Optimizing Coriolis Flowmeter Performance for the Brazilian O&G Industry: Influence Factors and Calibration Strategies

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Abstract. Coriolis flowmeters are reliable and accurate instruments used in a wide range of industries to measure fluid flow, with an increase of popularity in the oil and gas industry. One common misconception about these flowmeters is that they could measure mass flow with the same accuracy, regardless of the fluid properties and process conditions. Although they may be less sensitive to flow profile and fluid properties than volumetric meters, some effects must be considered, especially when custody transfer accuracy class is required. To reduce the impact of these effects, the Brazilian oil and gas regulatory authority requires either field ("*in situ*") calibration or laboratory calibrations that replicate the process conditions, including flowrate, temperature, pressure, viscosity, and density. Additionally, the calibrations must be performed on a volumetric basis rather than mass, making it critical to match the conditions precisely. However, many oil and gas facilities, particularly older ones, do not have provers available for oil calibration purposes. This poses a more significant problem for gas meters, where field calibration is a challenging task. Moreover, laboratory calibrations may not be able to perfectly replicate all process conditions. When suitable calibration facilities do exist, the costs of matching all process conditions may be prohibitively expensive. By understanding the factors that can impact Coriolis flowmeter performance, users can make informed decisions about how to calibrate and operate them. This, in turn, can improve measurement accuracy, reduce the risk of errors, and ensure that custody transfer requirements are met. This paper aims to provide a comprehensive overview of the effects that can influence the performance of Coriolis flowmeters, primarily caused by change in process conditions (temperature, pressure) and fluid physical properties (viscosity, density, composition), and how to assess them. Additionally, the transferability of calibrations between liquid and gas will also be addressed. Some suggestions about calibrations approach, as well as how to estimate measurement uncertainties will be discussed.

Keywords: calibration; Coriolis; flowmeter; transferability.

1. Introduction

In Brazil, the regulation and inspections of fiscal and custody transfer metering systems within oil and gas industry fall under the responsibility of the Petroleum and Natural Gas National Agency (ANP), while the Brazilian National Institute of Metrology (INMETRO) works to maintain the metrology primary standards, promote best measurement practices, and performs type approval and verification tests of flowmeters. The Joint Resolution ANP/INMETRO nº 001/2013 approved the Technical Regulation for Measurement of Oil and Natural Gas (RTM) [1] established the minimum conditions and requirements for oil and natural gas measurement systems to ensure accurate and complete results.

The RTM stipulates that flowmeters used for fiscal and custody transfer applications must be calibrated matching usual process conditions or within the limits of 20 % in density and in viscosity, 5 °C in temperature and 10 % in pressure and flowrate. Furthermore, the calibrations are performed on volumetric basis rather than mass basis for any technology, including Coriolis.

A review of this regulation is currently underway, and the revised proposal for the new oil and gas measurement regulation was presented in the public consultation in 2022 [2], with approval expected by the end of 2023. The new regulation will consider the possibility of flexibilization of calibration conditions – provided there is a consistent metrological technical background. The RTM will also define limits for calibration[1], and calibration frequencies[2] for each type of technology and measurement application.

This paper aims to provide a comprehensive overview about the most significant effects with potential to exert an influence on the performance of Coriolis flowmeters. These effects predominantly arise due to alterations in process conditions, encompassing temperature and pressure variation, and in fluid physical properties such as viscosity, density, fluid phase, speed of sound and composition. Furthermore, alternative calibration approaches and how to assess calibration transferability, as well as how to estimate measurement uncertainties will be discussed.

2. Background

2.1. Theory

The working principle of Coriolis flowmeters is based on the time lag detected on a pair of bent tubes that vibrates out of plane, driven at near their natural bending (about the vibrating axis) frequency (f_{nb}). In the absence of flow, both ends (inlet and outlet) of the vibrating tube will be in phase; if fluid is flowing throw the tubes, a Coriolis force will appear in the fluid, which will react and create a twisting motion on the tubes, with natural frequency (f_{nt}). This twist motion will create a phase difference between tube ends, which can be detected by pick-off sensors.

A generic mathematical model for a U-shaped Coriolis flowmeter can be determined as below [3]:

$$\dot{m} = \underbrace{\frac{K_u}{2SW^2}\left[1-\left(\frac{f_{nb}}{f_{nt}}\right)^2\right]}_{FCF}(\Delta t - \Delta t_0) \tag{1}$$

Where S is a dimensionless shape parameter, W is the width of the U-shaped flow tube, K_u is the tube spring constant for twisting, f_{nb} and f_{nt} are the natural frequencies for bending and torsion, respectively, Δt is the zero-crossing time difference (phase) between the two pickoffs, Δt_0 is the zero-flow time difference and FCF is the flow calibration factor.

In the context of Coriolis flowmeters, flowrates are typically constrained by the minimum acceptable accuracy at the lower range and the maximum allowable pressure drop at the upper range. For gases, errors induced by vibration and compressibility effects may serve as limiting factors. The minimum flowrate for Coriolis flowmeters can then be determined using equation (2):

$$\delta(Q) = \frac{\sigma(Q_0)}{Q} + \delta_{bl} \tag{2}$$

[1] In case of Coriolis flowmeter, the uncertainties are 0.20% for oil and 0.70% for natural gas fiscal measurement. The stipulated uncertainties when Coriolis flowmeter is used as a master meter are 0.50% for gas, and for oil is used a criterion of maximum difference of 0.10% between consecutive MF.

[2] The frequencies stipulated for oil fiscal measurement are 6 months for fiscal measurement and 18 months when is used as a master meter. For gas fiscal measurement: 4 months for on-site calibration, 24 months to laboratory calibration, and 30 months if is used as a master meter.

Where $\sigma(Q_0)$ is the zero-flow stability, δ_{bl} is the baseline accuracy and $\delta(Q)$ is the accuracy at flowrate Q. Sometimes equation (2) is defined as a piece-wise function, segregated into a low flow part, governed by the zero-point stability and a high flow part, governed by the base accuracy.

2.2. Influence Factors

To achieve peak performance across a wide range of conditions, it might be necessary to implement a set of correction to the FCF. Looking at equation (1), it becomes clear that Coriolis readings might be influenced by factors that changes Coriolis mechanical configuration. However, due to the inherit fluid-structure interaction of the meter, both flow characteristics and fluid properties may also have an impact on the readings [4].

In this section, we provide a comprehensive overview of influential factors and highlight certain corrections that have been documented in the literature. It is important to note that these corrections factors serve as illustrative examples rather than an exhaustive list.

2.2.1. Temperature

In the realm of flow metering technologies, the influence of temperature on meter performance is closely related to the meter's shape and size for most cases. In the context of Coriolis flowmeters, on the other hand, the impact of temperature on the measurements is closely tied to the dynamic behavior of the oscillating tubes. Coriolis flowmeters, in general, remain relatively immune to direct thermal expansion effects; however, alterations in temperature can cause changes in meter zero and in the oscillating tubes spring constant, caused by changes in the Young and Poisson modulus [3].

Temperature effects are expected to be proportional to the changes in Young’s modulus for most of the cases. For custody transfer like uncertainties, it might not be sufficient to make theoretical corrections and tests must be carried out. As those tests are usually material and shape dependent only, the characterization should stand to all instruments of the same exact geometry, diameter and material. For most applications, where temperature will remain within the linear region of Young modulus and Poisson coefficient, the temperature correction (f_t) will usually be on the form:

$$f_t = \frac{1}{1 + \alpha_T\left(T_{op} - T_{cal}\right)} \tag{3}$$

Where α_T is the temperature coefficient, T_{cal} is the temperature of calibration and T_{op} is temperature of operation.

Most Coriolis manufacturers will implement a built-in RTD sensor, making temperature effect corrections automatic and invisible for the end-user. It is important to notice that temperature can affect fluid’s viscosity and density, subsequently influencing the Reynolds number of the flow, which can be addressed as a flow effect.

