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Transferability of water calibration to energy-transition relevant fluids applications using Coriolis mass flowmeters

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Abstract. The results of a calibration round performed to Coriolis mass flowmeters, originally calibrated with water at factory conditions and re-calibrated with different fluids at several flow calibration facilities, are discussed in this paper. These calibrations were intended to prove the transferability concept from water to other fluids, some of them relevant to the energy-transition. The obtained results confirmed the robustness of the tested instruments performance and the viability to use the transferability approach as a reliable alternative.

1. Introduction

Metrological authorities and regulatory bodies have often discouraged the use of alternative fluids in flow calibrations due to concerns about the impact of fluid property variations, such as density and viscosity, on the flowmeter's performance. However, the use of advanced flow measurement technologies and the needs to handle fluids with diverse properties and process conditions, some of them associated to energy-transition era, has increased the discussion about the transferability concept. This concept supports the possibility of using alternative fluids, different from the process fluid for both the initial and subsequent calibrations of the flowmeters, providing a potential alternative to the conventional approach.

Coriolis mass flowmeters (CMF) have been particularly involved in the application of the transferability concept. This technology has been also one of the first choices to measure diverse fluids in applications such as custody transfer, but under challenging conditions e.g., very low density, high viscosity, dense phase, or close to critical conditions. However, the performance of the flowmeter under these operational conditions must be also proved by experimental means.

The results of a calibration round performed to a group of CMF, originally calibrated with water, and then re-calibrated without adjustments at several flow calibration facilities, using gas and high viscous fluids, is discussed in this paper. These calibrations were intended to prove the transferability concept from water to other fluids, relevant to the energy-transition global strategy.

2. Coriolis mass flowmeter principle of operation

The Coriolis mass flow measurement principle is based on the linear relationship between the mass flowing (q_m) through the measuring tubes of the device and the phase shift ($\Delta\varphi$) or delay (Δt) detected between two points (A and B in Figure 1) in the measuring tubes, equipped with electrodynamic sensors. Each measuring tube oscillates at its resonance frequency, imposed by the excitation driver. The phase shift ($\Delta\varphi$) is caused by the so-called Coriolis force, which is proportional to the mass flow rate (q_m). CMFs can also measure fluid density and temperature.

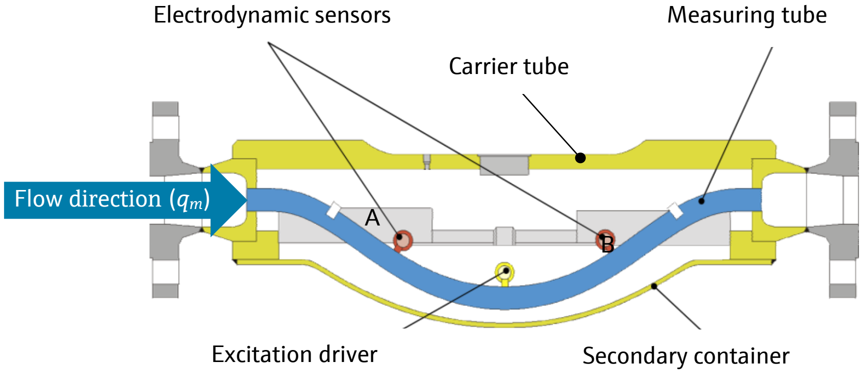

Figure 1. Coriolis sensor (simplified diagram).

Coriolis mass flowmeters can be initially calibrated using water as calibration fluid and the gravimetric approach as calibration method, following the standard ISO 4185 [1]. Water calibration is a preferred approach that allows a consistent evaluation of the flowmeter performance using a well-known fluid under reference conditions. Under these conditions deviations can be identified, isolated, and corrected, thus the obtained calibration factor (CALF) properly represents the sensitivity of the meter.

Depending on the manufacturer and the meter characteristics, this CALF can be also valid for liquids other than water. This *transferability* or extension of the CALF validity to other fluids, must be proved through experimental tests.

3. Coriolis mass flowmeter in gas applications

Coriolis mass flowmeters exhibit good performance in gas applications such as in natural gas (CH4), compressed natural gas (CNG), as well as in diverse H2 and CO2 applications, including custody transfer. Gas applications are particularly stringent for Coriolis mass flowmeters due to the low density of the fluid, and consequently its operation in the lower region of the flowmeter mass flow range, where the zero-point stability plays a relevant role. Coriolis mass flowmeters are designed with specific features allowing this effect to be reduced. Two examples of these features are the high homogeneity of the materials used to build these instruments and the strict low symmetry tolerances permitted during their construction. These features help to balance the mechanical behavior of the measuring tube dynamic, thus reducing the impact on zero-point stability.

However, gas flow measurement with CMF, is also affected by the compressible behavior and the low speed of sound (SoS) of the gas, responsible for introducing changes in the resonance frequency with respect to the driving frequency imposed on the measuring tubes. This gas-related frequency effect is mostly influenced by three elements: the SoS in the gas, the fluid velocity, and the measuring tube geometry. These three elements are taken into consideration when implementing corrections to mitigate their effect.

