Addressing Challenges in Direct Gas Density Measurement

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ABSTRACT

Gas density is a fundamental physical property playing a central role in various applications throughout the oil and gas industry, ranging from design of process- and production systems to fluid analysis and flow measurement. The density of a gas is normally established through calculation from composition, pressure and temperature. However, in fiscal gas metering, international standards used for calculating gas properties and for compositional measurement are primarily developed for lean export-quality natural gas. When gases deviate significantly from lean gas compositions, such as rich natural gases or gases with high concentrations of components like hydrogen or CO_2, these standards are no longer valid, and calculation may not meet the required accuracy. For such gases, direct measurement of gas density may be the only feasible option.
Paradoxically, these same gases also present the greatest challenges for direct measurement. Direct measurement using vibrating-element gas densitometers, as prescribed in NORSOK I-106, typically requires sampling via a slipstream and heating to stay above the dew point. This introduces issues with representative sampling and temperature control. Furthermore, the measured gas density is affected by differences in physical properties between the process gas and the calibration gas, which must be corrected for. The speed of sound accounts for most of this effect, and well-established methods exist for compensating measured density for the influence by speed of sound. However, simplified methods of correction have been frequently adopted by the industry and may cause significant errors if utilized outside the prerequisites of the simplifications.

This paper addresses both the practical challenges of installing and operating gas densitometers and the errors that arise from various corrections. The findings are demonstrated using examples from gas densitometers in Equinor. Although the gas densitometers are capable of highly accurate measurements by themselves, these challenges can produce errors exceeding requirements provided by the Norwegian Measurement Regulations.

1 INTRODUCTION

According to NORSOK I-106 [1], direct gas density measurement shall be conducted using the vibrating element technique, described in ISO 15970 [2]. The maximum permissible error of the density measurement should, under normal operating conditions, not exceed 0.3% according to the Norwegian Measurement Regulations, with an overall requirement on the uncertainty of total amount of gas measured in a month of ±1% [3]. The vibrating element technique is based on the principle of putting an element, for instance a cylinder, into vibration at the resonance frequency of the system. The resonance frequency will be related to the density of the surrounding fluid, and this relationship is established through calibration, which is normally conducted using nitrogen (N_2) at 20 °C.

The raw density measurement, ρ_r (kg/m3), can then be expressed as a second-degree polynomial, as a function of the measured frequency (*f*) or time period (*1/f*, normally reported in µs) and the calibration constants K_0, K_1 and K_2. Equation 1 is available in both ISO 15970, the densitometer user manuals and on densitometer calibration certificates.

$$\rho_r = K_0 + K_1\tau + K_2\tau^2 \quad (1)$$

On the Norwegian continental shelf, the Emerson Micro Motion 7812 (previously Solartron) and GDM (further development of the 7812) have been the most used densitometers and will therefore be the focus in this paper. According to the vendor, these meters are capable of ±0.1% accuracy for gas densities up to 400 kg/m^3 [4]. However, in field applications, significantly larger uncertainties can be expected due to practical challenges related to installation and operation, as well as uncertainties arising from the use of simplified or incorrect models to account for differences between calibration and actual conditions. These issues are particularly pronounced for rich natural gases, which paradoxically often fall outside the scope of the standards used for compositional measurement and gas property calculation [5, 6]. In this paper, the term rich natural gas refers to gases outside the *Pipeline quality range,* defined in AGA report nr. 8 – part 2 [7].

2 INSTALLATION AND OPERATIONAL CHALLENGES

Gas densitometers based on vibrating elements have two characteristic features that introduce a series of practical challenges related to installation and operations:

1) They are usually installed in a slipstream application (referred to as *on-line* installation in ISO 15970), where gas is continuously sampled from the main pipeline before it enters the densitometer
2) They are heavily influenced by the presence of heavier compounds such as liquid or solid particles, or changes in the meter body (e.g. due to corrosion)

In recent decades, there has been a trend on the Norwegian continental shelf to shift from directly measuring gas density towards calculated gas density. This change can partly be attributed to the practical challenges associated with the installation and operation of these meters. Although ISO 15970 provides guidelines for installation of gas densitometers (GDM), it focuses on installations where the densitometer is installed in a pocket in the pipeline to maintain the process temperature. However, this type of installation is not feasible for rich natural gases where the operating temperature is close to the dew point of the gas, making it prone to liquid condensation. The phase envelope of a rich natural gas metering station is presented in Fig. 1, demonstrating how a small drop in temperature or pressure, and in some cases even an increase in pressure, can cause condensation of liquid, either hydrocarbon and/or water.

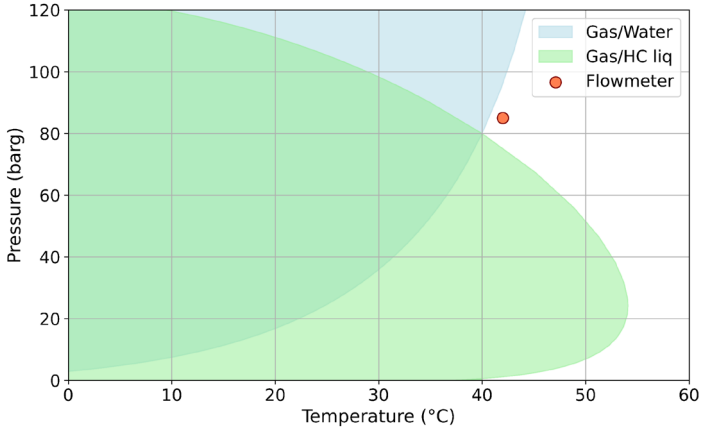

Fig. 1 – Phase envelope for a rich natural gas. Operating point of flowmeter is marked

Equinor fiscal requirements dictate that: *Gas densitometers shall normally be installed in an enclosure capable of keeping temperature of the measurement chamber 10 K above dew point.* For rich natural gases, this may require installation in a heated cabinet.
Fig. 2 shows the two types of installations with two densitometers in series, (1) GDM installed in a pocket and (2) GDM installed in a heated cabinet. For both types of installation, it is crucial to retrieve and maintain a representative sample throughout the system, while simultaneously minimizing the latency of the measurement, meaning the time it takes until the gas displaces the volume in the densitometer.