2.2.2. Pressure

Although a significant number of Coriolis meter manufacturers have created systems for automatic temperature adjustments, there is no knowledge of any manufacturer having established automatic pressure correction with built-in pressure sensors. In the case of most manufacturers, manual input of a constant value is required, or alternatively, an external pressure sensor must be installed and linked to the meter to enable automatic correction.

Pressure effects encompass the Bourdon effect, akin to tube straightening, and the Hoop effect, which involves tube stiffening. These effects appear to result in a linear decrease in readings for bent tube designs as pressure increases, while straight tubes may exhibit an overestimation [5]. The magnitude of these effects is contingent upon tube material and design characteristics such as diameter, thickness, and geometry [6]. These effects tend to be more pronounced in larger diameter tubes with thinner walls. Additionally, it is worth noting that pressure can also impact the meter's zero point. Pressure correction can be done by applying the factor (f_P) as shown in equation (4).

$$f_P = \frac{1}{1 + \alpha_P\left(P_{op} - P_{cal}\right)} \tag{4}$$

Where α_P is the pressure coefficient, P_{cal} is the pressure of calibration and P_{op} is pressure of operation. Similar to temperature effects, pressure influence is expected to be dependent of the mechanical configuration of the meter. Recent data from NEL presents compelling evidence that the pressure coefficient can be very consistent across various meters of identical models, materials, and sizes [7].

2.2.3. Reynolds Number

The interaction of the shear force caused by the measuring tubes walls and the inertial Coriolis force yields a secondary oscillating flow inside the measuring tubes. This secondary flow consumes part of the energy from the Coriolis force, thus causing an under-reading on the meter output [8].

As this phenomenon relies on the shear layer thickness, which exhibits an exponential increase as the Reynolds number decreases, the measurement error is strongly linked to the Reynolds number and is expected to influence the readings accordingly. This effect has been previously evidenced in scientific research as a viscosity effect [9] and its correlation with Reynolds number has been shown by Mills [10]. Similarly to the previous factors, the Reynolds correction (f_{Re}) can be applied directly into the FCF:

$$f_{Re} = \frac{1}{1 + \alpha_{Re}(Re)} \tag{5}$$

In this case, there is no theoretical formula for determining the low Reynolds number effect, and $\alpha_{Re}(Re)$ is a function that must be determined experimentally.

2.2.4. Compressibility and Speed of Sound

When the fluid being measured can be modelled as having an infinite speed of sound, the oscillating tubes will induce vibrations on the fluid with same frequency and phase. However, when accounting for the finite speed of sound, the fluid under measurement will become a resonator itself [4]. As the oscillating tube frequency approaches the resonant frequency of the fluid, the fluid's vibrations will undergo amplification, resulting in a higher reaction in the oscillating tubes [11].

The impact of this parameter depends on the diameter and frequency of the oscillating tubes, as well as the speed of sound on the fluid, but not on the fluid's velocity or flowrate. This influence can be corrected for by applying a constant factor (f_{SOS}) to the FCF [12]:

$$f_{SOS} = \frac{1}{1 + \alpha_{SOS}\frac{1}{2}\left(\frac{r\,\omega_d}{c}\right)^2} \tag{6}$$

Where α_{SOS} is the speed of sound coefficient, r is the tube radius, ω_d is tube angular frequency and c is the speed of sound on the fluid.

2.2.5. Fluid Velocity

The fluid velocity can impose a series of limitations to the maximum flowrate of gases. Elevated fluid velocity can introduce vibrations and compressibility effects, which can impact meter performance, as well as cause high pressure drop. For this reason, manufacturers frequently stablish a velocity limit in terms of Mach number.

Beyond these effects, high velocity can lead to a loss of independence between mass flowrate and density measurements [13]. The independence will happen when the fluid velocity (V_f) remains substantially lower than a critical velocity (V_{cr}) determined by geometry-specific parameters. However, as the condition $V_f^2 \ll V_{cr}^2$ can no longer be satisfied, both measurements may become coupled.

There is a lack of published data supporting these findings, but a simple theoretical correction has been suggested by Anklin [14] :

$$f_c = \frac{1}{1 + \alpha_v \frac{A_f \rho_f}{A_f \rho_f + A_t \rho_t} \left(\frac{2}{L \cdot \omega_d} v_f \right)^2} \tag{7}$$

Where A_f and A_t are areas of the cross sections of the fluid and the tube, respectively, and ρ_f and ρ_t are the density of the fluid and tube material, L is the length of the tube and v_f is the velocity of the fluid. The term α_v is the velocity coefficient.

2.2.6. Gas Measurement

While many parameters can be modeled and compensated for, using gas as a measurand poses significant challenges that are difficult to overcome. This is primarily due to the noise induced by turbulence in a compressible medium [15], which requires limiting the accuracy of Coriolis flowmeters to a much lower level for gases when compared to liquids. Additionally, due to speed limitations and lower density, gas flow rates must be kept in the lower range of the flowmeter, leading to a more pronounced zero effect on the accuracy.

2.3. Transferable Calibration

When a meter needs to be calibrated in laboratory facilities, replicating all operational conditions can be found to be challenging, if not impossible. Achieving some of the conditions found in real process can be hindered by budgetary, technical, and safety issues.

While ISO 10790 [16] provides valuable insights into the impact of various factors on measurements, it does not address them comprehensively. Extensive research has been conducted to gain a deeper understanding of the mechanics behind these factors and how to mitigate their effects [17]. NEL has conducted significant research with focus on industrial applications, particularly within the oil industry. Their research explored effects of temperature, pressure, fluid viscosity, and Reynolds number on various process conditions [10] [18]. Other work studied the performance of Coriolis flowmeter for gas under different conditions [19] [20]. In terms of liquid-to-gas transferability for Coriolis flowmeters, MP AGA Report No. 11 [21] states only that water-based calibration factors may be used for gases, provided demonstration through tests on third part laboratories and additional uncertainties stablished. Other studies have emphasized the capability of Coriolis flowmeters to exhibit consistent behavior across varying conditions. A study conducted by the Gas Research

Institute (GRI) stated the “The single fluid calibration tests show that a water calibration of a Coriolis mass flow meter can be used for natural gas applications without loss of accuracy” [22], while other studies, conducted by either manufacturers or independent laboratories have also been conducted [23] [24] [25].

While these references provide valuable insights into the assessment and transferable calibration, there is still a lack of solid guidelines for its evaluation.

3. Experimental Analysis

3.1. Experimental Setup and Methodology

Several Coriolis flowmeters with different geometries and dimensions, from different manufactures, as shown in Table 2 (flowmeters identified by codes), were tested. The calibrations were performed at National Institute of Standards and Technology (NIST), in USA, at Institute for Technological Research (IPT), in Brazil, at TÜV SÜD NEL, in United Kingdom and at Physikalisch-Technische Bundesanstalt (PTB) and PIGSAR, both in Germany. The tested flowmeters are usually applicable to fiscal metering and have type approval according to OIML and INMETRO’s Directorate of Legal Metrology (DIMEL) requirements. The choice of different laboratories was made to ensure that all the desired fluids and conditions were covered, respecting the designed test matrix, according to Table 3 andTable 4. Some of the conditions were overlapped in more than one laboratory, in order to guarantee the correlation between the obtained results.

Table 1: List of tested Coriolis flowmeters.

Meter Code	Size	Geometry	Correction Features			
			Low Reynolds	Pressure	Temperature	Speed of Sound
COR-1	1/2 in	A	No	No effect	Automatic	N/A
COR-2	1/2 in	A	No	No effect	Automatic	N/A
COR-3[3]	----	----	----	----	----	----
COR-4	2 in	B	No	Manual	Automatic	N/A
COR-5	3 in	B	No	Manual	Automatic	N/A
COR-6	4 in	B	No	Manual	Automatic	N/A
COR-7	6 in	B	No	Manual	Automatic	N/A
COR-8	3 in	C	Automatic	Manual	Automatic	Automatic

[3] During the data analysis, it was observed that COR-3 produced inconsistent results and it was excluded from this report.

