Comparison of high-pressure gas-flow facilities between NEL, PTB/Pigsar and FORCE

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EXECUTIVE SUMMARY

This document describes the tests completed under EURAMET project 1379 to determine the degree of equivalence in high-pressure gas flow measurement capability at facilities operated by TÜV SÜD National Engineering Laboratory (NEL) in the United Kingdom, FORCE Technologies (FORCE) in Denmark and the Pigsar facility, operated in collaboration with the Federal Institute of Physics and Metrology (PTB) in Germany. The study also aimed to examine the transferability of calibration with different fluids i.e. nitrogen and natural gas, which is of interest for applications involving carbon dioxide and hydrogen gas transmission.

The tests were performed using a transfer package consisting of two gas flow meters arranged in series: a DN150 orifice meter (β = 0.75) positioned upstream of a DN150 RMG 24546 turbine gas meter. The package also included associated flow conditioning pipework and additional components to minimise the flow measurement uncertainty.

The test protocol covered gas flow rates ranging of 100 m³/h to 1600 m³/h at three line pressures (10 bar(g), 30 bar(g) and 50 bar(g)) and with a nominal temperature of 20 °C. Each facility is designed to operate with a specific working fluid, PTB/Pigsar and FORCE used natural gas while NEL used nitrogen gas. Therefore, to ensure comparability while using different test fluids and transfer standards, each facility matched the Reynolds number and pressure for the tests. The following Reynolds numbers for the 6-inch pipework were covered:

- **10 bar(g):** $0.18 \times 10^6 < Re < 2.9 \times 10^6$
- **30 bar(g):** $0.5 \times 10^6 < Re < 8 \times 10^6$
- **50 bar(g):** $0.8 \times 10^6 < Re < 12.5 \times 10^6$

The comparisons were based on the average and standard deviation calculated from five repeat measurements.

The test results with the transfer package demonstrated that the performance of the three flow measurement facilities was generally comparable and within the Calibration & Measurement Capability (CMC) range of each facility. The orifice meter measurements followed the expected trend, with the discharge coefficient decreasing as the Reynolds number increased. For each test pressure, NEL reported the highest discharge coefficient followed by FORCE and with PTB / Pigsar reporting the lowest values.

The turbine meter showed no clear trend in its relative error with changes in Reynolds number, and no significant differences were observed between each test facility. These results indicate that using either natural gas or oxygen-free nitrogen gas had no influence on the turbine gas meter's performance. Thus, the test results from the orifice meter and turbine gas meter suggest that the transferability of calibrating with different fluids at each facility may depend on the specific type of flow meter being tested.

The Degrees of Equivalence (E_n) analysis undertaken for the three facilities using the flow measurement data showed that over 91% of the orifice meter test points and more than 98% of the turbine gas meter test points had $|E_n| < 1$. Only a single orifice meter test point exceeded the critical level of $|E_n| > 1.2$. This confirms that the three test facilities - PTB/Pigsar, FORCE and NEL – demonstrated consistency with the Comparison Reference Value, CRV. As a result, these facilities successfully passed the equivalency test for the flow conditions that were evaluated.

This inter-comparison test programme has therefore demonstrated the equivalence of high pressure gas flow measurement facilities at PTB/Pigsar, FORCE and NEL. The results validate the Calibration and Measurement Capability declared by each facility and helps support their ISO/IEC 17025 accreditation.

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1. INTRODUCTION

This document provides the details of an inter-comparison test programme undertaken between high-pressure gas flow measurement facilities at TÜV SÜD National Engineering Laboratory (NEL) in the United Kingdom, FORCE Technologies (FORCE) in Denmark and the Pigsar facility, operated in collaboration with the Federal Institute of Physics and Metrology (PTB) in Germany. The testing aimed to examine the transferability of calibration with different fluids i.e. nitrogen and natural gas, which is of interest for applications involving carbon dioxide and hydrogen gas transmission.

Each of the high-pressure flow measurement facilities involved in this test programme hold ISO/IEC 17025 accreditation. A key requirement of this accreditation is participation in inter-comparison measurements with other accredited flow laboratories [1]. Hence, this testing was necessary to ensure continued certification for these high-pressure gas flow measurement calibration facilities. The inter-comparison was conducted under EURAMET Technical Committee project number 1397.

2. TEST FACILITIES AND METER PACKAGE

2.1 NEL Gas Flow Facility

The NEL high-pressure 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. The gas properties are calculated from NEL's implementation of REFPROP from NIST [2]. The facility operates at a nominal temperature of 20 $^{\circ}$C, over a nominal pressure range of 10 bar(g) to 63 bar(g), which corresponds to a gas density range of 12.76 kg/m^3 to 74.54 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.

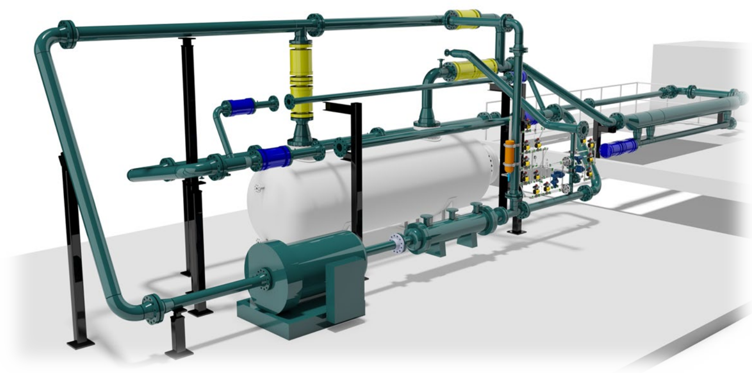

FIGURE 1 NEL HIGH-PRESSURE GAS FLOW FACILITY

It should be noted that the NEL facility was refurbished during the period of the intercomparison which included also the upgrade of the reference meters. The reference meter used to calibrate the orifice meter in step 1, see Figure 4, was a calibrated DN150 SICK Maihak FLOWSIC600 gas ultrasonic flow meter. The reference meter used to test both the orifice and turbine meter in step 4, see Figure 4, was an DN200 FLOWSIC600-XT ultrasonic gas meter (serial number 22101021 and calibrated K factor =7988 which was applied for the NEL tests).

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 device under test (DUT), is ±0.35 % (k = 2).

2.2 PTB / Closed Loop Pigsar Flow Facility

The Closed Loop Pigsar (CLP) facility, operated in collaboration with PTB serves as Germany’s national standard for high-pressure natural gas metering. This test facility, illustrated in Figure 2 was recently constructed as an extension to the 25 year old Bypass Pigsar facility and offers enhanced capability for flow meter calibration. The improvements include a broader flow rate range and pressure range, as well as the ability to accommodate larger flow meter sizes.

