
	31	34	2.21	Failed
	31	24	1.65	Failed
NEL	31	398	1.02	Warning level
	31	20	1.65	Failed

3.6 Transferability of calibration results

Additional tests were run at FORCE and NEL with natural gas and nitrogen respectively to investigate the transferability of calibration. The additional tests conditions are reported in Table 6.

The test results are presented in Figure 12 and Figure 13 for the Coriolis and turbine meter respectively.

The results with natural gas at FORCE agree well with those at NEL with carbon dioxide and nitrogen. This confirm previous findings [6], [21], [22] that a Coriolis meter when corrected for pressure [13], [15], [23] and compressibility effects [24], [25] can be calibrated with an alternative fluid and used with carbon dioxide.

It is also confirmed that in general a turbine meter can be calibrated with an alternative fluid and used with carbon dioxide within their uncertainty specification, as long as the Reynolds number is matched [26].

Table 6 - Large scale facilities transferability of calibration test conditions

Test Fluid	**Pressure (bar.a)**	**Temperature (°C)**	**Density (kg/m³)**	**Flow Rate Range (kg/s)**	**Flow Rate Range (m³/h)**	**NEL**	**DNV**	**FORCE** Coriolis	**FORCE** Turbine
N_2	38	20	44	0.3 to 4.1	25 to 334	Yes	No	No	No
Natural Gas	21	21	15	0.08 to 1.14	20 to 400	No	No	Up to 280 m³/h	Yes
Natural Gas	31	21	22	0.12 to 1.7	20 to 400	No	No	Up to 280 m³/h	Yes

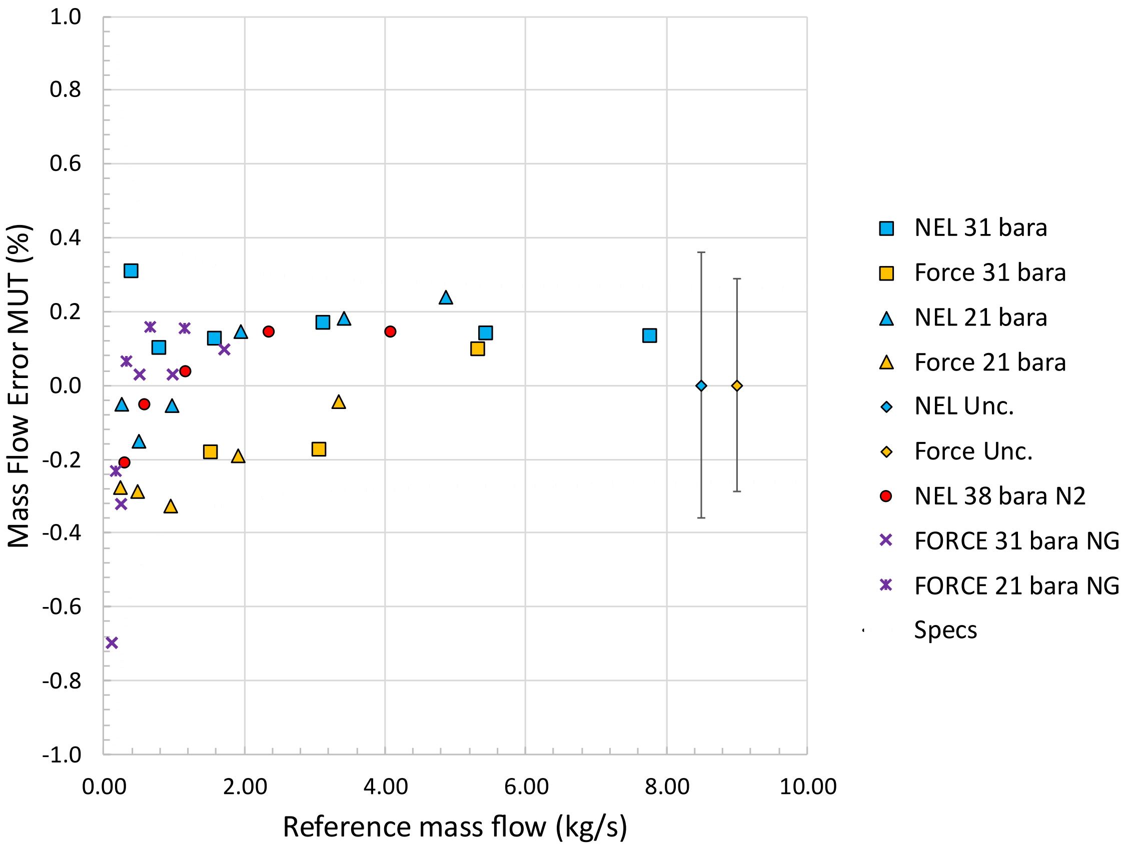

Figure 12 - Coriolis meter relative error in gas mas flow rate as a function of the reference mass flow rate. The figure shows the additional data collected at FORCE and NEL with natural gas and nitrogen respectively.

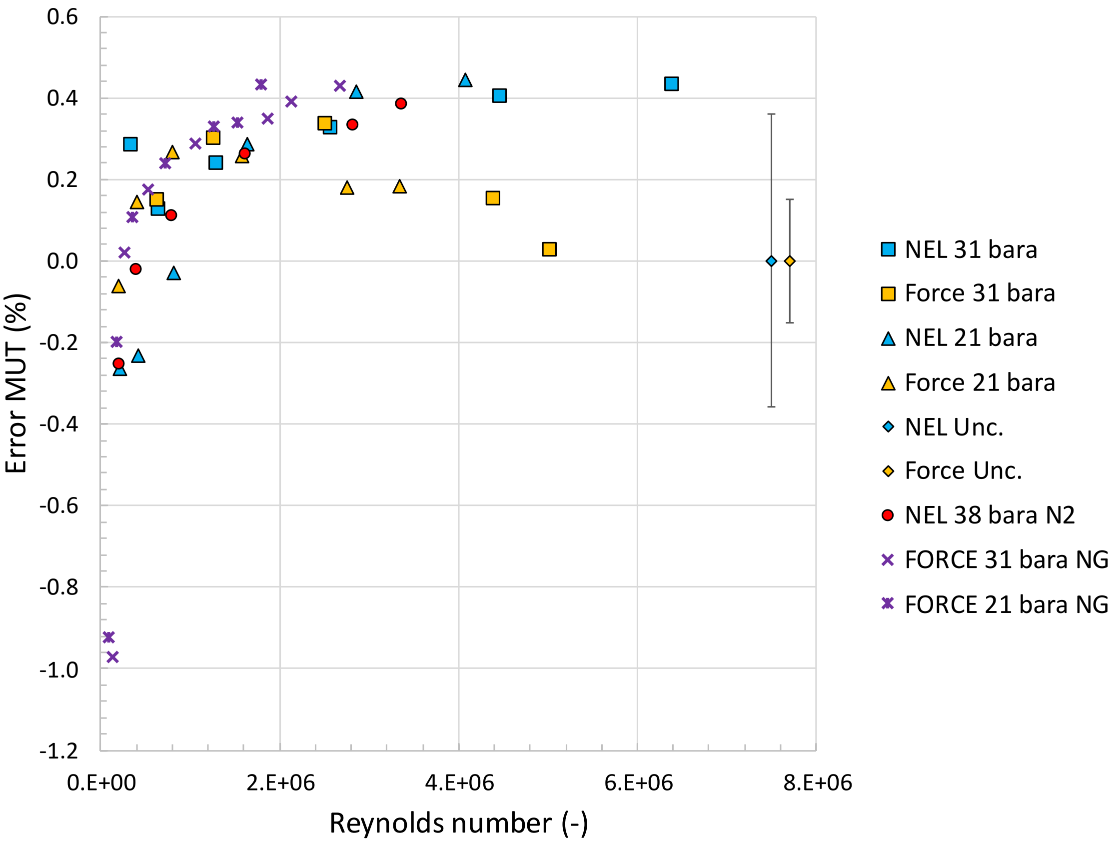

Figure 13 - Turbine meter relative error in gas volumetric flow rate as a function of the Reynolds number. The figure shows the additional data collected at FORCE and NEL with natural gas and nitrogen respectively.

Ultrasonic Meter Calibration at VSL with the GOPP

At VSL, a 3-inch SICK FLOWSICK 550 ultrasonic meter was also tested with CO_2 and natural gas at 25 bar using the GOPP, see Section 3.4. The calibration results as a function of flowrate are shown in Figure 14. The calibration results as a function of the Reynolds number are shown in Figure 15. A picture of the meter installed on the GOPP is shown in Figure 16. For the calibration with CO_2, the composition of the gas was approximately 98% CO_2 and 2% nitrogen by mol. The meter error is already corrected for the compressibility effect of the CO_2 gas.

During the calibration, the meter settings of the USM were not adjusted so that the transferability of the calibration from natural gas to CO_2 could be investigated without any alterations to the meter. An average negative shift of approximately -0.71% is observed between the natural gas and carbon dioxide curves. After consultation with the meter manufacturer, this shift was expected because the meter was intended and tuned for natural gas applications and therefore optimized for the range of speed of sounds encountered with natural gas. Additionally, this shift in meter error is in line with the shift observed with another Ultrasonic meter from another manufacturer that was optimized for natural gas and calibrated with natural gas and carbon dioxide at DNV [21], suggesting a general trend that is applicable to Ultrasonic meters.

Additionally, it was noticed that during the filling of the GOPP, the USM did not generate a signal until the pressure reached 10 bar(g) and this is due to the sound attenuation of CO_2. This effect was also noticed at tests with an Ultrasonic meter at NEL's facility [6].

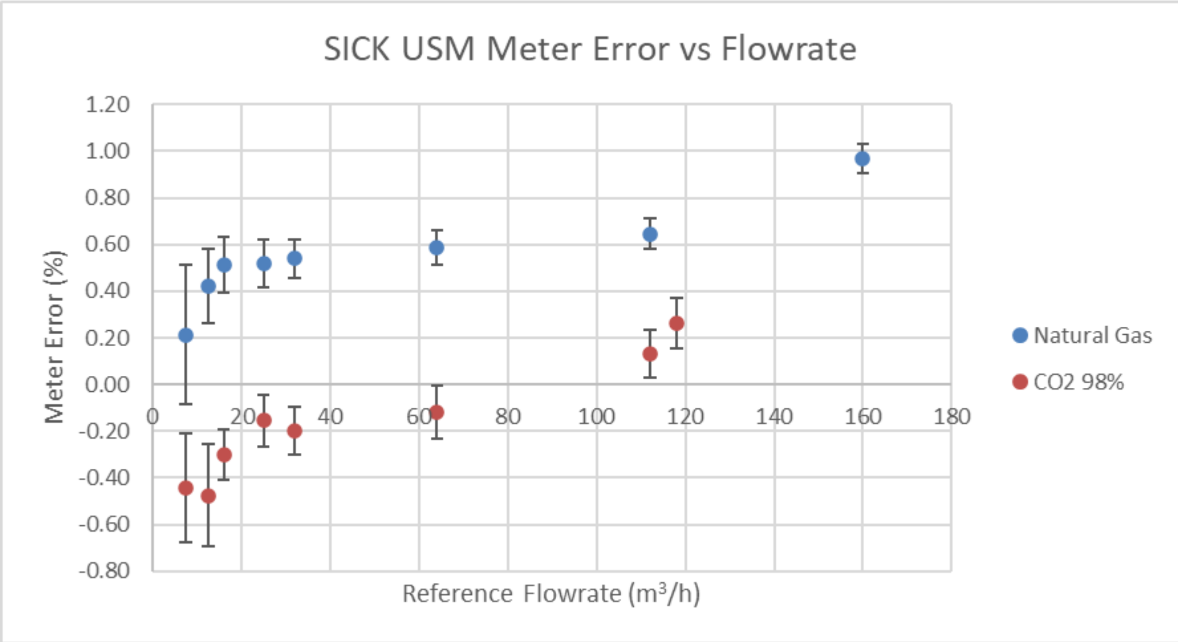

Figure 14 - SICK FL550 meter error as a function of the reference volumetric flow rate. The figure shows the data collected at VSL with 2% nitrogen and 98% carbon dioxide. The error bars indicate the measurement uncertainty.

