Nafta-Gaz 2026, vol. 82, no. 5, pp. 461–477, DOI: 10.18668/NG.2026.05.03

Effect of temperature and hydrogen content in gaseous fuel on the accuracy of rotary gas meters

Wpływ temperatury oraz zawartości wodoru w paliwie gazowym na dokładność gazomierzy rotorowych

Zbigniew Gacek

Oil and Gas Institute – National Research Institute, Flow Metrology Department

ABSTRACT: The transformation of the gas sector and the development of the hydrogen economy have created a need to assess the suitability of existing gas metering technologies for measuring natural gas-hydrogen mixtures and pure hydrogen. This paper presents the results of an investigation into the effects of test medium composition and temperature on the metrological performance of rotary gas meters. Three rotary gas meters were tested. The working media included E-group natural gas, natural gas–hydrogen mixtures containing 25% and 50% hydrogen by volume, and pure hydrogen. Meter errors were determined at laboratory temperature (20°C) and at gas temperatures of −25°C and 70°C. The results showed that increasing the hydrogen content mainly increased negative measurement errors at the lower end of the flow range, particularly at Q_{min}. At intermediate flow rates, the error curves approached zero, whereas at higher flow rates a tendency toward positive errors was observed for hydrogen. Both lowering the gas temperature to −25°C and increasing it to 70°C resulted in more negative meter errors at the lower end of the measuring range, with the effect being more pronounced at −25°C. The results indicate that rotary gas meters can maintain good accuracy over a substantial portion of their measuring range. However, the measurement of gas with a high hydrogen content requires particular attention to the lower limit of the measuring range and to the temperature conditions.

Keywords: hydrogen, natural gas, rotary gas meter, flow metrology, indication error, effect of temperature.

STRESZCZENIE: Transformacja sektora gazowniczego i rozwój gospodarki wodorowej powodują konieczność oceny przydatności istniejących technologii pomiarowych do pomiaru mieszanin gazu ziemnego z wodorem oraz czystego wodoru. W artykule przedstawiono wyniki badań wpływu składu medium badawczego i temperatury na charakterystyki metrologiczne gazomierzy rotorowych. Badaniom poddano trzy gazomierze rotorowe. Jako medium robocze zastosowano gaz ziemny grupy E, mieszaniny gazu ziemnego i wodoru zawierające 25% i 50% *v*/*v* wodoru oraz czysty wodór. Błędy wskazań wyznaczano w temperaturze laboratorium (20°C) oraz w temperaturach gazu –25°C i 70°C. Stwierdzono, że wzrost udziału wodoru powoduje przede wszystkim pogłębienie ujemnych błędów w dolnym zakresie strumieni objętości, szczególnie w Q_{min}. W zakresie strumieni średnich charakterystyki zbliżały się do zera, natomiast przy większych strumieniach dla wodoru obserwowano tendencję do dodatnich błędów. Zarówno obniżenie temperatury do –25°C jak i wzrost do 70°C zwiększał ujemne błędy wskazań w dolnym zakresie pomiarowym, przy czym wzrost ten w temperaturze –25°C był większy. Wyniki wskazują, że gazomierze rotorowe mogą zachowywać dobrą dokładność w znacznej części zakresu pomiarowego, jednak pomiar mediów o wysokiej zawartości wodoru wymaga szczególnej oceny dolnej granicy zakresu pomiarowego oraz warunków temperaturowych.

Słowa kluczowe: wodór, gaz ziemny, gazomierz rotorowy, metrologia przepływu, błąd wskazania, wpływ temperatury.

Introduction

The transition of the energy sector towards a low-carbon economy is driving rapid advances in hydrogen technologies and growing interest in the use of existing gas infrastructure for the transmission and distribution of natural gas-hydrogen blends and, in the longer term, pure hydrogen (Gacek, 2025). From a metrological perspective, however, changes in gaseous fuel composition present a significant challenge. Instruments currently used to measure natural gas have been designed and evaluated primarily for media exhibiting the physical properties typical of first-, second-, and third-family gases. The addition of hydrogen alters density, viscosity, compressibility, and flow conditions and may therefore affect the indication error curve

Corresponding author: Z.Gacek, e-mail: *zbigniew.gacek@inig.pl*

Article contributed to the Editor: 07.08.2026. Approved for publication: 21.10.2026.

specified in metrological standards and regulations (Jaworski et al., 2019; N1; N2).

