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Coriolis flow technology in H_2 and CO_2 measurement: key questions and answers to make reliable measurement happen in industrial applications

Technologia przepływu Coriolisa w pomiarach H_2 i CO_2: kluczowe pytania i odpowiedzi, aby umożliwić niezawodny pomiar w zastosowaniach przemysłowych

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Keywords: *carbon dioxide, Coriolis, measuring systems*

Abstract

The need for reliable measurements of H_2 and CO_2 is no longer an industrial challenge connected only to process optimization goals. Accurate accountability of H_2 and CO_2 has become an essential requirement with wider social responsibility to mitigate the impact of global warming and achieve Net Zero Energy targets. As the industry advances projects to produce and transport H_2, regulations and research projects attempt to develop the guidelines and legislations necessary to support accelerating readiness for the energy transition, while establishing a unified governance to the quality and measurement controls. Unlike H_2, there are various forms of regulations, standards and legislations to govern CO_2 emissions. These can vary significantly as it relates to the control measures and methods. While the global economy reaches a uniform approach to define and govern the elements of H_2 and CO_2 for the purpose of the energy transition, the most urgent question is how to accurately account and report H_2 and CO_2. The common consensus among industry leaders and technical researchers indicate that Coriolis Flow Metering is the most versatile and accurate technology to measure H_2 and CO_2 throughout the value chain in various phases.

Słowa kluczowe: *dwutlenek węgla, Coriolis, systemy pomiarowe*

Streszczenie

Potrzeba wiarygodnych pomiarów H_2 i CO_2 nie jest już wyzwaniem przemysłowym, związanym wyłącznie z celami optymalizacji procesów. Dokładne rozliczanie H_2 i CO_2 stało się zasadniczym wymogiem, który wiąże się z szerszą odpowiedzialnością społeczną, w zakresie łagodzenia skutków globalnego ocieplenia i osiągania celów zerowego zużycia energii netto.W miarę jak branża rozwija projekty dotyczące produkcji i transportu H_2, przepisy i projekty badawcze dążą do opracowania wytycznych i przepisów, niezbędnych do przyspieszenia przygotowań do transformacji energetycznej, przy jednoczesnym ustanowieniu jednolitego zarządzania kontrolą jakości i pomiarów. W przeciwieństwie do zagadnień dotyczących H_2, istnieją różne formy przepisów, norm i ustawodawstwa regulującego emisję CO_2, które mogą się znacznie różnić w odniesieniu do środków i metod kontroli. Chociaż globalna gospodarka osiąga jednolite podejście do definiowania i regulowania składników H_2 i CO_2 na potrzeby transformacji energetycznej, to najpilniejszym pytaniem jest, jak dokładnie rozliczać i raportować ilości H_2 i CO_2. Zgodnie ze wspólną opinią liderów branży i badaczy technicznych, przepływomierz Coriolisa jest najbardziej uniwersalną i dokładną technologią pomiaru dla H_2 i CO_2 w całym łańcuchu wartości na różnych etapach.

1. CO_2 operating conditions for Industrial applications

The expected operating phases of CO_2 for the industrial sector cover gas, liquid and supercritical physical states. What is important to consider is the temperature and pressure ranges. A number of existing publications discuss the potential operating temperature and pressure ranges for CO_2 applications across the value chain. For example, in publication [9] the authors evaluated a range of flow metering technologies at the following applications along the CO_2 transport line:

- ship loading/offloading liquid phase with vapour return
- pipeline injection in liquid phase
- offshore pipeline in liquid and gas phase
- onshore pipeline in supercritical phase

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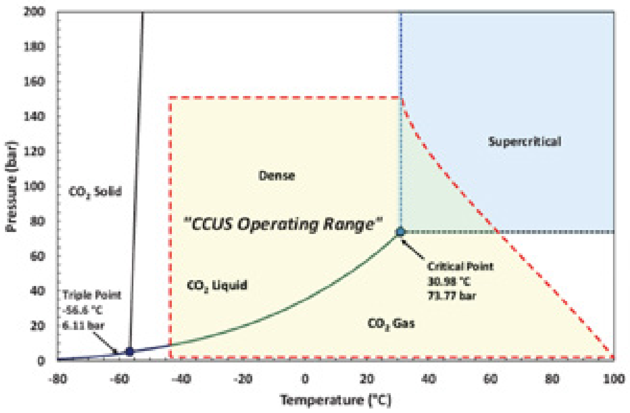

Fig. 1 – CCUS expected operating conditions for industrial applications as described in [11]

Rys. 1 – Oczekiwane warunki pracy CCUS dla zastosowań przemysłowych, jak opisano w [11]

The phase diagram of the CO_2, Figure 1, is used to propose the potential window of operation for the CCUS industry [11]. It describes the expected operating window to be in temperature ranges of – 40 °C to 100 °C with an expected operating pressure up to 150 bar, including the dense/supercritical phase. In some cases, higher operating pressure (nearly 200 bar) may be required to achieve higher transportation efficiency.

From a measurement standpoint, the main differences between gas, dense/liquid and supercritical phase include the density and the velocity of sound in CO_2.

2. Hydrogen operating conditions for industrial applications

Hydrogen is associated with more complex challenges due to its physical properties such as low normal density (0.083 kg/m3), high speed of sound (1320 m/s) and extremely cryogenic temperature conditions at liquid phase (-253 ºC). Therefore, numerous studies have been undertaken to identify efficient and economical methods for transportation and utilization of hydrogen as an energy carrier. The most discussed methods include:

- hydrogen enriched natural gas
- compressed hydrogen gas
- liquid hydrogen
- ammonia
- liquid organic hydrogen carriers

2.1. Hydrogen enriched natural gas

Mixing hydrogen with natural gas in existing distribution networks is one approach for utilization of hydrogen as an energy carrier with the desire to reduce carbon emissions in the near-term or to extract the hydrogen after transportation for other purposes. Some studies suggest that the addition of hydrogen would affect the transportation efficiency in terms of operating pressure, temperature, pipeline and energy capacity, etc. [15] [2]. Nonetheless, it is expected that most hydrogen enriched natural gas network will continue to operate in the range of 15 to 100 bar, assuming that measures are taken to address the effects of various hydrogen concentrations.

2.2. Compressed hydrogen gas

In the long term, compressed hydrogen gas will be transported via a network of new and retrofitted natural gas pipelines. The combined distribution network could operate in a similar way to the typical natural gas distribution networks, with operating pressures ranging from 20 to 78 bar as is anticipated for the European Hydrogen Backbone [18]. Compressed hydrogen gas will also be transported via tube trailers to the various hydrogen refuelling stations that will not be adjacent to hydrogen production platforms. The containers on the transportation trucks are pressurized up to 250 bar and can go to as low as 15 bar upon discharge at the fuelling stations [16]

2.3. Liquid hydrogen

In liquid phase, hydrogen has a density of approximately 80 kg/m3 at – 253 ºC and atmospheric pressure. That is multiple orders of magnitude higher than the density in gaseous phase at ambient conditions suggesting that long distance transportation of hydrogen in liquid phase may be more efficient [14]. Yet, due to the extremely cryogenic conditions, safe storage and transportation would require technologically complex and energy intensive means.

2.4. Ammonia and liquid organic hydrogen carriers

Another form of hydrogen transportation is through chemically binding the hydrogen into chemicals such as ammonia or through a process called hydrogenation where the hydrogen is bonded with organic chemicals such as toluene, dibenzyltoluene or N-ethylcarbazole. This facilitates high storage density and process conditions similar to existing storage and distribution infrastructure for fuel products such as diesel and gasoline.