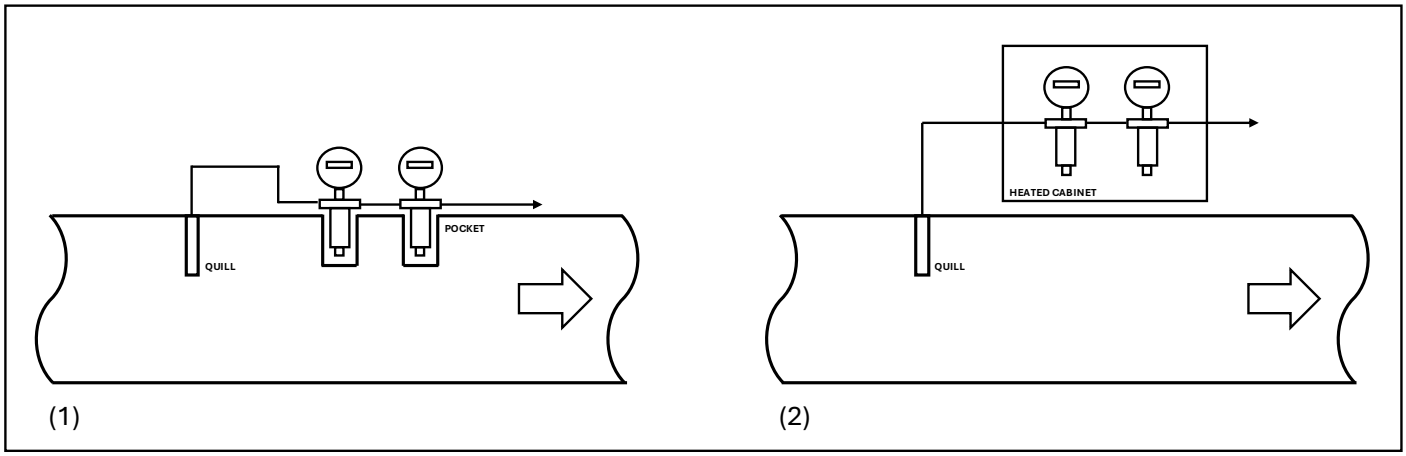

*Fig. 2 – Illustration of gas densitometer installation modes: (1) Pocket installation, (2) Heated cabinet. B*oth cases show two densitometers in series, where the gas is retrieved from the main pipeline using a sampling quill

Presented below are some of the factors that could cause uncertainties or measurement errors due to practical issues encountered during installation and operation of gas densitometers. In this paper, the term *measurement error* refers not only to errors that directly affect the measurement itself but also to issues that lead to inaccuracies in density when it is corrected to other conditions (such as flowmeter conditions or standard conditions), since the primary objective of the measurement is to determine the corrected density.

2.1 Representative gas sample

For the density measurement to be representative, the composition of the sample gas needs to be the same as the composition of the gas in the main pipe. An important part of this involves maintaining single phase gas throughout the system, including sampling probe, valves, tubing, filters and the gas densitometer itself. Ensuring single phase gas is usually achieved by heating the system to a certain temperature margin above the expected dew point temperature of the gas. However, a single cold bridge in the system may be sufficient to onset condensation of liquid from the gas, i.e. if a single point in the system lies within the pressure and temperature of the liquid region in Fig. 1. If liquid enters the gas densitometer it will cause an error in the measurement. On the other hand, if the liquid drains back into the main pipe, the heavier components in the gas will be lost, and the measured gas will not be representative of the gas of interest.

Another aspect of representative sample is the delay due to displacement of gas within the gas densitometers as the composition in the main line changes. If the process gas composition changes, the density measurement will not be representative until the gas has fully displaced the lines and the measurement chamber, resulting in a measurement error. In the 7812 user manual [4], this is referred to as response time and is calculated assuming a piston displacement. Displacing two gas densitometers (40 ml each) at a flowrate of 2.5 litre/hour would take 2 minutes based on this assumption. In practice, this is a gradual process rather than a piston displacement, and the example presented in chapter 2.4 shows that it takes up to 40 minutes until the gas in the two meters are fully displaced.

2.2 Temperature stability

When measuring gas density directly, it is essential to have a representative measurement of pressure and temperature at which the density is measured. The pressure and temperature are used when converting the measured gas density to other pressure & temperature conditions (e.g. flowmeter conditions), or when comparing measured and calculated density.
Therefore, gas densitometers are usually equipped with a temperature element within the measurement chamber to make sure that the measured temperature is representative of the fluid within the measuring chamber. A 1 °C error in measured temperature will correspond to a density error in the range 0.3-0.7% for temperatures exceeding 30°C, and even larger at lower temperatures. The relative error in density due to a +1 °C error in temperature is presented in Fig. 3 for a lean natural gas, plotted as contour lines in a pressure and temperature plot.

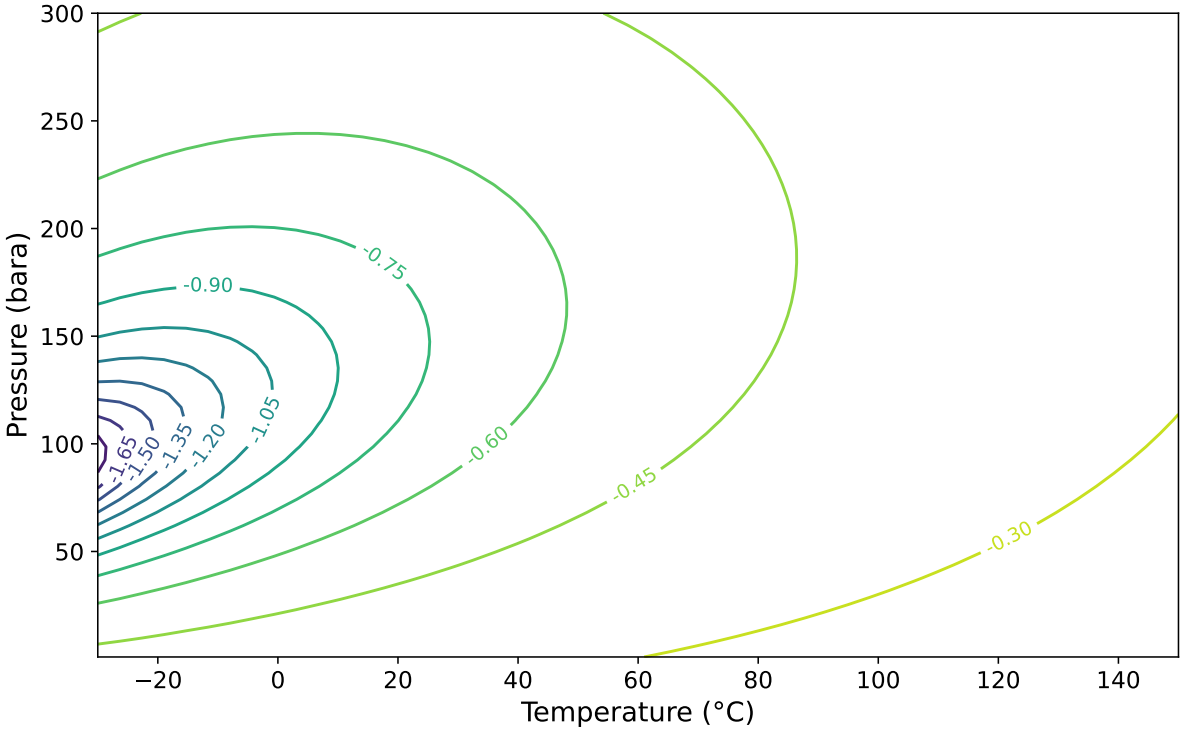

Fig. 3 – Relative error in gas density due to +1°C error in temperature for a lean natural gas as a function of pressure and temperature. Each contour line represents the percentage relative error in gas density

The dew point temperature of a rich natural gas is in general higher than for lean natural gases, and the operating conditions are often closer to the dew point. These applications therefore require a heated system and will be prone to the issue of temperature gradients, which can cause other issues such as non-representative temperature and/or local temperatures below dewpoint (resulting in liquid condensation), and eventually measurement errors.
If a thermostat is used to control the temperature of the heat trace and/or heaters in the cabinet, it tends to cause temperature fluctuations. This can result in temperature gradients or delay in temperature measurement, which will give a non-representative temperature reading and eventually cause an error in the density at the flowmeter conditions. Thermostat for temperature control should therefore be avoided if possible, and more sophisticated temperature controllers should be selected instead.