Accurate measurement of gaseous fuel quantities is directly relevant to commercial billing and the reduction of unaccounted-for gas. Although modern billing is based on units of energy, in many measurement systems the primary measured quantity remains gas volume under operating conditions, which is subsequently converted to reference conditions. Gas meter error therefore propagates into the determination of gas volume and, consequently, energy (Gacek and Jaworski, 2020).

Rotary gas meters belong to the family of positive-displacement measuring instruments widely used in gas distribution systems and industrial applications. Their advantages include a wide measuring range, stable performance, and the ability to operate under varying flow rates. Their actual metrological performance, however, depends on internal leakage, mechanical resistance, and the balance of torques acting on the rotors. These factors are sensitive to changes in the type of gas and in temperature.

The aim of this study was to experimentally evaluate the effects of increasing hydrogen content in gaseous fuel and gas temperature on the indication errors of rotary gas meters. The test program included natural gas, two natural gas–hydrogen blends, and pure hydrogen, as well as three temperature levels corresponding to laboratory conditions and the limits of the declared operating range of the instruments under investigation.

Properties of natural gas and hydrogen

Natural gas and hydrogen differ substantially in their physical properties. Under normal conditions, hydrogen has a much lower density than methane and also exhibits a lower dynamic viscosity. At the same volumetric flow rate, these differences alter the Reynolds number and the relationship between inertial and viscous forces. For a rotary gas meter, a particularly important consideration is that the driving torque generated by the gas flow must overcome the mechanical resistance of the system. The low density of hydrogen results in a substantial reduction in the driving torque acting on the gas meter rotors, while its high diffusivity promotes increased internal leakage (Molkov, 2012; Workamp and Schakel, 2021). From a metrological perspective, the following effects are particularly important when measuring hydrogen using rotary gas meters:

1. A reduction in the Reynolds number at the same volumetric flow rate (Altfeld, 2013),
2. An increase in the relative contribution of mechanical losses to the overall torque balance (Bergervoet, 2003),
3. An increase internal leakage.

The much lower density of hydrogen also results in a lower driving torque generated by the gas flow than in the case of natural gas. Consequently, the total torque available to drive the rotors decreases, whereas the torque associated with mechanical losses – arising from bearing friction, seal resistance, and meshing of the register gears – remains at a similar level because it depends primarily on the design and mechanical condition of the gas meter rather than on the type of medium. As a result, when hydrogen is measured, mechanical losses account for a larger proportion of the overall torque balance, particularly at low volumetric flow rates. This may result in poorer meter start-up performance, an increased minimum flow rate, reduced indication accuracy at low flow rates, and greater sensitivity to wear and the lubrication condition of moving components. This phenomenon represents one of the key limitations in adapting rotary gas meters for hydrogen measurement and must be taken into account when selecting materials, defining mechanical tolerances, and establishing calibration procedures (Bergervoet, 2003). Table 1 summarizes the physical properties of the gases considered for gas meter testing, i.e. air, natural gas, and hydrogen, with nitrogen and methane included as reference gases for comparison.

Table 1. Basic properties of the gases under standard conditions (0°C, 101.325 kPa) (N3; Perry, 1999; Szymczyk, 2003)

Physical parameter	Unit	Nitrogen (N_2)	Natural gas (methane CH_4)	Hydrogen (H_2)
Molar mass	g/mol	28.014	16.040	2.016
Density	kg/m^3	1.146	0.717	0.082
Dynamic viscosity	µPa·s	16.5	10.9	8.8
Effective molecular diameter	10^{-10} m	3.64	3.80	2.89
Diffusivity	–	low	low	very high

The loss torque associated with the bearings, seals and gear train does not decrease in proportion to the density of the medium. For hydrogen, its relative contribution to the overall torque balance may therefore increase, particularly at low flow rates. At the same time, hydrogen's lower viscosity and smaller effective molecular diameter, combined with its high diffusivity, may increase leakage through operating clearances. Both mechanisms tend to produce more negative errors in the lower part of the measuring range (Molkov, 2012; Workamp and Schakel, 2021). Temperature affects both the physical properties of the gas and the mechanical components of the meter. Changes occur in the density and viscosity of the medium, operating clearances resulting from thermal expansion, and the properties of lubricants. At low temperatures, mechanical

resistance may increase, whereas at high temperatures changes in clearances and viscosity may affect internal leakage. The effects of temperature should therefore not be considered independently of gas composition.