In this paper, the focus will be on the flow measurement applications for pure hydrogen and hydrogen enriched natural gas.

3. Coriolis Flow meter vs H_2 And CO_2

Coriolis technology has been extensively used for decades in applications with extremely harsh conditions while mandating high measurement accuracy requirements. For example, in low temperature applications, Coriolis meters have been successfully used for accurately measuring LNG and LN_2 at temperatures as low as – 190 ºC [Wu T.Y. and co., 2021] and even in super cryogenic applications with temperatures ranging from – 250 ºC to – 270 ºC [8]. In high temperature applications such as asphalt production, Coriolis flow meters are operated successfully at temperatures up to +350 ºC. In terms of high-pressure applications, one example is CNG measurement with a typical operating pressure up to 300 bar. Another good example of a Coriolis meter application at high pressure is the hydrogen refuelling station where the operating pressure can go up to 700 bar [1].

Considering that H_2 and CO_2 applications fall within these extremes, the conclusion of this paper is that Coriolis flow meters will be more than suitable for H_2 and CO_2 measurement applications discussed in section 1 and 2. Safety considerations like material compatibility relevant to supercritical conditions as described in [4] are out of the scope of this paper.

The potential influences of impurities to the boundaries of the CO_2 phases and potential two-phase operations have been discussed extensively in numerous publications. For example, Liu and Fuent attempt to propose a method for correcting accuracy performance of mass measurement in multi-phase flow [10]. However, for the purpose of this paper, the topic is metrological performance of Coriolis meters at single phase (either gas, liquid or supercritical), since single phase measurement is the basis for custody transfer applications and the primary driver for development of metering standards.

3.1. Main influencing factors on Coriolis mass measurement

As mentioned previously, the Coriolis flow meter technology covers a wide range of applications with different conditions. There is a list of commonly known effects which impact the final results of the measurement with the Coriolis flow meter. The contribution of each of these effects to the final measurement uncertainty will vary from one application to another. Examples of the uncertainty analyses can be found in different publications such as [5]. However, regardless of the application, the general factors to consider when using Coriolis flow meter technology include:

- temperature effect
- pressure effect
- zero effect
- viscosity effect
- compressibility effect; also known as Velocity of Sound (VoS) effect

Except for the zero effect, the above-mentioned effects can be modelled and corrected for each application, potentially facilitating the transferability of accuracy performance from water to intended measurement applications. This is called the water transferability concept and will be discussed in section 7 of this paper.

To minimize the zero effect, the meter shall be installed in accordance with the manufacturer recommendations. After proper determination of the zero effect in the final installation at process conditions, it can be stated with confidence that the zero effect will have limited influence on the specified measurement range.

3.2. Determining flow rate boundaries for Coriolis flow meters

A Coriolis flow meter offer a unique advantage because it can be used to directly measure mass flow and produce mass totals. Typically, the minimum flowrate of a Coriolis flow meter is determined by its behaviour under no flow conditions, the so-called zero effect. In a manufacturer product datasheet, this item is typically referred to as zero stability specification.

Zero stability specification Z_{spec} becomes relevant when the flow rate reaches the low end of the flow range, where the meter accuracy begins to deviate from the stated accuracy rating as depicted in the turndown section. When operating at flow rates Q where meter accuracy begins to deviate from the stated accuracy rating, the accuracy is governed by equation (1) [Micro Motion Product Data Sheet, 2023]:

$$A = {}^{Z_{spec}}\!/_{Q} * 100\% \qquad [1]$$

Vice versa, if you have a targeted maximum permissible error E_{perm}, the corresponding minimum flow rate Q_{min} can be calculated using equation (2) below, where Z_{spec} is a characteristic of the Coriolis meter, usually expressed in a mass flowrate unit, for example kg/h.

$$Q_{min} = \frac{Z_{spec}}{E_{perm} / 100\%} \qquad [2]$$

Determination of the maximum flowrate Q_{max} for gas applications relates to the speed of sound value in the medium and the desired minimum pressure drop. This in turn, depends on various factors like operating temperature, pressure and gas composition [Micro Motion Product Data Sheet, 2023]. The recommended approach to calculate maximum flowrate is described in equation (3) below, where S is the cross-sectional area of the measuring tubes inside the flow meter, M is the maximum Mach factor allowed for the meter, SoS_{gas} is the speed of sound in the measured fluid and ρ_{gas} is the operating fluid density.

$$Q_{max} = S \cdot M \cdot SoS_{gas} \cdot \rho_{gas} \qquad [3]$$

Equation (3) shows that Q_{max} is dependent on the application conditions. Equation (2) shows that Q_{min} is determined by the meter's construction. In other words, Q_{min} is medium independent. Instead, Q_{min} determination depends on the construction of the Coriolis meter among other factors such as accuracy requirements. Q_{max}, however, depends on the gas medium characteristics leading to significantly variable rangeability in gas applications for different gases.

3.3. How does CO_2 and H_2 measurement with Coriolis differ from other common gases?

Table 1 presents properties of multiple fluids including hydrogen (H_2) and carbon dioxide (CO_2). They are primarily associated with sustainability and energy transition applications. Table 1 also includes methane (CH_4) and Nitrogen (N_2). They are common fluids used in performance tests at different laboratories globally.

Table 1. Properties of different common fluids used for testing at laboratories globally
Tabela 1. Właściwości różnych powszechnie stosowanych płynów wykorzystywanych do badań w laboratoriach na całym świecie

Property	H_2	CH_4	N_2	CO_2
Molecular Weight, (kg/kmol)	2.016	16.04	28.01	44.01
Density (gas), @ 15°C, 1 bar, kg/m3	0.085	0.68	1.17	1.85
Boiling point, °C	-252.8	-161.5	-195.8	-56.6
Critical point, °C	-234	-82	-147	31
Critical point, bar	13.3	45.9	33.9	73.77
Speed of Sound @ 15°C, 1 bar, m/s	1294	441	346	264

By comparison to the other listed gases in Table 1, CO_2 is the heaviest gas with the lowest speed of sound. The relatively higher density of CO_2 results in a greater mass flow for an equivalent volume flow compared to the other gases in the table. This facilitates favourable flow rate rangeability in comparison to H_2, for example. However, the low speed of sound of CO_2 generates a larger velocity of sound effect (VoS effect) for Coriolis meters compared to H_2. This effect will be discussed in depth in section 4.

The behaviour of methane (CH_4) and nitrogen (N_2) can be extrapolated as air-equivalent at laboratory conditions such as 10-30ºC and 10-80 bar. The density and speed of sound of these gasses change linearly and the amplitude of the changes is relatively small. Furthermore, the transition from gas to supercritical phase have little to no influence on the measurements and is usually considered as one state. The same can be said for H_2 but with three major exceptions. The speed of sound in H_2 is orders of magnitude higher and its density is orders of magnitude lighter than the listed gases in Table 1. In addition, H_2 is liquid at a much lower temperate in comparison to methane and nitrogen. How these differences relate to the measurement with Coriolis will be discussed in section 5 of this paper.

For CO_2, the critical point and transitional curve between the different phases happens at relatively similar laboratory conditions, Figure 2. Whereas the other gases listed in the table require energy to reduce the temperature in order to reach the critical point. Furthermore, the state transition of CO_2 is sensitive to presence of impurities. A discussion on how the CO_2 properties relate to the measurement with Coriolis is in section 4 of this paper.