CLP is supplied with natural gas directly from a high-pressure gas transmission network, while facility’s high-pressure compressors enable testing flow meters over a pressure range of 8 bar(g) to 65 bar(g). Three parallel blowers are used to generate the continuous gas flow for this closed loop, while water cooled heat exchangers remove the heat from the blowers, thus providing optimal temperature stability during testing.

During flow meter testing, the reference value is determined by six runs fitted with a measurement standard. It consists of three DN150 / G400 and three DN500 / G6500 turbine meters which are used as standard meters while ultrasonic flow meters are installed upstream as reference standards. The facility features two test runs with DN400 and DN500 which are capable of testing flow meters sizes from DN200 (8 inch) to DN600 (24 inch). The length of the test sections is 37 m, and thus allowing large ultrasonic flow meters to be tested with sufficiently long upstream straight lengths, even if the flow meters are connected in series.

This facility has a third DN200/DN250 meter run for primary and secondary standards from PTB, which are used to calibrate and routinely verify the CLP’s working standards. CLP has a natural gas flow rate measurement range of 40 to 30,000 m^3/h with calibration and measurement uncertainties ranging from 0.137 % to 0.193% (k = 2).

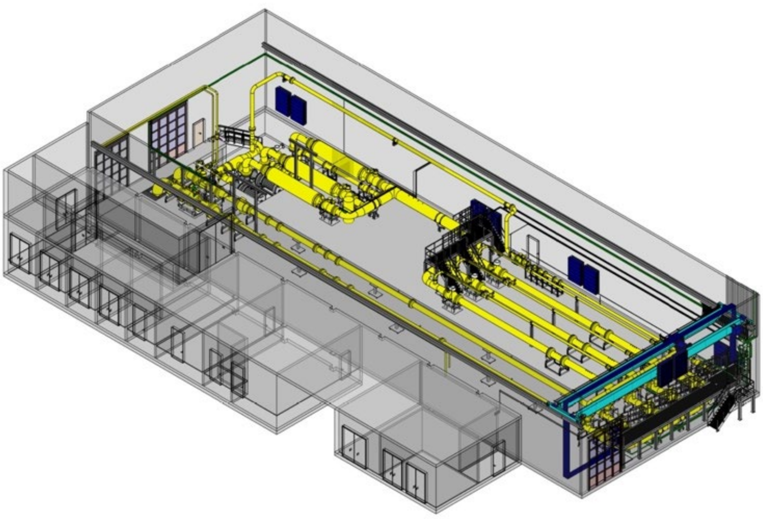

FIGURE 2 CLOSED LOOP PIGSAR FLOW FACILITY USED BY PTB FOR THE TEST

2.3 FORCE Technology High-Pressure Calibration Facility

The high-pressure calibration facility at FORCE Technology (No. C03-002) is a closed loop system where natural gas is circulated using two eight-stage axial high-pressure blowers. It is designed to calibrate natural gas flow meters under conditions equivalent to on-site environments. The facility operates within a pressure range of 3 to 65 bar, at a nominal temperature of 20°C, and supports the calibration of flow meters across a flow rate range of 8 m^3/h to 32,000 m^3/h.

As shown in Figure 3, the facility comprises seven reference lines, each equipped with a working standard—one DN600 / G16000, four DN300 / G2500, one DN150 / G650, and one DN100 / G250—along with one device test line.

The test facility is traceable to EuReGa, the harmonised value for the cubic meter.

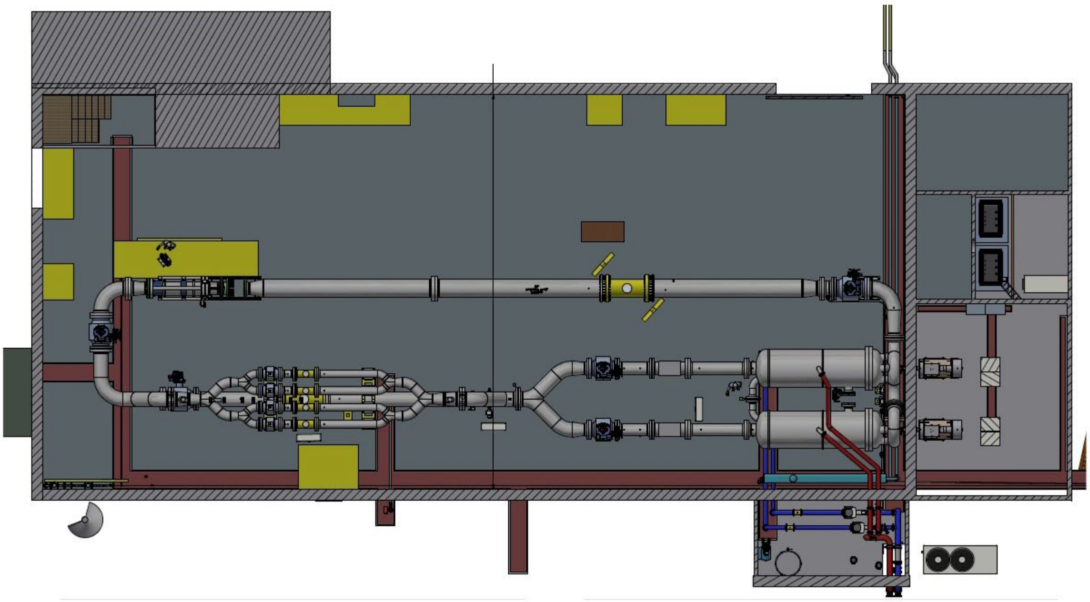

FIGURE 3 FORCE TECHNOLOGY HIGH-PRESSURE CALIBRATION FACILITY

2.4 Intercomparison Package

As detailed in the EURAMET project 1397 report describing the protocol for this testing [3], two meters were selected as the transfer package for the intercomparison. The first was a DN150 orifice meter, designed and manufactured by NEL. This meter had an internal orifice pipe diameter of 139.76 mm and an orifice size of 104.82 mm, resulting in a $\beta = 0.75$ The second flow meter was a DN150 RMG 24546 turbine gas meter provided by PTB. Employing two different types of transfer standards allows evaluation of whether the intercomparison results vary using different meter types.

The sequence in which the transfer standard was tested at each flow measurement facility is presented in Figure 4. The new orifice meter developed for this transfer package was initially calibrated at NEL in April 2022. First test of the complete intercomparison package, comprising both the orifice flow meter and the turbine meter was conducted by PTB at the Pigsar Flow Facility in September 2022. The transfer package was then tested by Force in November 2022, after which NEL completed the last of the intercomparison tests in November 2023 before returning the turbine meter and its associated pipework to PTB.