AGA Report No. 11 API MPMS Chapter 14.9, section 7 [2] states: “Calibration with an alternative calibration fluid (e.g., water) is valid with Coriolis sensor designs where the transferability of the alternative calibration fluid, with an added uncertainty relative to gas measurement, has been demonstrated by the meter manufacturer through tests conducted by an independent flow calibration laboratory.” This statement in principle validates the calibration results obtained in gas measurement with Coriolis mass flowmeters originally calibrated with water, whenever the new accuracies and uncertainties values of are clearly stated. This approach gives some flexibility to the expensive initial gas calibration/verification, which could be difficult to implement due to the absence of appropriate flow calibration facilities.

4. Coriolis mass flowmeters and low Reynolds number applications

Reynolds number (Re), one of the most important dimensionless numbers of fluid mechanics, accounts for the relation between the inertial and viscous forces acting in a fluid transport application. CMF performance is sensible to low Reynolds number condition, as reported in Miller et. al. [3] and Mills [4]. The mechanism behind these under readings is a complex interaction between the oscillating Coriolis forces and the shearing forces under the low Reynolds dynamic condition, dominated by the viscous effect at that flow regime. This interaction results in a secondary induced oscillatory force which is function of the Re, as discussed by Kumar et. al [5].

This low Reynolds dynamic condition is driven by high viscous fluids. The knowledge of the flow stream Re in the meter is relevant to compensate this effect. Coriolis mass flowmeters used in this work determine dynamically the Re number values, since the fluid viscosity is also estimated, thus, the low Reynolds number effect is compensated. The algorithm employed in this compensation is patented by Endress+Hauser Flowtec AG. This compensation technique has been shown to be effective for addressing the effects of low Reynolds on Coriolis meters by independent notified bodies, such as NMi Certin B.V. [6], to a level to be compliant with OIML R 117 [8].

5. Calibration round of Coriolis mass flowmeters using gas and viscous fluids

The goal of this calibration round using gas and viscous fluids as calibration fluids, is to prove that the tested flowmeters perform equal or better than the maximum permissible error (MPE) stated in the corresponding standard document, without adjustments in the CALF obtained in the initial water calibration. A summary of these calibration results is shown in Table 1.

A first group of calibration performed in Pigsar facilities (Germany's national standard for high-pressure natural gas metering) to a Promass F DN25 and a Promass Q DN25 are shown in Annex 1. The calibration fluid was natural gas at densities between 17 kg/m^3 and 40 kg/m^3.

The deviations throughout the complete calibration range, as well as the instrument contributions to the measurement uncertainty ($U_{meter\ (95\%)}$) and the total measurement uncertainty ($U_{tot\ (k=2)}$) of the calibrations are shown in Table 1. The maximum deviation values remained within the OIML R 137 MPE for Accuracy Class 1.0. This confirms the validity of the extension of the CALF obtained in water and applied to this gas application.

Table 1. Summary of the results of liquid and gas calibration for Coriolis mass flowmeters.

Fluid	Calibration flow range [kg/h]	Turndown ratio [-]	Density [kg/m^3]	Pressure [bar]	Temp. [ºC]	Max. Deviation [%]	Max. $U_{meter\ (95\%)}$ [%]	Max. $U_{tot\ (k=2)}$ [%]	Calibration facility
Promass F DN25 (Annex 1)									
CH_4	84 – 2800	33:1	17.0	21.2	17.0	-0.18	0.12	0.28	Pigsar
Promass Q DN25 (Annex 1)									
CH_4	84 – 2800	33:1	17.0	21.2	17.0	-0.17	0.19	0.30	Pigsar
Promass F DN80 (Annex 1)									
CH_4	2824 – 26804	10:1	24.3	30.1	21.0	0.41	0.43	0.49	Pigsar
CH_4	8962 – 33913	4:1	39.7	48.6	20.0	-0.67	0.15	0.29	Pigsar
Promass Q DN80 (Annex 2)									
H_2	455 – 746	1.6:1	2.36	30.2	33.0	0.25	0.23	0.42	DNV
N_2	493 – 1091	2.2:1	2.56	2.3	33.0	0.23	0.16	0.57	DNV
H_2	466 – 1337	2.9:1	3.13	40.0	33.0	0.39	0.14	0.38	DNV
Promass Q DN200 (Annex 2)									
CH_4	2400 – 70000	29:1	16.3	20	20.0	-0.11	0.14	0.27	Pigsar
Promass Q DN80									
Siptech 132 cSt	8665 – 117816	14:1	868.72	2.5	22.0	-0.32	0.01	0.25	NEL

Another group of calibrations was performed to a Promass Q DN80 in DNV (Det Norske Veritas, Groningen) flow facilities, this time using hydrogen at 30 bar and 40 bar and nitrogen at 2.3 bar, see Annex 2. This flowmeter was also initially calibrated with water with ± 0.05 % o.r. of maximum permissible error. The error (deviation) during the gas calibrations, the uncertainty of the repeatability, and the expanded measurement uncertainty are shown in Table 1 and in Annex 2.

As shown in Figure 2, the "as-found" gas calibrations were performed at low mass flow rates, between approximately 1.3 % and 4 %, relative to the maximum calibrated flowrate in water. An additional challenging condition was the low gas density, ranging from 2.3 kg/m^3 to 3.13 kg/m^3, a common scenario in hydrogen applications.