Characteristics of rotary gas meters

Rotary gas meters have been in use since the early 20th century. They are generally preferred for low- and medium-flow-rate applications, primarily in the natural gas distribution sector. The most common configuration consists of two counter-rotating, figure-eight-shaped rotors (Bergervoet, 2003).

Clearances are provided between the rotors and the body in order to avoid an excessive pressure drop and impeller wear. The rotors themselves do not come into contact, while their relative phase is maintained by gears mounted on the impeller shafts. This design results in gaps between the meter components, through which internal leakage occurs. The magnitude of such leakage depends on gas viscosity and gives rise to a difference between the theoretical and actual gas volume displaced during a single impeller revolution. The pressure difference between the meter inlet and outlet generates a force acting on the rotors, which are mechanically coupled by external timing gears. The measurement cycle can be divided into four phases. In the first phase, a volume of gas enters the meter and is trapped between the rotors and the meter body. In the second phase, this volume is transported downstream as the impeller turns, while the second impeller begins to trap another volume of gas. During the third and fourth phases, the trapped gas is discharged and a subsequent volume is captured, initiating the next cycle. Thus, four discrete volumes of gas are displaced during each complete revolution of the rotors. The cyclic volumes of rotary gas meters range from 0.25 dm^3 to more than 5 dm^3, corresponding to impeller speeds of approximately 700 to 5700 rpm (Guzzini et al., 2024).

The metrological performance of rotary gas meters operating with natural gas is well established. At the lower end of the flow range (Q_{min}), a negative indication error is typically observed, remaining within the permissible limit of ±2%. This error results mainly from internal leakage between the meter body and the rotors and from the limited driving torque available to the rotors. Within the nominal flow range, errors are generally close to zero, whereas small positive deviations may occasionally occur at higher flow rates. The use of hydrogen and of natural gas–hydrogen blends changes the physical properties of the medium, in particular its density and viscosity, which may affect the magnitude and nature of the measurement errors. Assessing these effects requires experimental investigation, the results of which are presented later in this paper.

Available studies indicate that rotary gas meters can be successfully used to measure natural gas–hydrogen blends containing up to 20% hydrogen by volume (Guzzini et al., 2024). Important evidence was provided by the NewGasMet project (NewGasMet, 2022), which showed that gas meter indication errors remained within the maximum permissible error (MPE) limits, with only a slight shift in the error curve towards more negative values. In addition, long-term testing carried out within the project confirmed that hydrogen concentrations of up to 20% by volume do not adversely affect either the metrological performance or the durability of rotary gas meters.

Despite these findings, a number of issues still require further investigation. For example, no publications were identified that analyze the effect of hydrogen addition on the magnitude of internal leakage in rotary gas meters. From a fluid-flow perspective, it may be expected that, because hydrogen has a lower dynamic viscosity (approximately 8.8 μPa·s) than natural gas (approximately 10.9 μPa·s), internal leakage will increase with increasing hydrogen content in the mixture. This may result in larger indication errors at low volumetric flow rates and, consequently, a reduction in the meter's measuring range, particularly in the vicinity of the minimum flow rate Q_{min}.

Research methodology and test samples

The gas meter should be suitable for operation throughout its declared temperature range, taking into account both ambient temperature and the temperature of the gas being measured.

Metrological testing of the gas meters was carried out in accordance with PN-EN 12480:2018−06, Gas meters. Rotary displacement gas meters (N1), specifically Section 5.2.2 at an ambient temperature of 20°C and Section 5.6.1.2 at gas temperatures of −25°C and 70°C. Measurements were performed using natural gas, two natural gas–hydrogen blends, and pure hydrogen at a gauge pressure of approximately 2 kPa. Details of the test gas mixtures are presented in Table 3. For G16 gas meters, indication errors were determined at volumetric flow rates of Q_{min}, $0.05Q_{max}$, $0.1Q_{max}$, $0.25Q_{max}$, $0.4Q_{max}$, $0.7Q_{max}$ and Q_{max} (0.4 m^3/h; 1.25 m^3/h; 2.5 m^3/h; 6.25 m^3/h; 10.0 m^3/h; 17.5 m^3/h; 25 m^3/h). Due to the maximum capacity of the test facility (25 m^3/h), indication errors for the G40 gas meter were determined at volumetric flow rates of Q_{min}, $0.05Q_{max}$, $0.1Q_{max}$, $0.25Q_{max}$ and $0.4Q_{max}$ (0.4 m^3/h; 3.25 m^3/h; 6.5 m^3/h; 16.25 m^3/h; 25 m^3/h). The error curves were first determined at laboratory temperature (20°C), followed by measurements at gas temperatures of −25°C and 70°C. This experimental design made it possible to distinguish between the effects of gas composition, volumetric flow rate, and temperature. Particular attention was given to the lower end of the measuring range, where changes