4. CO_2 measurement: what do you need to know?

4.1. What is important for CO_2 measurement with Coriolis flow meter?

Considering the five effects listed in section 3.1, it can be said that Viscosity effect and Zero effects are not relevant or inconsequential. Viscosity effect is only applicable for high viscous fluids like fuel oils; CO_2, in any state, has a viscosity smaller $20 \cdot 10^{-6}$ Pa.s which is significantly smaller than water or high viscos fluids. Also, the Zero effect is a standalone effect which determines the low-end of the mass flow range based on the application rangeability requirements, which has been discussed in section 3.2.

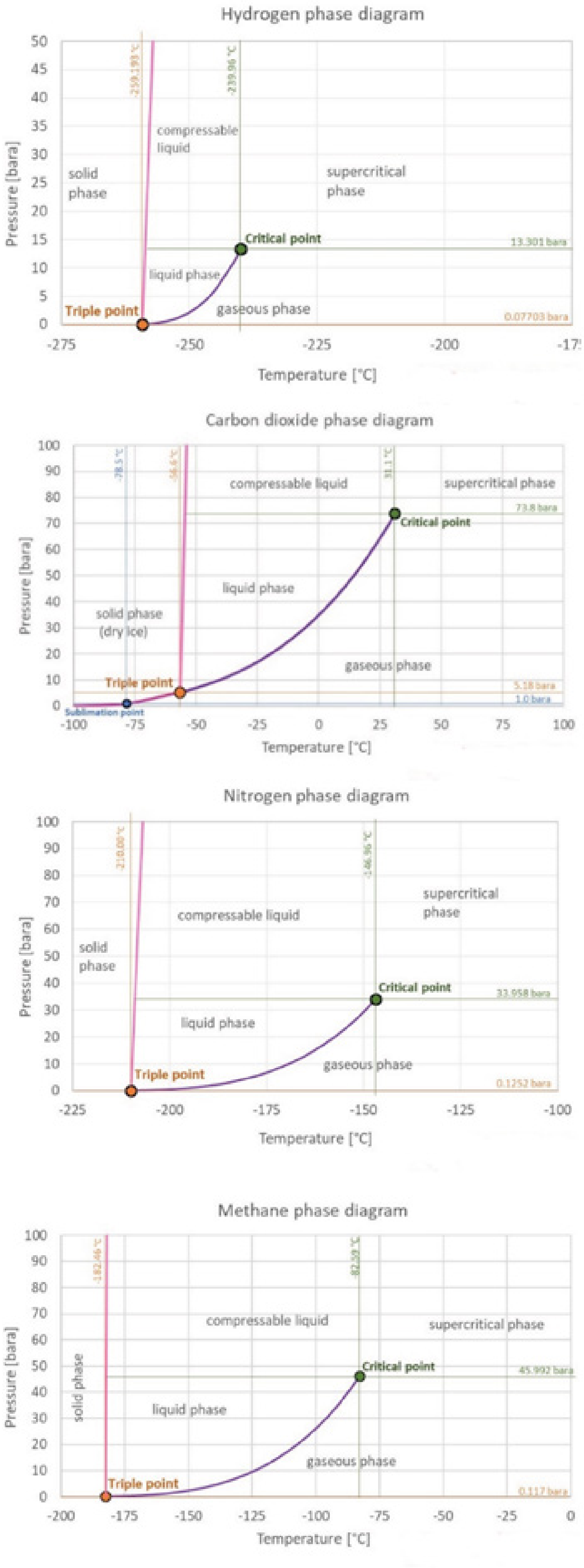

Fig. 2. Phase diagram for different fluids: H_2, CO_2, N_2 and CH_4

Rys. 2. Diagram fazowy dla różnych płynów: : H_2, CO_2, N_2 and CH_4

Furthermore, any temperature effect during CO_2 measurement is not uniquely different from other common industry applications as temperature effect is a function of tube materials used for Coriolis meter production. The temperature effect on measurement using a Coriolis flow meter is well-known and commonly compensated automatically in modern Coriolis meters based on the measurement input of an internal RTD element.

Similarly, the pressure effect is not unique to CO_2, it is fluid independent. This effect is dependent on the construction and geometry of a Coriolis flow meter. This implies that pressure corrections can be applied for supercritical CO_2 applications like in high demand oil and gas industry applications.

That leaves the compressibility / VoS effect as the remaining element for further discussion in this paper. The phenomenon was explained by Hemp and Kutin in [7]. In their paper, Hemp and Kutin conclude that the mass error E_m can be estimated by equation (4), where SF is a scale factor determined for each type of Coriolis meter dependant on construction which addresses assumptions made in the publication [7], f is the natural frequency of the Coriolis tube vibration, c is the speed of sound in a measured fluid and r is the inner radius of the Coriolis tubes.

$$E_m = SF\,\frac{1}{2}\left(\frac{2\,\pi\,f}{c}\,r\right)^2, \qquad [4]$$

It can be derived from equation (4), that the velocity of sound effect plays a significant role for larger Coriolis meters with a high natural frequency, at applications where fluids have a low speed of sound. In Table 2 below, the theoretical velocity of sound effect values are calculated for 2 inch, 3 inch and 4 inch meters with different natural frequencies, for a medium with a speed of sound equal to 250 m/s. This is assumed for pure CO_2 in gas phase at 20 ºC and 20 bar.

Table 2. Comparison of the VoS effect at gas CO_2 phase for different meter sizes with ultra-low natural frequency (100 Hz) and low frequency (200 Hz)

Tabela 2. Porównanie efektu VoS w fazie gazowego CO_2 dla różnych rozmiarów liczników o bardzo niskiej częstotliwości drgań własnych (100 Hz) i niskiej częstotliwości (200 Hz)

Size	D mm	Frequency Hz	Em %
2 inch	30	100	0.07
2 inch	30	200	0.28
3 inch	45	100	0.16
3 inch	45	200	0.64
4 inch	70	100	0.39
4 inch	70	200	1.55

One clear conclusion from Table 2 is that Coriolis meters smaller than 2 inch and with operating frequency below 200 Hz, have negligible VoS effect. For larger meters with low natural frequencies or small meters with high natural frequency, the assessment of VoS effect should be done separately. The table also shows that a 3-inch meter with a natural resonance frequency of 100 Hz has a small effect, while a similar size meter with higher frequency (200 Hz) can experience a significantly larger mass error.

CO_2 is one of the industrial gases with the lowest speed of sound. Theoretical mass errors have been calculated using equation (4) to visualise potential VoS effect for different gasses in comparison to CO_2 at 1 bar and 0 ºC. Figure 3 presents a theoretical estimation of the velocity of sound effect for different sizes of Coriolis meters with low natural frequency (less than 100 Hz) at different gases. Compensation for this effect has the same amplitude but with an opposite sign.