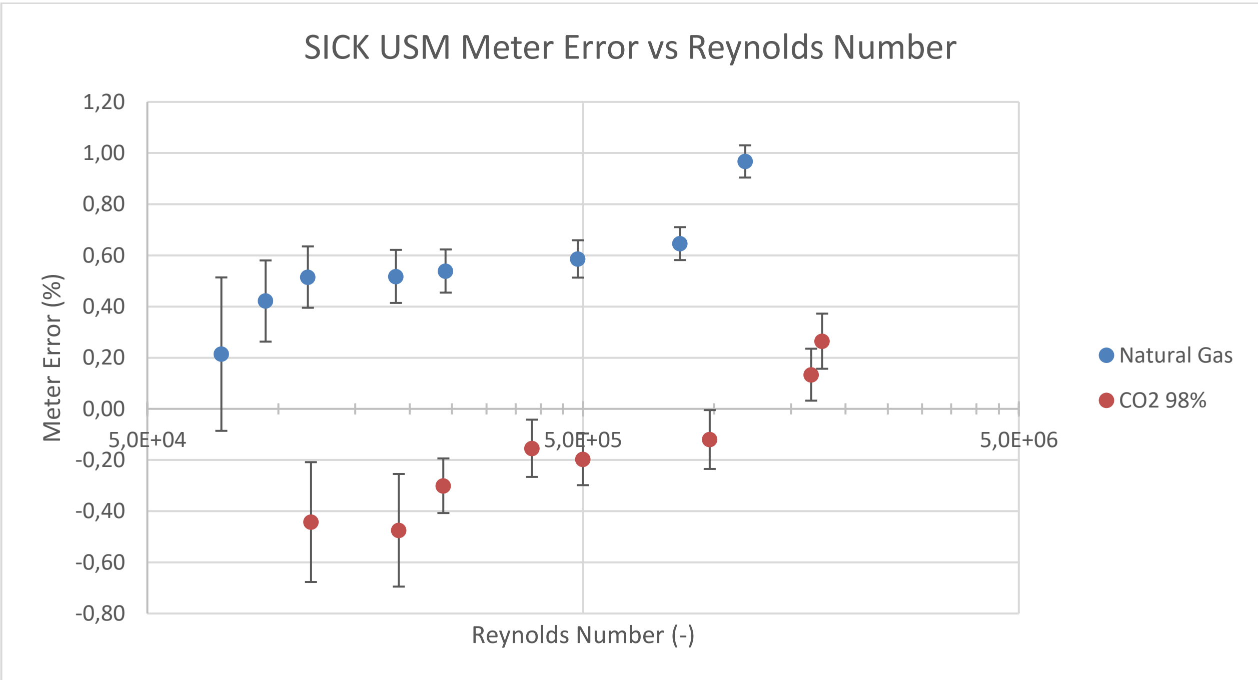

Figure 15 - SICK FL550 meter error as a function of the Reynolds number. The figure shows the data collected at VSL with 2% nitrogen and 98% carbon dioxide. The error bars indicate the measurement uncertainty.

Figure 16 - A picture of the SICK FL550 installed on the GOPP for calibration with CO_2 and Natural gas

4 Intermediate scale facilities

4.1 INRIM piston prover

INRIM used, for the intermediate scale comparison, its large piston prover (MeGAS) and its bell prover (BellGAS) for the lowest flow rates.

The MeGas test rig is a single-stroke, plunger-type piston prover. It was designed and built at the then-IMGC (now INRIM) in the mid-1980s. The plunger type (namely a long, vertical cylindrical piston forced to sink through a gasket into a slightly larger, rigid but mechanically unfinished chamber containing the gas) was preferred over a traditional piston-cylinder system because of metrological (the external diameter can be measured more accurately than the internal one) and practical reasons (it is easier and cheaper to machine the piston than the cylinder, and the gasket is more easily accessible).

The resulting device is a structure 6 m high Figure 17, with at its top a platform where a finely controlled brushless motor drives, through a gearbox, the female ball-screw of a lead screw connected with the piston. This apparatus causes the vertical movement of the piston and the emission of pulses from a rotating encoder fitted on the female screw. The piston is constituted by a 1000 mm nominal diameter, 1630 mm long and 14 mm thick carbon-steel cylinder fitted to a massive bottom flange. The external surface of the cylinder is chromium plated, ground and polished. The leak-proof gasket at the top of the chamber is a Teflon-coated, 1000 mm diameter O-ring compressed to the necessary and adjustable extent by an upper flange.

The internal diameter of the measurement chamber is 1095 mm; in the clearance between its walls and the piston, 10 Platinum Resistance Temperatures (PRTs) are installed at different heights and positions in order to measure the average gas temperature and to detect possible non uniformities. The chamber rests on the 1950 mm diameter base of the prover. A bended pipe is connected to a 100 mm bore at the center of the base which conveys the gas displaced by the piston towards the test line. A group of automatically operated valves (a safety valve, one for admission of atmospheric air and one for gas delivery to the test line) are installed at the facility exit. The internal volume of the prover is about 1500 L when the piston is at its upper rest position; the volume of the piston is more than 1200 L, however, considering the parts of the piston stroke that must be devoted to acceleration, deceleration and the emergency stop switches installed at both ends, the largest gas volume that can be displaced and measured is about 800 L.

The claimed uncertainty of the facility MeGAS is of 0.1%.

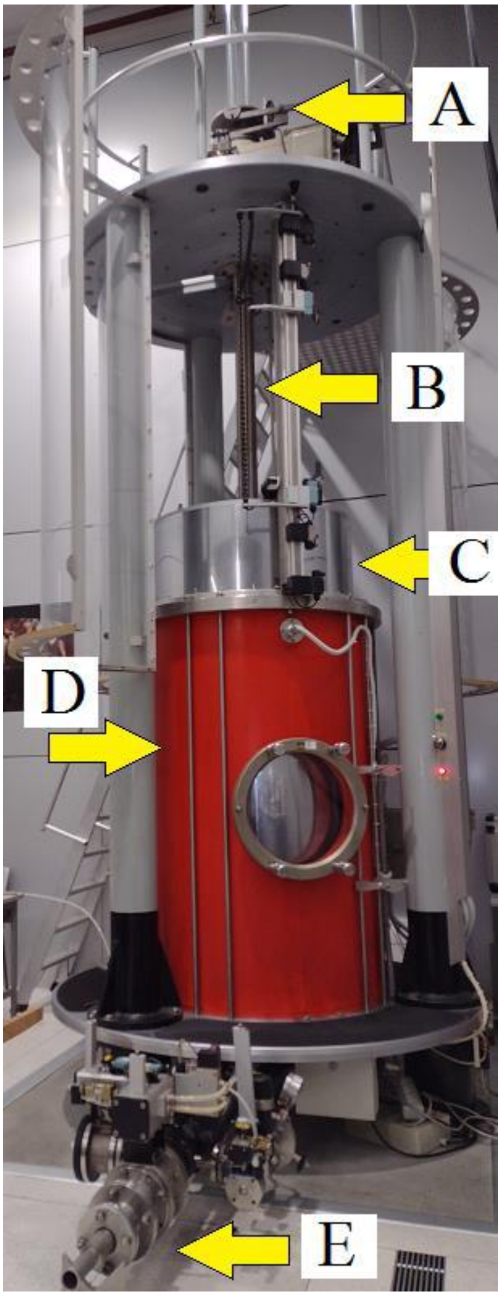

Figure 17 - MeGas Facility, A: MeGas encoder and piston control, B: screw, C: Piston, D: measurement chamber, E: facility outlet.

The BellGAS facility is essentially a standard bell prover, with an internal volume of about 150 L; the original facility was improved by modifying the position reading through addition of a high resolution encoder, allowing a reading of the movement with a resolution of about 0.5 mL/pulse, and a special movable compensation weight, which allows to maintain the stability of the pressure within the bell to +/- 2 Pa throughout the bell run.

The flow capacity of the device ranges between approximately 0.5 L/min and 120 L/min; The claimed uncertainty of the facility BellGAS is of 0.12%.

4.2 VSL Mercury-Seal Piston Prover

The VSL mercury-seal piston prover is a primary flow measurement standard for calibration of flow meters and other mercury piston provers. The system consists of four Mass Flow Controllers (MFCs) and four mercury ring tubes, also called measuring tubes. The mercury ring tubes serve as reference meters for calibrations. The system is ISO 17025 certified and has a range of 0.1 l/h to 3500 l/h at ambient conditions, with a CMC of 0.4% - 0.2%. The system can calibrate Volume and flow rate measuring instruments.

The MFCs are used to generate the most constant flow rate possible and consist of a control valve and a thermal mass flow meter. When a desired flow rate is set using a setpoint, the MFC will regulate this flow rate and attempt to maintain a constant flow rate. To maintain a constant inlet pressure, an El-press pressure regulator has been added to each panel, just before the inlet of the MFCs. This allows the MFCs to maintain the desired flow rate even more consistently.

The panel with 4 MFCs has maximum flow rates of 50 l/min, 5 l/min, 0.5 l/min, and 25 ml/min respectively.

A mercury ring tube consists of a precision glass tube containing a piston with a mercury seal. By using mercury, the piston can move through the glass tube virtually friction-free, while the mercury ensures a gas-tight seal.

Infrared and laser sensors are located at various heights on guides placed parallel to the tube. These sensors emit an electrical pulse when the piston interrupts the light beam. The size of a single volume therefore depends on:

- the difference in height between two sensors
- the diameter of the tube between the two sensors.

The length between the two sensors and the diameter of the tube between the two sensors are calibrated with direct traceability to the “meter”, ensuring SI-traceability. The system also includes calibrated timers that are directly traceable to the “second”. Since the calibration of the internal volume is independent of the gas, the provers can provide SI-traceable calibrations with any gas.

A diagram of the Mercury Seal Piston Prover system is shown in Figure 18. A picture of the provers is shown in Figure 19.

Flow measurement with a mercury ring tube works as follows:

The MFCs generate a flow rate, which is directed to the flow meter under test and then a mercury ring tube via the valves. To initiate a flow measurement, a valve behind the tube is closed, causing the piston to move. When the piston passes the first sensor (s0), a time measurement is initiated. When the piston passes the next sensor, the time between s0 and this sensor is stored. A temperature measurement is also initiated while passing s0, which stops once the stop sensor is reached. Using the measured time and the known volume, the flow rate can now be determined.

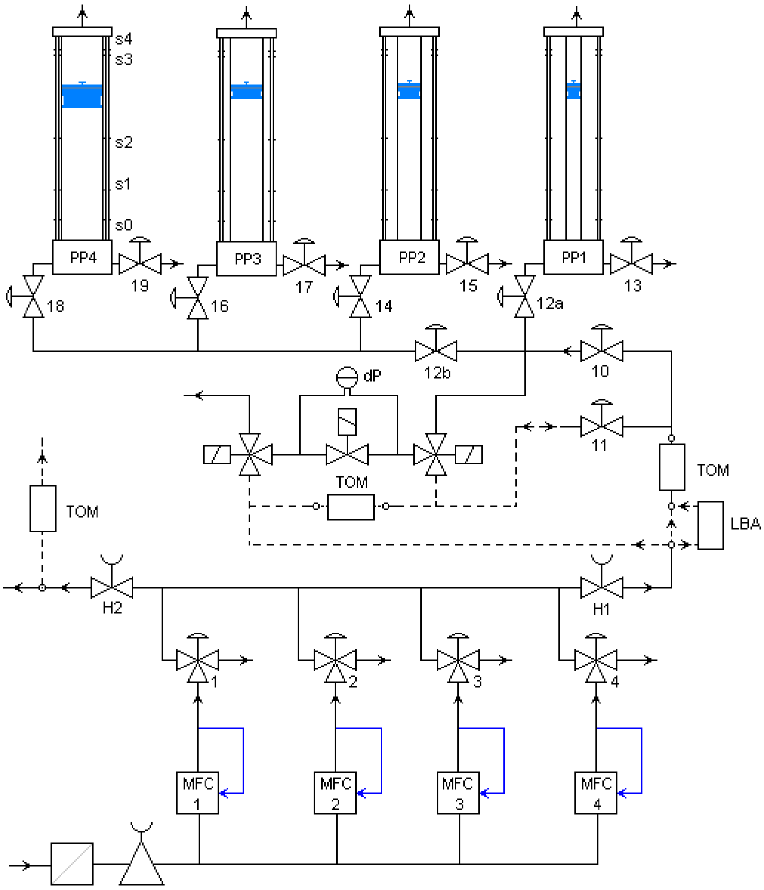

Figure 18 - The Mercury Seal Piston Prover facility. TOM stands for Meter Under Test. LBA stands for an air handling unit that moisturizes the air when the system is used to calibrate a drum meter