Table 2: List of test fluids and laboratories.

Code	Tested Fluids	Laboratory
COR-1	Water (gravimetric)	NIST-USA
	Water, Mineral Oil (3 viscosities), Air	IPT-Brazil
COR-2	Water, Kerosene, Mineral Oil (3 viscosities), Air	IPT-Brazil
COR-4	Water (gravimetric), Mineral Oil (4 viscosities)	IPT-Brazil
COR-5	Water (gravimetric), Mineral Oil (4 viscosities)	IPT-Brazil
COR-6	Water (gravimetric), Mineral Oil (4 viscosities)	IPT-Brazil
COR-7	Water, Kerosene, Diesel, Siptech (3 viscosities), N2	NEL-UK
COR-8	Water, Kerosene, Diesel, Siptech (3 viscosities), N2	NEL-UK
	Water (gravimetric) and White Spirit	PTB-Germany
	Natural Gas (NG)	PIGSAR-Germany

Table 3: Test conditions for liquids.

Flowmeter	Ref. Flowrate tested for Liquids [kg/h]	Reynolds Number for Liquids [-]	Fluids Viscosities for Liquids [cSt]
COR-1	32 to 6,598	24 to 203,710	0.85 to 302
COR-2	167 to 5,547	24 to 153,450	1 to 293
COR-4	161 to 79,362	194 to 553,585	1 to 89
COR-5	3,766 to 183,244	470 to 807,000	1 to 90
COR-6	5,249 to 288,903	530 to 1,008,621	1 to 90
COR-7	44,116 to 370,708	1,468 to 856,214	1 to 137
COR-8	8,836 to 137,014	325 to 626,837	1 to 142

Table 4: Test conditions for gas.

Flowmeter	Ref. Flowrate tested for Gases [kg/h]	Reynolds Number for Gases [-]	Pressure tested for Gases [bar]
COR-1	20 to 333.8	7,654 to 119,029	4 for air
COR-2	20 to 197.3	7,732 to 76,203	4 for air
COR-8	2,814 to 54,733	1,088,493 to 13,680,250	30 and 55 for N2 30 and 36 for NG

For all tests, the flow facility was prepared for the required conditions (pressure, temperature, viscosity, and flowrate) and allowed to stabilize. The stabilization period varied by laboratory but was typically around 30 minutes. Once satisfied that the device was stable[4], the upstream and downstream valves of the meter were closed to perform the zero-point check. Some laboratories, by procedure, perform the zero procedure three to five times, until the zero-point value varies within a predetermined tolerance. Other laboratories perform

[4] Some Coriolis manufacturers recommend checking that the Coriolis tube temperature is within ± 1 °C of the fluid temperature.

pre calibration zero check, post zero check[5] (if applicable), and post calibration zero check for each calibration.

In the preparation of the test matrix, the parameters were determined to assure the proper functioning of the flowmeter, considering the minimum and maximum limits of mass flow, maximum flow velocity, number of repeat test points, installation positions, cavitation and condensation conditions.

3.2. Results

3.2.1. Results for Liquids

Figure 1 shows the results for the calibrations of flowmeter COR-4 to COR-7 (2 to 6 inches) for all liquids according to Table 23, where the error is plotted as function of pipe Reynolds number. For COR-4 to COR-6, the average expanded uncertainty for water was 0.093% (varying between 0.060% to 0.340%) and for other liquids was 0.11% (varying between 0.080% to 0.380%). For COR-7 the expanded uncertainties were 0.15% for water, 0.080% for diesel and kerosene and 0.25% for Siptech. No correction factors for pressure or Reynolds number were applied to any of the meters.

The deviation in meter error exhibits a logarithmic pattern within the lower Reynolds number range, for Re<25,000, with variations observed for each specific diameter. Dotted lines represent the logarithmic regression fitted with the weight function outlined in equation (8), while the shaded region indicates the 95% confidence intervals[6].

$$w_i = \frac{1}{\sqrt{\left(\frac{U_i}{2}\right)^2 + \left(\frac{\delta(Q_i)}{\sqrt{3}}\right)^2}} \tag{8}$$

Where U_i is the expanded uncertainty and $\delta(Q_i)$ is the manufacturer's stated accuracy for each point.

The slope coefficients reveal that the impact of Reynolds numbers is more pronounced for larger diameters, except in the instances of COR-6 and COR-7. However, in these cases, the confidence intervals for slope overlap, making it statistically inconclusive to determine which one possesses a steeper slope. The curve fittings coefficients and uncertainties are shown in Table 5.

[5] The post zero check is a method used by TÜV SÜD NEL to ascertain whether the new zero is acceptable prior to the calibration commencing.

[6] The curve adjustments presented here are not intended as recommendations, and they should be decided by either the user or the manufacture.

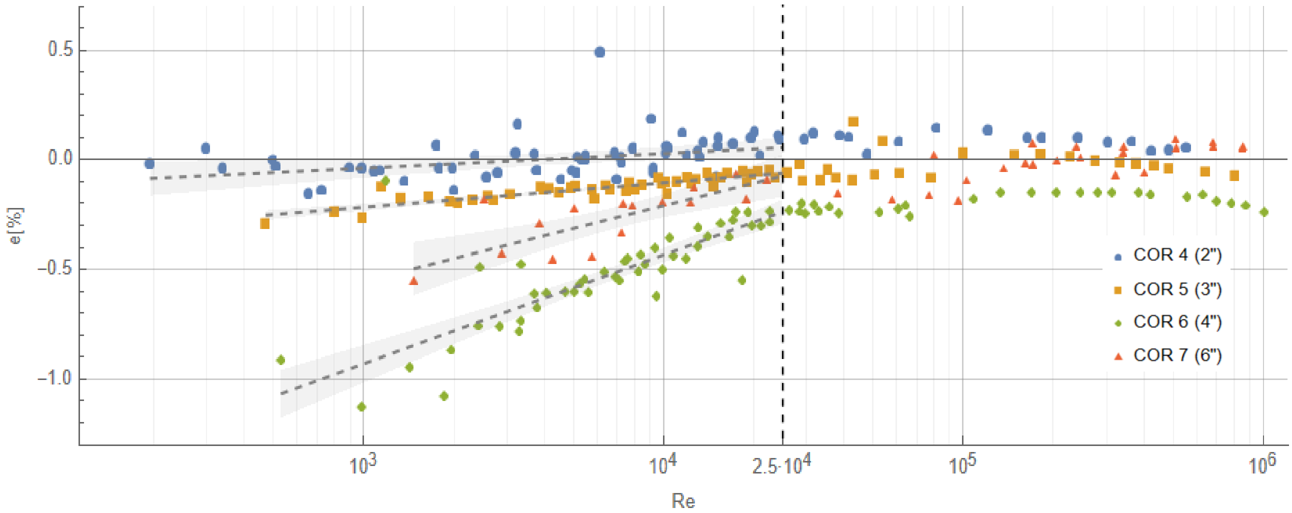

Figure 1: Error as function of pipe Reynolds number for COR-4 to COR-7 (all liquids).

Table 5: Low Reynolds curve fitting for COR-4 to COR-6.

	Before Correction	**Fitted curve**		**After Correction**
	Error Band[7] [%]	Re Range	Coefficients ($aLog(Re) + b$)	Error Band [%]
COR-4 (2")	+0.14 to -0.16	Re<25000	a=0.028±0.023, b=-0.237±0.19	+0.14 to -0.04
COR-5 (3")	+0.03 to -0.30	Re<25000	a=0.048±0.008, b=-0.551±0.07	+0.03 to -0.10
COR-6 (4")	-0.15 to -1.13	Re<25000	a=0.215±0.039, b=-2.417 ±0.35	-0.11 to -0.37
COR-7 (6")	+0.09 to -0.55	Re<25000	a=0.149±0.070, b=-1.584±0.61	+0.09 to -0.19
COR-8 (3")	+0.14 to -0.66	Automatic correction		+0.14 to -0.12

Figure 2 and 3 provides a beakdown for COR-5 and COR-6. Following the correction for low Reynolds numbers, all data points for COR-5 fall within the meter accuracy as specified by the manufacturer, while COR-6 shows errors as low as -0.37%. In both cases, an aditional mass factor adjustment could be completed and an "as left" calibration performed, which would bring both of them to within manufacturer specified performance. The error bands before and after low Reynolds number correction can be checked on Table 5.