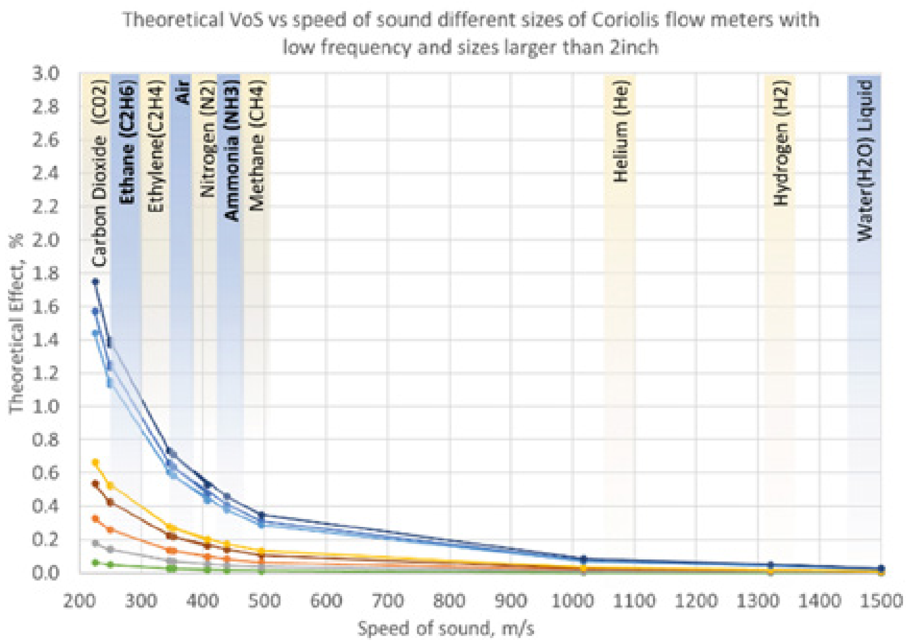

Fig. 3. Comparison of the VoS effects for different sizes of low natural frequency Coriolis meters for different gases (Lines represent different sizes, vertical bars indicate rough values of the speed of sound for different medias at 1 bar and 20 C)

Rys. 3. Porównanie efektów VoS dla różnych rozmiarów mierników Coriolisa o niskiej częstotliwości drgań własnych dla różnych gazów (linie oznaczają różne rozmiary, słupki pionowe wskazują przybliżone wartości prędkości dźwięku dla różnych mediów przy ciśnieniu 1 bara i temperaturze 20 C)

One approach to avoid or mitigate influences of VoS effect in CO_2 measurement would be to design measurement systems with multiple, parallel runs made of smaller size meters. However, this may not be desirable due to large throughput needs, space or pressure drop limitations. Alternatively, if larger sizes are desired, the best option would be to select Coriolis flow meters with the lowest possible natural frequency. This will become more relevant when impurities are present.

It is important to highlight that it is possible to estimate and correct for this effect. In some modern Coriolis flow meters, this is already implemented. One approach is described in a recent patent "Method of compensating for mass flow using known density [12]", that enables the determination of the speed of sound in CO_2 by using process pressure and process temperature. This is used to calculate the actual VoS effect and deploy the relevant correction accordingly.

4.2. Influences of impurity in gaseous and supercritical CO_2 phases on Coriolis flow meters

The impurity of CO_2 is of crucial relevance in the emission control directives. For example, impurity determination indicates the amount of CO_2 that has actually been captured, stored and used. If purity is determined as 99%, this indicates that 99% of the measured amount is actual CO_2 molecules and 1% is made of other gasses. This simple example shows the significance of analytical devices in the process of actual content measurement. This, however, is not the subject of this paper and will be left for further evaluation and discussion in future publications.

Presence of impurities in CO_2 alters its speed of sound. Therefore, use of equation (4) without consideration of the impact of impurities on the speed of sound, could lead to incorrect estimation of the mass error shift. For example, the speed of sound for gaseous CO_2 is around 250 m/s and for supercritical CO_2 it is 450 m/s and higher [19]. A logical assumption would be that supercritical CO_2 measurement is affected less by impurity as it is relatively less sensitive to variation. However, [19] shows that potential variation in the speed of sound in supercritical CO_2 due to impurity can be much more significant.

In [19], analysis has been done to evaluate the impact on the speed of sound for 12 different mixtures of CO_2 at both gas and dense/supercritical conditions. For example, at 20º C and 30 bar (gas state) the speed of sound of CO_2 mixtures varies between 240 m/s

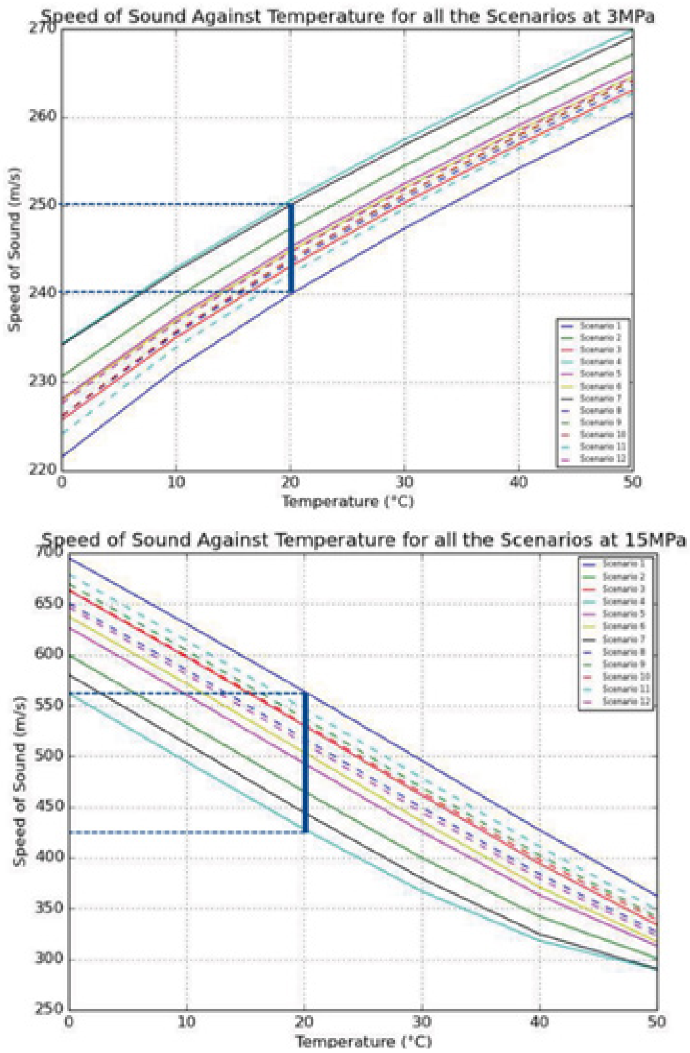

Fig. 4. Speed of sound dependence for gaseous and dense CO_2 mixtures with a different impurity published in a work [19]. Exact % of contamination for each of scenario can be found in [19]

Rys.4. Zależność prędkości dźwięku dla mieszanin gazowych i gęstych CO2 z różną zawartością zanieczyszczeń, opublikowana w pracy [19]. Dokładny % zanieczyszczenia dla każdego ze scenariuszy można znaleźć w [19] and 250 m/s, showing a bandwidth of 10 m/s see Figure 4. For dense phase CO_2 at 20º C and 150 bars, the speed of sound of the same CO_2 mixtures can vary between 420 m/s and 570 m/s, showing a bandwidth of 150 m/s. The concentration of CO_2 evaluated in [19] varied from 90% to 100%.

Calculating the difference in mass error shift (ΔEm) using equation (5) for these cases for a meter with inner radius r = 36.5mm, natural frequency f = 200 Hz and an assumed scale factor of 1, it can be derived that for gas phase, the potential mass error difference can be 0.14%, while for the dense phase the potential difference is 0.27%.

$$\Delta E_m = \frac{1}{2}\left(\frac{2\pi f}{c_{min}}r\right)^2 * 100\% - \frac{1}{2}\left(\frac{2\pi f}{c_{max}}r\right)^2 * 100\% \quad (5)$$

Table 3. Comparison of impurity influence to VoS effect on a 4-inch meter with different natural frequencies

Tabela 3. Porównanie wpływu zanieczyszczeń na efekt VoS w mierniku 4-calowym o różnych częstotliwościach własnych

Speed of sound difference		gas phase (240…250) m/s	
Size	r, mm	Frequency, Hz	*ΔEm*, %
4-inch	36.5	100	0.036
4-inch	36.5	200	0.143
Speed of sound difference		dense phase (420…570) m/s	
Size	r, mm	Frequency, Hz	Em, %
4-inch	36.5	100	0.068
4-inch	36.5	200	0.272

Table 3 presents the results for a Coriolis flow meter (4 inch) with two natural frequencies f 100 Hz and 200 Hz calculated using equation (5). The comparison in Table 3 indicates that Coriolis flow meters with low natural frequencies have lower sensitivity to impurities both in the gas and dense phase.