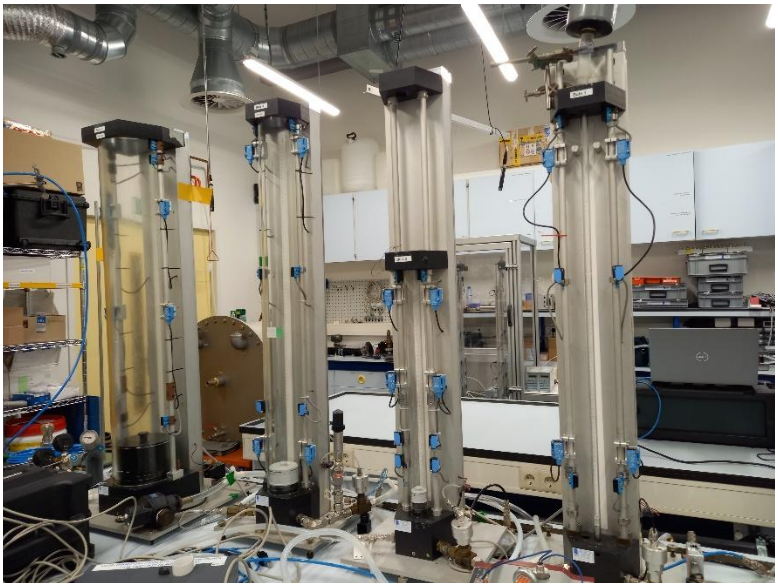

Figure 19 - A picture of the Mercury-Seal Piston Provers

4.3 NEL high pressure low flow facility

The NEL high pressure low flow facility, illustrated in Figure 20, is built around a DN25 nominal bore line, with gas supplied via an off take from the NEL high pressure gas flow facility's 60 bar(g) gas supply line. The inlet pressure to the Device Under Test (DUT) is regulated using a pressure regulator. A plate heat exchanger installed between the pressure regulator and DUT compensates for temperature changes due to the pressure regulator and also enables testing at different gas temperatures from 0 °C to 40 °C. Gas flow rates are controlled using a needle valve installed downstream of the DUT. The reference flow rate is determined using a range of Critical Flow Nozzles (CFN) installed further downstream and the outlet piping from the CFN is open to the atmosphere. All static pressure, differential pressure, and temperature measurements are taken with traceable calibrated instrumentation. Like the NEL high pressure gas flow facility, gas properties are calculated using NEL's implementation of REFPROP from NIST [5]. The expanded uncertainty of the reference flow measurement is ±0.3% (k = 2).

When the facility operates with nitrogen gas at 40 bar(g) and 20 °C, it has the capability to test flow meters at gas flow rates from 0.2 kg/min (0.259 m3/hr) to 4 kg/min (5.18 m^3/hr). The recent upgrade to this facility includes the capability to test with carbon dioxide gas. The reference CFNs used for the tests described in this report are listed in Table 7.

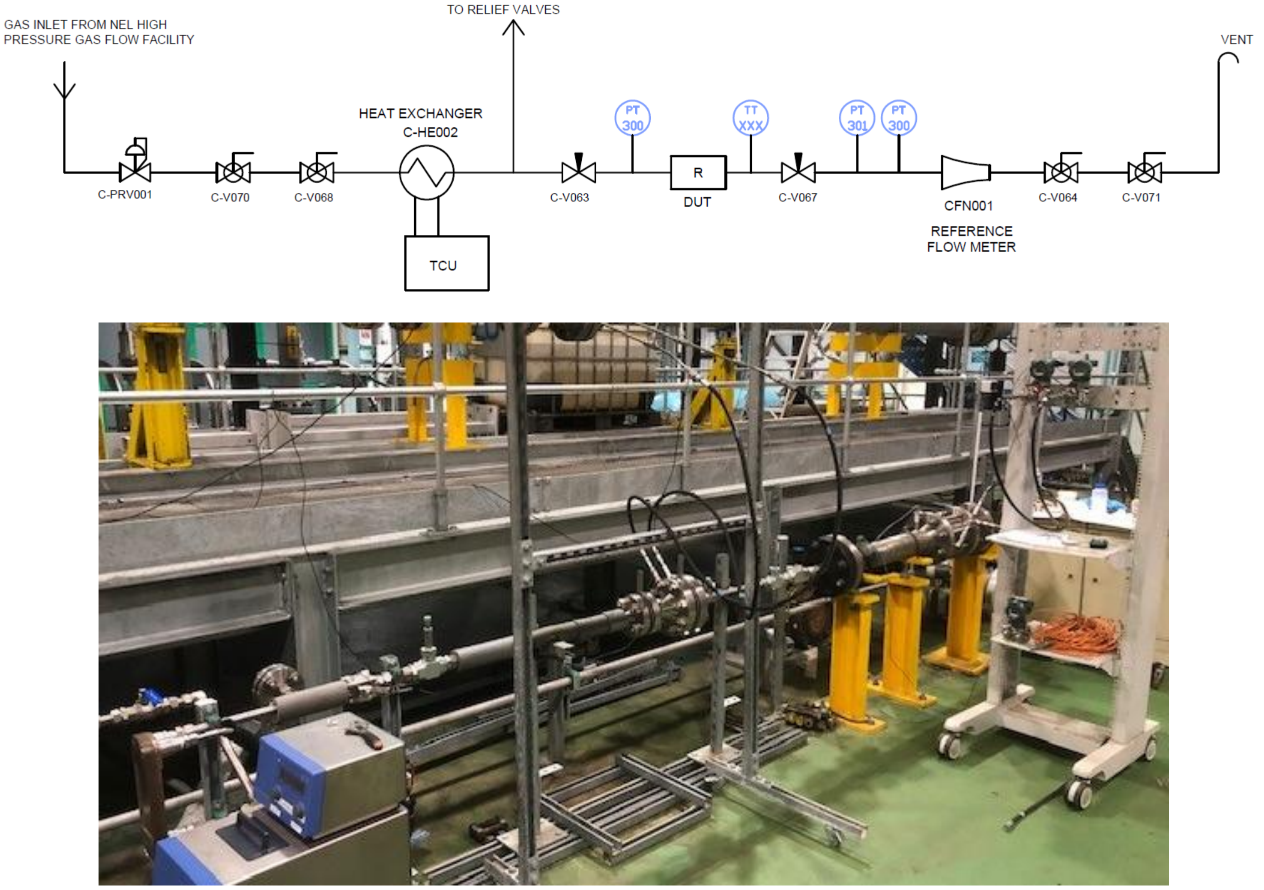

Figure 20 - Schematic (top) and picture (bottom) of the NEL high pressure low flow facility.

Table 7 - Reference CFNs used for the NEL high pressure low flow facility tests with CO2 and N2 gas

CFN ID #	NOT#	Throat ID (mm)	Test gas
GR1	1060	2.894	CO_2, N_2
GR2	1061	3.9994	CO_2, N_2
GR3	1062	5.6715	CO_2, N_2
GR4	1063	8.035	CO_2, N_2
GR5	1064	11.134	CO_2, N_2
RS6	0676	1.943	CO_2
RS8	0675	1.2598	CO_2, N_2

4.4 Intercomparison results

Test meters

Two meters were selected as the transfer package for the intercomparison. The first is a DN2 (1/10 inch) Emerson Coriolis meter (CMF010 serial number 11024020) provided by VSL. The second flow meter is a DN50 PGM rotary gas meter provided by NEL (PGM triple master meter G16 serial number 100218/2023) with a flow range of 0.25 m^3/h to 30 m^3/h. The PGM flow meter was tested with upstream and downstream 2-inch spools as shown in Figure 22 and Figure 23. Installation of the Coriolis meters at VSL and INRIM is shown in Figure 24 and Figure 25 respectively.

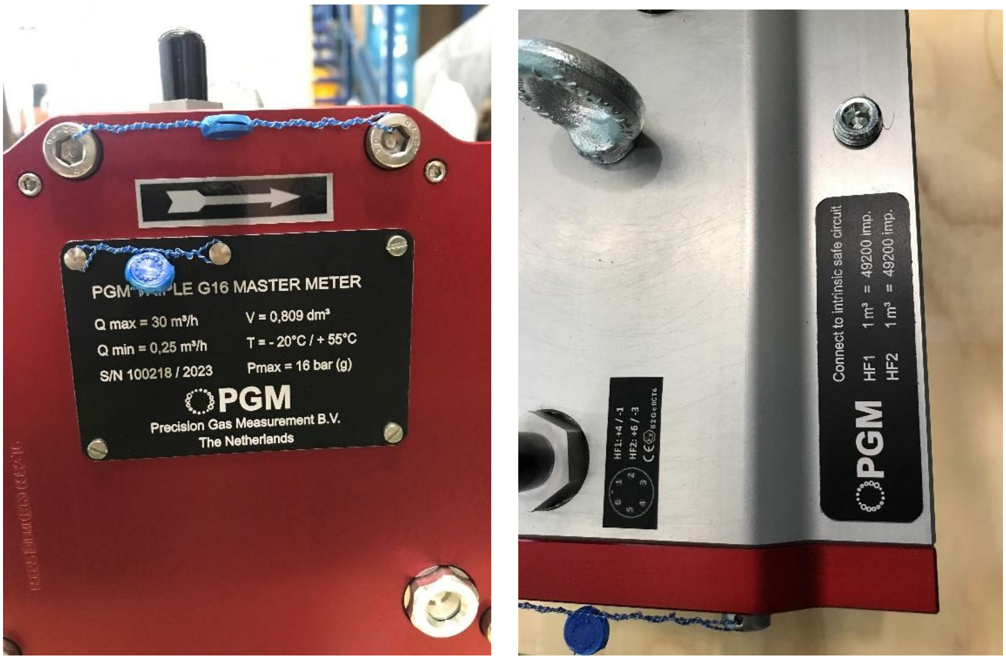

Figure 21 – Pictures of the PGM triple G16 master meter

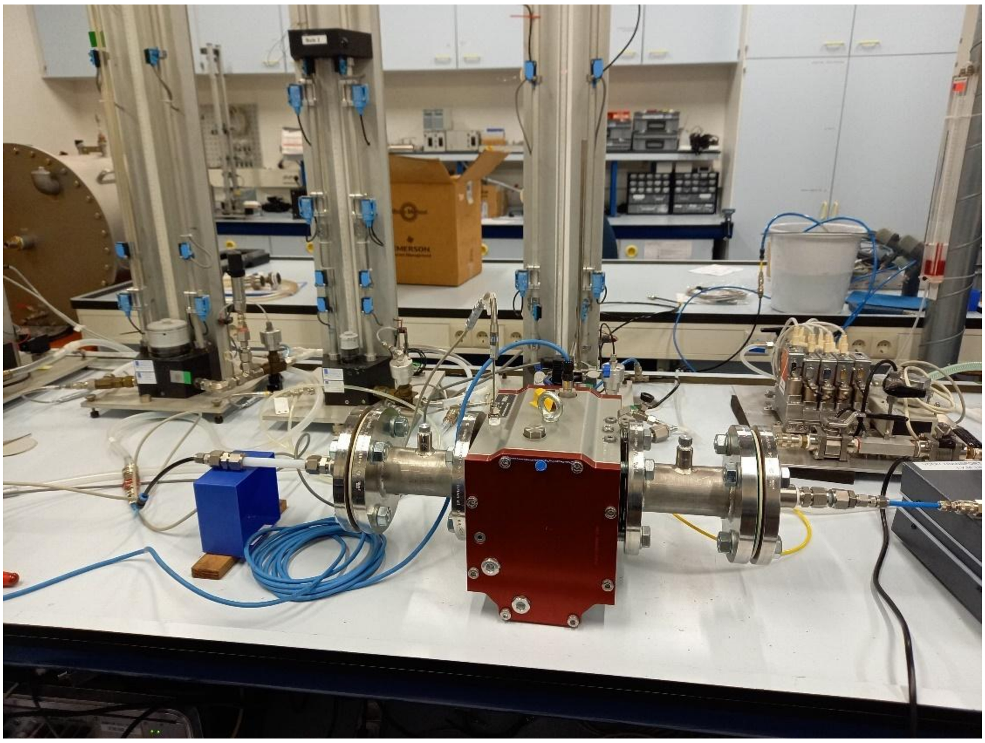

Figure 22 - Pictures of the PGM G16 DN50 rotary meter installed at VSL. The meter is installed upstream of the VSL mercury piston prover. The flow is from right to left.