Table 2. Rotary gas meters tested in this study

No.	Identification	Year of manufacture	Size	Measuring range [m³/h]	Transitional flow rate Q_t / Nominal flow rate [m³/h]	Cyclic volume [dm³]	Rangeability (Q_{min} : Q_{max})	Ambient and gas temperature range [°C]
1.	Sample 1	2022	G16	0.4 ÷ 25	1.3 / 16	0.16	1:60	−25 ÷ 70
2.	Sample 2	2022	G16	0.4 ÷ 25	1.3 / 16	0.16	1:60	−25 ÷ 70
3.	Sample 3	2022	G40	0.4 ÷ 65	3.2 / 40	0.16	1:160	−25 ÷ 70

in density, viscosity, and mechanical resistance were expected to have the greatest effect. Table 2 lists the gas meters tested.

All the meters listed above are intended for the measurement of gases from the first, second, and third gas families in accordance with EN 437 (N4).

The initial maximum permissible errors (MPE) specified in PN-EN 12480:2018-06 were adopted as the primary criterion for evaluating the test results: ±2% over the range $Q_{min} \leq Q < Q_t$ and ±1% over the range $Q_t \leq Q \leq Q_{max}$. The weighted mean error (WME) was also evaluated and was required to remain within ±0.4%. Where Q_t is transitional flow rate.

Test facility

The metrological performance of the meters was determined using accredited methods at the SG25-G measurement and test facility (Figure 1). Table 2 provides the parameters of the meters tested, while Table 3 lists the gases used in the tests.

The test facility operates in a closed loop. The system was maintained at an overpressure of 2 kPa, while gas circulation was provided by an intrinsically safe side-channel blower. The blower speed was controlled by adjusting the inverter setting and the control valve settings (Nos. 3 and 4). This arrangement enabled precise control of the volumetric flow rate of the test medium. The facility was equipped with two reference gas

Table 3. Gases used in the study

Designation	Mixture used
2E	Group E natural gas
2E/25%H_2	Natural gas blend containing 25% hydrogen
2E/50%H_2	Natural gas blend containing 50% hydrogen
H_2	Hydrogen