5. H_2 measurement: what do you need to know?

5.1. What is important for H_2 measurement with Coriolis flow meter?

Similar to the discussion in section 4.1, viscosity effect is negligible due to the low viscosity of hydrogen; approximately 8.76 10^{-6} Pa.s at ambient conditions. Furthermore, the Zero effect is a standalone effect that is relevant only to the determination of minimum flow rate at the specified measurement accuracy required for the measurement applications. Except for liquid hydrogen (will be discussed later in this chapter), temperature and pressure effects on Coriolis measurement on pure hydrogen gas or hydrogen enriched natural gas are not unique and can be considered similar to the conditions applied in traditional gaseous applications. Most modern Coriolis meters are equipped with the means to compensate for those effects using the on-board internal RTD element.

The key differentiators for hydrogen compared to other gases when measuring with Coriolis flow meters are the high speed of sound value and the low density. These properties influence the relevant VoS effect and limit the maximum mass flow rate. Looking at formula (4) and Figure 2, the high speed of sound makes hydrogen VoS properties close to water and practically eliminates the need for VOS correction; Only the biggest meters of 12 inch (diameter of the Coriolis tubes ~150mm) with high natural frequency (>200Hz), can be theoretically slightly affected with a bias less than 0.3%. For smaller meters with low natural frequency, the VoS effect is negligible. This leads to a logical conclusion that water test results for Coriolis meters can be more representative to hydrogen performance than test results on other gases like natural gas or air.

Table 4. Comparison of flow rate rangeability for different gases assuming 30 bar and 20 C

Tabela 4. Porównanie zakresowości przepływu dla różnych gazów przy założeniu 30 barów i 20 C

Fluid:	CO_2	N_2	CH_4	H_2
Velocity of sound (m/s)	239.9	354.3	436.4	1329.5
Actual Density (kg/m3)	66.16	34.66	20.88	2.44
SoSgas · P gas	4761.7	3683.2	2733.2	972.2

As discussed in section 3, the maximum flow rate for gas applications is governed by the maximum velocity allowed through the meter. Typically, this is limited to maximum of 0.3 Mach of any given gas. For H_2, that would translate to 330 m/s (1320m/s*0.3 Mach). Given the very low density of H_2, this will generate lower maximum possible flow rate in comparison to other gases, see table 4.

5.2. Liquid hydrogen (LH_2)

Liquid hydrogen (LH_2) applications are challenging due to extremely low temperatures of – 253 ºC (20 ºK above absolute zero). For all previous cases, we mentioned that temperature effect is known and well established. However, for temperatures below – 200ºC, the mechanical properties (young's and shear modulus) of the 316 stainless steel become nonlinear and difficult to estimate accurately. Furthermore, Temperature measurement of LH_2 with a standard Pt100 thermo-sensor is not possible.

To overcome the potential impact on measurement accuracy, a unique patented methodology [12] has been developed to perform mass measurements by Coriolis meter at ultra cryogenic applications based on known (calculated) density. The method facilitates an option to accurately measure hydrogen at those conditions without the need to estimate the Young's modulus value and the life temperature measurement from the on-board RTD element on the Coriolis meter. The analysis on the performance of this approach will be discussed in section 6.

6. Test results of Emerson's Coriolis flow meters on H_2 and CO_2

In relation to the discussion in sections 4 and 5, this paper presents recent test results to further illustrate the performance of Coriolis Flow meters in H_2 and CO_2 measurement. The presented results are of different sizes of Coriolis meters measuring H_2 in gas and liquid phases and CO_2 in gas and supercritical phases. It is all assumed on single phase measurement.

6.1. H_2 gas tests

Emerson collaborated with RMA to conduct flow testing of 5 different sizes of Coriolis flow meters on H_2 gas at their laboratory which is located in Rheinau near Strasbourg [RMA pure hydrogen laboratory]. Figure 5 combines the results of the meter testing on H_2 at RMA. Due to limitation at RMA, the meters were tested at relatively low flow rates in comparison with the maximum flow rate capabilities of each meter.

The presented results are based on calibration factors determined on water with no additional correction except of well know temperature and pressure corrections. The results are within ±0.5% for all tested meters.

The primary challenge during testing at RMA was the density determination. The density estimates for H_2 has high sensitivity to uncertainty in concentration determination. For example, a bias of 0.02% in impurity for the 99% hydrogen to 1% nitrogen mix gives an estimated bias of 0.23% in density which translates into 0.23% bias in mass measurement.

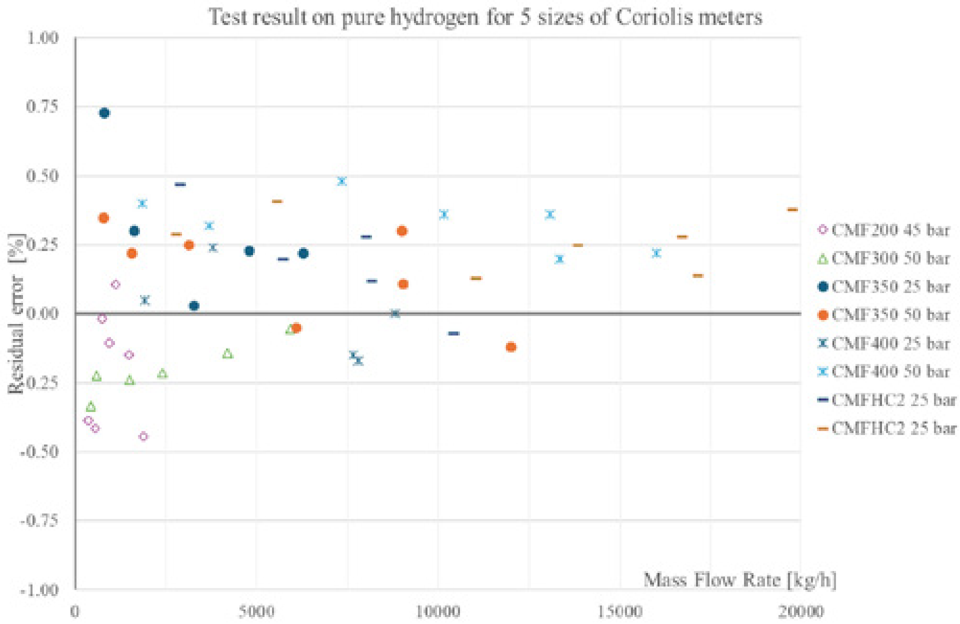

Fig. 5 . Test results for 5 different sizes of Emerson Elite meters at 98-99% hydrogen at RMA facility

Rys. 5 . Wyniki testów 5 różnych rozmiarów liczników Emerson Elite przy stężeniu wodoru 98−99% w ośrodku RMA

The laboratory is designed for nearly pure hydrogen gas testing using Turbine flow meters as the primary volumetric reference system. These meters are calibrated on air and natural gas by PTB. The laboratory is also equipped with differential pressure flow element compliant to ISO 5167 that are used as control devices and installed in the reference section. Downstream of the reference system, a set of nozzles, turbine meter and ultrasonic meter are installed in series. This secondary system is in parallel with the meter under test (MUT) section. A schematic overview of the test lab is represented in Figure 6.