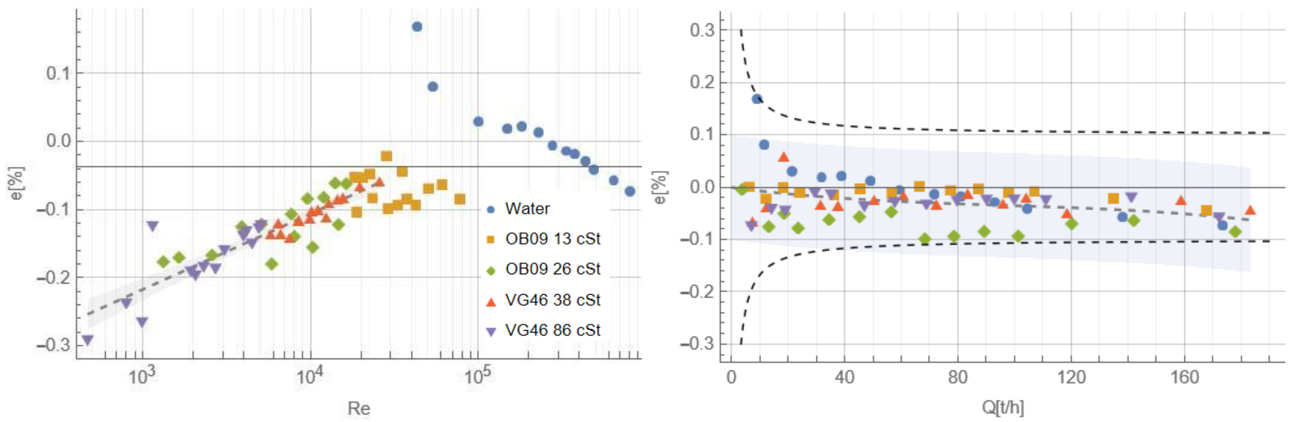

Figure 2: Results uncorrected (left) and after low Reynolds number correction (right) for COR-5 (3").

[7] Excluding outliers and points affected by zero-point stability.

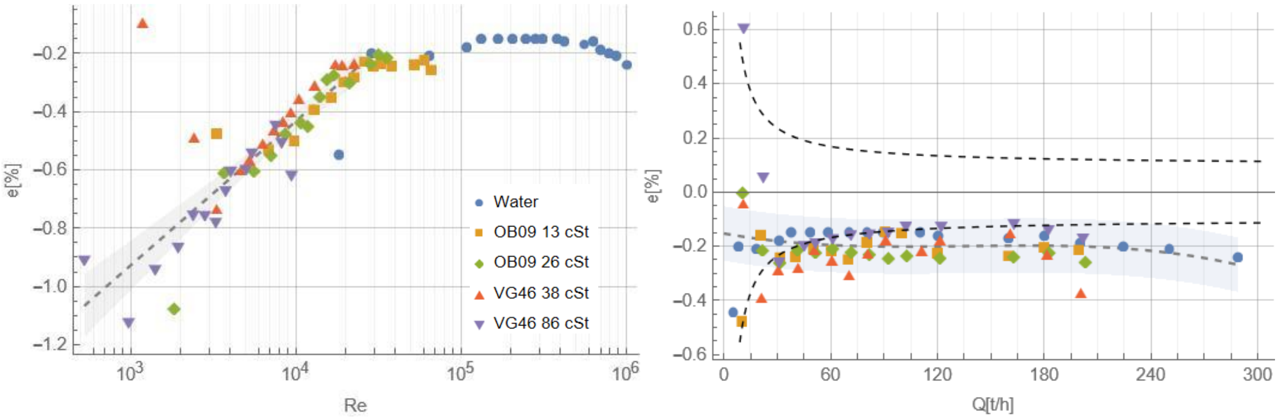

Figure 3: Results uncorrected (left) and after low Reynolds number correction (right) for COR-6 (4”).

Figure 4 shows the results for the calibrations of COR-8 (3 inches), with errors plotted as function of Reynolds number and as function of mass flowrate. This flowmeter has an internal automatic low Reynolds number correction feature which can enhance the meter performance for high viscosity fluids. The graphic shows that the most of the meter errors stay within 0.1% error for flows at Reynolds as low as 1,000, except for a few points at the low end of mass flowrate range. For Siptech 132 cSt, Reynolds number correction feature was disabled to compare the results with and without this feature. Figure 4 shows in details the results for Siptech with and without Reynolds number automatic correction. The average expanded uncertainty for water was 0.155% at NEL and 0.020% at PTB, 0.031% for diesel, 0.080% for kerosene, 0.10% for white spirit and 0.25% for Siptech. The error bands with and without the automatic low Reynolds number correction feature can be checked on Table 5.

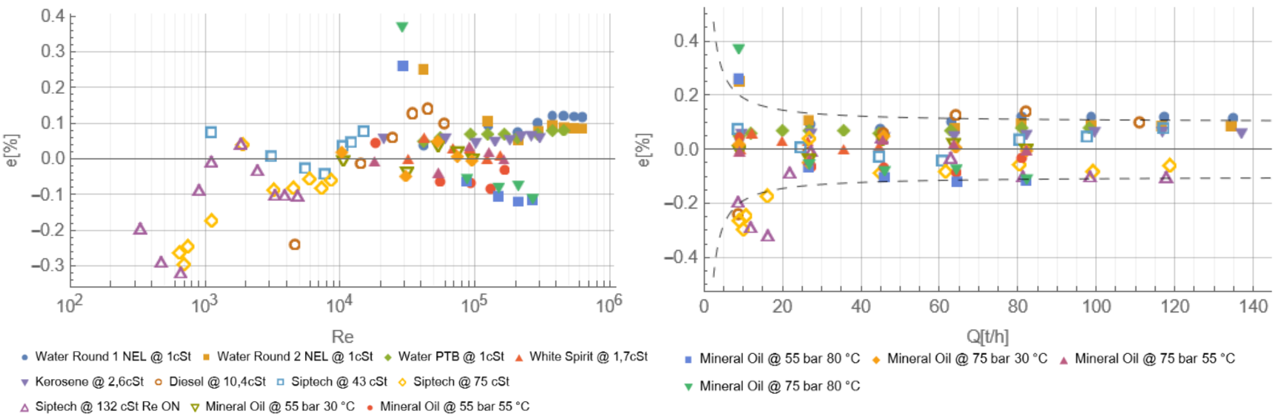

Figure 4: Error as function of pipe Reynolds number (left) and ref. mass flowrate (right) for all liquids for COR-8 (3”).