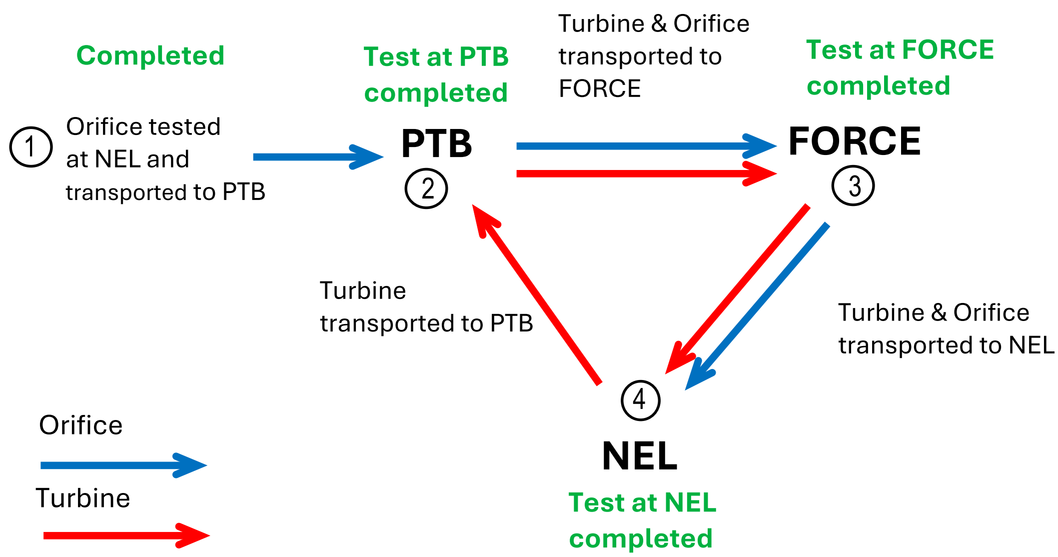

FIGURE 4 THE ORDER OF TESTING WITH THE TRANSFER STANDARD.

As illustrated in Figure 5 the orifice meter and the turbine flow meter were installed in series, with the orifice meter upstream of the turbine meter. To ensure similar flowing conditions at the two meters during testing at each test facility, this transfer package included flow conditioning designs upstream of each meter. In the case of the orifice meter this consisted of ten diameter lengths of DN150 pipework followed by a Zanker type flow conditioner and 8.5 diameter lengths of DN150 pipework before the meter. The turbine meter package from PTB had a DN150 diameter spool piece with ten diameter lengths of straight pipework upstream of this meter which connected to the orifice meter package from NEL.

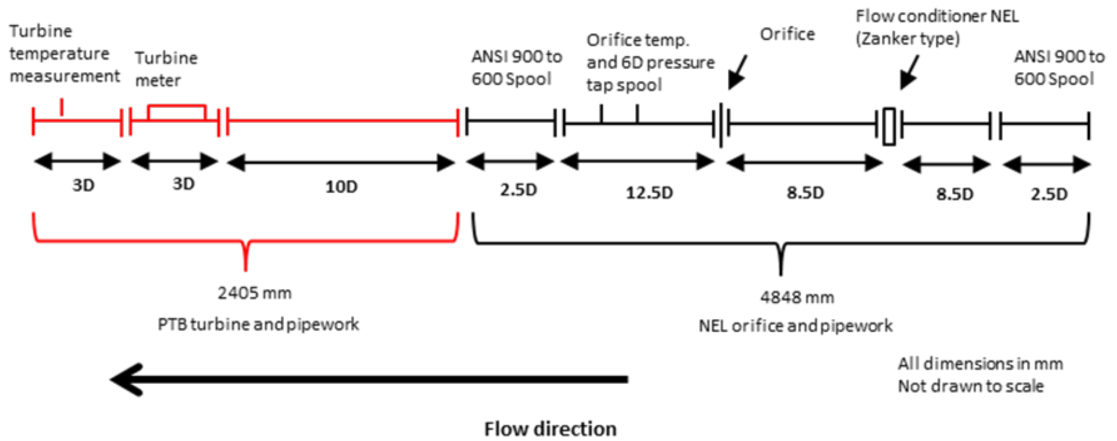

FIGURE 5 SCHEMATIC OF THE TRANSFER PACKAGE WITH THE ORIFICE METER, TURBINE METER AND ASSOCIATED PIPEWORK

Figure 6 shows the orifice meter when it was initially calibrated at NEL in April 2022. Figure 7 and Figure 8 show the complete transfer package during testing at the Closed Loop Pigsar facility in September 2022 and NEL high-pressure gas flow facility in November 2023, respectively.