At the time of publication of this paper, the test loop is not equipped with a traceable method for direct density measurement, concentration measurement and mass measurement. Therefore, to achieve mass flow testing, the real density of H_2 in the loop was estimated through in-direct calculations of the gas concentration taking advantage of the pressure and temperature sensors installed around the tested meters.

All concentration calculations below start with the assumption that only hydrogen and nitrogen may be present in the loop. This is assumed based on RMA's procedures for sourcing pure Hydrogen and using Nitrogen to flush the test loop. The hydrogen flow test results presented in this section are based on 3 different methods for concentration measurement. Method 1 was tested on a 2" meter (CMF200). Method 2 was tested on a 3" meter (CMF300). Method 3 was tested on 3 different meters with sizes starting from 4" to 6" (CMF350, CMF400 and CMFHC2).

Method 1: In this approach, the density/concentration is extrapolated based on 4 pairs of relative errors correlated as below:

- Meter Under Test – Coriolis meter vs Reference Turbine meter
- Meter Under Test – Coriolis meter vs Reference Orifice plate
- Meter Under Test – Turbine Meter vs Reference Turbine meter
- Meter Under Test – Turbine meter vs Reference Orifice plate

The density extrapolation depends on the fact that density changes have a different influence amplitude and direction on the different correlations. A spare turbine flow meter was installed in the Meter Under Test section to facilitate the 4 points of comparison.

Method 2: In this approach, a simple gas analyzer was used to determine the concentration of Hydrogen. However, the density estimation had higher uncertainty due to the high repeatability specification of this analyzer (± 1%) combined with the potential errors due to ambient temperature changes. Therefore, it was not possible to guarantee uncertainty controls that aligns with performance assessment in line with OIML R 137 requirements for accuracy class 1.0

Method 3: In this approach, an assessment of concentration/density of the gas in the gas loop by correlating the speed of sound measurement by the USM in the parallel system (line 3) to the MUT section with the approach described in method 1. This method facilitated the smallest possible uncertainty for the mass measurement in the closed loop.

6.2. H_2 Liquid tests

At this moment, the availability of a traceable testing system or laboratory for LH_2 is extremely limited. This can be attributed mostly to the safe and economic restrictions associated with the handling of LH_2. However, the relatively new interest in LH_2 as a potentially economic and efficient state for long distance transportation merits assessment of flow technology capabilities to measure it at such extremely cryogenic conditions.

Emerson collaborated with VSL in an effort to understand the viability of Coriolis flow meters as potential measuring instruments for LH_2 measurement and to mathematically derive the measurement uncertainty relative to functionality at such low operating temperature (-253 ºC). In [6], a 1" Coriolis flow Meter was tested at the Deutsches Zentrum für Luft und Raumfahrt (DLR). The 1" meter was constructed with a unique vacuum seal secondary containment (external case of the Coriolis meter). The primary benefits of having a vacuum seal secondary containment include mitigating liquid formation inside the secondary containment and minimizing heat transfer through convection and conduction. This has proven as an effective solution for extremely cryogenic applications at CERN laboratory for Liquid Helium application [12]

The performance at DLR demonstrated the potential for Coriolis flow meters as a measuring instrument and as a reliable primary reference system for Liquid Hydrogen applications. As a result of the work in [6], a mathematical model was developed to estimate the uncertainty of measurement using the Emerson patented approach for correcting the tube elasticity using the known density of the fluid as described in [12]

6.3. CO_2 gas tests

At the time of publication of this paper, flow meter tests against a traceable reference on CO_2 in gas phase are considerably more feasible compared to testing on CO_2 in liquid/supercritical phases [9]. Conditions of CO_2 in gas phase are close to typical natural gas test conditions with minor considerations such as temperature and pressure control.

The work done by Putten and Kruithof in [12], presents test results of Emerson Coriolis Flow Meters CMF200 and CMF300 in series against a unique reference system consisting of nozzles, turbine meters and Coriolis meters. In this test, the meters were tested on natural gas with various compositions at different operating pressures to establish a base line measurement. After this, the meters were tested on different compositions of CO_2 at varying

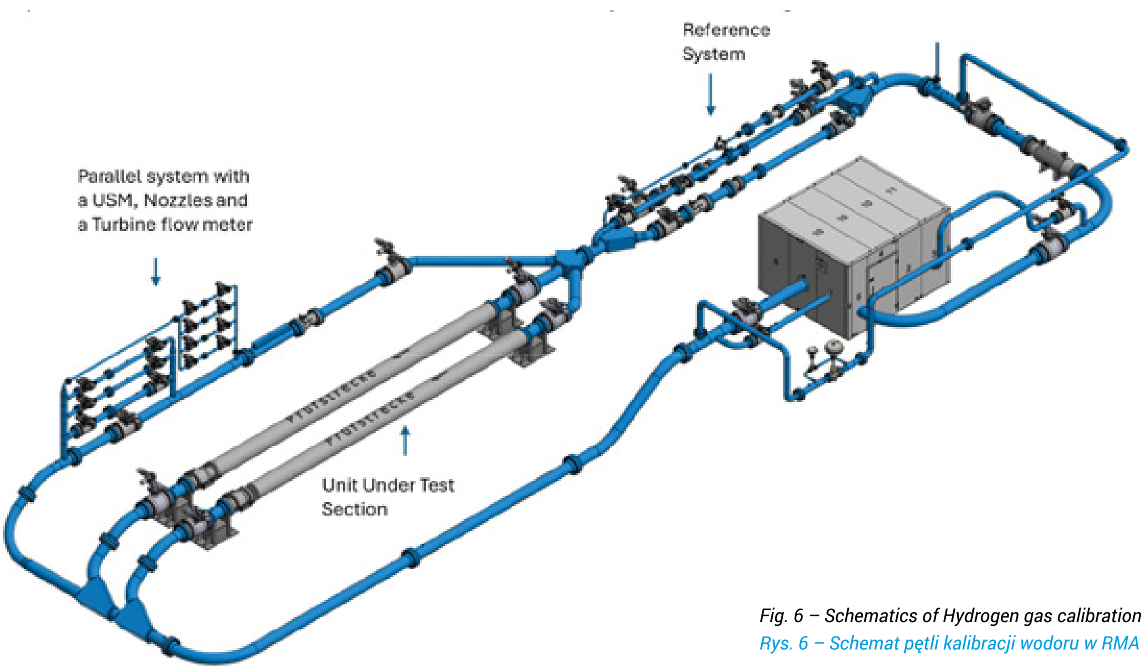

Fig. 6 – Schematics of Hydrogen gas calibration loop at RMA
Rys. 6 – Schemat pętli kalibracji wodoru w RMA