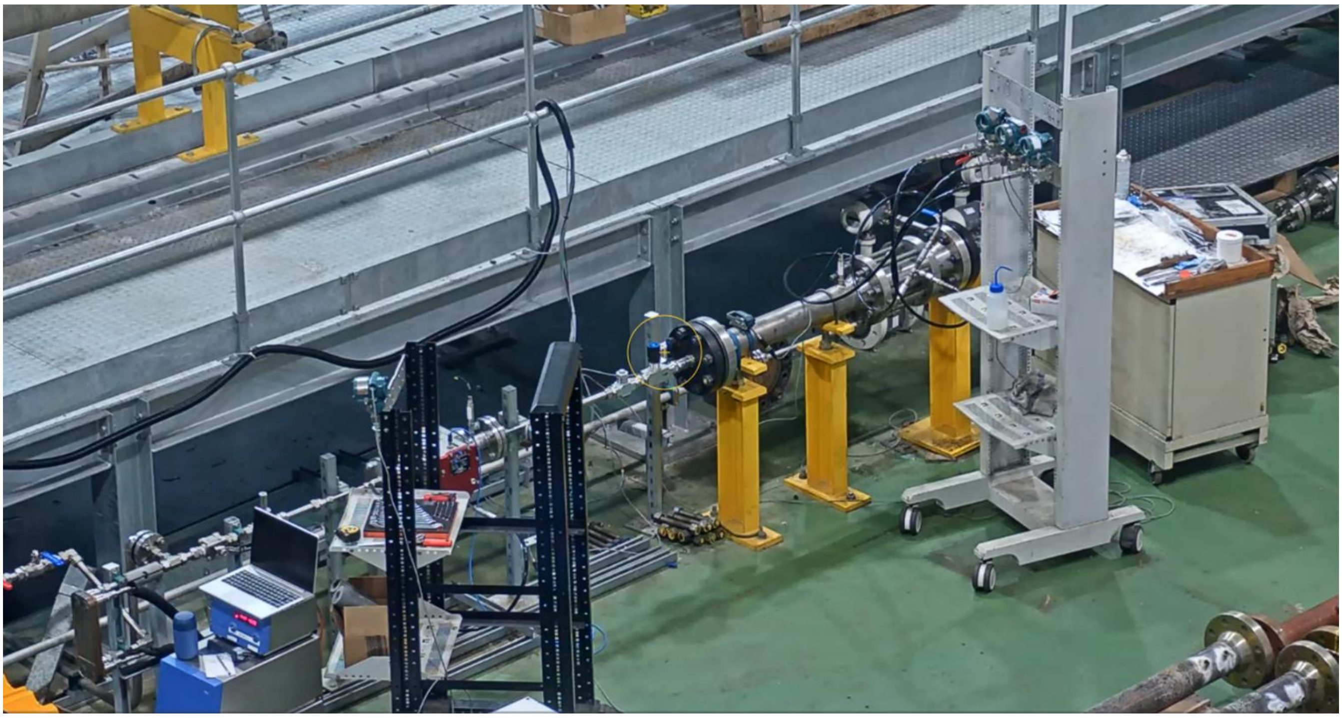

Figure 23 - Pictures of the DN50 rotary meter installed at NEL. The meter is installed upstream of the reference sonic nozzle holder. The flow is from left to right.

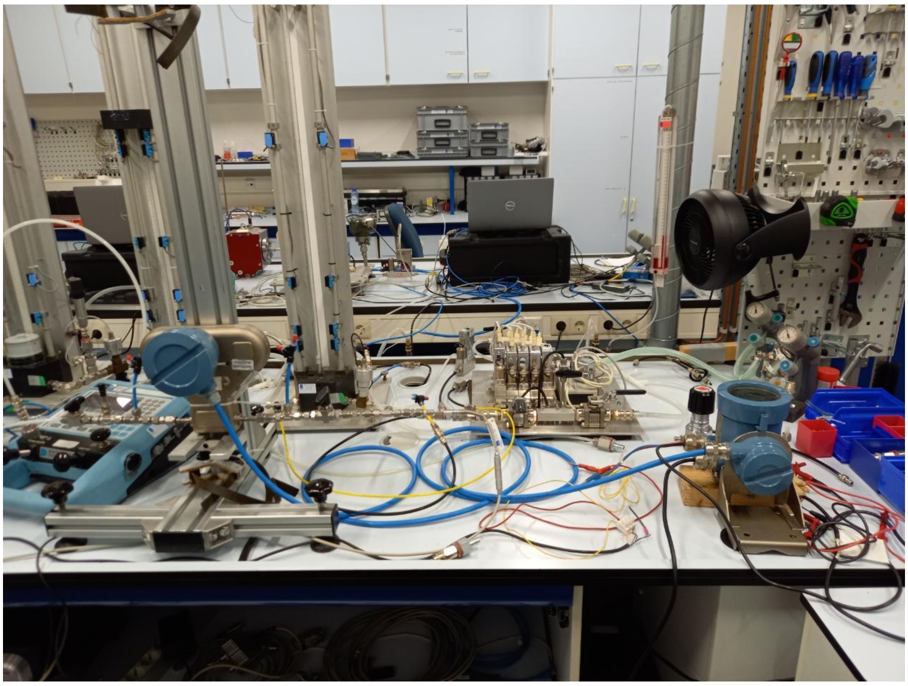

Figure 24 - Pictures of the DN2 CMF010 Coriolis meter installed at VSL.

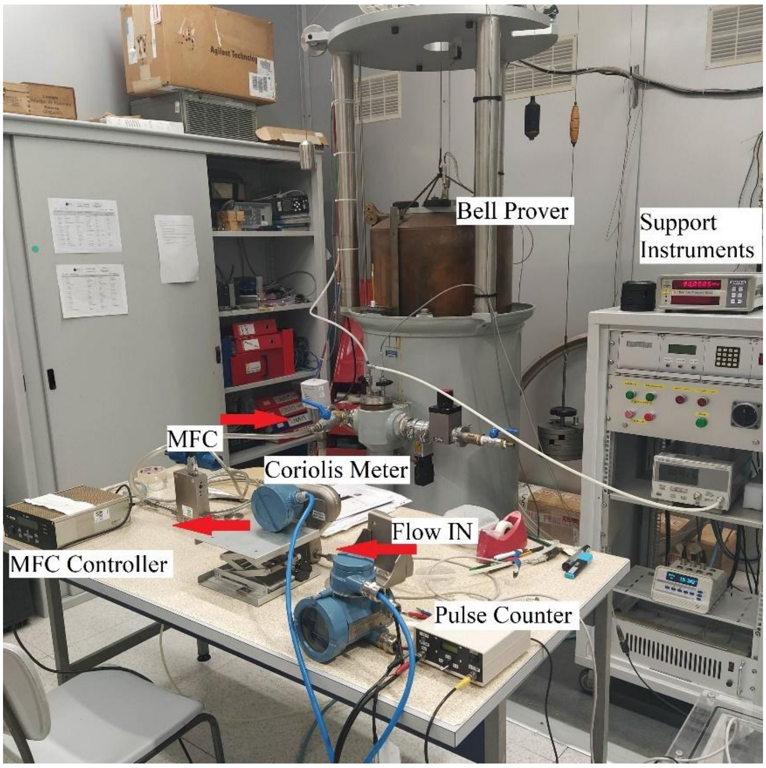

Figure 25 - Pictures of the DN2 CMF010 Coriolis meter installed at INRIM.

Sequence of testing

The meters were initially tested at VSL in July 2024. The meter package was subsequently tested by NEL in March 2025, followed by the final set of intercomparison tests conducted by INRIM in June 2025.

Test conditions

The intercomparison was performed between VSL, NEL and INRIM for carbon dioxide and nitrogen. Intercomparison test conditions are reported in Table 8. It should be noted that test pressure at NEL was higher than at VSL and INRIM. The reason is because NEL uses sonic nozzles as reference meters which required sufficient upstream pressure to ensure sonic velocity at the nozzle throat. Three consecutive repeats were taken for each test point.

Table 8 – Intermediate scale facilities intercomparison test conditions for the PGM rotary meter

Test Fluid	Pressure (bar.a)	Temperature (°C)	Density (kg/m^3)	Flow Rate Range (m^3/h)	VSL	INRIM	NEL
N_2	Armospheric (6 to 11 at NEL)	20	1.13 to 1.2 (7 to 13 at NEL)	0.1 to 30	0.1 to 3 m^3/h	Yes	Yes
CO_2	Armospheric (3 to 7 at NEL)	20	1.16 to 1.8 (6 to 12 at NEL)	0.1 to 30	0.1 to 2.23 m^3/h	Yes	0.6 to 15 m^3/h

Table 9 – Intermediate scale facilities intercomparison test conditions for the DN2 Coriolis meter

Test Fluid	Pressure (bar.a)	Temperature (°C)	Flow Rate Range (kg/h)	VSL	INRIM	NEL
N_2	Armospheric (1.2 to 2.2 at NEL)	20	0.12 to 3.5	Yes	Yes	1.8 – 4.9 kg/h
CO_2	Armospheric (1.2 to 2.2 at NEL)	20	0.19 to 5.7	0.19 to 4.2 kg/h	Yes	2.2, 4.3, 6.2 kg/h

Measured values

Each facility used its own pressure and temperature measurement devices. The pressure was measured at pressure port located at the rotary meter body. VSL measured the temperature at temperature port located at the rotary meter body. NEL and INRIM measured the temperature in the downstream rotary meter spool. Pulse output was collected for the rotary meter.

Intercomparison calculations

The intercomparison calculations for the intermediate scale facilities are the same as described for the large scale facilities intercomparison, see Section 3.5. The CMC values for each of the intermediate scale facility is shown in Table 10.

Table 10 – Calibration and Measurement Capabilities (CMC) for each intermediate scale facility

Transfer Meter	Calibration and Measurement Capability (%) (k = 2)		
	NEL	VSL	INRIM
PGM meter (volume flow)	0.39	0.2	0.1
Coriolis meter (mass flow)	0.39	0.2 – 0.43	0.12 – 0.58

Test results

The comparison results for the rotary meter along with the average uncertainties associated with each facility are presented in Figure 26 and Figure 27 for nitrogen, Figure 29 and Figure 28 for carbon dioxide. Each plotted test result is the averaged value of 3 consecutive repeats. It should be noted that the average uncertainties plotted in the figures also include the repeatability associated to the three repeats.

The results indicate that the facilities show better agreement when using nitrogen than with carbon dioxide. The most notable deviation is observed in the NEL test results with carbon dioxide. This discrepancy is attributed to the performance of NEL's reference sonic nozzles, which are known to be affected when operated with CO_2. A detailed discussion of this issue is provided in Section 4.5.

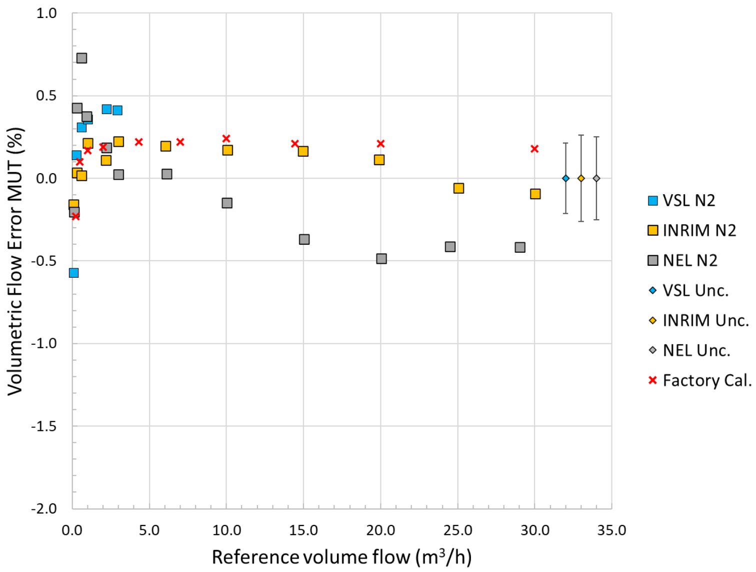

Figure 26 - Rotary meter relative error in gas volumetric flow rate at each facility as a function of the reference volumetric flow rate. Results are for nitrogen. Factory calibration with air is also shown.