In a heated cabinet, the temperature near the heater will be higher than further away from the heater, which in turn will produce temperature gradients and potential measurement error. In such applications, injected air is sometimes used to distribute the heat evenly throughout the cabinet. However, at high temperatures (e.g. > 50°C), injecting cold air into the heated cabinet can by itself cause issues of

temperature gradients, and should be used with caution. Preferably, other methods of heat distribution should be used, such as ATEX fans or ejectors, which has less cooling effect on the system. However, it can be challenging to find ATEX fans that can handle high temperature applications.

Fig. 4 shows two examples of two gas densitometers (GDM1 and GDM2) installed in a heated cabinet where the temperature is controlled by a thermostat and air is injected to distribute the heat. In example 1, the temperature fluctuations peak-to-peak is approximately 1 °C, while the difference in temperature between GDM1 and GDM2 is also approximately 1 °C. However, the difference in density is approximately 0.7%, corresponding to a temperature fluctuation of 2 °C, suggesting that the temperature measurements are not representative. In example 2, the fluctuations are much smaller but also more frequent. In this case, the peak-to-peak temperature fluctuations are approximately 0.3 °C and the difference in temperature between GDM1 and GDM2 around 0.15 °C. However, the peak-to-peak density difference for GDM1 is approximately 0.7%, corresponding to a temperature fluctuation of approximately 1.5 °C. This may suggest that the relatively rapid fluctuations in temperature in the cabinet are too quick for the temperature measurements to respond, and that the real fluctuations are actually larger than the measured fluctuations.

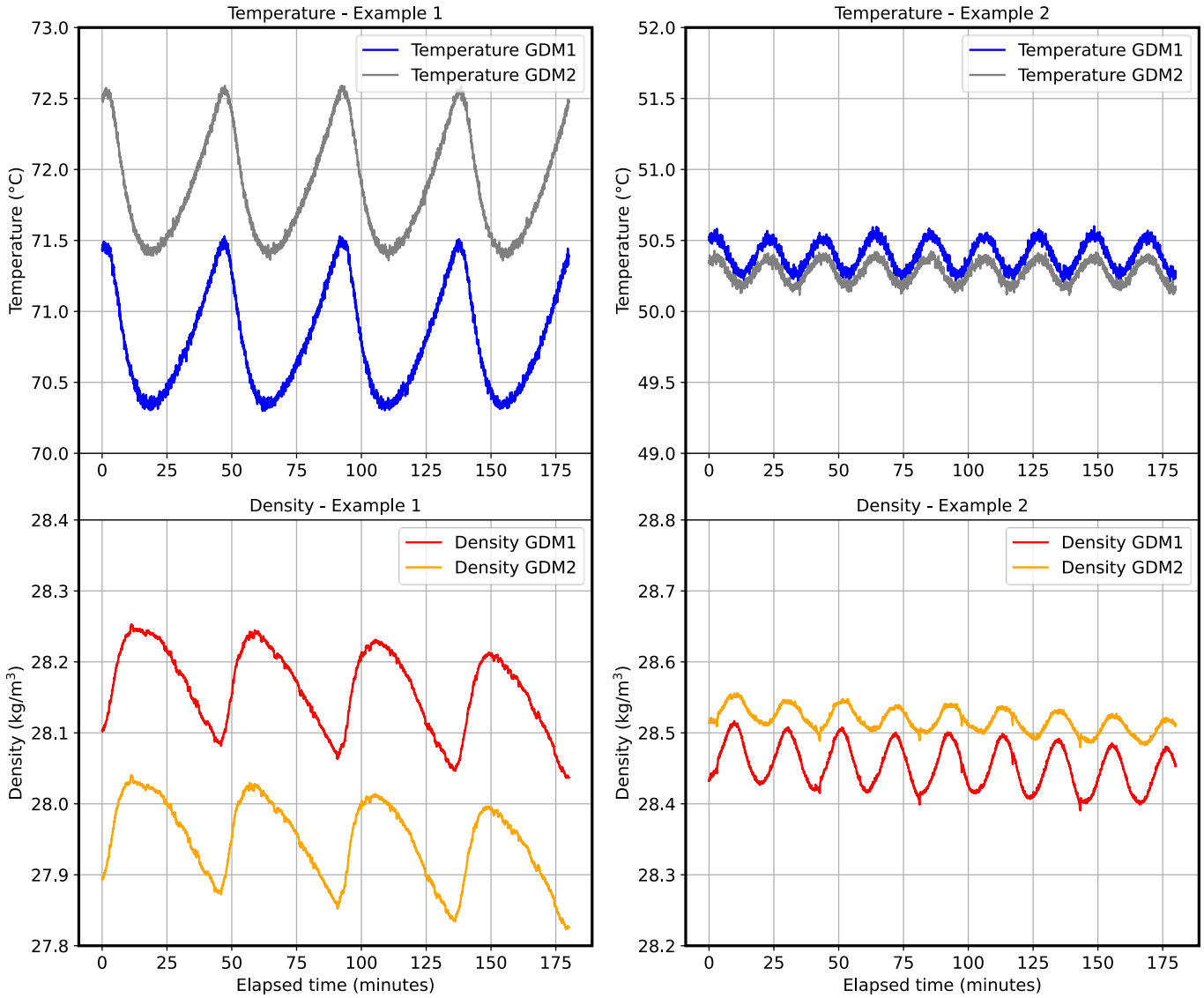

Fig. 4 – Two examples of fluctuations in temperature and density in installations with two gas densitometers (GDM) in series in a heated cabinet. Temperature is measured by an internal PT100 element in the densitometers

Temperature gradients in a gas density cabinet can be difficult to detect, unless one has multiple temperature measurements within the cabinet, and/or multiple densitometers. Comparing the measured density between two densitometers can help identify several issues, including issues with temperature gradients and non-representative temperature measurement. However, it is important that the measured densities are compared at the same conditions (P&T). This can be done by correcting the measured density from one densitometer to the conditions of the other densitometer and then calculating the relative deviation between the two. If the relative deviation in density exceeds 0.1%, it could indicate temperature gradient issues. The temperature between the meters should also be as low as possible, preferably below 0.5°C, although this may be difficult in high temperature applications.

The influence of temperature gradients and/or non-representative temperature measurement is demonstrated by the example shown in Fig. 5. In this example, two densitometers in series, located in an external heated cabinet, were vacuumed after a maintenance period, and then purged with 5.0 (99.999%) purity nitrogen. The relative deviation between measured density and theoretical N_2 density at the measured pressure and temperature was calculated for both gas densitometers (GDM1 and GDM2). The temperature in the heated cabinet where the densitometers were located was then raised from around 30 °C up to 67 °C to reach the target operating temperature before being put into operation. The pressure in the densitometers was approximately 45 bara, measured by two separate pressure transmitters.
As the temperature changes, the relative deviation in measured density drops down to almost -2% as the change in temperature is at its maximum, before it converges towards 0% when the temperature stabilizes around 67 °C. This clearly indicates that the measured temperature is not representative of the measured density, even though the PT100 element is located inside the densitometer. The error in density corresponds to an error in temperature up to 6 °C. The explanation for this could be either due to temperature gradients in the system during heating, delay in the temperature measurement, or both. But in either case, it illustrates the importance of maintaining an even and stable temperature throughout the system. Note that for a natural gas, a 6 °C error in temperature would produce an even higher (~4%) error in the density, since natural gas density is more temperature sensitive than nitrogen density.