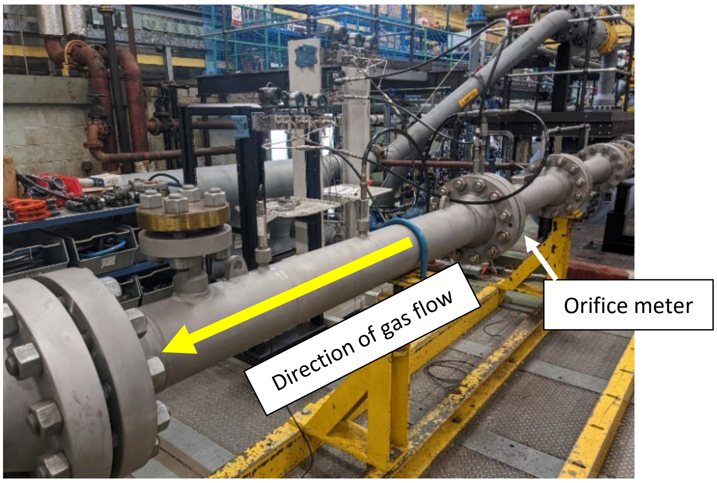

FIGURE 6 SETUP FOR THE ORIFICE METER'S INITIAL CALIBRATION AT NEL

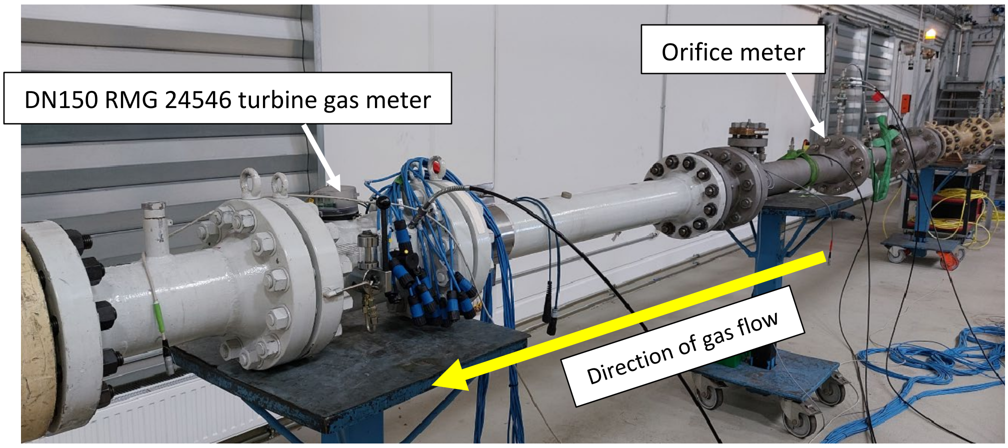

FIGURE 7 SETUP FOR THE TESTING THE TRANSFTER PACKAGE AT CLOSED LOOP PIGSAR FACILITY

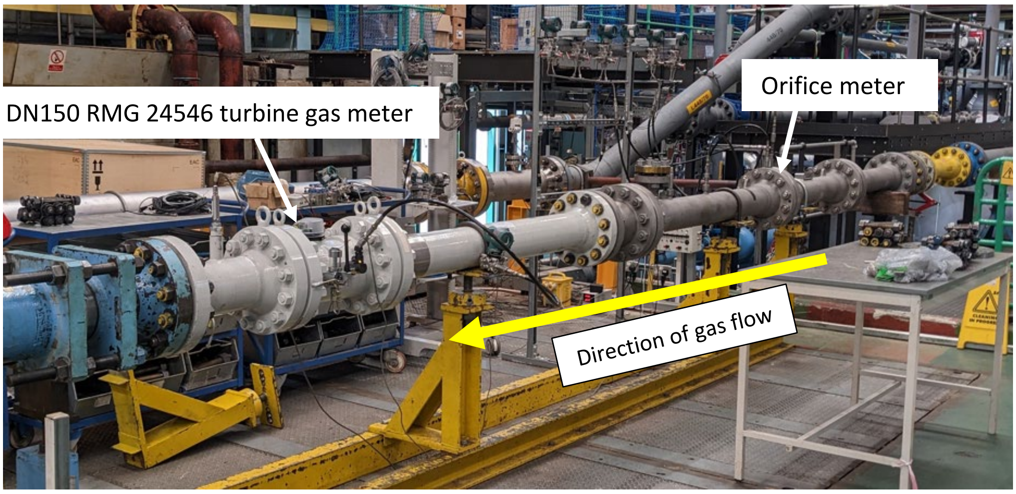

FIGURE 8 SETUP FOR THE TESTING THE TRANSFTER PACKAGE AT NEL

2.4.1 Expression for the errors of the transfer standard's flow meters

For the orifice meter, the discharge coefficient derived from the test data was used to determine the equivalency of each test facility. The gas expansibility, ε, and the discharge coefficient were calculated using equations in ISO 5167-2:2003 [4]. The gas discharge coefficient, C for the upstream-downstream differential pressure measurement were determined using Equation (1) [4]

$$C = \frac{4\, q_m \sqrt{1-\beta^4}}{\pi\, \varepsilon\, d^2 \sqrt{2\Delta p\, \rho_1}} \tag{1}$$

Where q_m is the reference gas mass flow rate (kg/s), β is the diameter ratio (-), ε is the gas expansibility (-), d is the throat diameter (m), ρ_1 is the upstream gas density (kg/m^3) and Δp is the measured upstream-downstream differential pressure (Pa). The gas density at the orifice meter was calculated based on the absolute pressure measured upstream of the orifice (i.e. at upstream flange pressure tapping) and the temperature downstream of the orifice meter. The Joule-Thomson effect across the meter, which is sometimes taken into account to determine the upstream temperature, was not considered in this calculation [3] due to its negligible influence on the test results.

For the turbine meter, the intercomparison was based on comparing the relative error of this transfer standard as determined by the participating labs. The relative error, e (%) was defined as follows using Equation (2) [3]

$$e = 100\,\frac{q_{indicated} - q_{ref}}{q_{ref}} \tag{2}$$

Where in the case of the turbine transfer standard, $q_{indicated}$ is the flow rate measured by the turbine transfer standard (kg/s), while q_{ref} is the flow rate measured by each test facility's reference flow meter (kg/s).

3. TEST PROCEDURE

The calibration protocol for this test programme is detailed in a previous EURAMET project 1397 report published in 2022 [3]. For each test run, the flow loops were set up for the required test conditions (i.e. pressure, temperature, and flowrates) and allowed to stabilise for at least five minutes. Natural gas was used as the fluid for the Force and PTB/ Pigsar tests, while NEL used oxygen-free nitrogen gas. The duration for each test point depended on the operational procedures of the test facility: PTB's test at Pigsar had 60 seconds, NEL used 180 seconds while the collection time for FORCE ranged between 36 seconds and 72 seconds.

3.1 Test Matrix

This investigative programme was based around 6-inch pipe work. A summary of the test matrix that was followed is provided in Table 1. The transfer package was tested across a gas flow rate range of 100 m³/h to 1600 m³/h. Due to the differences in fluids used by each facility and the type of transfer standards for this intercomparison, each facility matched the Reynolds number and pressure for the comparison. The flow conditions were set up for the Reynolds number calculated using the orifice meter's pipe diameter of 139.76 mm. Since the turbine gas meter was installed downstream of the orifice meter, the Reynolds number at the turbine gas meter was slightly less due the pressure drop along the transfer package. Additionally, as gas density increases with pressure, the Reynold number progressively increased as the line pressure was raised from 10 bar to 30 bar and then to 50 bar.

The test runs were carried out at a line pressures of 10 bar(g), 30 bar(g) and 50 bar(g), while maintaining a constant gas temperature of 20 °C. Flow measurements were taken sequentially, starting from the highest achievable flow rate and decreasing stepwise to the lowest. Each test condition was repeated five times.

Table 1 also shows the test points where the Degree of Equivalence, E_n was calculated (i.e. data from two or more test facilities). Mickan et al. [5] reported that internal resonance effects caused the turbine meter that was used to deviate significantly from its expected Reynolds behaviour when the flow rate was 1000 m³/h. Hence the turbine meter data for Re = 6.0×10^6 at 30 bar(g) and Re = 8×10^6 at 50 bar(g) were excluded from the test matrix.