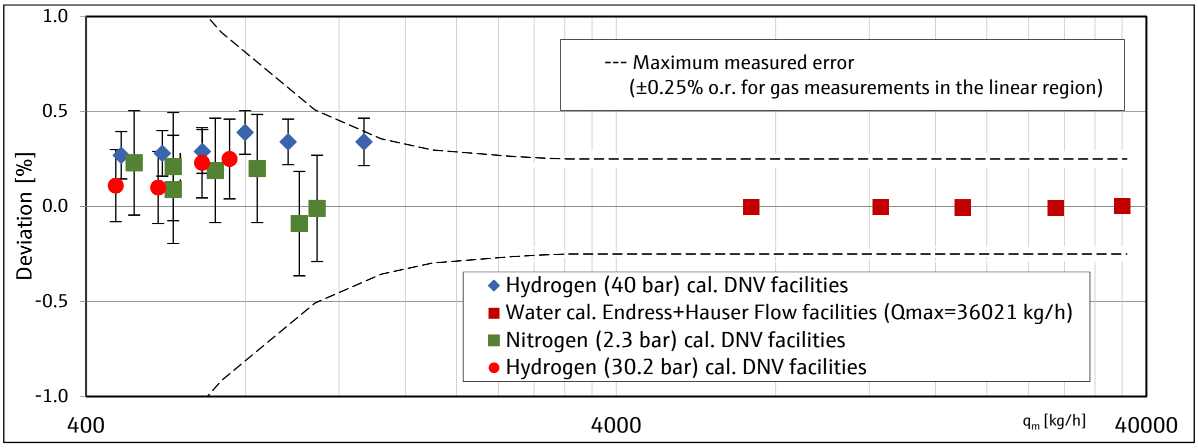

Figure 2. Promass Q DN80 errors, measuring H_2, N_2 (DNV) and in its initial calibration with water.

Even in this region of the flowmeter range, where the influence of the zero-point stability is relevant, the error values obtained during the calibration were within the band of the maximum measured error (dashed line) for gas fluids at these flow rates in the non-linear region. It is also remarkable, that most of the error values were also within the maximum measured error value specified in the instrument's technical information for gas flow measurement in the linear region (± 0.25 % o.r.).

Figure 3 shows the calibration performed to a large diameter (DN200) Coriolis mass flowmeter Promass Q. This device was included to extent the diversity of the instruments already tested, ranging DN25 and DN80 to larger sizes, but using the same approach, starting by water calibration at factory conditions where the CALF is determined, and then calibrating the instrument without adjustments with alternative fluids in this case natural gas in Pigsar.

The error curves in Figure 3, combine natural gas (see Annex 2) and water calibration results of the Promass Q DN200. The initial calibration in water was performed at two points, 57698 kg/h and 229184 kg/h with ± 0.1 % o.r. as tolerance limit, and an expanded measurement uncertainty, U (k=2), equal to 0.054 %. The results of the second calibration show a good agreement between both calibrations and the validity of the CALF obtained during the water calibration. The maximum error obtained in this calibration was -0.11 % (at the lowest flow rate) with maximum U_{meter} (uncertainty of repeatability) of 0.14 %.

This gas calibration, as can be seen in Figure 3, was covering only the low range of the water calibration range, however the results are consistently good. This performance is possible due to the instrument's high zero-point stability, repeatability, and linearity, also shown under gas measurement conditions.

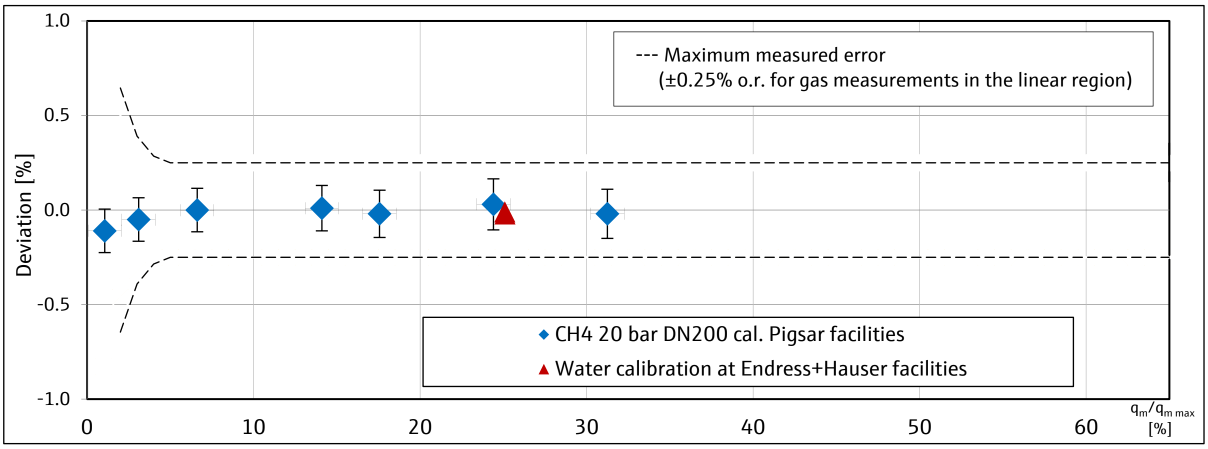

Figure 3. Promass Q DN200 errors, measuring CH_4 (Pigsar) and in its initial calibration with water.

The last group of calibrations reported are the results obtained in NEL (National Engineering Laboratories, Glasgow). A Promass F DN80 was calibrated with nitrogen, light mineral oils, and white oil Siptech 132 cSt. This last one, shown in the Table 1 and in Figure 4, was intended to evaluate the effectivity of the Low Reynolds compensation algorithms.