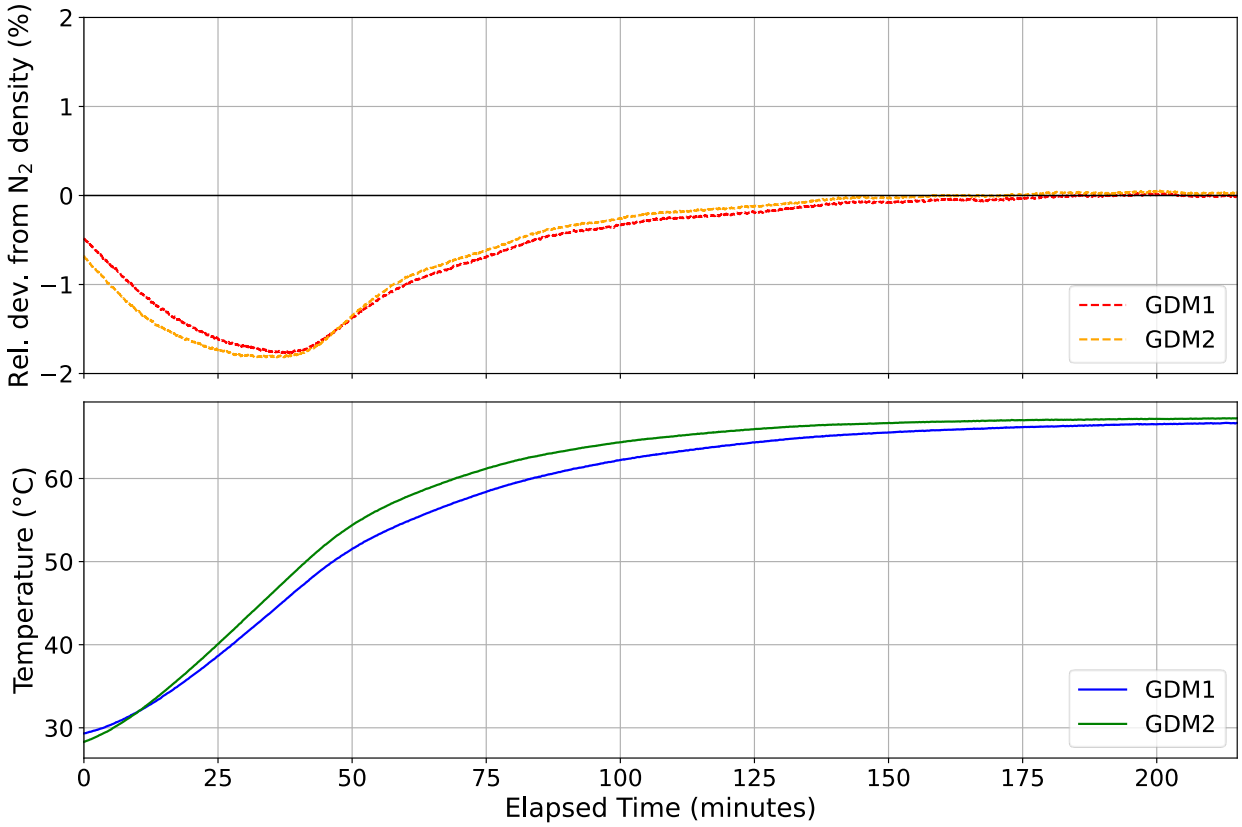

Fig. 5 – Relative deviation between measured density and theoretical N_2 density for two gas densitometers in series, when temperature is increased from 30 to 67 °C

2.3 Representative pressure

Pressure is usually measured separately from the densitometer. While representative temperature is important, it is even more crucial that the pressure accurately reflects the conditions within the chamber of the vibrating element. 1% error in measured pressure will correspond to approximately 1% error in the density corrected to the flowmeter conditions. It is usually easier to maintain representative pressure than a representative temperature. However, it is important to make sure that the equipment in the system (such as filters, valves etc.) does not produce significant pressure drops, and that the vertical distance between the gas densitometer and the pressure transmitter does not cause significant static pressure, unless it is accounted for. Filters in the system are particularly prone to clogging, so regular maintenance routines for replacing filters are important.

2.4 Flow rate through the densitometer

A sufficient flow rate through the meter is necessary to reduce the time delay from when the gas is extracted by the sampling quill until it enters and fills the chamber of the vibrating element. If the gas composition changes, the displacement of the *old* gas in the density chamber is a gradual process, and the density measurement will not be representative until the entire chamber has been displaced. For a natural gas metering application with minor changes in gas composition, it is difficult to quantify the effect of gas displacement. Furthermore, too high flowrates through the meter introduces a series of challenges that can cause measurement errors, such as:

- Pressure drops leading to non-representative pressure measurement
- Pressure drops causing liquid condensation
- Temperature gradients, as the gas does not have time to reach temperature equilibrium
- Vibrations influencing the density measurement

Micro Motion recommends keeping a flowrate between 1-10 litre/hour to avoid these issues. The flowrate through the gas densitometers is, in many applications, driven by a pressure drop through the main pipe or by a differential pressure device, in which the flowrate through the densitometers will depend upon the flowrate in the main pipe. Maintaining a flowrate within the recommended range can therefore be difficult to achieve, especially in a metering station with varying flowrates.

The delay time of displacing the gas densitometers from one gas composition to another will influence the measurement. During the time of displacement, the gas density corrected to the flow meter condition will not be representative and consequently produce a measurement error. This effect is illustrated in Fig. 5, which shows two gas densitometers in series (GDM1 and GDM2), initially filled with nitrogen, and then gradually being displaced to natural gas after being put into operation. The process is illustrated using the relative deviation between the measured and calculated density. The calculated density is based on the composition in the main pipeline, which is hydrocarbon gas.
Initially the gas densitometers are filled with nitrogen, indicated by a density deviation exceeding 30%. As the nitrogen is gradually displaced to natural gas, the relative deviation in density drops, converging towards 0%. It takes approximately 1 minute from gas enters GDM1 until it is observed in GDM2. Most of the nitrogen is displaced after 10 minutes, with a remaining density deviation of ~0.7%, indicating some remaining nitrogen. Nevertheless, it takes almost 40 minutes until the meters are fully displaced with natural gas. This example illustrates that the displacement process from one gas composition to another is a gradual process, where the rate of displacement decreases over time. The time required to fully displace the gas in a densitometer will depend on the flowrate through the system, which in this example was 2-3 litre/hour, which lies within recommended flowrates of the meters (1-10 litre/hour). At lower flowrates, the displacement process would be slower. It is important to note that the example demonstrates a displacement of nitrogen with natural gas and will not necessarily represent a real scenario where one natural gas is displaced by another. Effects such as molecular diffusion and viscosity will influence the displacement process.