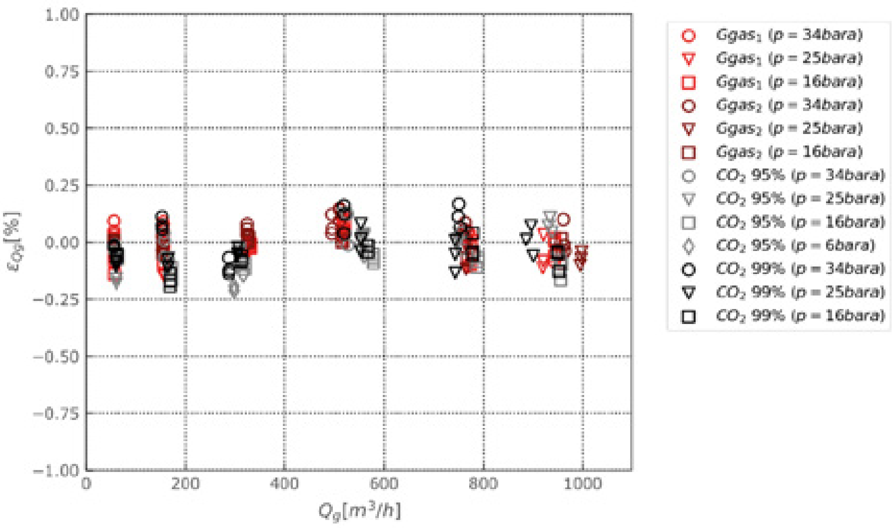

Fig. 7 – test results of the Coriolis meter CMF 200 and CMF300 on natural gas and CO_2 gas vs DNV NL reference system [12]
Rys. 7 – wyniki testów przepływomierzy Coriolisa CMF 200 i CMF300 na gazie ziemnym i CO_2 w porównaniu z układem odniesienia DNV NL [12]

operating pressures. Figure 7. test results of the Coriolis meter CMF 200 and CMF300 on Natural Gas and CO_2 gas vs DNV NL reference system [12].

The relative performance of the two Coriolis meters within 0.25% in comparison with the reference system. Even though VoS correction values are considered to be negligible for the CMF200 and CMF300, the VoS effect has been automatically implemented during the test. The meter calibration factors were determined through water calibration and no additional meter factors were implemented.

Figure 8 shows another set of tests which have been performed on CO_2 gas with CMF300 and CMF400 at FortisBC in Canada. FortisBC is ISO17025 accredited to operate a traceable reference system on CO_2. More information on the history of traceability and uncertainties of the laboratory can be found in the work of Tang [17].

Average process conditions for these tests have been 99% pure CO_2 gas at 16 bar and at 23°C. During the test, the temperature deviation through the test remained below ±2 °C. Prior to the tests at FortisBC, both Coriolis meters have been calibrated under normal conditions on water. During the tests at Fortis BC, the published pressure correction has been applied. Also, the embedded VoS correction was enabled for the CMF400 while the CMF300 was tested without any VoS correction.

Results show that both Coriolis meters meet the expected specifications, yet the CMF300 has a slight positive bias. This can either be attributed to the VoS or the uncertainty of the laboratory. As discussed in section 3, a theoretical VoS correction may apply. In this scenario however, it is smaller in magnitude than the combined accuracy specification of the meter and the uncertainty of the lab. The decision to introduce the correction or not requires more testing and analysis.

Another set of results have been obtained during the recently concluded Joined Industry Project (JIP) CO2MET conducted by DNV Energy System Fuel and Flow Advisory Netherlands in Groningen. The test results presented on a Figure 9 can be compared with the result on Figure 8 as the same meters (same serial numbers) have been used with the same configuration. This presents the first round-robin test In between two laboratories capable to operate on gaseous CO_2

6.4. CO_2 liquid/supercritical tests

As highlighted earlier, capabilities for testing flowmeters at liquid /supercritical CO_2 conditions are extremely limited. Only few publications exist, presenting test results for liquefied or supercritical tests. Furthermore, they are often limited to small flow meter sizes. Significant pressure 70-200 bar and temperature control capabilities are required to reproduce supercritical CO_2 conditions, thus making it less feasible now.

Yet, Brown and Chinello [3] from TÜV SÜD National Engineering Laboratory experimented with a 1-inch Coriolis meter CMF100.

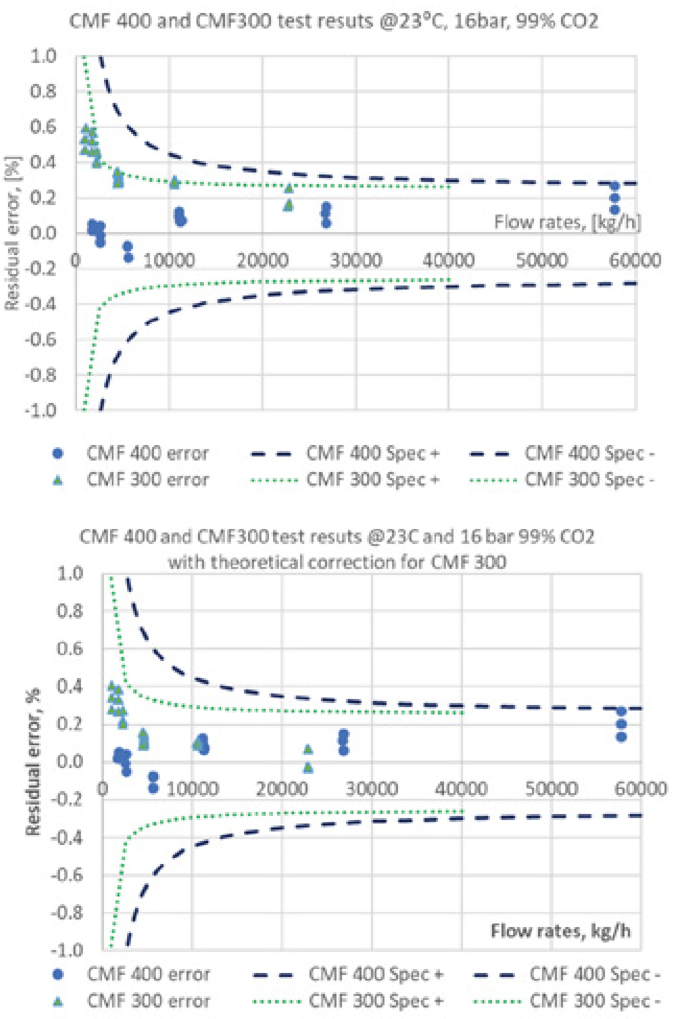

Fig. 8. Test results of the CMF 300 and CMF 400 meters at 99% CO2 gas test (23±2 C 16.5 ± 0.5 bar). The doted lines represent manufacturers specification for the meters. On the right graph, the theoretical VoS correction was introduced for CMF 300 results

Rys. 8. Wyniki testów mierników CMF 300 i CMF 400 w warunkach 99% stężenia CO_2 (23 ± 2 C, 16,5 ± 0,5 bara). Linie przerywane oznaczają specyfikacje producenta mierników. Na prawym wykresie wprowadzono teoretyczną korektę VoS dla wyników CMF 300