The Low Reynolds compensation is a permanent feature in Promass flowmeters, but in this case, it was deactivated, Figure 4 (a), and activated, Figure 4 (b), to show the difference between the compensated and uncompensated measurement results. Error values shown in Figure 4 (b), confirm the capability of this feature to reduce the effects of the low Reynolds hydrodynamic conditions. Error values mainly remained better than ±0.2 %, two points at very low flow were higher than ±0.2 % (-0.29% and -0.32).

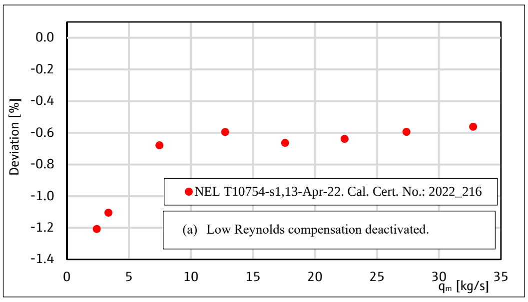

Figure 4 (a). Promass F DN80 measuring Siptech 132 cSt, without Low Re compensation

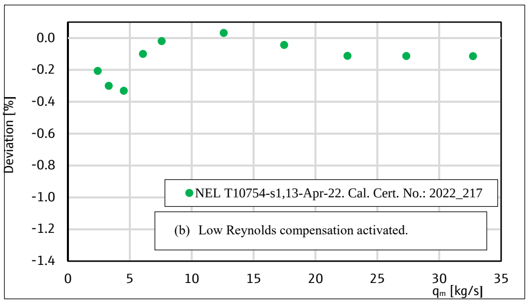

Figure 4 (b). Promass F DN80 measuring Siptech 132 cSt with Low Re compensation

Figure 5 shows the general agreement of all the measurement deviations vs. Reynolds number. The error values can be also compared against the indicated MPE of ±1 % and ±0.5% for gases, according to OIML R 137 [7] Classes 1 and 0.5, respectively, and against ± 0.2 % for liquids according to OIML R 117 [8] Class 0.3. The obtained values mainly remained within the acceptable error range throughout the entire range of Reynolds number. All the gas measurements, except CH_4 @50 bar, overperformed staying within the band of error of ±0.5% (OIML R 137 Class 0.5), considering that these flowmeters are currently approved according to Class 1.

The combination of high zero-point stability with high repeatability and linearity, also at an extended turndown ratio (up to 33:1) exhibited by these instruments, allows to achieve good agreement throughout the calibrated ranges, between the calibration results in water, in gas, and in liquids other than water. Also, the compensations implemented to correct deviations associated to low Reynolds conditions helped to maintain the error under the expected limits even under these conditions.

This favorable behavior reinforces, with experimental data, the transferability approach from water to gas and from water to viscous fluids addressed in this paper.

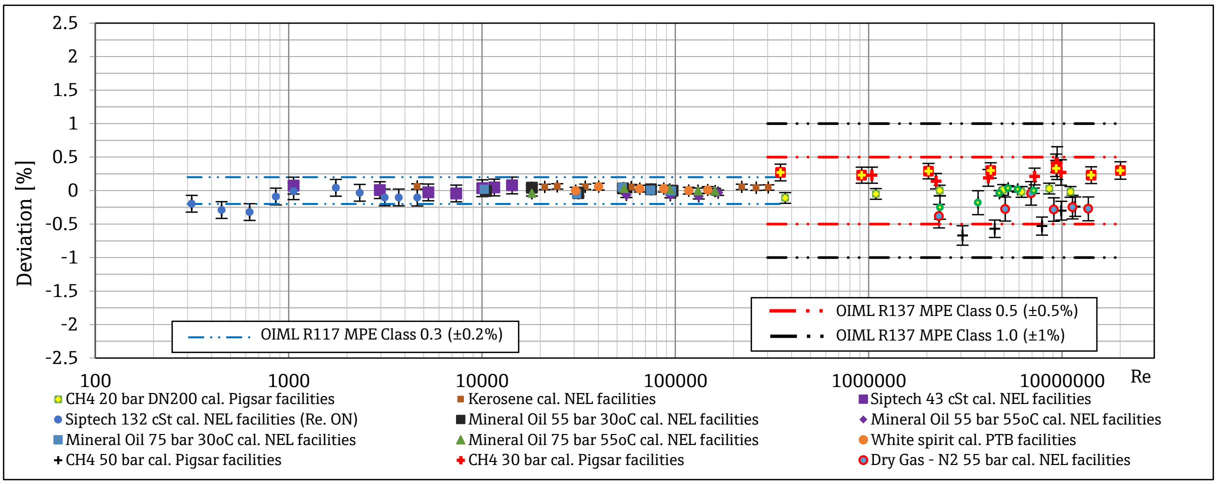

Figure 5. Deviations vs. Reynolds for five Coriolis mass flowmeters measuring different fluids.

6. Conclusion

Coriolis mass flowmeters tested in this calibration round have consistently shown high performance in diverse gas and viscous fluids applications, using the same CALF obtained during their initial water calibration. Beyond the theoretical considerations, there are trustable results obtained in third-party calibration facilities with different sensors, different nominal diameters, pressures, fluids with different densities and viscosities, all of them initially calibrated using water and with no further adjustments.