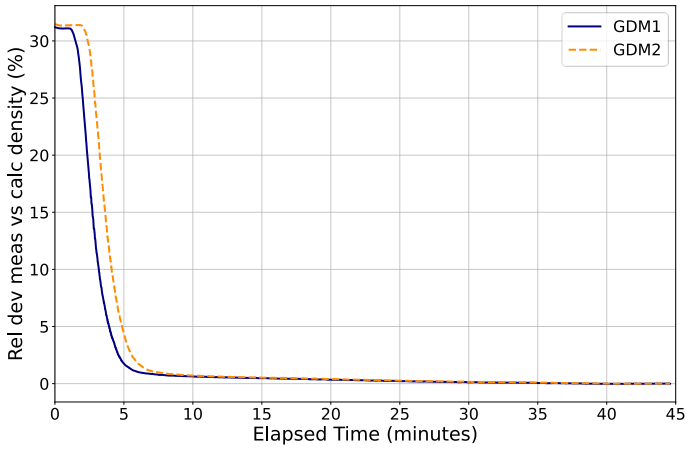

Fig. 6 – Relative deviation (%) between measured and calculated density during the displacement of N_2 with natural gas at a flowrate of 2-3 litre/hour in two gas densitometers in series. Calculated density is based on the composition of natural gas in the main pipeline

2.5 Process disturbances

In natural gas processing systems, process disturbances are unavoidable. Some examples are listed below:

- Compressor trip, causes changes in pressures and temperature
- Process blowdown, rapidly depleting pressure
- Power failure, losing power and thereby heating
- Malfunctioning heater, losing heating

All these scenarios can potentially cause liquid condensation in the gas densitometers, leading to measurement errors. Once liquid has formed, it can be difficult to get rid of. Fig. 6 shows a power failure in a rich gas metering station, shutting down the heating of the gas density cabinet. As the temperature drops, liquid condensation can be observed by a significant increase in measured density. The filter located upstream the densitometer was drained after the event, confirming large amounts of liquid in the system. The system was drained, purged with nitrogen and vacuumed to remove the liquid, but one of the gas densitometers did not recover and had to be removed and sent for cleaning, maintenance and recalibration.

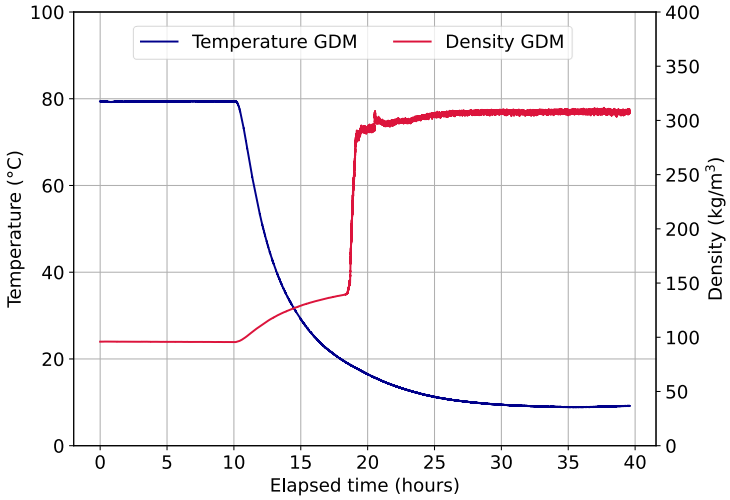

Fig. 7 – Power failure in GDM cabinet, causing loss of heat and liquid condensation

3 COMPENSATING FOR DIFFERENCES FROM CALIBRATION CONDITIONS

Even if all practical challenges related to installation and operation are resolved, the measured gas density must still be corrected for differences between calibration conditions and actual process conditions. The relationship between calibration gas density and the instrument's time period (equation 1) is valid only for the calibration gas at its calibration temperature. As the densitometer is applied to a different gas and/or operating conditions, these deviations must be compensated for.
For convenience, the term *magnitude of correction* (MOC) is introduced and calculated as the relative deviation between the corrected density (ρ_{corr}) and the density before correction (ρ_{uncorr}), as shown in equation 2.

$$MOC = \frac{\rho_{corr} - \rho_{uncorr}}{\rho_{uncorr}} \times 100\% \quad (2)$$

3.1 Pressure and temperature correction

The material properties of the densitometer are influenced by pressure and temperature, affecting the measured density when utilized at different pressures and temperatures than the calibration conditions. The effect of pressure is normally negligible [2], while the effect of temperature can be corrected for by equation 3, where ρ_r is the raw density obtained by equation 1, T_d is the temperature measured in the densitometer, T_c is the calibration temperature (normally 20 °C) and K_{18} and K_{19} are constants established during calibration.

$$\rho_t = \rho_r[1 + K_{18}(T_d - T_c)] + K_{19}(T_d - T_c) \quad (3)$$

The temperature correction is normally assumed to be relatively small and also well-established, where the calibration factors K_{18} and K_{19} are established based on instrument time period during vacuum, measured at two different temperatures in the calibration, typically 20 and 70 °C [4].
However, when comparing calibration factors (K_{18} and K_{19}) for a single meter that had been calibrated at two different calibration facilities, differences exceeding 1% in the temperature corrected density was observed. The MOC for the two sets of calibration factors are presented in Fig. 7, plotted against density and operating temperature. The effect increases with increasing temperature and decreasing density. Three additional gas densitometers were investigated, with same deviations observed in temperature corrected density. These meters were calibrated at the same two laboratories, suggesting a potential systematic bias in one of the laboratories. After consulting with the meter vendor and various calibration laboratories, it has been identified that calibration factors K_{18} and K_{19} are, in fact, temperature dependent. This finding challenges the assumption that temperature correction is well established and indicates that this dependency could represent a significant source of error in gas densitometers, particularly when measuring rich natural gases at elevated temperatures (typically significant above 50 °C, depending on density).

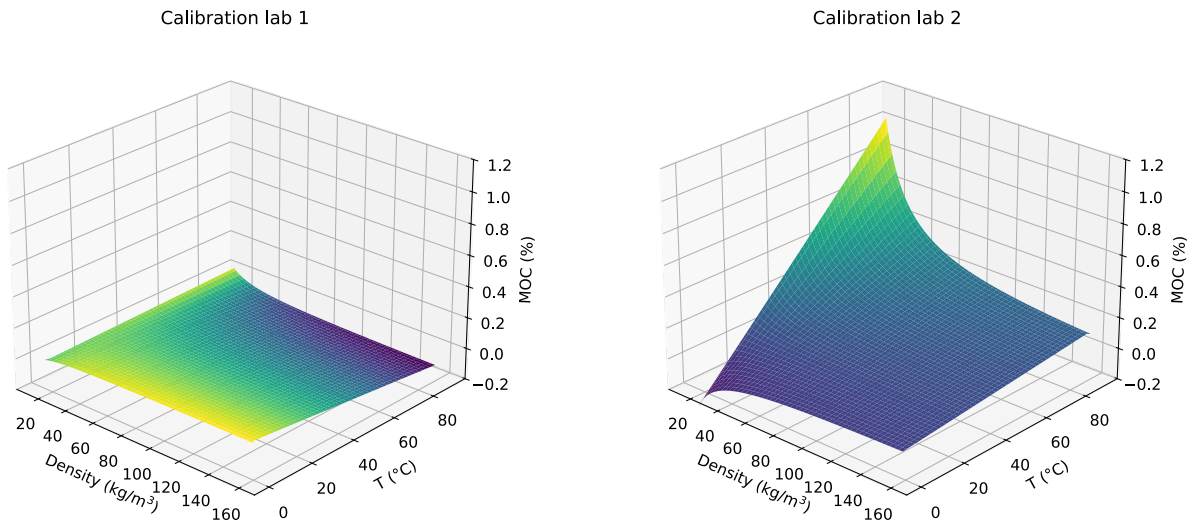

Fig. 8 – Magnitude of correction (MOC) for the temperature correction plotted against the density and temperature. The MOC has been calculated for the same meter, but with calibration factors (K_{18} and K_{19}) from two separate calibration labs