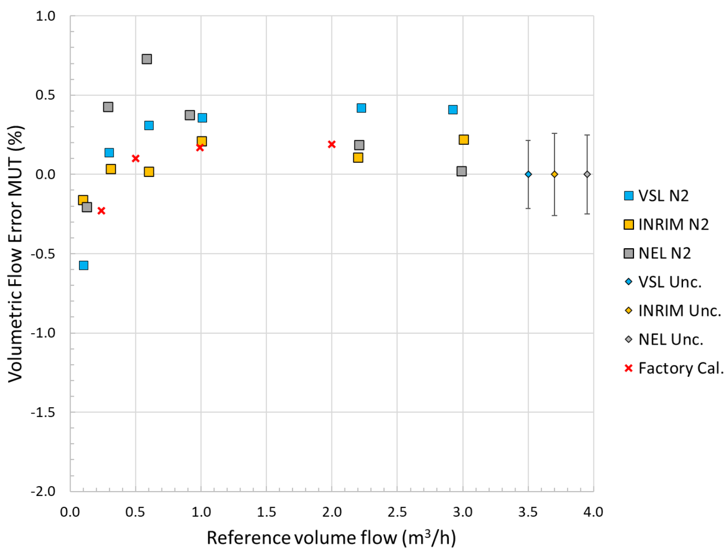

Figure 27 - Rotary meter relative error in gas volumetric flow rate at each facility as a function of the reference volumetric flow rate. Results are for nitrogen. Zoomed graph to better visualise the test results below 3 m³/h. Factory calibration with air is also shown.

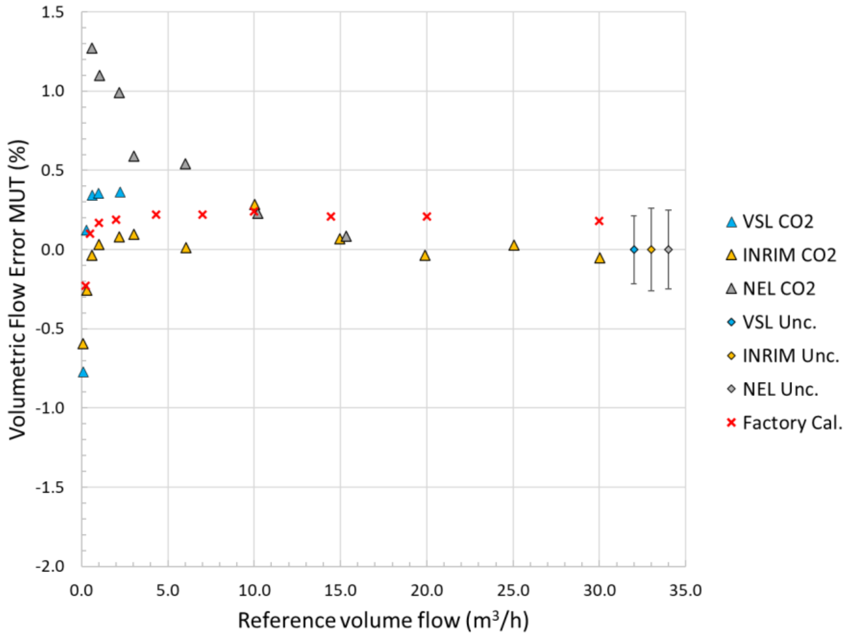

Figure 28 - Rotary meter relative error in gas volumetric flow rate at each facility as a function of the reference volumetric flow rate. Results are for carbon dioxide. Factory calibration with air is also shown.

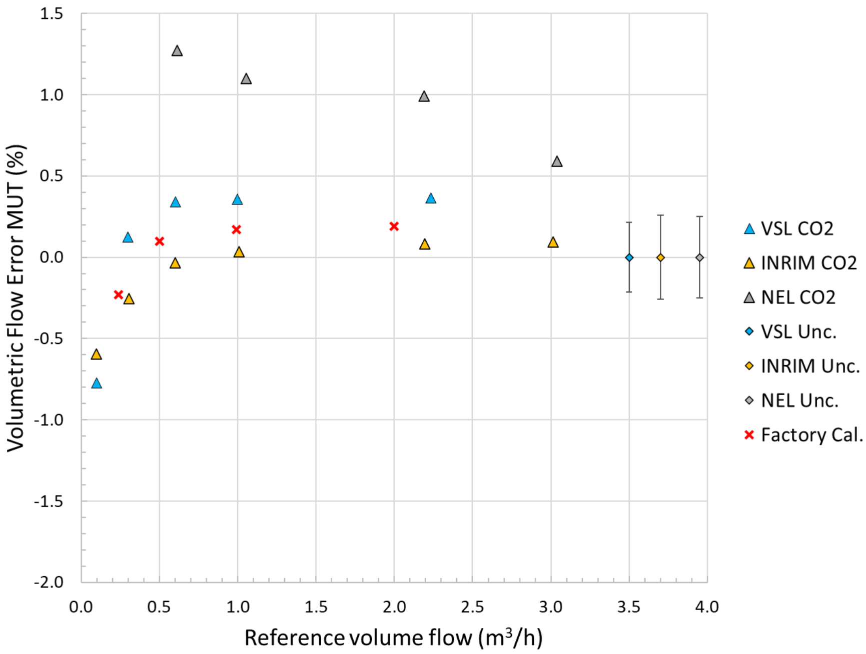

Figure 29 - Rotary meter relative error in gas volumetric flow rate at each facility as a function of the reference volumetric flow rate. Results are for carbon dioxide. Zoomed graph to better visualise the test results below 3 m^3/h. Factory calibration with air is also shown.

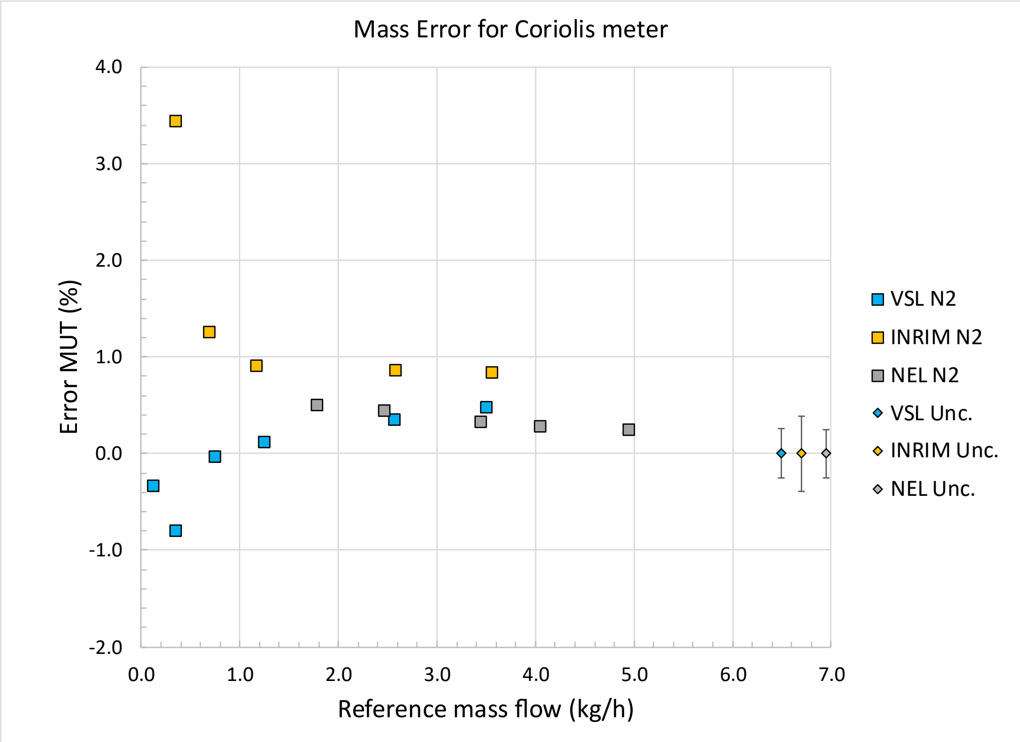

Figure 30 – DN2 Coriolis meter relative error in gas mass flow rate at each facility as a function of the reference mass flow rate. Results are for nitrogen.

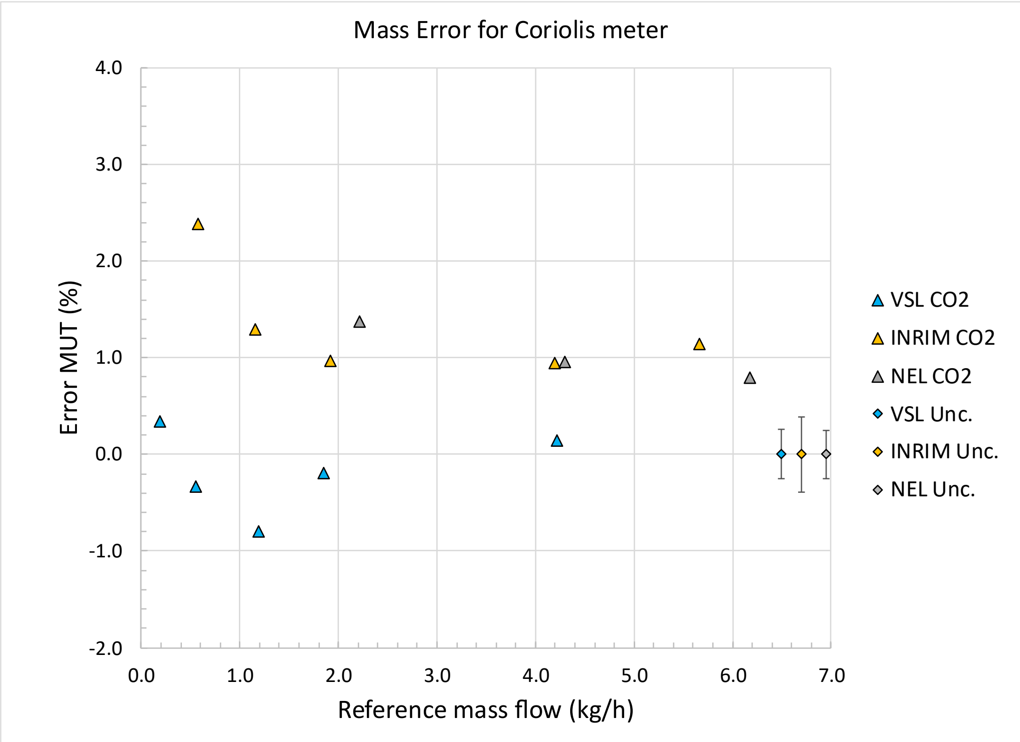

Figure 31 – DN2 Coriolis meter relative error in gas mass flow rate at each facility as a function of the reference mass flow rate. Results are for carbon dioxide.

Degree of equivalence

Figure 32 presents the Degrees of Equivalence, $|E_n|$ values for each test facility based on the PGM meter measurements with nitrogen. Approximately 80% of the test points shown in this graph have $|E_n| < 1$, demonstrating that the three test facilities - NEL, VSL and INRIM - are consistent with the CRV. However, being below 90% it cannot be concluded that the facilities have successfully passed the equivalency test for the specific flow conditions maintained during these test runs.

Figure 32 also highlights six test points where $|E_n|$ exceeded 1. One of these points had $|E_n|$ value between 1 and 1.2, suggesting a potential warning regarding the measurement processes at these facilities under the respective test conditions. Five results had $|E_n|$ >1.2, indicating that the test facility failed the equivalency test under these specific flow conditions. However, it should be noted that the rotary meter tests at NEL where not run at atmospheric pressure like at INRIM and VSL, but with pressures between 3 and 11 bar. The PGM is known to be affected by line pressure, potentially explaining the intercomparison results.