These results are possible thanks to the consistency of the design of the tested Coriolis mass flowmeters, which combines high zero-point stability with high repeatability and linearity at an extended turndown ratio. In addition to that the tested flowmeters are equipped with an algorithm to compensate the effect of low Reynolds number condition, associated to high viscous fluids, as well as other correction relevant for gases with low speed of sound and/or at high velocities.

These results also represent a reliable set of data to support and expand the concept transferability for Coriolis mass flowmeters, sustaining the concept that their initial or subsequent water calibration can be valid when the meter is measuring gas or viscous fluids. This validity, which implies to fulfil the MPE values stated in custody transfer standards, such as OIML R 137 or OIML R 117, is considered by the notified bodies when granting the tested Coriolis mass flowmeters for custody transfer applications measuring liquid and gas.

7. Acknowledgment

Petróleo Brasileiro S.A. – PETROBRAS, for their support to the research project under grant number 4600615426.

8. References

[1] ISO-4185, *Measurement of liquid flow in closed conduits Weighing method,* 1980.

[2] A. MPMS/AGA, *API MPMS, Chapter 14.9/AGA Report No. 11: Measurement of Natural Gas by Coriolis Meter,* 2013.

[3] G. Miller and B. Belshaw, "An investigation into the performance of Coriolis and ultrasonic meters at liquid viscosities up to 300 cSt," in *International North Sea Flow Measurement Workshop*, 2008.

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[5] V. Kumar, M. Anklin and B. Schwenter, "Fluid-structure interaction (FSI) simulations on the sensitivity of coriolis flow meter under low Reynolds number flows," in *15th Flow Measurement Conference (FLOMEKO)*, Taipei, 2010.

[6] NMI-Certin_BV, "Evaluation Certificate Number TC7149," 2017 - 2023.

[7] OIML R 137, *International Organization of Legal Metrology,* Gas meters, 2012.

[8] OIML R 117, *International Organization of Legal Metrology,* Dynamic measuring systems for liquids other than water, 2019.

Annex 1:

Promass F DN25; 84 kg/h – 2800 kg/h CH4 @20 bar

pigsar ™

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Certificate Number: 19225/2021
Date: 2021-05-06

Applicant Endress & Hauser Flowtec AG

Meter under Test

Type	Coriolis meter Promass F
Manufacturer	Endress+Hauser
Serial number	S31AE202000
Nominal Size	1"
Year of manufacture	2021

Test Conditions

Test medium	Natural gas		CO_2	1,57	mole %
Pressure, absolute	21,2	bar	H_2	0,0	mole %
Gas Temperature	17	°C	Calorific value,s	10,35	kWh/m³
Gas density (p, T)	17,0	kg/m³	Density,normal	0,8306	kg/m³
Dyn. viscosity (p, T)	1,15E-5	Pa s	Normal conditions (273,15 K; 101,325 kPa)		

Results (as left)

Qi / Qmax	Qi (kg/h)	Reynoldsnumber	Deviation (%)	n	Umeter (%)	Utot (%)
0,03	**82,77**	$0,10 *10^6$	**0,09**	5	0,05	0,28
0,05	**128,17**	$0,16 *10^6$	**0,17**	5	0,04	0,25
0,10	**282,89**	$0,35 *10^6$	**0,09**	5	0,05	0,24
0,21	**600,77**	$0,74 *10^6$	**-0,06**	5	0,03	0,23
0,46	**1296,39**	$1,61 *10^6$	**-0,12**	6	0,12	0,26
0,64	**1794,62**	$2,22 *10^6$	**-0,18**	5	0,08	0,24
1,02	**2843,55**	$3,48 *10^6$	**-0,03**	5	0,12	0,26

Weighted mean error, with continuous and linear decrease of weighing factor between 0,7 Qmax and Qmax: **-0,1 %.**

The *deviation* is defined as: $$Deviation = \frac{(Indicated\ Value - Reference\ Value)}{(Reference\ Value)} \cdot 100\,\%$$

where the reference volume refers to the conditions at the meter under test. The reported values of this deviation are the arithmetical means of *n* single repeat measurements at each flow-rate.

The reported *total uncertainty* is defined as: $$U_{tot} = \sqrt{U^2_{harmonized} + U^2_{meter}}$$

where $U_{harmonized}$ is the expanded uncertainty of the harmonized reference value, stated as the standard uncertainty of measurement multiplied by the coverage factor k=2, and U_{meter} is the expanded standard uncertainty of the meter under test, determined on the base of n repeats at each flow-rate, multiplied by Student-t-factor (n) / $n^{0,5}$, with a probability of 95%.

Remarks Security marks are applied
At customer´s request the meter had not been adjusted.
The meter had been calibrated at 20 bar and at 40 bar.
The results at 40 bar are presented in certificate no. 19224/2021.