It should be noted that the K_{18} and K_{19} factors in equation 3 are described in both Micro Motion user manuals, flow computer documentations as well as third party calibration certificates for the 7812 and GDM transducers. However, in ISO 15970, the same factors are called K_3 and K_4, which can lead to confusion, as Micro Motion uses the term K_3 and K_4 in their simplified speed of sound correction (User Gas Equation).

3.2 Gas type correction (speed of sound and viscosity)

The relationship between density and the measured time period is also influenced by the difference in properties between the process gas and the calibration gas, which can be referred to as the *gas type effect*. According to ISO 15970, this effect is best described by the difference in speed of sound between the process gas and the calibration gas. However, a comprehensive study was conducted by Jaeschke et. al. involving 12 gas densitometers, where the *gas type effect* was investigated using six pure gases and six natural gases [8, 9]. It was found that the *gas type effect* is dominated by both the difference in speed of sound, but also the difference in viscosity between the process gas and the calibration gas. Especially for gas densitometers based on vibrating forks, a significant part of the error originates from the viscosity effect [8]. For the 7812 transducer, which is among the most used gas densitometers in the North Sea, it was shown that the speed of sound effect was approximately three times smaller compared to the 7810 transducer, while the viscosity effect was approximately three times larger for the 7812 [9]. In their paper, Jaeschke et. al. published a new and improved method for compensating for the *gas type effect*, considering both the speed of sound effect as well as the viscosity effect. The new method was shown to obtain uncertainties of less than ±0.1%. Unfortunately, the meter specific viscosity constant is not published in the paper, nor is it available from the vendor or any other public sources, to the knowledge of this paper's authors.

ISO 15970 Speed of Sound correction

While the effect of viscosity is usually not considered (and not even mentioned in the ISO), the speed of sound effect has been known for many decades, and metering vendors has attempted to minimize the effect in the design of their gas densitometers. In addition, various methods for correcting for the speed of sound effect has been developed. In 1986 J.W. Stansfeld from Solartron proposed a method derived from physical theory, shown in equation 4, which was later incorporated in ISO 15970.

$$\rho_c = \rho_t \left[\frac{1 + \left(\frac{K}{\tau c_c}\right)^2}{1 + \left(\frac{K}{\tau c_g}\right)^2} \right] \tag{4}$$

where ρ_c is the speed of sound corrected density (kg/m^3), ρ_t is the temperature corrected density from equation 3 (kg/m^3), τ is the instrument time period (µs), c_c is the speed of sound of the calibration gas (m/s) at the corresponding time period and the calibration temperature, c_g is the speed of sound of the process gas (m/s) at the GDM conditions and K is the speed of sound correction constant, which is meter dependent. K=2.10 x 10^4 for the Micro Motion 7812 transducer [4], and should be the same for the GDM model according to Micro Motion, as the 7812 and GDM uses the same measurement body.

For pure component gases, the magnitude of the speed of sound correction can become very large, as shown in Table 1 (N_2 is used as calibration gas). The table presents the range of relative deviations between the speed of sound corrected density (ρ_c) and the temperature corrected density (ρ_t) from equation 4. N_2 is used as calibration gas, and the evaluation has been conducted for pressures up to 200 bara and temperatures between 0 to 50 °C, discarding points with liquid. Temperatures above 50 °C has negligible effects on the values presented in the table.

Table 1 – Magnitude of speed of sound correction (equation 4) for pure component gases in the temperature range 0 to 50 °C and pressures up to 200 bara. N_2 is used as calibration gas, and numbers are calculated for the Micro Motion 7812 and GDM models

Component	Magnitude of speed of sound correction [%]	
	Lower	Upper
CO_2	-1.7	-0.9
C_1	0.2	0.5
C_2	-3.9	-0.5
C_3	-91.1	-1.6
H_2	0.4	1.2
Ar	-0.3	-0.2

Fortunately, in a mixture of components, the lighter and heavier components will to a certain extent cancel each other out, resulting in a magnitude of correction of up to around 0.5% for typical natural gases. However, for novel metering applications, such as hydrogen or CO_2 measurement, it is important to be aware that the speed of sound influence can be larger. In addition, for pure components like CO_2, the effect of viscosity can also become significant, and should be considered. For such applications, these effects can be almost eliminated by using the actual process gas (e.g. CO_2) as the calibration gas. However, nitrogen and argon are often the only available options at most accredited calibration facilities. Note that the numbers presented above are only valid for the Micro Motion 7812/GDM transducers, calibrated on nitrogen. The magnitude of correction for other type of transducers has been found to be greater [9]. The MOC is calculated using equation 2 and 4.

User Gas Equation method

Based on the correction given in equation 4, Solartron developed a simplified correction, referred to as the *User Gas Equation Method*, shown in equation 5, which has been widely adopted by the industry. Although both the *User Gas Equation Method* and the ISO 15970 method is available in the Micro Motion 7812 manual [4], the ISO method has been removed in the manual for the newer gas densitometer, Micro Motion GDM [10]. The *User Gas Equation Method* is also typically the only one being provided on calibration certificates, whether issued by the factory or third-party calibration facilities.

$$\rho_{VOS} = \rho_t \cdot \left[1 + \frac{K_3}{\rho_t + K_4} \cdot \left(A - \frac{G}{T + 273}\right)\right] \tag{5}$$

ρ_{VOS} is the measured density corrected for the speed of sound effect by the *User Gas Equation Method*, the equivalent to ρ_c from equation 4. The term ρ_{VOS} is commonly used in calibration certificates and flow computer documentation. ρ_t is the temperature corrected density from equation 3 (kg/m^3), K_3 and K_4 are calibration constants for the given transducer, T is the temperature at the densitometer (°C), A is a parameter representing the calibration gas (usually assumed to be constant at 0.00236 for nitrogen) and G represents the calibration gas, given by equation 6.

$$G = \frac{SG}{\gamma_0} \tag{6}$$

In equation 6, SG is the specific gravity of the gas and γ_0 is the low-pressure specific heat ratio, i.e. C_p/C_v. In the 7812 user manual [4], it is not clearly defined at what conditions C_p and C_v should be calculated at. However, after consulting the vendor, it was confirmed that C_p/C_v should be calculated at base conditions, which is 1.01325 bara and 20 °C. Although the specific gravity (SG) is not defined in the 7812 user manual, the GDM user manual [10] defines it as the molecular weight of the process gas (MW_{Gas}) divided by the molecular weight of air (MW_{Air}).