Figure 33 presents the Degrees of Equivalence, $|E_n|$ values for each test facility based on the Coriolis meter measurements with nitrogen. For NEL facility $|E_n|$ values are all below 1, while for INRIM and VSL $|E_n|$ values increase for decreasing flow rate.

The degree of equivalence for the carbon dioxide intercomparison is not presented due to issues encountered when using sonic nozzles as reference meters with carbon dioxide at NEL (see Section 4.5.). Specifically, the use of sonic nozzles calibrated in air introduced significant errors when applied to carbon dioxide, rendering the intercomparison results unreliable and unrepresentative. However, it can be commented that the carbon dioxide results for VSL and INRIM agree well within their respective CMC values.

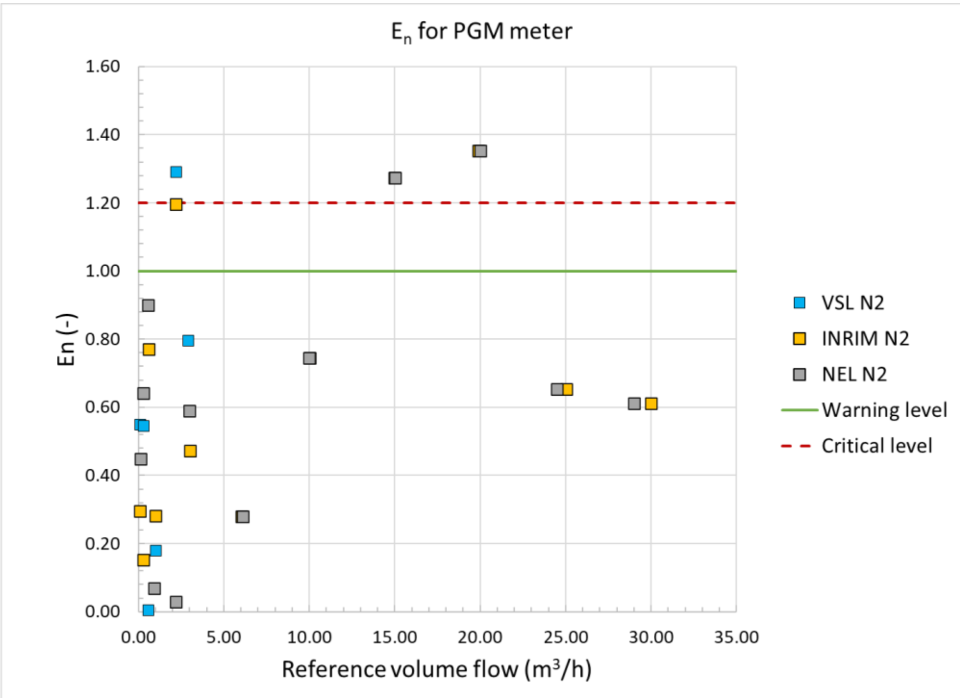

Figure 32 - Degrees of Equivalence for each test facility's measurements with the rotary gas meter for nitrogen.

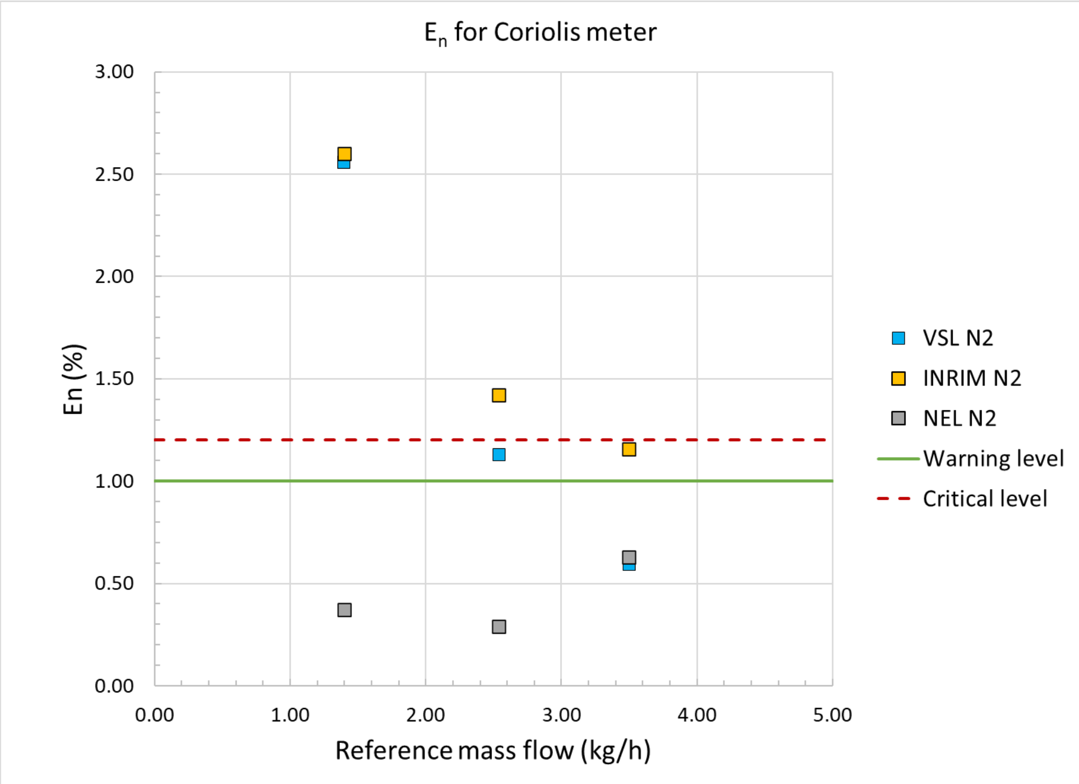

Figure 33 - Degrees of Equivalence for each test facility's measurements with the Coriolis meter for nitrogen.

4.5 Note on NEL reference sonic nozzle performance with carbon dioxide

As part of the 21GRD06 MetCCUS project NEL undertook a carbon dioxide flow measurement test programme on the high pressure low flow facility. The reference flow meters on this flow measurement facility are Critical Flow Nozzles (CFN) which have been calibrated in air at the Korea Research Institute of Standards and Science (KRISS). Hence there was a requirement to examine how the calibration of the CFNs with air could be translated when the flow measurement facility used carbon dioxide gas. A literature review was therefore undertaken to see if earlier studies have developed suitable methods that could be applied to the air calibration of the CFNs that were used.

In 1998 Johnson et al. [27] reported a comparison of the CFN discharge coefficients from an analytical model by Ishibashi et al. [28] and numerical analysis against experimental data from Nakao et al. [29] for four gases which included hydrogen, nitrogen and carbon dioxide. For nitrogen and hydrogen the numerical results from Computational Fluid Dynamics (CFD) matched the trends from the experimental data and the experimental expanded uncertainty was less than 0.5%. However, the analytical and numerical results for carbon dioxide, which were for a reference Reynolds number between 5,500 and 24,000, did not match experimental results. Since the expanded experimental uncertainty was approximately 2%, the experimental measurements were repeated at the NIST calibration facility, and the NIST experimental results confirmed the carbon dioxide experimental data from Nakao et al. [29]. Sensitivity analysis by Johnson et al. [27] demonstrated that the effects of the wall thermal boundary condition could not be the reason for the observed differences with carbon dioxide.

Johnson et al. [27] therefore further investigated the possible physical mechanisms unique to carbon dioxide which might explain the observed difference. They specifically examined the vibrational relaxation time, the time necessary for redistribution of internal energy to vibrational degrees of freedom when a fluid particle is subjected to a change in thermodynamic conditions. Their study reported that the vibrational relaxation time for carbon dioxide is on the order of 10^{-5} s at T = 300 K and P = 101330 Pa (1 atm). Given that the CFN in their study had a throat diameter of 0.5935 mm, they noted that due to the small spatial size of the CFN nozzle, the flow is accelerated from nearly stagnant upstream conditions to sonic conditions at the nozzle throat over a small distance. Hence the vibrational relaxation time (10^{-5} s) was on the same order as the time taken for the fluid to travel from the nozzle inlet to the throat (10^{-5} s). As a result, they suggested vibrational non-equilibrium may potentially contribute to the observed discrepancy for the higher discharge coefficients of the experimental results for carbon dioxide. However, they emphasized that further research was needed to confirm this.

Later in 2000, Nakao and Takamoto [30] reported results from a study where the gravimetric calibration facility at the National Research Laboratory of Metrology (NRLM) was used to measure the discharge coefficient for carbon dioxide flow through four small-scale CFNs with throat diameters ranging from 0.295 mm to 2.360 mm. The experiments which covered a Reynolds number range of 2,500 to 131,000, showed that the measured discharge coefficient was approximately 2% higher than the theoretical prediction based on the assumption of an isentropic perfect gas. While introducing real gas effects did not account for this discrepancy, they observed that narrower the flow field, the larger the discharge coefficient deviated from the theoretical value. Nakao and Takamoto suggested that this was due to non-equilibrium conditions at the nozzle throat because carbon dioxide gas could not completely redistribute the internal energy to a new flow condition due to the short and narrow flow field.

In a later study Johnson et al. [31] used CFD to model carbon dioxide gas flow though the same four small-scale CFNs Nakao and Takamoto [30] and tested at NRLM. They postulated that vibrational non-equilibrium phenomena could influence the gas dynamics of carbon dioxide flow because of the contribution of vibrational energy is comparatively large compared to the overall energy, and due to the presence of vibrational relaxation effects in the flow field for small-scale CFNs. To validate their hypothesis, they compared the CFD results against the NRLM measurements and conducted a second experiment in which they aimed to reduce vibrational relaxation effects by diluting carbon dioxide with small concentrations of water vapor. The study found that incorporating vibrational non-equilibrium effects into the CFD model reduced the error in the discharge coefficient predictions by a factor of five over the previous models ([27], [28]). The updated CFD predictions closely matched the experimental data, with discrepancies no more than 0.4% at the lower reference Reynolds numbers and further improved at the larger reference Reynolds numbers. Johnson et al. [31] concluded that their independent experiments and the numerical results confirmed the proposition that vibrational relaxation effects can play a significant role in discharge coefficient behaviour for carbon dioxide CFN flows. Their non-equilibrium CFD model demonstrated that vibrational relaxation increases mass flow through the nozzle, leading to a higher discharge coefficient. The experiments highlighted the significance of the ratio between the vibrational relaxation time to the flow residence time in characterizing vibrational non-equilibrium behaviour. They also demonstrated the anticipated drop off in discharge coefficient at low values of this ratio.

In 2003, Wright [32] reported that as the CFN throat diameter becomes smaller, the assumption of sonic velocities across the entire CFN throat becomes less valid and the viscous boundary layer becomes a more significant portion of the throat cross section. The paper included experimental results from two calibration laboratories for discharge coefficients for four gases including air, nitrogen and carbon dioxide with CFN throat diameters of 0.3937 mm and 0.5935 mm. The systematic effect for carbon dioxide when compared to the other gases, where the difference in discharge coefficient was greater than 2% was verified by the experimental data. This paper also reported that the observed difference was due to the vibrational relaxation effects of carbon dioxide. The smaller systematic differences between the gases other than carbon dioxide was attributed to viscous heating of the boundary layer where at low Reynolds numbers (i.e. less than 63,000 in the case of this study) and small nozzle throats, gases with larger specific heat ratio led to thicker thermal boundary layers and therefore smaller discharge coefficients.

In a follow-up study, Johnson et al. [33] enhanced their CFD model for CFNs by incorporating a rate equation for a species-dependent relaxation time. They applied this improved model to four different gases including carbon dioxide. The values for species-dependent relaxation time, that characterises the equilibration of the vibrational degrees of freedom with the translational and rotational degrees of freedom were obtained from ultrasonic relaxation data. Predictions for carbon dioxide using the augmented CFD model aligned with the previously published experimental data within ±0.1% which was a significant improvement compared to earlier models that deviated by up to 2.3%. Additionally, they introduced a linear CFN theory which defined an approximate form of the effective critical flow function that could be used to mitigate the effects of vibrational relaxation. Their paper in 2006 proposed that the effective values of the specific heat ratio and the critical flow function derived in their work could be applied to calibration data from nitrogen gas testing to calculate carbon dioxide flow through a CFN without requiring CFD modelling. However, the latest version of ISO 9300 [34] issued in 2022 did not reference the above method as a suitable option for determining CFN carbon dioxide gas flow by using calibration data from a different gas. This omission suggests that further research may be needed to fully establish the suitably of the proposed method.