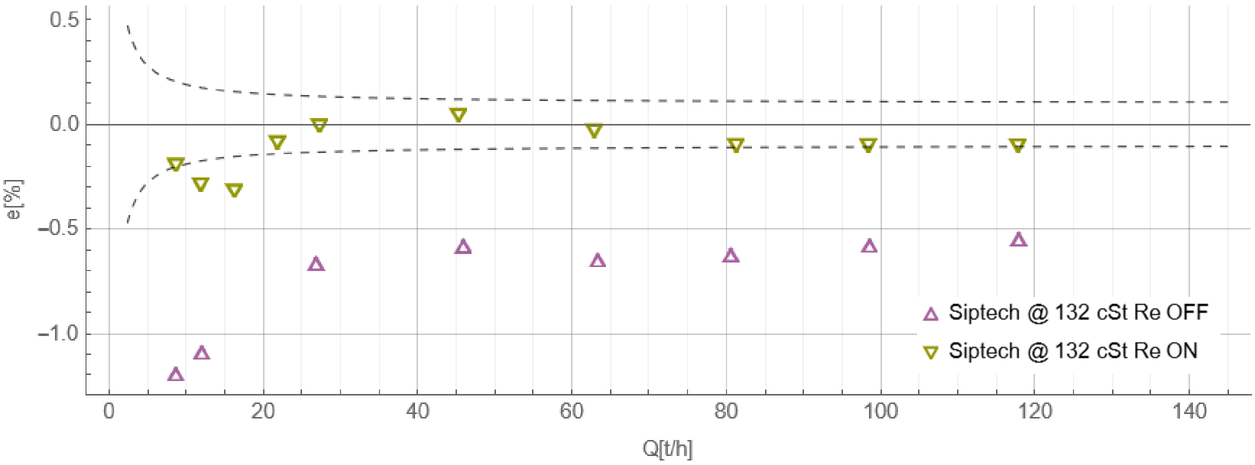

Figure 5: Results of COR-8 (3") with and without automatic low Reynolds number correction feature activated.

Figure 4 and 7 presents the outcomes of the calibrations for COR-1 and COR-2 (both ½ inch) across various liquids, as outlined in Table 2 and 3. The calibration errors are depicted as a function of the pipe Reynolds number and mass flowrate. Notably, the graphic reveals a pronounced zero effect in both COR-1, which could potentially stem from inadequate zeroing procedures. Despite the presence of these undesirable data points, they do not compromise the integrity of the analysis. Furthermore, it is evident that both meters exhibit more pronounced errors at higher flowrates, though they do not appear to exhibit a strong correlation with the Reynolds number. COR-1 and COR-2 were calibrated in the same piston prover at IPT, and the average expanded uncertainty for water was 0.078% (varying between 0.052% to 0.425%) and for other liquids was 0.087% (varying between 0.050% to 0.417%). COR-1 was also calibrated with water at NIST and the average expanded uncertainty was 0.031%. No correction factors for pressure or Reynolds number were applied to any of the meters.

Both meters exhibit a consistent underreading tendency, with deviations reaching as low as -0.87%. This trend is especially evident when measuring more viscous fluids. The results of COR-1 were verified against a second uncorrelated standard, which produced similar results. The mechanism behind this effect remains unknow but it might be connected to the significant pressure variation within the measuring tubes.

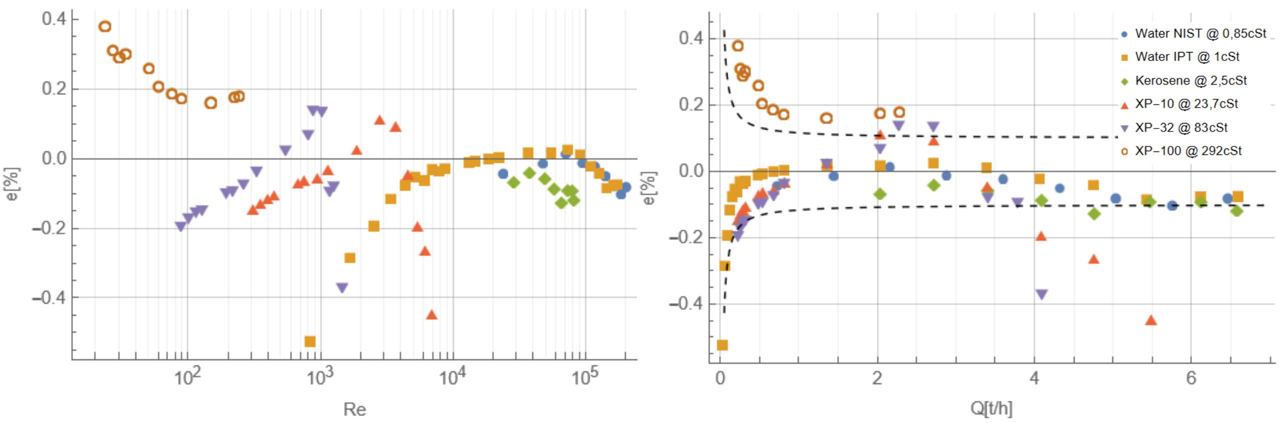

Figure 6: Error as function of Reynolds number (left) and ref. mass flowrate (right) for all liquids for COR-1 (½").

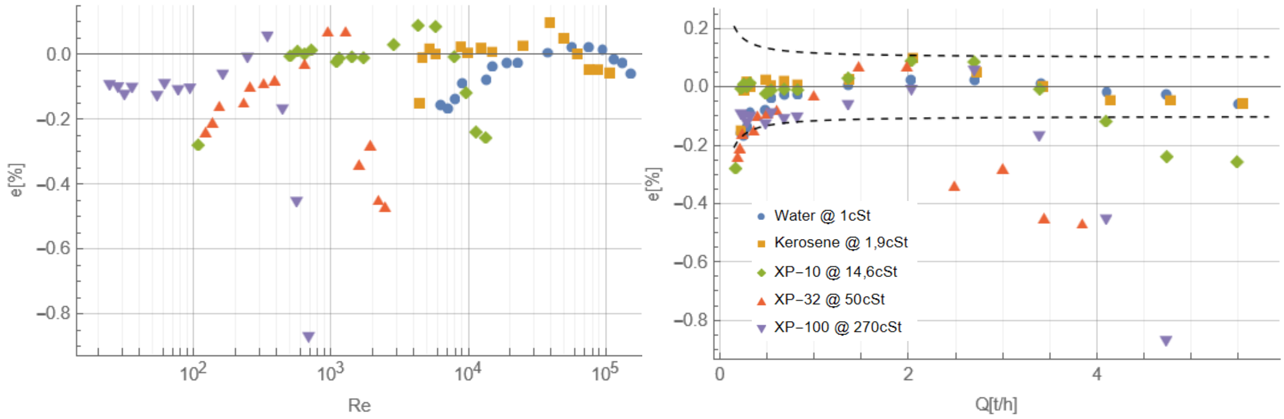

Figure 7: Error as function of Reynolds number (left) and mass flowrate (right) for all liquids for COR-2 (½”).

3.2.2. Results for Gas

Figure 8 shows the results for COR-1 with water and air. The results show good agreement with water baseline calibration. However, low flowrates (< 100 kg/h) diverge from water calibration, due to meter zero-point influence. COR-1 average expanded uncertainty for water was 0.078% (IPT) and 0.031% (NIST), and 0.51% for air. Excepting for the low flowrate region, the deviations varied from 0.02% to -0.09% for water and 0.10% to 0.25% for air.

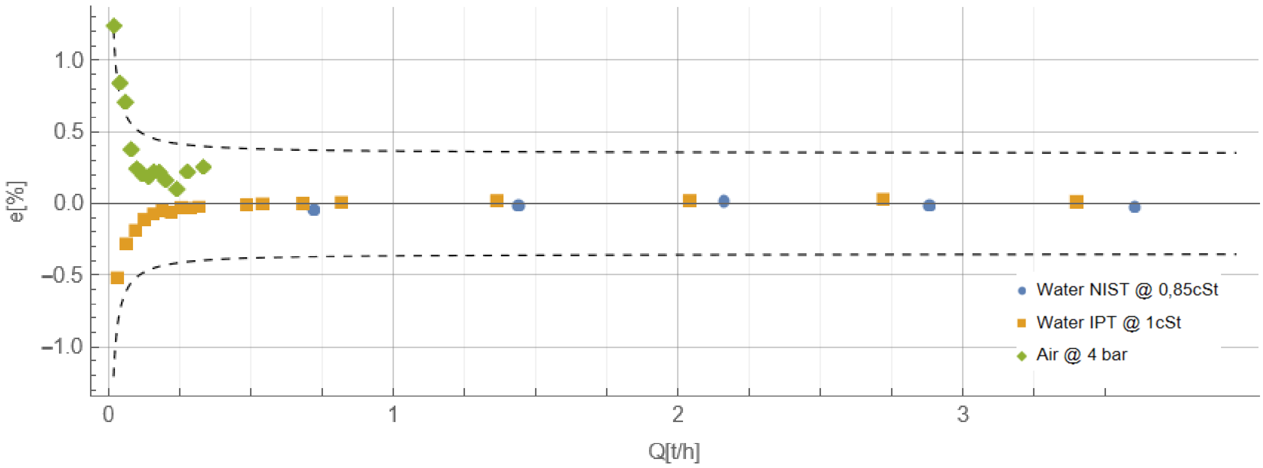

Figure 8: Results for water and air for COR-1 (½”).