Following parameters have been used during the calibration and have an influence to the test results:

Measuring mode: Gas	Stored zero(pipo): 1,4
Gas type: Methane	Sensor pressure corr. (bar): 20
Meter factor: 2,0496	Zero offset before calibration (g/3 min): 6,121
	Zero offset after calibration (g/3 min): 4,338

Tested in Dorsten at *pigsar*, on 2021-05-06 Göbbeler

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Promass Q DN25; 84 kg/h – 2800 kg/h CH4 @20 bar

pigsar ™

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Certificate Number: 19189/2021
Date: 2021-04-23

Applicant Endress & Hauser Flowtec AG

Meter under Test

Type	Coriolis meter Promass Q
Manufacturer	Endress+Hauser
Serial number	RB0F7202000
Nominal Size	1"
Year of manufacture	2020

Test Conditions

Test medium	Natural gas		CO_2	1,53	mole %
Pressure, absolute	21,2	bar	H_2	0,0	mole %
Gas Temperature	17	°C	Calorific value,s	10,36	kWh/m³
Gas density (p, T)	17,0	kg/m³	Density,normal	0,8312	kg/m³
Dyn. viscosity (p, T)	1,15E-5	Pa s	Normal conditions (273,15 K; 101,325 kPa)		

Results (as left)

Qi / Qmax	Qi (kg/h)	Reynoldsnumber	Deviation (%)	n	Umeter (%)	Utot (%)
0,03	**85,09**	$0,11 *10^6$	**-0,11**	6	0,12	0,30
0,05	**132,83**	$0,16 *10^6$	**0,04**	5	0,05	0,25
0,10	**281,18**	$0,35 *10^6$	**0,13**	5	0,03	0,24
0,22	**602,46**	$0,74 *10^6$	**0,03**	5	0,03	0,23
0,46	**1278,39**	$1,56 *10^6$	**-0,17**	5	0,10	0,25
0,64	**1804,60**	$2,22 *10^6$	**-0,13**	5	0,19	0,30
0,98	**2735,50**	$3,35 *10^6$	**-0,01**	6	0,14	0,27

Weighted mean error, with continuous and linear decrease of weighing factor between 0,7 Qmax and Qmax: **-0,08 %.**

The *deviation* is defined as: $$Deviation = \frac{(Indicated\ Value - Reference\ Value)}{(Reference\ Value)} \cdot 100\,\%$$

where the reference volume refers to the conditions at the meter under test. The reported values of this deviation are the arithmetical means of *n* single repeat measurements at each flow-rate.

The reported *total uncertainty* is defined as: $$U_{tot} = \sqrt{U^2_{harmonized} + U^2_{meter}}$$

where $U_{harmonized}$ is the expanded uncertainty of the harmonized reference value, stated as the standard uncertainty of measurement multiplied by the coverage factor k=2, and U_{meter} is the expanded standard uncertainty of the meter under test, determined on the base of n repeats at each flow-rate, multiplied by Student-t-factor (n) / $n^{0,5}$, with a probability of 95%.

Remarks Security marks are applied
At customer´s request the meter had not been adjusted.
The meter had been calibrated at 20 bar and at 40 bar.
The results at 40 bar are presented in certificate no. 19222/2021.

Following parameters have been used during the calibration and have an influence to the test results:

Measuring mode: Gas	Stored zero(pipo): -43,1
Gas type: Methane	Sensor pressure corr. (bar): 20
Meter factor: 0,83113	Zero offset before calibration (g/3 min): -5,281
	Zero offset after calibration (g/3 min): -0,151

Tested in Dorsten at *pigsar*, on 2021-04-23 Görgülü

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Promass F DN80; 2824 kg/h – 26804 kg/h CH4 @30 bar

pigsar ™

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Certificate Number: 20389/2022
Date: 2022-09-09

Applicant INMETRO Brazil

Meter under Test

Type	Coriolis meter Promass 300
Manufacturer	Endress+Hauser
Serial number	SA111F02000
Nominal Size	3"
Year of manufacture	2021

Test Conditions

Test medium	Natural gas		CO_2	1,01	mole %
Pressure, absolute	30,1	bar	H_2	0,0	mole %
Gas Temperature	21	°C	Calorific value,s	10,32	kWh/m³
Gas density (p, T)	24,3	kg/m³	Density,normal	0,8346	kg/m³
Dyn. viscosity (p, T)	1,20E-5	Pa s	Normal conditions (273,15 K; 101,325 kPa)		

Results (as left)

Qi / Qmax	Qi (kg/h)	Reynoldsnumber	Deviation (%)	n	Umeter (%)	Utot (%)
0,10	**2824,10**	$1,04 *10^6$	**0,23**	4	0,05	0,24
0,22	**6072,58**	$2,23 *10^6$	**0,14**	3	0,04	0,23
0,42	**11322,56**	$4,16 *10^6$	**0,19**	3	0,09	0,25
0,72	**19613,22**	$7,22 *10^6$	**0,21**	3	0,11	0,25
0,93	**25267,73**	$9,32 *10^6$	**0,41**	6	0,13	0,27
0,95	**25615,65**	$9,44 *10^6$	**0,41**	5	0,43	0,49
0,99	**26804,30**	$9,88 *10^6$	**0,27**	6	0,30	0,38

Weighted mean error, with continuous and linear decrease of weighing factor between 0,7 Qmax and Qmax: **0,28 %.**

The *deviation* is defined as: $$Deviation = \frac{(Indicated\ Value - Reference\ Value)}{(Reference\ Value)} \cdot 100\,\%$$

where the reference volume refers to the conditions at the meter under test. The reported values of this deviation are the arithmetical means of *n* single repeat measurements at each flow-rate.