As part of the EMPIR MetHyInfra project, Bobovnik et al. [35], [36] investigated the discharge coefficient for two CFNs with throat diameters of 0.175 mm and 0.436 mm, calibrated with six gases including dry air, nitrogen, hydrogen and nitrous oxide. The range of Reynolds number tested with each gas was different due to the different properties for density and viscosity of each gas. Air and nitrogen tests had Reynolds number range from 4,500 to 40,000. For hydrogen the range was 2,500 to 22,000, while for nitrous oxide it was 6,750 to 59,000. The study compared the experimental results against the discharge coefficient calculated according to ISO 9300:2005 for accurately machined toroidal nozzles. When compared to the other gases the experimental results for nitrous oxide had significantly higher discharge coefficients (about 1 % higher than for air). The study found that theoretical models which also included the influence of the isentropic coefficient could not account for this difference. Bobovnik et al. [35], [36] suggested this discrepancy observed with the experimental results for nitrous oxide could be due to the relatively low purity (99.5%) of nitrous oxide used, or the effects of vibrational relaxation similar to the effects in carbon dioxide and sulphur hexafluoride (SF6) flow through small scale CFNs as reported by Johnson et al. [31] [33] and Nago et al. [37].

The 2022 update to ISO 9300: "Measurement of gas flow by means of critical flow nozzles" 2022 [34] incorporates findings from studies by Johnson et al. [33] on the effect of gases with significant vibrational effects, such as carbon dioxide and sulphur hexafluoride (SF6). The previous 2005 version of ISO 9300 did not account for how vibrational energy may influence the discharge coefficient. ISO 9300:2022 states that for gases exhibiting substantial vibrational relaxation effects, the discharge coefficient calculated using the expression in Clause 10.4 of the standard may deviate by more than 1% when the steady-state critical flow function (C*) is applied to small CFNs.

Annex B of ISO 9300:2022 provides an informative section on the critical flow function, with Clause B.5 in the standard specifically discussing "gases with significant vibrational relaxation effects." This clause explains that gases like carbon dioxide, which store significant energy in their vibrational modes, may not reach thermal equilibrium when passing through the CFN throat. When these gases flow though small CFNs, there isn’t sufficient time for the redistribution of vibrational energy into translational and rotational modes. Thus it leads to partially “frozen” critical flow function values which are closer to their upstream state rather than achieving steady-state thermodynamic values.

The ISO standard states that if the CFN throat is sufficiently large, the critical flow function from REFPROP [5] or Annex B of ISO 9300:2022 [34] may remain accurate. However, for toroidal-throat CFNs with diameters of only a few millimetres i.e. resulting in Reynolds numbers below 10^5, the use of the steady-state critical flow function for carbon dioxide could introduce mass flow rate errors exceeding 1%. To address this, Annex G of ISO 9300:2022 which provides an informative section on the discharge coefficient, states that the CFNs should be flow calibrated for gas that may have significant vibrational effects.

Throat diameters of the CFNs evaluated with carbon dioxide at NEL’s high pressure low flow facility during the EMR017 MetCCUS project are listed in the table below along with the tested Reynolds number range. This table also has the range of Reynolds numbers maintained during the air calibration undertaken by KRISS for each nozzle, which shows that some of the carbon dioxide tests had Reynolds numbers exceeding the air calibration range of the nozzles.

Table 11 - CFNs tests at NEL NEL's high pressure gas flow facility with carbon dioxide gas

CFN	Throat ID (mm)	Reynolds number range	
		NEL CO_2 test	KRISS air calibration
RS8 (NOT 677)	1.260	166,154 (14 Nov. 2024)	58,570 – 176,048
RS6 (NOT 676)	1.943	86,737 – 254,634 (15 Nov. 2024)	50,157 – 149,558
		164,997 – 985,105 (21 Nov. 2024)	
GR1 (NOT 1060)	2.894	138,934 – 418,396 (18 Nov. 2024)	74,968 – 224,467
		386,4008 – 1,505,584 (21 Nov. 2024)	
GR2 (NOT 1061)	3.9994	191,523 – 575,029 (19 Nov. 2024)	103,954 – 309,580
		1,099,688 – 1,522,478 (20 Nov. 2024)	

The four CFNs NEL tested with carbon dioxide had throat diameters between 1.26 to 2.9 mm. Previous studies discussed earlier in this document including the current 2022 version of ISO 9300 indicate that vibration relaxation effects may alter the carbon dioxide gas flow though CFNs when the throat diameter is a few millimetres. This suggests that vibration relaxation may have influenced NEL's tests with carbon dioxide gas. These earlier studies also suggested the influence was mainly at Reynolds numbers below 10^5, meaning the effect of vibration relaxation on NEL's test may be mainly limited to the six test points identified in Table 12 below.

Table 12 - NEL carbon dioxide tests with Reynolds number close to or below 10,000

CFN	Throat ID (mm)	Reynolds number
RS8 (NOT 677)	1.260	166,154 (14 Nov. 2024)
RS6 (NOT 676)	1.943	86,737 (15 Nov. 2024)
		172,924 (15 Nov. 2024)
		164,997 (21 Nov. 2024)
GR1 (NOT 1060)	2.894	138,934 (18 Nov. 2024)
GR2 (NOT 1061)	2.894	191,523 (19 Nov. 2024)

During the EMR017 MetCCUS test programme, NEL used a 1-inch orifice meter (β= 0.140) as a transfer standard to study the effect of different gases on CFNs performance. This was undertaken by testing the orifice meter using the domestic gas meter facility's CFNs with hydrogen gas [7] and the high pressure low flow facility's CFNs with nitrogen and carbon dioxide gas. Moreover, the orifice meter was tested at Heriot-Watt University with carbon dioxide against a gravimetric standard [38], [39].

The results presented in Figure 34 show that the hydrogen gas measurements from NEL domestic gas meter facility follows the trend for nitrogen gas on the NEL high pressure low flow facility. Thus, CFNs calibrated using nitrogen gas can be translated when the nozzle is used with hydrogen gas which corresponds to the findings for previous studies [27], [35], [36].

The carbon dioxide results are however considerably different. This is possibly due to the effects of vibrational relaxation as previously reported by Johnson et al. [31] [33] and Nago et al. [37]. Since these studies reported that the discharge coefficient for carbon dioxide could be up to 2% higher, the graph in Figure 34 also include "corrected" carbon dioxide points, where the discharge coefficient was increased by 1.5%. The carbon dioxide values adjusted by a 1.5% increase in the discharge coefficient, appear to align with the general trends observed for the nitrogen and hydrogen gas tests at NEL and the carbon dioxide tests at Heriot Watt University. While the data adjusted by 1.5% suggests that vibrational relaxation may have contributed to NEL's tests for carbon dioxide, it is important to also note that only five of these twelve test points had Reynolds numbers close to or less than 10^5. Previous studies have suggested that this is the threshold where vibrational relaxation effects have the most significant impact on carbon dioxide flow through CFNs with throat diameters of a few millimetres.

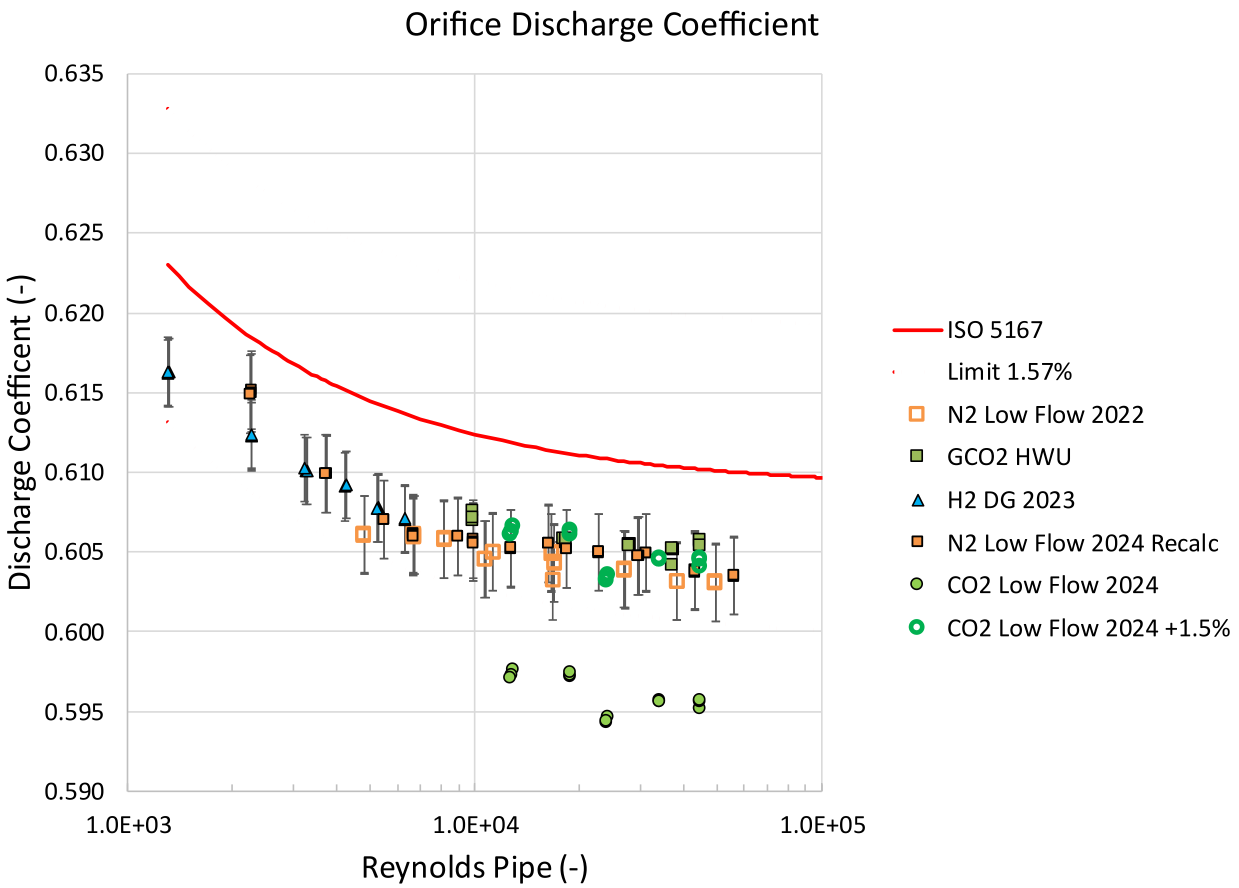

Figure 34 – Experimental discharge coefficient for the 1-inch orifice meter tested against reference Critical Flow Nozzles (CFNs) with hydrogen in the NEL domestic gas facility, carbon dioxide and nitrogen in the NEL high-pressure low flow facility. The orifice was also tested with carbon dioxide against a primary gravimetric standard at Heriot Watt university ("GC02 HWU" in the legend). The plot also shows the NEL carbon dioxide results ("CO2 Low Flow 2024") increased by 1.5%.

4.6 Transferability of calibration results at intermediate scale

A comparison between nitrogen and carbon dioxide calibrations results of a PGM G16 rotary meter is shown in Figure 35 for VSL and in Figure 36 and Figure 37 for INRIM.

For both VSL and INRIM the results with nitrogen agree well with those with carbon dioxide at different size of meters. This confirm previous findings [26] that a rotary meter can be calibrated with an alternative fluid and used with carbon dioxide.