Figure 9 shows the results for COR-7 with both water and nitrogen. The meter shows good agreement between water baseline calibration with a maximum error of around 0.30%. The average uncertainty for water was 0.15% and for nitrogen was 0.153%. The errors varied from -0.096% to 0.090% for water, -0.002% to 0.29% for N2 at 45 bar, and 0.14% to 0.27% for N2 at 57 bar. The correction factor for pressure was applied according to the factor indicated by the manufacturer’s manual.

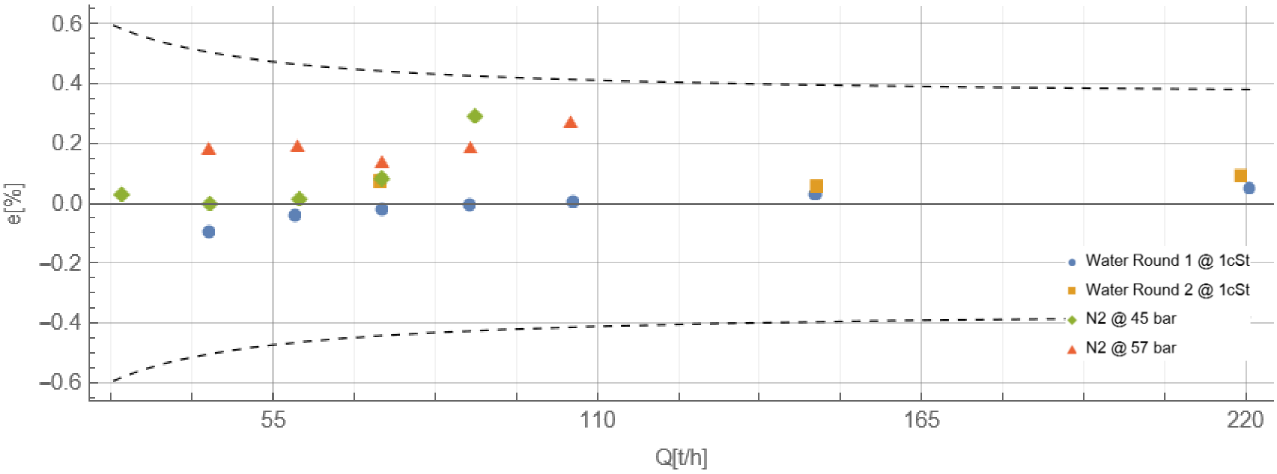

Figure 9: Results for water and nitrogen for COR-7 (6").

Figure 10 shows the results for COR-8 with water (NEL and PTB), nitrogen and natural gas. The meter shows good agreement between water baseline calibration with a maximum error of around 0.67%. The average expanded uncertainty was 0.35% for nitrogen and 0.28% for natural gas. The errors varied from 0.037% to 0.25% for water at NEL, 0.049% to 0.079% for water at PTB, -0.042% to -0.28% for N2 at 30 bar, -0.26% to -0.42% for N2 at 55 bar, 0.14% to 0.41% for NG at 30 bar and 0.13% to 0.19% for NG at 36 bar. The correction factor for pressure was applied according to the factor indicated by the manufacturer's manual.

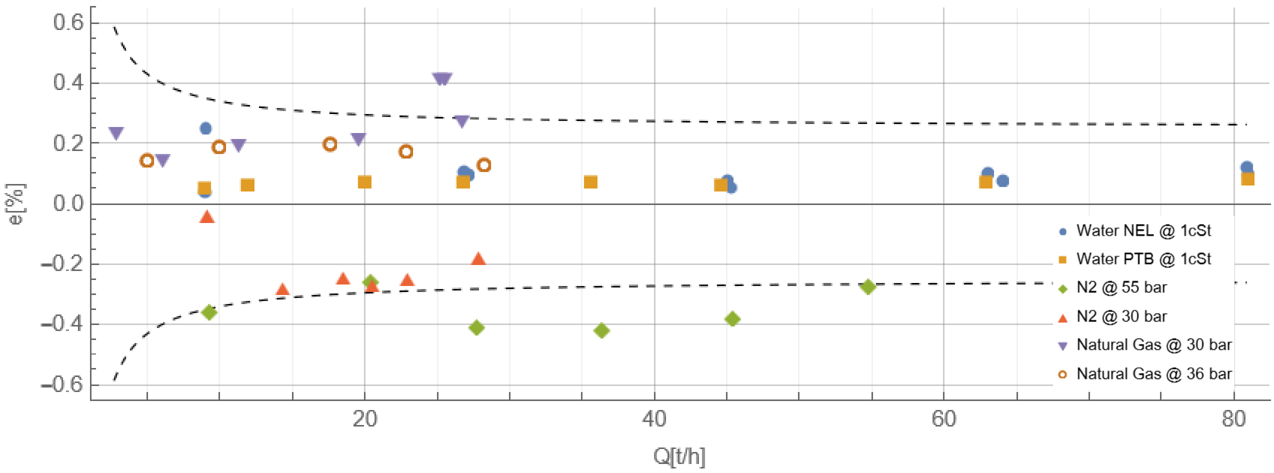

Figure 10. Results for water, nitrogen and natural gas for COR-8 (3").

3.2.3. Pressure and Temperature Influence

COR-8 flowmeter was tested at pressures up to 75 bar and temperatures up to 80 ºC. Pressure correction was disabled but the meter had no option to disable temperature correction. Figure 11 shows the results before and after pressure correction, highlighting the importance of pressure correction. Upon its application, all deviations remain within the manufacturer's stipulated specifications. The average uncertainty for mineral oil was 0.080%. The linear regressions showed a slope of -0.0100%/bar with an uncertainty of 0.0004%/bar (at 95% confidence level), which differed from manufacturer's specification by only 0.001%/bar. This difference can be explained by the calibration uncertainties.

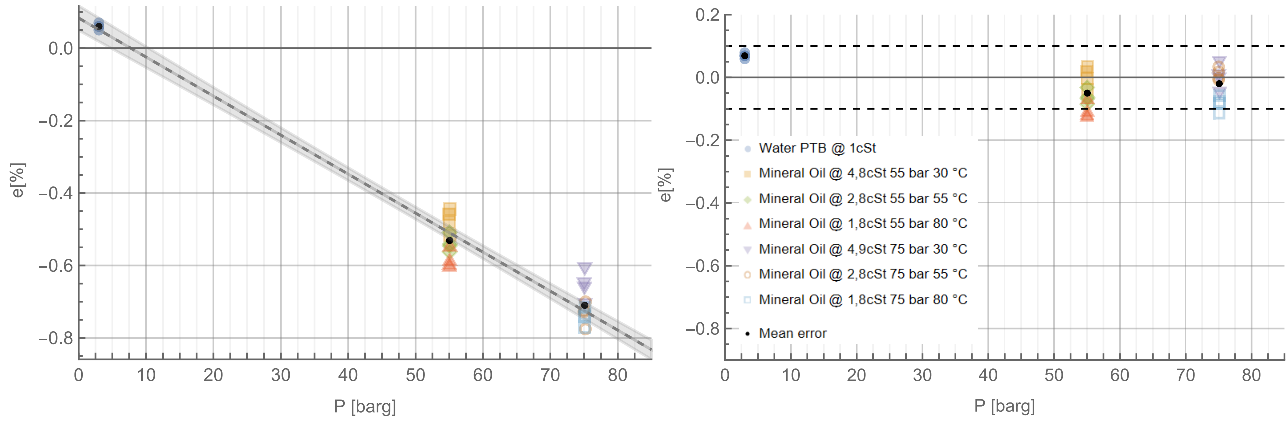

Figure 11: Results of COR-8 (3”) for high temperature and pressure tests (EPAT). Without pressure correction (left) and after applying manufacturer’s pressure correction in post processing (right).