The reported *total uncertainty* is defined as: $$U_{tot} = \sqrt{U^2_{harmonized} + U^2_{meter}}$$

where $U_{harmonized}$ is the expanded uncertainty of the harmonized reference value, stated as the standard uncertainty of measurement multiplied by the coverage factor k=2, and U_{meter} is the expanded standard uncertainty of the meter under test, determined on the base of n repeats at each flow-rate, multiplied by Student-t-factor (n) / $n^{0,5}$, with a probability of 95%.

Remarks Security marks are applied

At customer´s request the meter had not been adjusted.

Tested in Dorsten at *pigsar*, on 2022-09-09 Göbbeler

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Calibration certificates without signature and seal on the first page are not valid.

Promass F DN80; 8962 kg/h – 33913 kg/h CH4 @30 bar

pigsar ™

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Certificate Number: 20392/2022
Date: 2022-08-22

Applicant INMETRO Brazil

Meter under Test

Type	Coriolis meter Promass 300
Manufacturer	Endress+Hauser
Serial number	SA111F02000
Nominal Size	3"
Year of manufacture	2021

Test Conditions

Test medium	Natural gas		CO_2	1,31	mole %
Pressure, absolute	48,6	bar	H_2	0,0	mole %
Gas Temperature	20	°C	Calorific value,s	10,12	kWh/m³
Gas density (p, T)	39,7	kg/m³	Density,normal	0,8166	kg/m³
Dyn. viscosity (p, T)	1,29E-5	Pa s	Normal conditions (273,15 K; 101,325 kPa)		

Results (as left)

Qi / Qmax	Qi (kg/h)	Reynoldsnumber	Deviation (%)	n	Umeter (%)	Utot (%)
0,27	**8962,43**	$3,06 *10^6$	**-0,67**	3	0,18	0,29
0,40	**13152,40**	$4,49 *10^6$	**-0,57**	3	0,13	0,26
0,69	**22991,10**	$7,88 *10^6$	**-0,53**	3	0,13	0,27
0,87	**28842,28**	$9,91 *10^6$	**-0,30**	4	0,16	0,28
1,02	**33913,40**	$11,70 *10^6$	**-0,24**	5	0,17	0,29

Weighted mean error, with continuous and linear decrease of weighing factor between 0,7 Qmax and Qmax: **-0,45 %.**

The *deviation* is defined as: $$Deviation = \frac{(Indicated\ Value - Reference\ Value)}{(Reference\ Value)} \cdot 100\,\%$$

where the reference volume refers to the conditions at the meter under test. The reported values of this deviation are the arithmetical means of *n* single repeat measurements at each flow-rate.

The reported *total uncertainty* is defined as: $$U_{tot} = \sqrt{U^2_{harmonized} + U^2_{meter}}$$

where $U_{harmonized}$ is the expanded uncertainty of the harmonized reference value, stated as the standard uncertainty of measurement multiplied by the coverage factor k=2, and U_{meter} is the expanded standard uncertainty of the meter under test, determined on the base of n repeats at each flow-rate, multiplied by Student-t-factor (n) / $n^{0,5}$, with a probability of 95%.

Remarks Security marks are applied

At customer´s request the meter had not been adjusted.

Tested in Dorsten at *pigsar*, on 2022-08-22 Göbbeler

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Annex 2:

Promass Q DN80; 455 kg/h – 746 kg/h H2 @30 bar

DNV

Meter: Serial No: T6040202000
Meter type ID: Promass Q 300, DN80
Manufacturer : Endress+Hauser Flowtec AG
Type: Coriolis

Certificate No: **H003**
Page: 2 of 2

Adjustment [%]: no
FWME As Lft [%]: 0,18

Results:

Rev. flow	MUT flow	Deviation	CMC (95%)	Std Dev (95%)	U-tot (95%)	Reynolds
[m³/h]	[kg/h]	[%]	[%]	[%]	[%]	[-]
316	746	0,25	0,36	0,23	0,42	301236
280	662	0,23	0,36	0,08	0,37	268579
232	547	0,10	0,36	0,13	0,38	222647
193	455	0,11	0,36	0,12	0,38	185220
Location	Date		Medium	P [bar](abs)	T [ºC]	Rho [kg/m³]
Groningen	2022-07-20		Hydrogen	30,2	33,0	2,36

Deviation: Formula = ((IndicatedFlow / ReferenceFlow) - 1) * 100%

CMC: Test and Measurement Capability is the (95%) uncertainty that is normally available for Tests.

U-tot: U-tot is the total (95%) measurement uncertainty.

Ambient conditions: 33 ± 2 °C

Disclaimer: Please note that this report reflects the performance of the calibrated device only at the time of test and in the circumstances prevailing during the Test.

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T +31 50 700 97 00 | Trade register 09006404

Promass Q DN80; 493 kg/h – 1091 kg/h N2 @2.3 bar

DNV

Meter: Serial No: T6040202000
Meter type ID: Promass Q 300, DN80
Manufacturer : Endress+Hauser Flowtec AG
Type: Coriolis

Certificate No: **H002**
Page: 2 of 2

Adjustment [%]: no
FWME As Lft [%]: 0,08

Results:

Rev. flow	MUT flow	Deviation	CMC (95%)	Std Dev (95%)	U-tot (95%)	Reynolds
[m³/h]	[kg/h]	[%]	[%]	[%]	[%]	[-]
426	1091	-0,01	0,55	0,10	0,56	219011
395	1010	-0,09	0,55	0,08	0,55	202612
330	841	0,20	0,55	0,15	0,57	168421
276	701	0,19	0,55	0,08	0,55	140813
230	584	0,09	0,55	0,16	0,57	117709
194	493	0,23	0,55	0,01	0,55	99388
231	584	0,21	0,55	0,02	0,56	118187
Location	Date		Medium	P [bar](abs)	T [ºC]	Rho [kg/m³]
Groningen	2022-07-19		Nitrogen	2,3	33,0	2,56

Deviation: Formula = ((IndicatedFlow / ReferenceFlow) - 1) * 100%

CMC: Test and Measurement Capability is the (95%) uncertainty that is normally available for Tests.