TABLE 1

NOMINAL TEST MATRIX

P [bar(g)]	T [ºC]	Nominal Pipe Re	PTB / Pigsar	FORCE	NEL R4	E_n Calculated
10	20	2.9×10^6	X			
10	20	2.6×10^6	X		X	X
10	20	2.4×10^6	X			
10	20	2.3×10^6	X			
10	20	2.0×10^6	X	X	X	X
10	20	1.5×10^6	X	X	X	X
10	20	1.25×10^6	X	X†		X
10	20	1.0×10^6	X	X†	X	X
10	20	0.8×10^6	X	X†		X
10	20	0.7×10^6	X	X	X	X
10	20	0.5×10^6	X	X†		X
10	20	0.35×10^6	X	X†	X	X
10	20	0.18×10^6	X	X†	X	X
30	20	8.0×10^6	X			
30	20	7.7×10^6	X			
30	20	7.0×10^6	X		X	X
30	20	6.5×10^6	X	X†		X
30	20	6.0×10^6	X‡	X‡		X‡
30	20	5.0×10^6	X	X	X	X
30	20	4.0×10^6	X	X		X
30	20	3.0×10^6	X	X	X	X
30	20	2.5×10^6	X	X		X
30	20	2.0×10^6	X	X	X	X
30	20	1.5×10^6	X	X		X
30	20	1.0×10^6	X	X	X	X
30	20	0.5×10^6	X‡	X‡	X	X
50	20	12.6×10^6	X			
50	20	12×10^6	X			
50	20	11×10^6	X		X	X
50	20	10×10^6	X			
50	20	9.5×10^6	X	X	X	X
50	20	8×10^6	X‡	X‡	X‡	X‡
50	20	6×10^6	X	X	X	X
50	20	5×10^6	X	X	X	X
50	20	4×10^6	X	X	X	X
50	20	3×10^6	X	X	X	X
50	20	2×10^6	X	X	X	X
50	20	1.5×10^6	X	X	X	X
50	20	0.8×10^6	X	X	X	X

Note: † - Test with turbine gas meter transfer standard only ‡ - Test with orifice meter transfer standard only

3 CONDUCT OF THE INTER-COMPARSION

Each flow measurement facility conducted the tests and processed the recorded data in accordance with their respective internal procedures and the protocol detailed in the previous EURAMET project 1397 report published in 2022 [3]. The comparison calculations were based on standardised methods as found in [6] [7] [8] [9].

The uncertainty analysis for the orifice meter and turbine gas meter was processed separately. Comparison of the orifice meter test data was based on the Reynolds number calculated using the orifice meter's pipe diameter of 139.76 mm, while the turbine gas meter test data was compared using the Reynolds number based on its nominal pipe diameter of 150 mm.

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

$$U_r = \frac{t^*\sigma}{\sqrt{n}} \quad (3)$$

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. 5).

In the case of this inter-comparison tests, the degrees of freedom for each test point, $v = n - 1 = 4$

Hence, for a t-distribution with 4 degrees of freedom at 95 % confidence, $t_{(4,95\%)}$; $t^* = 2.776$

Thus Equation (3) becomes:

$$U_r = \frac{2.776\,\sigma}{\sqrt{5}} \quad (4)$$

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 [7].

$$U_i = \sqrt{{U_{lab}}^2 + {U_r}^2} \quad (5)$$

Calibration and Measurement Capability values for each test facility were used as the reference uncertainty, U_{lab}. Table 2 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" [10] 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 2

CALIBRATION AND MEASUREMENT CAPABILITY FOR EACH FACILITY

Transfer Meter	Pressure [bar(g)]	Calibration and Measurement Capability (%) (k = 2)		
		PTB / Pigsar	FORCE	NEL
Orifice meter	10	0.21 to 2.07	0.30	0.45
	30	0.20 to 0.58	0.30	0.45
	50	0.20 to 0.34	0.30	0.45
Turbine meter	10	0.14 to 0.16	0.17	0.35
	30	0.14 to 0.16	0.17	0.35
	50	0.14 to 0.16	0.17	0.35

The Degree of Equivalence, E_n between each laboratory's results and the Comparison Reference Value, CRV was calculated following the procedure outlined by M. G. Cox [8] and is detailed 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, e_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).

4. RESULT OF TEST MEASUREMENTS

The comparison results using the orifice meter at each test facility is shown in Figure 9. As described in the previous section 3, the Reynolds number for the orifice meter test is based on the orifice meter's pipe diameter. The initial test undertaken by NEL in April 2022 to confirm the orifice meter met the specifications in ISO 5167 (i.e. NEL Run 1) have also been included in the graph to illustrate the stability of this meter's performance during the intercomparison test programme. Figure 9 also has the uncertainties associated with each test facility.

The results indicate that the average discharge coefficient calculated for each test condition, using the measurement from each facility generally falls within the respective facility's uncertainty range. Figure 10 provides separate graphs for the orifice meter tests at each line pressure. The results from each test facility show a reduction in the discharge coefficient as the Reynolds number increases. This trend is expected for an orifice meter, as shown by the Reader-Harris/Gallagher (1998) equation in ISO 5167-2:2003 [4] .

Figure 10 also shows consistent pattern with each line pressure, where NEL reported the highest discharge coefficient, followed by FORCE, and PTB/Pigsar showing the lowest values. In contrast, the turbine gas meter measurements, discussed later in this section, did not show a similar trend.