For COR-7 the regression results indicates a pressure infleuence of -0.022±0.002%/bar, in agreement with manufacturer specification, as shown in Figure 12.

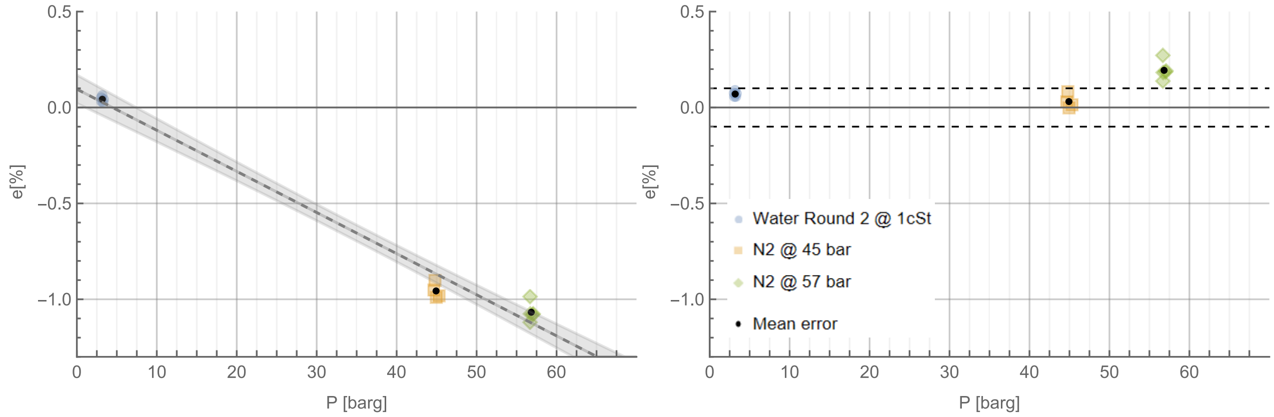

Figure 12: Results of COR-7 (6”) for water and nitrogen at two different pressures without pressure correction (left) and after applying manufacturer’s pressure correction in post processing (right).

4. Suggestions for Transferable Calibration

To assess the feasibility of operating Coriolis flowmeters under conditions different from the operating environment, it is essential to evaluate the meter for its sensitivity to each parameter's influence and its ability to correct results accordingly. To facilitate this process, we recommend a testing protocol to be applied both in a "type test" and initial verification stages. Furthermore, we provide guidelines for conducting subsequent calibrations. Additionally, we propose a simplified method for determining measurement uncertainty after applying all necessary corrections.

4.1. Test Protocol

The main concept of this protocol is to provide guidelines for a comprehensive characterization of the meter, in order to determine limits in which the meter can perform within the desired accuracy[8].

[8] It is important to emphasize that these tests do not replace the necessity for type approval; therefore, meters must still undergo the standard type approval process.

The reference conditions must be stablished prior to the testing, so that a baseline calibration can be performed. The reference condition will be typically water or a low viscosity oil at low pressure. The correction curves need to be established before conducting the tests, or alternatively, the automatic correction features should be activated. The analysis of the data will be based on the differences between the test condition after corrections and the reference condition.

The protocol will comprehend a type test, initial verification and subsequent calibration, as shown below.

- Type testing[9,10]
    - Calibrate in reference fluid[11].
    - Determine temperature coefficient/influence:
        - Determine temperature interval.
        - Test at least 3 temperatures, evenly distributed.
        - Apply corrections (if any) and calculate maximum deviations to baseline calibration
    - Determine pressure coefficient/influence:
        - Determine pressure interval (or maximum pressure available).
        - Test at least 3 pressures, evenly distributed.
        - Apply corrections (if any) and calculate maximum deviations to baseline calibration.
    - Determine Reynolds number influence
        - Determine desired limits for viscosity and Reynolds number.
        - Test the meter with at least the reference fluid and another 2 extra fluids and 3 viscosities, 6 flowrates each over entire mass flowrate range. Neighbor viscosities should have overlapping points in terms of Reynolds number.
        - Apply corrections (if any) and calculate maximum deviations to baseline calibration.
    - Gas flow
        - Determine gas velocity range.
        - Test in natural gas over the mass flowrate range and velocity ranges[12].
        - Test in alternative gas over the mass flowrate range and velocity ranges.
        - Apply corrections (if any) and determine maximum difference between baseline calibration and at different gases.
- Initial verification/calibration[13]
    - Calibrate in reference fluid.
    - For liquids: calibrate with 2 viscous fluids over entire mass and Reynolds range.
    - For gas: calibrate with NG or alternative gas over mass flowrate.
- Subsequent calibrations
    - Over the desired mass flowrate range with reference fluid (water)
    - First recalibration:

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[9] For each model/geometry/diameter

[10] In order to provide confidence and guarantee that results are repeatable, it is a good measure to repeat the "type test" with multiple samples.

[11] For this study, the reference fluid was water, being used as baseline calibration for transferability analyses.

[12] The gas mass flow is typically reduced to 20% of the liquid mass flow due to differences in fluid density. As such, when calibrating in water for gas use, the meter is now being calibrated at a much lower mass flow range. This results in the potential for zero effects from the Coriolis meter to be contended with. Precautions must be taken when sizing a flow meter with respect to calibration requirements, differences in density, and the resultant mass flow range. One potential approach could involve matching the turndown of the meter. For example, if, in gas operation, the meter is operated from 15% to 80% of the Coriolis meter's gas mass flow range, then the calibration in water would match the 15% to 80% turndown for the liquid mass flow range rather than the actual mass flow.

[13] Initial verification/calibration should be carried out for each unit

        - For liquids: with reference fluid and viscous fluid over Reynolds number/mass flowrate range
        - For gas: with reference fluid and gas over mass/turndown[12].
    - Other recalibrations: only with reference fluid over mass flowrate[12][14].

4.1.1. Transferability Evaluation

The combined uncertainty arising from calibration and corrections, referred to as measurement uncertainty (U_m) here, must conform to a maximum uncertainty (U_{max}), which should be specified by the regulatory bodies. The guide to the expression of uncertainty in measurement (GUM) [26] should be used as a reference for the calculation. A simplified equation can be derived [27] [15]:

$$U_{m,\%} = t_{95\%}\sqrt{\left(\frac{U_{cal,\%}}{2}\right)^2 + \sum\left(\frac{U_{i,\%}}{k_i}\right)^2} \leq U_{max} \quad (9)$$

Where $U_{cal,\%}$ is the relative baseline expanded calibration uncertainty and $U_{i,\%}$ and k_i are the relative expanded uncertainty and coverage factor for each of the correction factors.

To estimate the measurement uncertainty (U_m), we that propose temperature and pressure to be treated as linear corrections with defined coefficient and uncertainty. For alternative fluids (Reynolds number correction and liquid-to-gas transferability), the associated uncertainty could be estimated as the composition of calibration uncertainties and the maximum deviation to baseline calibration ($k = \sqrt{3}$)[16], after corrections. **Feil! Fant ikke referansekilden.** shows U_m at the most critical points for some of the tested flowmeters:

Table 6: Analysis and uncertainty budget for calculation of measurement uncertainty.