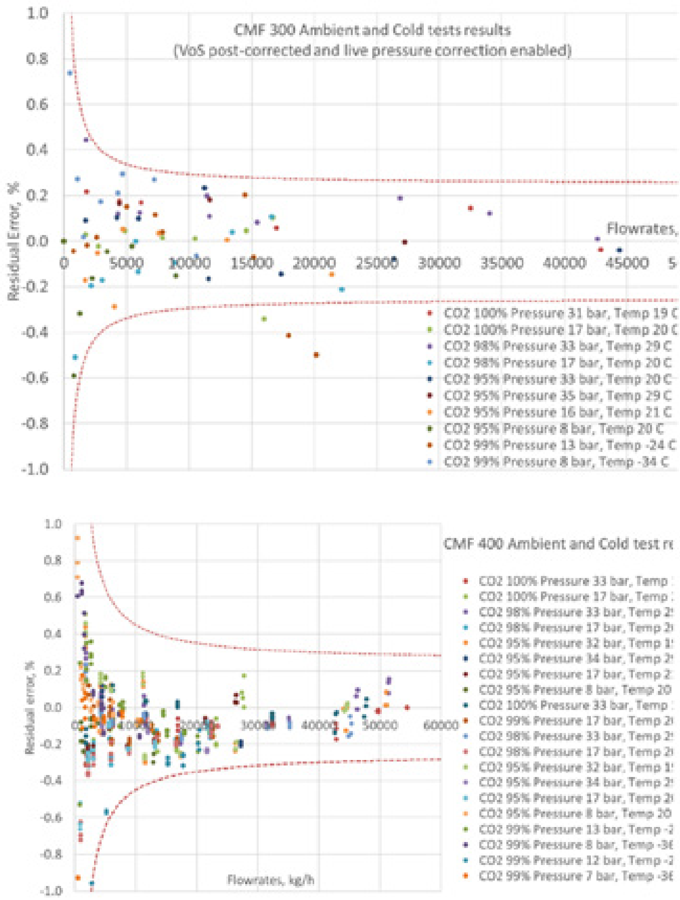

Fig. 9. Test results from JIP CO2MET for CMF 300 and CMF400 meters

Rys. 9. Wyniki testów JIP CO2MET dla mierników CMF 300 i CMF 400

The Coriolis meter was tested against an orifice plate at liquid and supercritical conditions. Results and schematic representation of the test setup are presented in Figure 10. Before the test at CO_2, the Coriolis meter was calibrated on water and no VoS corrections have been applied. As we discussed in section 3 of the paper, small meters are much less sensitive to VoS effect. In addition to this, the meter has ultra-low natural frequency (<100Hz). During the tests, published temperature and pressure corrections have been applied.

As can be seen in Figure 10, all results are within the specification of the Coriolis meter (dash lines), the error bars are a combination of the reference orifice mass flow uncertainty and the meter repeatability over three or more consecutive repeats. The same as for previously mentioned gas tests the calibration settings of the Coriolis meter have not been changed after the standard water calibration but standard corrections for pressure effect has been applied.

7. Water transferability for coriolis flow meters intended to measure H_2 and CO_2

Water Transferability in Coriolis flow meters, as a principle, takes advantage of the flow meter capabilities for direct mass measurement. In other words, the meter measures the amount of molecules flowing through the meter regardless of what kind of molecule passes through. With that principle in mind, the Coriolis flow meter performance on water can be transferred with confidence to other fluids where physical tests are not feasible due to either technical, commercial or safety constraints. To prove water transferability, extensive meter's type tests have been performed by calibrating meters on water and tested on other mediums such as gases, oils and hydrocarbons. The outcome of these tests is that the calibration factors determined on water, need no further modification for accurately measuring a wide variety of fluids in either liquid, gas or supercritical phase (in case of CO_2 for example).

For the purpose of this paper, all test results presented in section 6 have been achieved without any preliminary calibration and characterization of the meter performance on H_2 or CO_2. The Coriolis meters were initially calibrated on water at ambient temperature and 1 bar pressure. It is critical to highlight that this does not imply or suggest that water transferability is viable without correction or consideration of the conditions and physical properties of the measured product. For example, if the meter is intended to operate at higher pressure, then the pressure correction must be applied for the water transferability to be viable. Similarly for temperature and in the case of CO_2 application of VoS corrections.

8. CONCLUSIONS

Hydrogen (H_2) and carbon dioxide (CO_2) have become integral to the discussions surrounding the transition to Net Zero Energy. Notably, these gases occupy opposite extremes when compared against metrics such as density, impurity, physical state or speed of sound. Thus, their physical properties necessitate special considerations for transportation, processing and measurement.

While the use of Coriolis meters for measuring H_2 and CO_2 is not unprecedented in the industry, the higher demand for these application on the context of the energy transition means utilization of larger flow

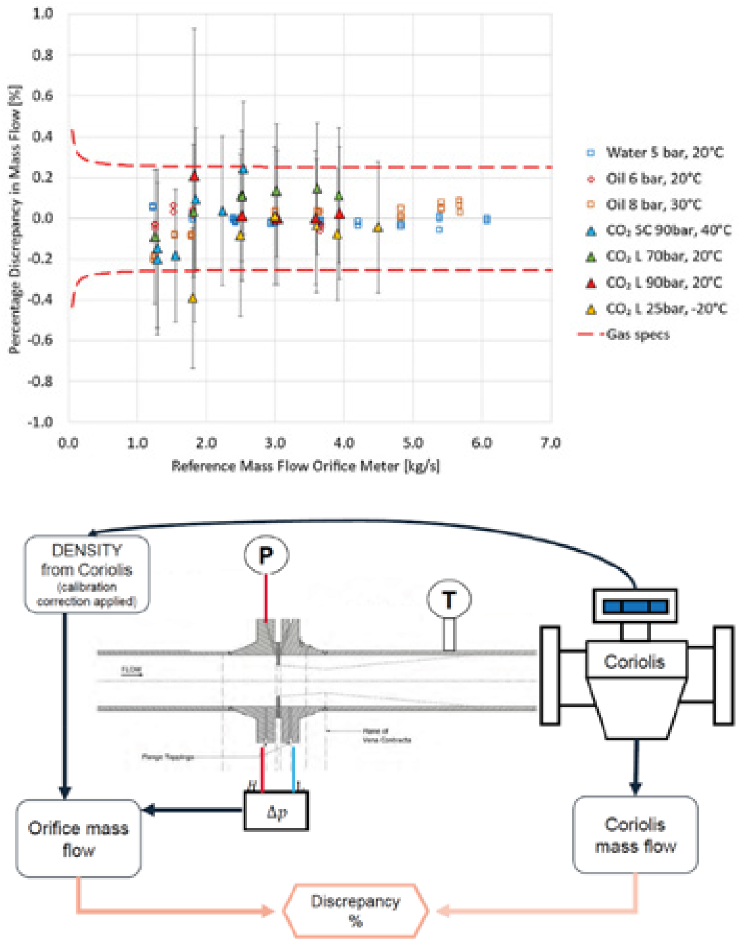

Fig. 10. Test results of the CMF100 on CO_2 liquid and Supercritical against an Orifice flow meter at TUV SUD [3] and the test setup

Rys. 10. Wyniki testów CMF100 na ciekłym CO_2 i w stanie nadkrytycznym w porównaniu z przepływomierzem orifice w TUV SUD [3] i stanowiskiem testowym

metes. Thus numerous studies were undertaken to investigation their performance for the purpose of fiscal measurements in this domain. Coriolis flow meters have long been recognized for their accurate and reliable direct mass measurement in traditional fiscal applications in industries such as the oil and gas sector and it is in the opinion of the authors of this paper that this is transferable to the H_2 and CO_2 measurement.

Factors such as temperature and pressure corrections that are occasionally necessary in most fiscal transfer applications can be applied in a similar way to the H_2 and CO_2 measurement. Other factors to consider especially with CO_2 measurement is the Velocity of Sound (VoS) effect. This effect can be easily estimated and corrected. Most modern Coriolis flow meters are equipped with the tools necessary to do correct for this effect. However, choosing a Coriolis flow meter with the lowest natural frequency offers a higher advantage in minimizing the amplitude of the correction and generating less sensitivity to presence of impurities.

Laboratory test results of large Coriolis meters confirm that VoS corrections is not necessary to accurately measure mass flow rates of pure H_2. This suggests that calibration factors based on water may serve as the most representative method for validating Coriolis meters intended for pure H_2 applications. Tests with alternative gases such as air or natural gas may not be transferable since VoS corrections may be necessary for these gases with larger Coriolis flow meters or Coriolis flow meters with higher natural frequency.

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