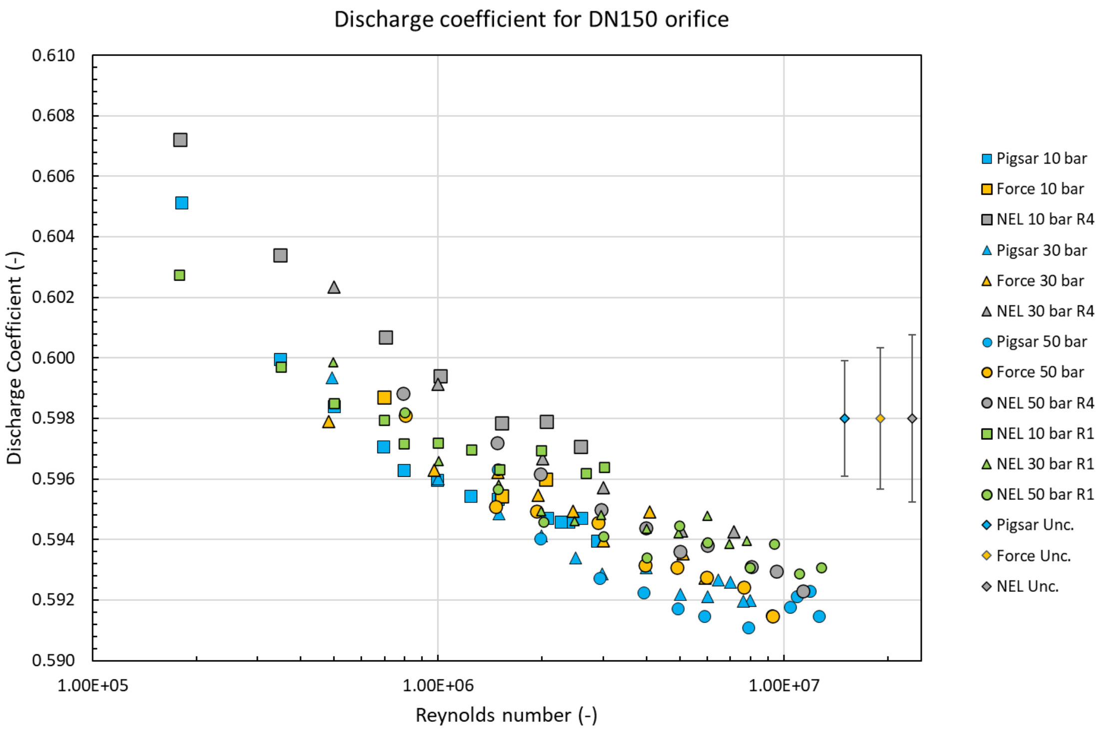

FIGURE 9 DISCHAGE COEFFICIENT FROM THE ORIFICE METER TESTS AT EACH TEST FACILITY

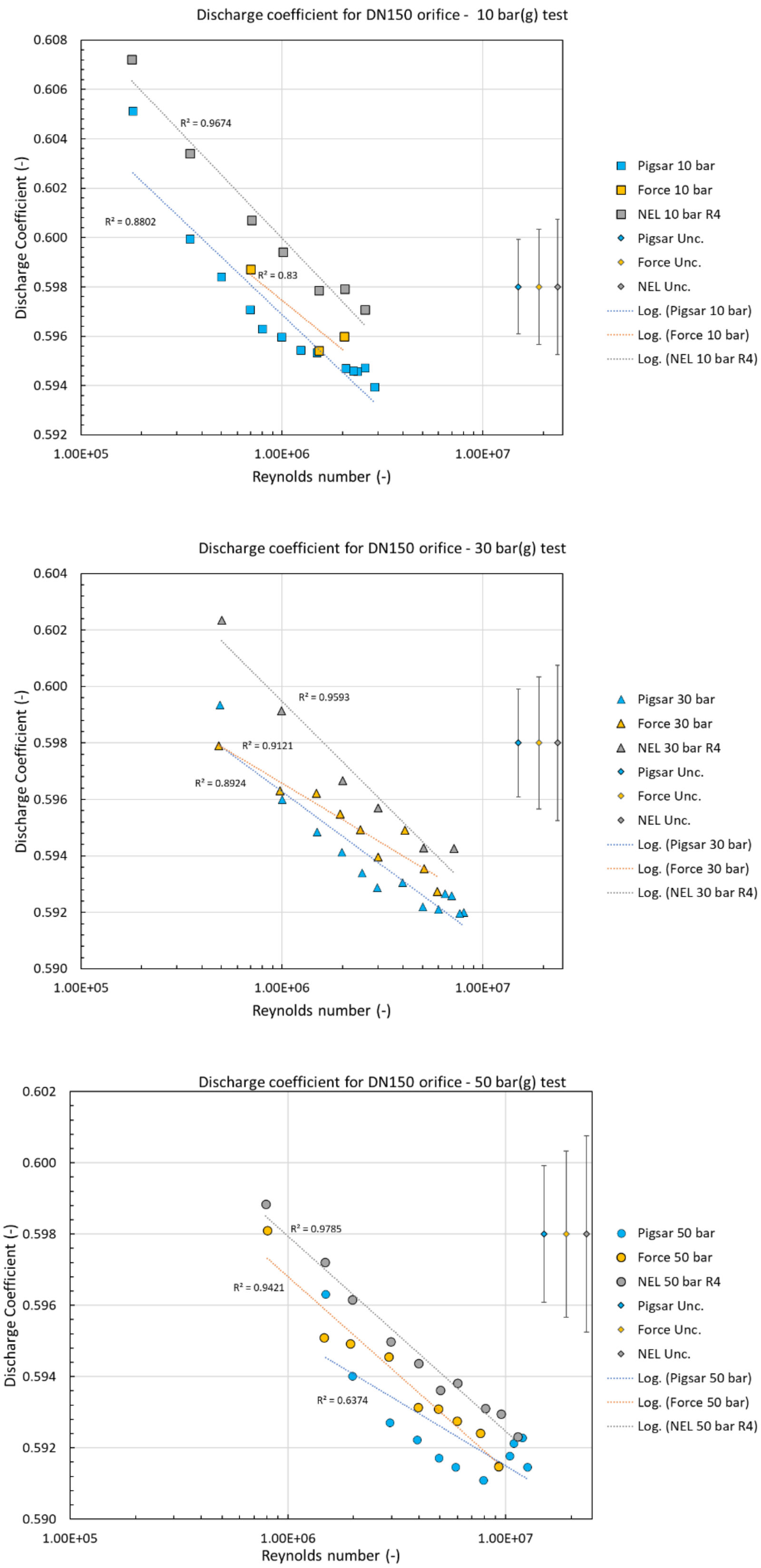

FIGURE 10 TRENDLINES FOR THE DISCHAGE COEFFICIENT FROM THE ORIFICE METER TESTS FOR EACH TEST PRESSURE AT EACH TEST FACILITY

The comparison results for the turbine gas meter at each test facility along with the uncertainties associated with each facility are presented in Figure 11. As described in the previous section 3, the Reynolds number for the turbine gas meter test is based on this meter's nominal pipe diameter. The results indicate that the average relative error in the flow measurements with the turbine gas meter by the different test facilities generally fall within the uncertainty range of these test facilities.

The turbine gas meter data does not show any clear trend in the relative error with changes in Reynolds number. Additionally, no significant differences were observed between the test facilities, which demonstrates the transferability of calibrating with different fluids at each facility, when the meter under test is a turbine gas meter.