$$SG = \frac{MW_{Gas}}{MW_{Air}} \tag{7}$$

The simplified *User Gas Equation Method* is based on a series of assumptions, with some of them listed below:

1. Assumption that the process gas behaves as an ideal gas.
2. Assumption that the isentropic exponent equals the specific heat ratio, $\kappa = C_p/C_v$
3. Assumption that the speed of sound of the calibration gas can be represented by a constant, A

In reality, the process gas behaves as a real gas, the isentropic exponent does not equal the specific heat ratio, and the speed of sound of the calibration gas will vary with pressure and temperature. In addition, the calibration constants K_3 and K_4 depend on the process gas composition. During calibration, a mixture of methane and nitrogen is typically used to represent the customer's process gas while determining these constants. If the actual gas composition deviates significantly from this assumption, errors in the speed of sound correction will occur.

In addition, K_3 and K_4 are established for a specific density range. For meters with a wide calibration range, it might be necessary to establish multiple sets of constants K_3 and K_4 for different density intervals. Given these assumptions and the complexity involved in determining K_3 and K_4, it is worth considering whether the so-called *simplified User Gas Equation Method* has, in practice, become more elaborate than the original ISO method described in equation 4.

The procedure for establishing K_3 and K_4 can be found in the 7812 user manual [4].

Another challenge associated with the *User Gas Equation Method* is related to incorrect implementation of the method. In flow computers, the correction is often implemented based on the real gas relative density [11] instead of specific gravity (equation 7), and the C_p/C_v at process conditions rather than base conditions, as prescribed by Micro Motion. This misapplication may be partly due to unclear definitions in the user manuals. However, such incorrect use of the method can cause errors in the correction.

3.3 Comparing methods for speed of sound correction

To investigate potential errors originating from the *User Gas Equation Method*, a comparison has been conducted for 6 different gases.

Three different correction methods for the speed of sound effect were applied:

- *Method 1: The ISO 15970 method.* Using equation 4.
- *Method 2: User Gas Equation Method – ideal conditions.* Using equation 5 with specific gravity (equation 7) and specific heat ratio at base conditions
- *Method 3: User Gas Equation Method – actual conditions:* Using equation 5, with real gas relative density [11] and specific heat ratio at process conditions

The ISO 15970 method can be considered as the reference method in the comparison. The method is derived from fundamental physical principles [12] and has proven to be the most accurate method available for compensating for the speed of sound in multiple studies conducted by Jaeschke et. al [8, 9].

The gases evaluated (presented in Table 2) have been selected to cover a wide range of natural gases, where 4 of them originate from real gas metering stations. *Gas 3 [5]* and *Gas 4 [13]* both represent gas export metering stations in the North Sea, where the compositions exceed the limitations given by the AGA reports no. 8, and where direct density measurement may be the only feasible option to achieve sufficient accuracy in density. *Gas 1* is a lean natural gas and *Gas 2* is a rich natural gas with relatively high C6+ content. In addition, pure H_2 and CO_2 was included in the investigation.

Table 2 – Molar composition (mol%) of gases evaluated in comparison of speed of sound corrections

	Gas 1	Gas 2	Gas 3	Gas 4	H_2	CO_2
N2	3.1	0.83	2.03	1.11		
CO2	1.69	1.84	0.33	2.76		100
C1	84.91	83.34	62.21	48.76		
C2	9.36	5.62	16.32	15.93		
C3	0.71	1.73	14.89	20.04		
iC4	0.05	0.45	1.62	3.52		
nC5	0.04	1.16	0.16	0.83		
iC5	0.02	1.19	0.21	0.96		
nC4		2.77	2.2	5.77		
nC6		0.53	0.03	0.27		
nC7		0.35		0.04		
nC8		0.14		0.04		
nC9		0.03				
nC10		0.01				
H2					100	

Method

The speed of sound corrections was evaluated in a density range from 15 to 160 kg/m^3, at a fixed temperature for each gas. The temperature was obtained by calculating the Cricondentherm of each gas, and adding 10 °C, to provide a realistic temperature estimate, including a margin to the Cricondentherm. For the lean natural gas (*Gas 1*) and the pure components, 20 °C was used.

For each density, temperature correction was applied using equation 3. The temperature corrected density was then used as input to the three different correction methods (Method 1-3), calculating the speed of sound corrected density. The magnitude of the corrections (MOC) was calculated (by equation 2) as the relative difference between the speed of sound corrected density and the temperature corrected density (ρ_t).

Results

The results of the comparison are presented in Fig. 8, with one plot for each gas. As method 1 has been shown to be the most accurate method, the difference from method 1 will indicate the error of utilizing the *User Gas Equation Method.*

For all the natural gases (Gas 1 – Gas 4), the *User Gas Equation Method* overpredicts the corrected density, especially for method 3 (actual conditions). Also, method 2 (ideal conditions), which follows vendor recommendations, yields better results than method 3 (actual conditions) for these gases.

For gas 3 and 4, which have high ethane and propane content, the *User Gas Equation Method* will result in a correction in the opposite direction, and it would actually be better to skip the correction, especially for method 3. Method 3 deviates up to almost 0.4% for gas 3, and 0.6% for gas 4, which exceeds the maximum permissible error given by the Norwegian Measurement Regulations. It should also be noted that using a combination of method 2 and method 3, (e.g. using specific gravity in combination with specific heat ratio at process conditions) would yield even larger errors.