U-tot: U-tot is the total (95%) measurement uncertainty.

Ambient conditions: 33 ± 2 °C

Disclaimer: Please note that this report reflects the performance of the calibrated device only at the time of test and in the circumstances prevailing during the Test.

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Promass Q DN80; 466 kg/h – 1337 kg/h H2 @40 bar

DNV

Meter: Serial No: T6040202000
Meter type ID: Promass Q 300, DN80
Manufacturer : Endress+Hauser Flowtec AG
Type: Coriolis

Certificate No: **H001**
Page: 2 of 2

Adjustment [%]: no
FWME As Lft [%]: 0,33

Results:

Rev. flow	MUT flow	Deviation	CMC (95%)	Std Dev (95%)	U-tot (95%)	Reynolds
[m³/h]	[kg/h]	[%]	[%]	[%]	[%]	[-]
426	1337	0,34	0,36	0,14	0,38	538583
307	962	0,34	0,35	0,03	0,36	387866
255	798	0,39	0,36	0,03	0,36	321464
212	663	0,29	0,36	0,13	0,38	267650
178	557	0,28	0,36	0,10	0,37	225427
149	466	0,27	0,36	0,10	0,37	188677
Location	Date		Medium	P [bar](abs)	T [ºC]	Rho [kg/m³]
Groningen	2022-07-20		Hydrogen	40,0	33,0	3,13

Deviation: Formula = ((IndicatedFlow / ReferenceFlow) - 1) * 100%

CMC: Test and Measurement Capability is the (95%) uncertainty that is normally available for Tests.

U-tot: U-tot is the total (95%) measurement uncertainty.

Ambient conditions: 33 ± 2 °C

Disclaimer: Please note that this report reflects the performance of the calibrated device only at the time of test and in the circumstances prevailing during the Test.

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Promass Q DN200; 2400 kg/h – 70000 kg/h CH4 @20 bar

pigsar™

page 3 of 4

Certificate Number: 19756/2021
Date: 2021-12-15

Applicant Endress+Hauser Flowtec AG

Meter under Test
Type: Coriolis meter Promass Q
Manufacturer: Endress+Hauser
Serial number: TEST0002145
Nominal Size: 8"
Year of manufacture: 2021

Test Conditions

Test medium	Natural gas		CO_2	1,41	mole %
Pressure, absolute	20,6	bar	H_2	0,0	mole %
Gas Temperature	20	°C	Calorific value,s	10,36	kWh/m³
Gas density (p, T)	16,3	kg/m³	Density,normal	0,8299	kg/m³
Dyn. viscosity (p, T)	1,15E-5	Pa s	Normal conditions (273,15 K; 101,325 kPa)		

Results (as left)

Qi / Qmax	Qi (kg/h)	Reynoldsnumber	Deviation (%)	n	Umeter (%)	Utot (%)
0,03	**2426,27**	0,37 $\cdot 10^6$	**-0,11**	7	0,03	0,23
0,10	**7089,82**	1,09 $\cdot 10^6$	**-0,05**	6	0,04	0,23
0,22	**15157,84**	2,33 $\cdot 10^6$	**0,00**	6	0,02	0,23
0,46	**32303,27**	4,96 $\cdot 10^6$	**0,01**	6	0,04	0,24
0,57	**40249,26**	6,18 $\cdot 10^6$	**-0,02**	6	0,08	0,25
0,80	**55909,73**	8,59 $\cdot 10^6$	**0,03**	7	0,14	0,27
1,02	**71591,80**	11,06 $\cdot 10^6$	**-0,02**	8	0,12	0,26

Weighted mean error, with continuous and linear decrease of weighing factor between 0,7 Qmax and Qmax: **0 %.**

The *deviation* is defined as:

$$Deviation = \frac{(Indicated\ Value - Reference\ Value)}{(Reference\ Value)} \cdot 100\,\%$$

where the reference volume refers to the conditions at the meter under test. The reported values of this deviation are the arithmetical means of *n* single repeat measurements at each flow-rate.

The reported *total uncertainty* is defined as:

$$U_{tot} = \sqrt{U^2_{harmonized} + U^2_{meter}}$$

where $U_{harmonized}$ is the expanded uncertainty of the harmonized reference value, stated as the standard uncertainty of measurement multiplied by the coverage factor k=2, and U_{meter} is the expanded standard uncertainty of the meter under test, determined on the base of n repeats at each flow-rate, multiplied by Student-t-factor (n) / $n^{0.5}$, with a probability of 95%.

Remarks Security marks are applied

The meter had been calibrated at 20 bar and at 40 bar.
The results at 20 bar are presented in certificate no. 19756/2021.

Tested in Dorsten at *pigsar*, on 2021-12-15 Görgülü

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