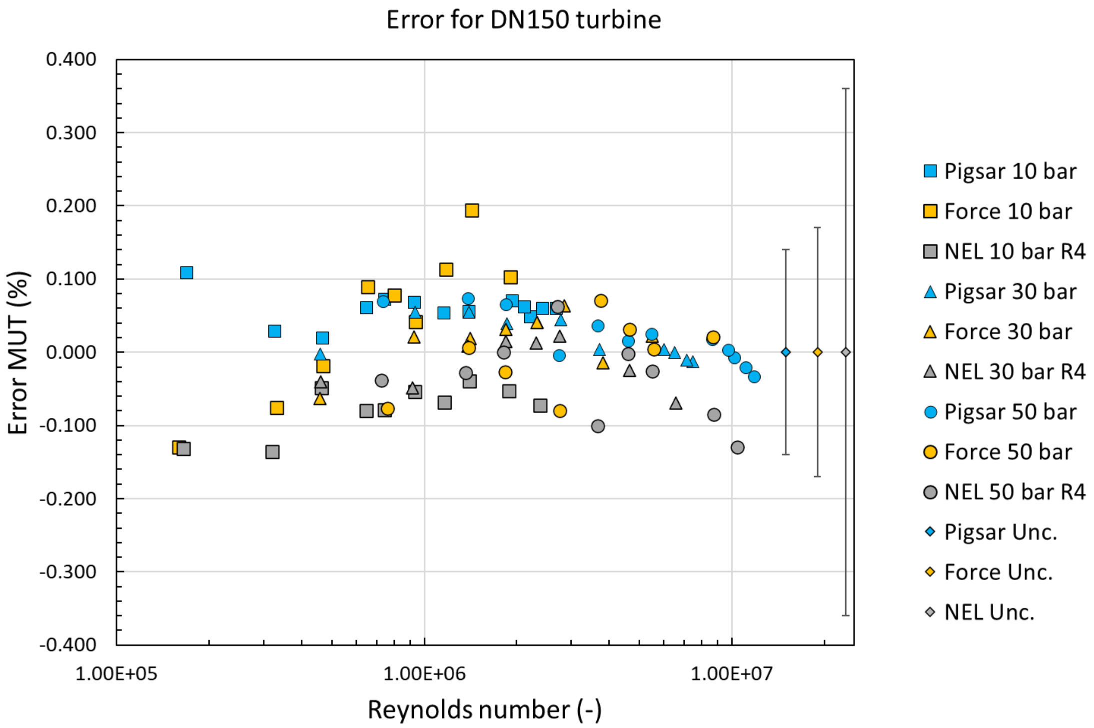

FIGURE 11 RELATIVE ERROR FROM THE TURBNE GAS METER TESTS AT EACH TEST FACILITY

4.1 Degrees of Equivalence for Each Test Facility

Figure 12 presents the Degrees of Equivalence, E_n values for each test facility based on the orifice meter measurements. Over 91% of the 70 test points shown in this graph have $|E_n| < 1$, demonstrating that the three test facilities - PTB/Pigsar, FORCE and NEL - are consistent with the CRV, and therefore have successfully passed the equivalency test for the specific flow conditions maintained during these test runs.

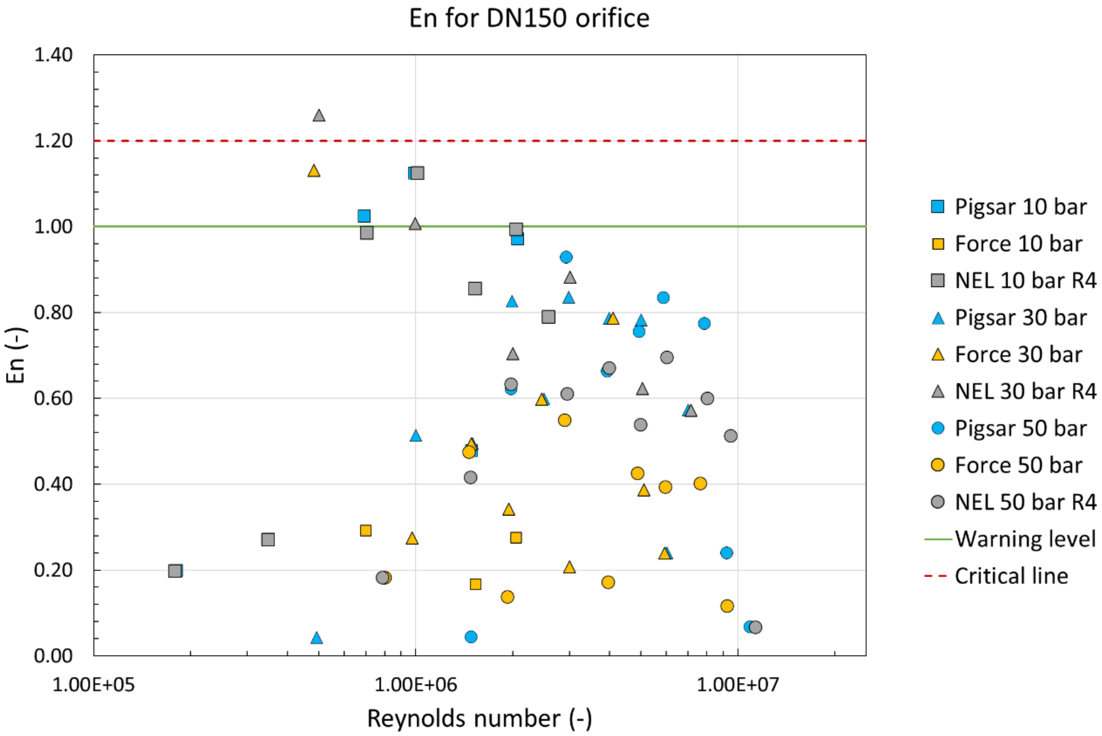

FIGURE 12 EACH TEST FACILITY'S DEGREES OF EQUIVALENCE WHEN USING THE ORIFICE METER

The figure also highlights six test points where $|E_n|$ exceeded 1, which are listed in Table 3 below. Five 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, the measurement at NEL for 30 bar(g) and Reynolds number of 0.5 x 10^6 had a $|E_n| > 1.2$, indicating that the test facility failed the equivalency test for this particular flow condition. Further insights into these discrepancies can be gained by comparing the results from the turbine gas meter which was also tested at the same time, and are discussed later in this section.

TABLE 3

ORIFICE METER TEST POINTS WITH $|E_n| > 1$

Test Facility	Pressure [bar(g)]	Reynolds number	$\|E_n\|$	Equivalency Test
PTB / Pigsar	10	0.7 x 10^6	1.02	Warning level
	10	1.0 x 10^6	1.12	Warning level
FORCE	30	0.5 x 10^6	1.13	Warning level
NEL	10	1.0 x 10^6	1.12	Warning level
	30	0.5 x 10^6	1.26	Fail
	30	1.0 x 10^6	1.01	Warning level

Figure 13 presents the Degrees of Equivalence, E_n values for each test facility based on the turbine gas meter measurements. Over 98% of the 79 test points shown in this graph have $|E_n| < 1$, demonstrating that the three test facilities - PTB/Pigsar, FORCE and NEL - are consistent with the CRV, and therefore have successfully passed the equivalency test for the specific flow conditions maintained during these test runs.