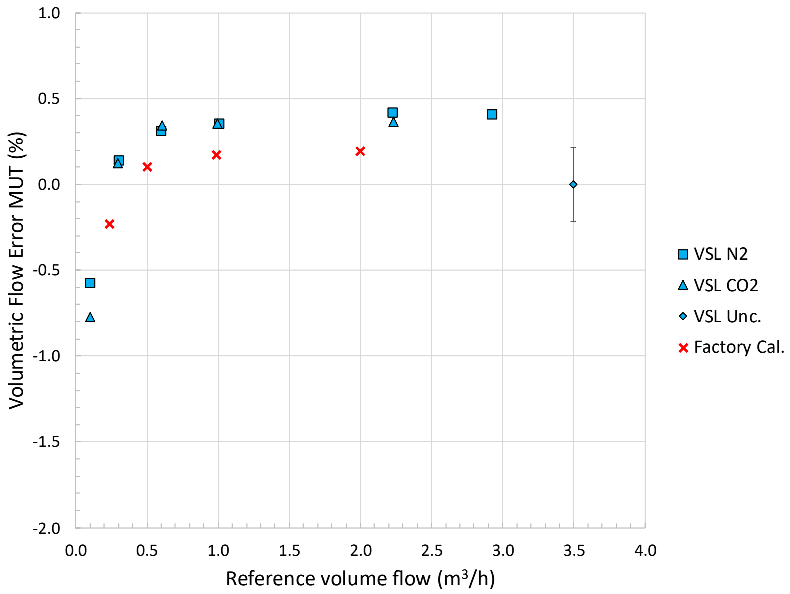

Figure 35 – PGM G16 Rotary meter relative error in gas volumetric flow rate as a function of the reference volumetric flow rate. The figure shows the data collected at VSL with nitrogen and carbon dioxide. Factory calibration with air is also shown.

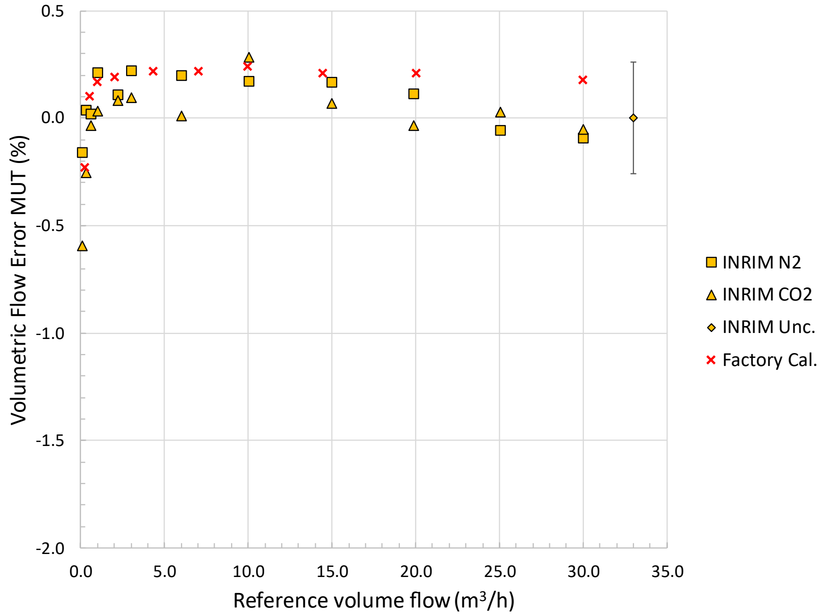

Figure 36 – PGM G16 Rotary meter relative error in gas volumetric flow rate as a function of the reference volumetric flow rate. The figure shows the data collected at INRIM with nitrogen and carbon dioxide. Factory calibration with air is also shown.

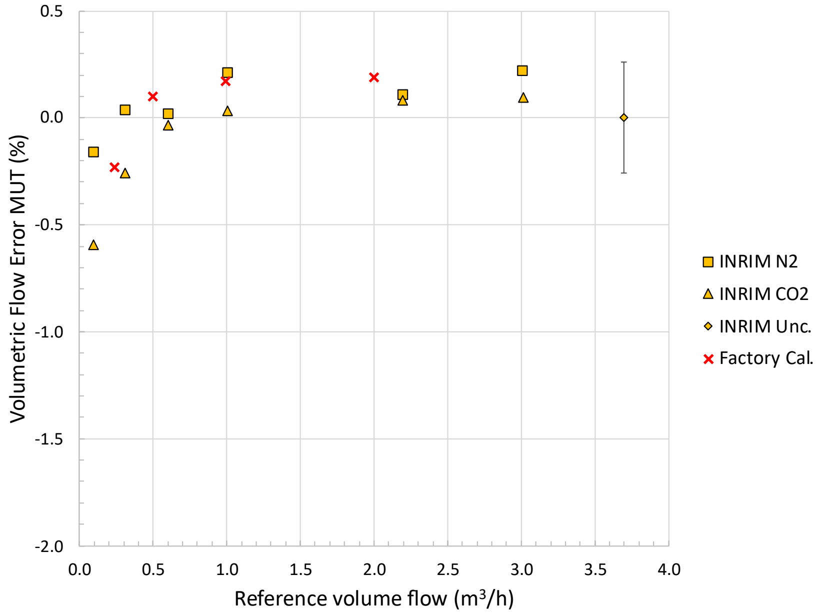

Figure 37 – PGM G16 Rotary meter relative error in gas volumetric flow rate as a function of the reference volumetric flow rate. The figure shows the data collected at INRIM with nitrogen and carbon dioxide. Zoomed graph to better visualise the test results below 3 m³/h. Factory calibration with air is also shown.

Tests at VSL with an additional rotary meter

Additionally, VSL tested a PGM G10 meter with nitrogen and CO_2 using the mercury-seal piston prover. The test results are shown in Figure 38. A picture of the meter during the calibration is shown in Figure 39.

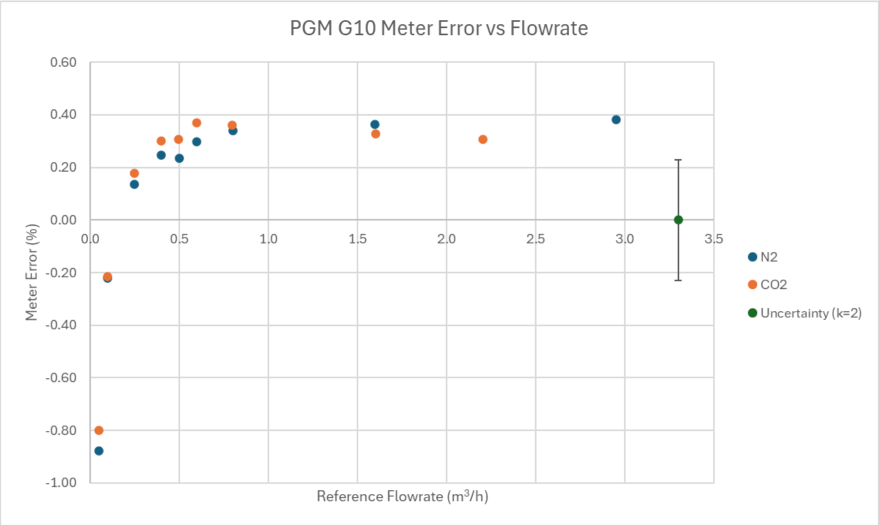

Figure 38 – PGM G10 Rotary meter relative error in gas volumetric flow rate as a function of the reference volumetric flow rate. The figure shows the data collected at VSL with nitrogen and carbon dioxide.

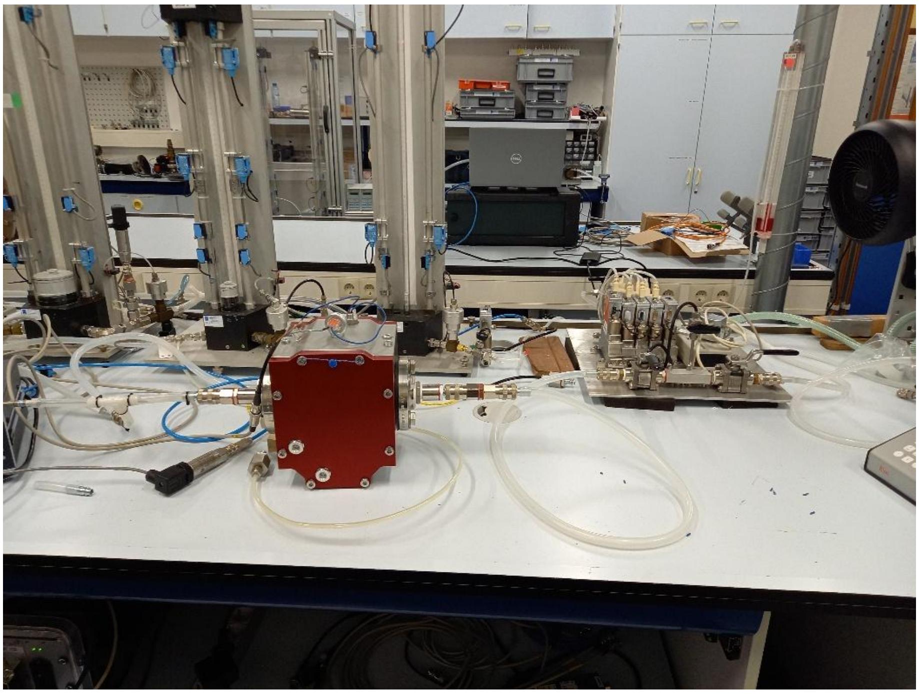

Figure 39 - A picture of the PGM G10 rotary meter during calibration with VSL's mercury-seal piston provers. The meter is installed in series with and upstream of the VSL mercury piston prover. Flow is right to left.

5 Conclusions and recommendations

This report summarises the development, evaluation, and intercomparison of large- and intermediate-scale flow calibration facilities using gaseous carbon dioxide to support accurate flow metering across the Carbon Capture and Storage (CCS) chain. The project involved upgrading piston provers, performing extensive inter-laboratory comparisons, and assessing the transferability of calibrations using alternative gases such as nitrogen and natural gas. The findings confirm the feasibility of establishing traceable flow calibration standards for CO_2 across a broad range of flow rates and pressures.

Key Conclusions:

- Large-scale intercomparisons between FORCE, DNV, and NEL demonstrated agreement in the flow range of 20 m³/h to 400 m³/h, particularly with the Coriolis meter, confirming traceability for carbon dioxide across facilities. Results with the turbine meter below 85 m³/h were less satisfactory, primarily due to known limitations in turbine meter performance at low flow rates.
- Intermediate-scale intercomparisons between INRIM, VSL, and NEL confirmed traceability for nitrogen across all facilities when using the PGM rotary meter as transfer standard. Agreement was also observed between VSL and INRIM for carbon dioxide. However, NEL's results for carbon dioxide differed significantly, which was traced to the use of small-diameter sonic nozzles calibrated in air, known to produce errors when used with carbon dioxide.
- The developed calibration facilities have low enough overall uncertainties to verify whether the tested flow meters meet the target uncertainty of ±1.5% to ±2.5% (k=2).
- It was confirmed that Coriolis meters can be calibrated using nitrogen or natural gas and reliably used with CO_2 when appropriate pressure and compressibility corrections are applied.
- Gas turbine also demonstrated calibration transferability, provided the Reynolds number is matched during calibration of turbine meter.
- It was confirmed that Ultrasonic meters will under-read with high pressure carbon dioxide when they are calibrated with high pressure Natural Gas.
- The difference between meter errors of rotary meter calibrations with nitrogen and carbon dioxide were within the uncertainty of the calibrations.

Identified Limitations:

- Critical Flow Nozzles (CFNs) calibrated in air exhibited significant errors when used with carbon dioxide, primarily due to vibrational relaxation effects, particularly at low Reynolds numbers – these findings are consistent with existing literature.
- Turbine meters showed inconsistent performance at flow rates below 85 m³/h due to mechanical and facility-related limitations. In contrast, Coriolis meters yielded more accurate results in this range.

Recommendations:

- Conduct additional intercomparisons at flow rates above 400 m³/h between the large-scale facilities at NEL, DNV, and FORCE to extend the validated range.
- Further experimental and theoretical investigations are recommended into the performance of Critical Flow Nozzles with CO_2, with the aim of developing suitable correction methodologies to mitigate vibrational relaxation effects.
- In the intermediate scale intercomparison between NEL, VSL, and INRIM, it is recommended to conduct an intercomparison with a meter of a different technology that is compatible with all the facilities to gain more confidence in the traceability of the facilities with carbon dioxide.

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