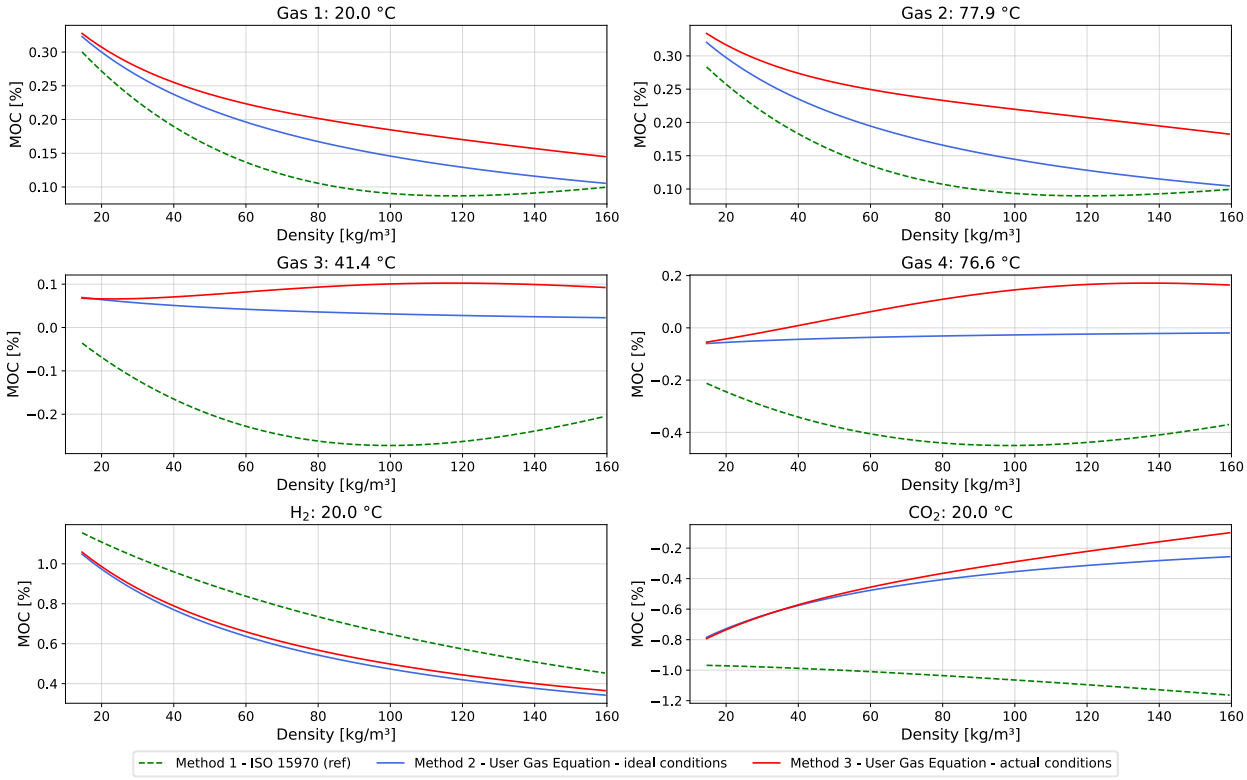

Fig. 9 – Magnitude of speed of sound correction (MOC) for measured density from a Micro Motion GDM, evaluated for 6 different gases (4 natural gases, H_2 and CO_2), using three different correction methods

For pure H_2 and CO_2, the MOC is significant, and the *User Gas Equation Method* would provide incorrect results, especially for CO_2. For CO_2, the viscosity effect should also be considered, which is not included in this analysis. The reason for these deviations is obviously that N_2 is used as calibration gas. The effect could be minimized if the actual gas was used for calibration. Note that there would still be a small effect, as speed of sound changes with temperature.

4 CONCLUSIONS

- Rich natural gases may violate the boundary conditions of the standards currently used to calculate gas density, making direct measurement the most reliable solution for achieving sufficient accuracy in fiscal applications.
- Paradoxically, these gases also pose the greatest challenges for direct measurement, primarily due to higher dew point temperatures and overall operating temperatures.
- As a result, gas densitometers in rich gas applications are prone to challenges related to maintaining single-phase gas, temperature stability, and adequate flow rates through the meters.
- Additionally, rich natural gases carry an increased risk of uncertainties and systematic errors stemming from the use of simplified or incorrect models to compensate for differences between process conditions and calibration conditions.
- These challenges can individually or collectively cause uncertainties and systematic errors that exceed the requirements specified in the Norwegian Measurement Regulations.

4.1 Recommendations

Below is a series of recommendations aimed at addressing some of the challenges encountered for gas densitometers in rich gas applications:

- Comparing density measured by two gas densitometers in series (corrected to the same conditions) will help identify many operational issues, such as temperature stability, temperature gradients, liquid dropout and issues with slipstream flowrate (too high or too low). A relative deviation of less than 0.1%, when the densitometers are compared at same conditions of pressure and temperature, is a good indicator of a representative measurement.
- Temperature gradients and fluctuations should be minimized. The findings in this paper suggest that representative temperature and density measurements can be achieved by keeping peak-to-peak temperature fluctuations for a single densitometer below 0.1 °C, and temperature difference between two densitometers in series below 1 °C. However, these numbers may vary for different applications.
- Thermostats tend to cause unstable temperatures. Instead, using more sophisticated temperature controllers in heated cabinets/ heat trace for gas densitometer systems will significantly reduce the issue of temperature fluctuations.
- Adding extra insulation and/or thermal shields to reduce radiation heat are both methods that can help reduce temperature instabilities.
- Monitoring and maintaining flowrates through the gas densitometers within the recommended range is crucial to ensure reliable measurement, especially in applications where the flow through the densitometers is driven by the flowrate/pressure drop in the main pipeline.
- Using air injection for heat distribution in GDM cabinets should be avoided, and methods that have less influence on temperature themselves should rather be used, such as fans or ejectors.
- The speed of sound correction provided in ISO 15970 should be used, while the *User Gas Equation Method* should be avoided.
- If the *User Gas Equation Method*, for some reason, must be used, it should be implemented using *Ideal conditions*, i.e. ideal gas specific gravity and ratio of specific heats at base conditions (1.01325 bara and 20 °C). In addition, calibration labs should deliver a set of K_3 and K_4 factors relevant to the customer's gas, rather than K_3 and K_4 values for a mixture of methane and nitrogen.
- For novel metering applications, such as hydrogen and CO_2 flow metering, both the effect of viscosity and speed of sound can become significant and should be considered. For these applications, the *gas type effect* would be minimized by using the actual gas as the calibration gas. However, this option is currently unavailable in many of the accredited calibration facilities.

5 REFERENCES

1. NORSOK I-106: Fiscal metering systems for hydrocarbon liquid and gas, 2014
2. ISO 15970: Natural gas - Measurement of properties, Volumetric properties: density, pressure, temperature and compression factor, 2014
3. *Forskrift om fiskal måling i petroleumsvirksomheten (måleforskriften)*. 2023; URL: https://lovdata.no/LTI/forskrift/2023-04-21-532.
4. *Micro Motion Installation and Maintenance Manual - 7812 Gas Density Meter*. 2012
5. Hågenvik, C. and D. Mæland, *Uncertainty in Gas Density Originating from Equation of State.* Global Flow Measurement Workshop, 2023
6. Hågenvik, C., D. Van Putten, and D. Mæland, *Exploring the Relationship between Speed of Sound, Density, and Isentropic Exponent.* Global Flow Measurement Workshop, 2024
7. AGA Report No. 8 Part 2 First Edition, Thermodynamic Properties of Natural Gas and Related Gases - Gerg-2008 Equation of State, 2017
8. Jaeschke, M., et al. *A new accurate method for correcting the vos effect on vibrating gas density transducers*. in *Preprints of the 1995 international gas research conference (Cannes, 6-9 November 1995. Volume III, Transmission and storage, distribution)*. 1995.
9. Jaeschke, M., et al. *An Improved Evaluation Procedure for Density Transducers used in Natural Gas Pipelines*. in *INTERNATIONAL GAS RESEARCH CONFERENCE*. 1998. GOVERNMENT INSTTUTES INC.
10. *Micro Motion® Gas Density Meters (GDM): Configuration and Use Manual*. 2016
11. ISO 6976: Natural gas — Calculation of calorific values, density, relative density and Wobbe indices from composition, 2016
12. Stansfeld, J.W., *Velocity of Sound Effect on Gas Density Transducers - The theory, measurement results and methods of correction.* North Sea Flow Measurement Workshop, 1986
13. Glen, N., et al. *Errors Due to Use of the AGA8 Equation of State Outside of Its Range of Validity*. in *North Sea Flow Measurement Workshop*. 2016.