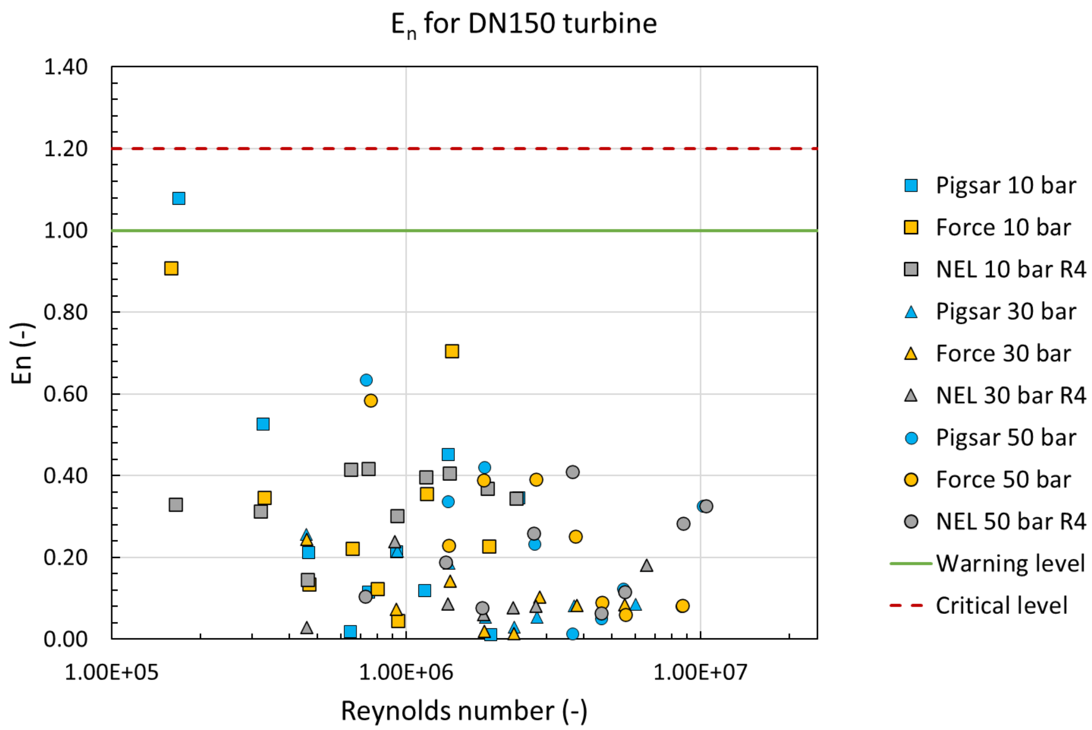

FIGURE 13 DEGREES OF EQUIVALENCE FOR EACH TEST FACILITY'S MEASUREMENTS WITH THE TURBINE GAS METER

The figure also highlights a test point measured by PTB/Pigsar where $|E_n|$ was between 1 and 1.2, suggesting a potential warning regarding the measurement processes at this facility for the test condition listed in Table 4 below.

TABLE 4

TURBINE GAS METER TEST POINTS WITH $|E_n| > 1$

Test Facility	Pressure [bar(g)]	Reynolds number	$\lvert E_n \rvert$	Equivalency Test
PTB / Pigsar	10	0.17×10^6	1.08	Warning level

During each test run, the test facilities had performed flow measurements using the transfer package – comprising both the orifice meter and the turbine gas meter – simultaneously against the respective reference meters. Therefore, the following conclusions can also be drawn by comparing the Degrees of Equivalence results from both transfer standards.

- The six test runs where the orifice meter's measurements resulted in $|E_n| > 1$, the turbine gas meter's measurements remained within $|E_n| < 1$.
- Conversely, single test point there the PTB / Pigsar facility had $|E_n|$ between 1 and 1.2 for the turbine gas meter's measurement, the orifice meter's measurement remained within $|E_n| < 1$.

It is recommended that each test facility investigates possible reasons for why the six test points with the orifice meter and the single test point with the turbine gas meter did not pass the equivalency assessment.

5. CONCLUSIONS

Three independent flow measurement facilities - NEL in the United Kingdom, FORCE in Denmark and the Pigsar facility operated in collaboration with PTB in Germany - participated in the EURAMET project 1379. This project aimed to assess the degree of equivalence in the high-pressure gas flow measurement capabilities across the facilities. The tests were undertaken using a transfer package consisting of an orifice meter and a turbine gas meter installed in a series configuration. Due to the differences in the configuration of each test facility, NEL used oxygen-free nitrogen gas as the test fluid, while FORCE and PTB/Pigsar used natural gas. The transfer package was tested over a gas flow rate range of 100 m^3/h to 1600 m^3/h at three line pressures: 10 bar(g), 30 bar(g) and 50 bar(g), and at a temperature of 20 °C. To ensure comparability while using different test fluids and transfer standards, each facility matched the Reynolds number and pressure for the tests.

The test results indicated that the performance of the three flow measurement facilities was comparable and within the uncertainty range of each with facility. The orifice meter measurements followed the expected trend, with the discharge coefficient decreasing as the Reynolds number increased. For each test pressure, NEL reported the highest discharge coefficient followed by FORCE and with PTB / Pigsar reporting the lowest values.

The turbine meter did not show a clear trend in the relative error with changes in Reynolds number, and no significant differences were also observed between each test facility. This suggests that using different fluids did not influence the turbine gas meter's performance, indicating its potential suitability for applications involving other gases including carbon dioxide and hydrogen gas. The test results from orifice meter and turbine meter also demonstrated that the transferability of calibration with different fluids at each facility may vary depending on the type of flow meter being tested.

The Degrees of Equivalence, E_n analysis undertaken for the three facilities using the flow measurement data showed that over 91% of the orifice meter test points and more than 98% of the turbine gas meter test points had $|E_n| < 1$, with only one orifice meter test point exceeding the critical level of $|E_n| > 1.2$. This confirmed that three test facilities - PTB/Pigsar, FORCE and NEL – were consistent with the Comparison Reference Value, CRV. These facilities therefore successfully passed the equivalency test for the flow conditions that were evaluated.

It is suggested that each facility investigates potential reasons as to why a small number of test points did not meet the equivalency threshold.

This inter-comparison test programme demonstrated the equivalence of high pressure gas flow measurement facilities at PTB/Pigsar, FORCE and NEL. It thereby validated the Calibration and Measurement Capability (CMC) declared by each facility and supports their ISO/IEC 17025 accreditation.

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