	Transferability	U_{cal}	U_i		U_m	Application
		Baseline	Re	Water-Gas		
COR-5	Liquid-liquid	0.06%	0.14%	-	0.16%	Fiscal/Custody Transfer
COR-6	Liquid-Liquid	0.06%	0.18%	-	0.19%	Fiscal/Custody Transfer
COR-7	Liquid-Liquid	0.15%	0.27%	-	0.31%	-
COR-7	Liquid-Gas	0.15%	-	0.35%	0.38%	Master meter
COR-8	Liquid-Liquid	0.02%	0.22%	-	0.22%	-
COR-8	Liquid-Liquid[17]	0.02%	0.16%	-	0.20%	Fiscal/Custody Transfer
COR-8	Liquid-Gas	0.02%	-	0.58%	0.58%	Fiscal/Custody Transfer

The results indicates that most of the flowmeters meet the requirements for fiscal and custody transfer applications, considering limits indicated in the draft of the regulation[1]. The exceptions are COR-7 for liquid-liquid transferability, which showed a measurement uncertainty of around 0.31%, and COR-8 for viscosities above 76 cSt. COR-7 would be accepted for both fiscal/custody transfer application and as a master meter for gas.

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[15] Simplified equation for relative uncertainties and baseline calibration with coverage factor k=2 for 95% confidence level.

[16] According to section 9.9.1.1 of the draft regulation (RTM), when it is not possible to fully or partially compensate for systematic errors, residual errors must be included in the measurement system's uncertainty.

[17] Fluid Siptech 132 cSt and high pressure and temperature points disconsidered.

4.2. Alternative Fluids

To ensure accurate results when using alternative fluids, it is important that these substitutes have properties that are similar to the original fluid. The graphics below show speed of sound and density for four specimens: natural gas, air, nitrogen and carbon dioxide. The data were obtained by AGA 8 equations for natural gas [28] and NIST's Refprop 9.1 [29] for the other 3 fluids. Figures 13 and 14 shows density and speed of sound for natural gas (78% methane, 2% nitrogen, 6% CO2, 8% ethane and 3% propane composition), air, nitrogen and carbon dioxide, as function of pressure and temperature.

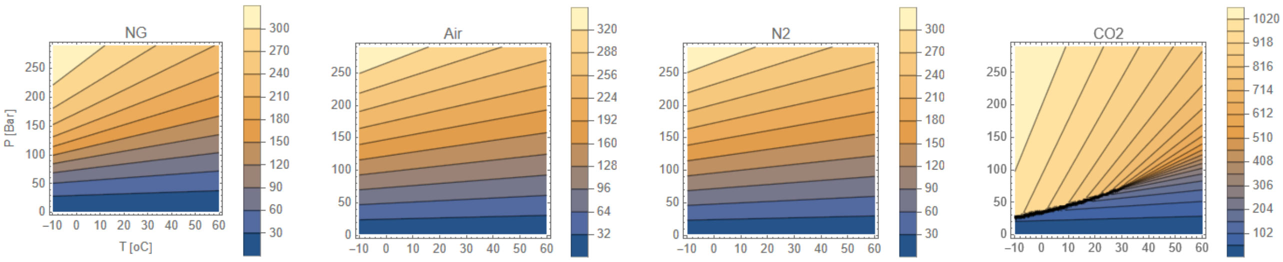

Figure 13: Density [kg/m3] for different gases as function of pressure (vertical axis) and temperature (horizontal axis).

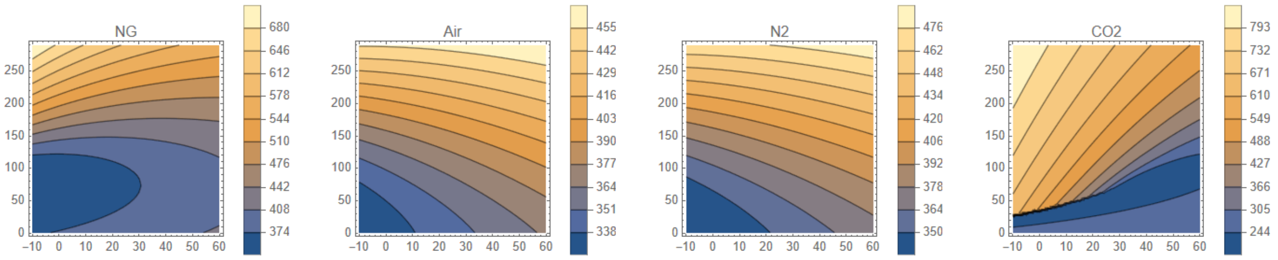

Figure 14: Speed of sound [m/s] for different gases as function of pressure (vertical axis) and temperature (horizontal axis).

Although under standard temperature and pressure (20 °C and 1 atm), there are significant differences in both the speed of sound and density between these fluids and natural gas, as pressure increases, these properties tend to converge towards those of natural gas, making them good alternatives for calibration, as shown in Figure 15. On the other hand, carbon dioxide could be a good alternative when trying to match the mass flowrate of natural gas at higher pressures.

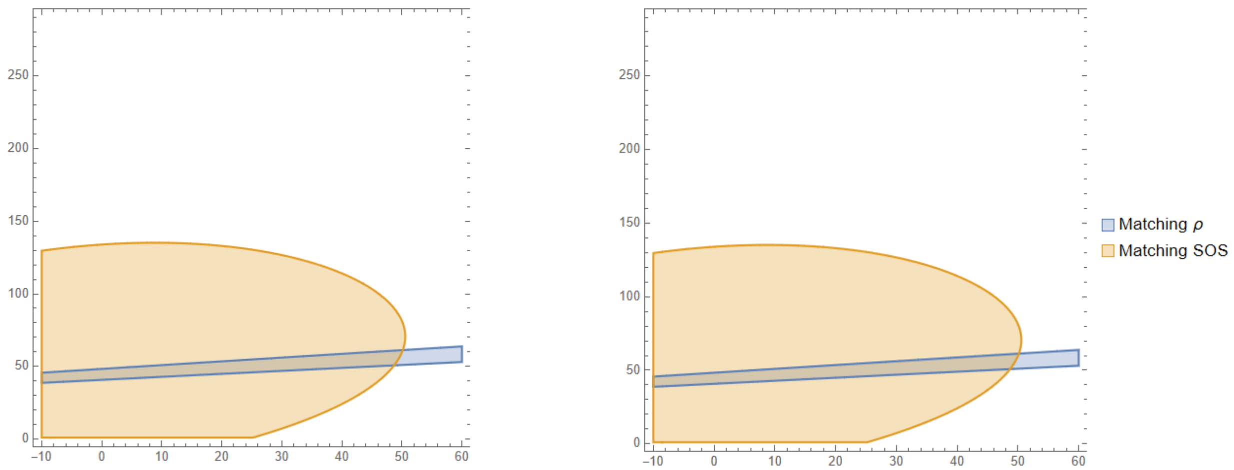

Figure 15: Matching density and speed of sound (withing 10%) region for air (left) and nitrogen (right) with natural gas. Air and Nitrogen are plotted for T=25 °C and P=40 bar.

5. Conclusions

This study, along with other published data, shows that Coriolis flowmeters have some unique advantages over other technologies. The fact that it is a true mass meter allows it to measure the flowrate of any kind of fluid, regardless of operational conditions. The same flowmeter can be used to measure liquids of different properties and gases of different compositions, with a similar calibration factor.

It is necessary, however, that, for fiscal measurements-like uncertainties to be achieved, a series of corrections must be applied, as exposed in section 2.2. In order to guarantee that the measurement uncertainty comply with the regulations, the meter must be tested at different condition and a measurement uncertainty must be calculated, accounting for the correction factors and unexplained errors. The decision of whether a meter could be calibrated under alternative conditions or not will fall ultimately on the analysis of the measurement uncertainty.

6. Final Remarks

The conclusions and suggestions presented here are exclusively relevant under the following conditions: single-phase, homogeneous flow and dry gas[18], and pertain solely to the application of beam mode Coriolis flowmeters. It's essential to note that the results and conclusions derived from this study do not, in any way, negate the requirement for type approval as dictated by current regulations. The authorization and implementation of the conclusions drawn from this work fall within the exclusive jurisdiction of regulatory authorities.

7. Acknowledgments

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