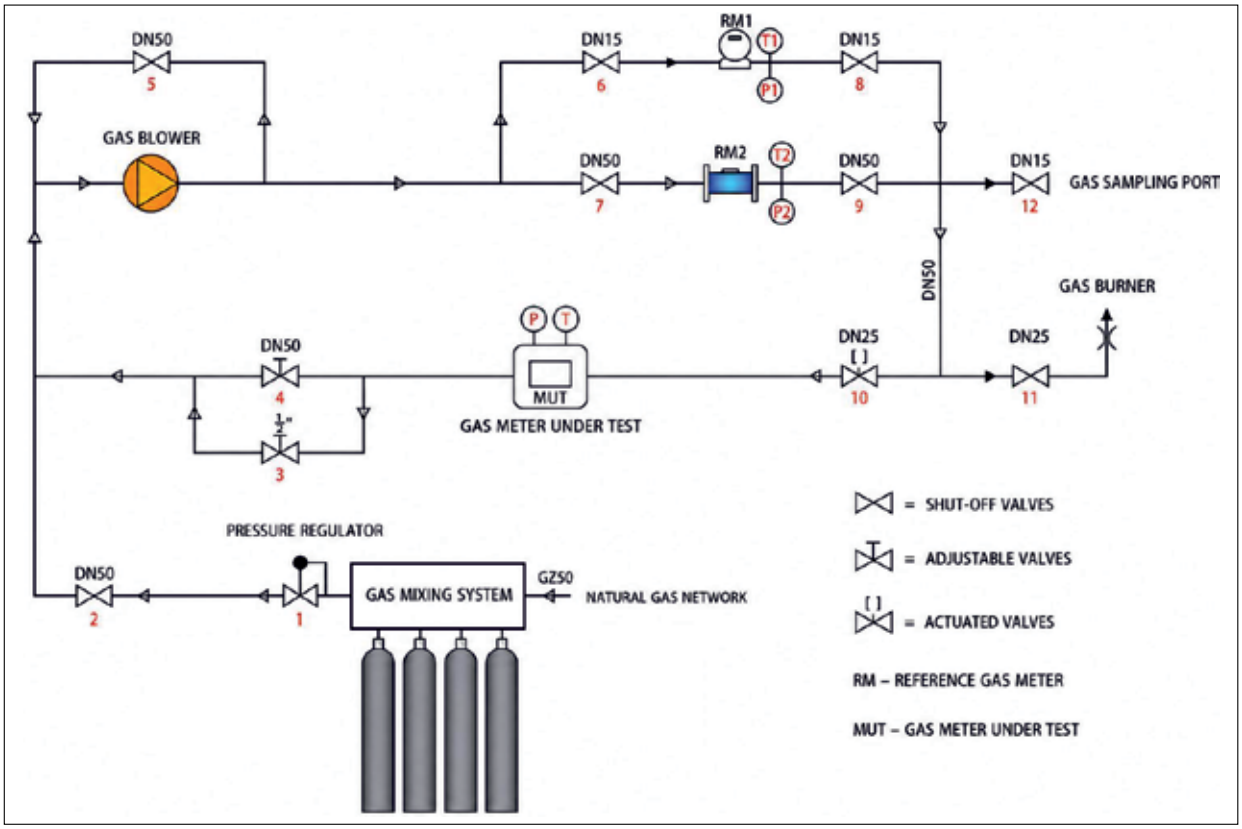


Figure 1. Schematic diagram of the SG25-G test facility (measurements performed at the laboratory ambient temperature of 20°C)

meters operating on the positive displacement principle. For volumetric flow rates of up to and including 2 m^3/h, a wet-drum gas meter was used (RM1), whereas at flow rates above 2 m^3/h, a CGR-01 rotary gas meter (RM2) was used; its suitability for hydrogen measurement has been confirmed. Metrological traceability to the International System of Units (SI) was established for both gas meters using air as the calibration medium at the Oil and Gas Institute's Calibration Laboratory (AP 152).

The use of a wet-drum gas meter as a reference standard for hydrogen flow measurements offers several metrological advantages, particularly at low flow rates. Due to its positive-displacement operating principle, the measurement of gas volume is relatively insensitive to gas density and viscosity compared with many other flow measurement technologies. The use of oil as a sealing liquid provides effective sealing of the measuring chambers, minimizing internal gas leakage, which is particularly important when measuring hydrogen due to its low density and high diffusivity. Unlike rotary gas meters, which rely on small mechanical clearances between moving components, wet-drum gas meters employ a liquid seal that helps reduce gas leakage and associated measurement errors at low flow rates. This makes them particularly suitable for accurate hydrogen volume measurements in the lower flow range.

At higher flow rates, a specially selected rotary gas meter was used as the reference standard due to its good repeatability and relatively low-pressure loss. Its positive-displacement operating principle also makes it suitable for measuring gases with different physical properties, including hydrogen. To maintain metrological traceability and minimize potential systematic errors arising with differences in gas properties, the rotary gas meter was calibrated using hydrogen, with the wet-drum gas meters serving as reference standards. This approach ensured consistent measurement conditions and reliable determination of gas meter indication errors. The test facility allowed simultaneous testing of up to three domestic gas meters or one industrial gas meter.

Before each test, the test facility was filled with the test gas. During filling, the facility operated in a closed measurement loop with a continuous supply of the test medium and a controlled bleed-off. This arrangement ensured stable operation of the gas mixing system and enabled the production of gas mixtures with compositions as close as possible to the target values. The facility was then operated for 30 minutes while being supplied from the natural gas network, the gas mixing system in the case of natural gas–hydrogen blends, or a hydrogen cylinder in the case of hydrogen measurements. At the same time, gas was continuously withdrawn at a rate of not less

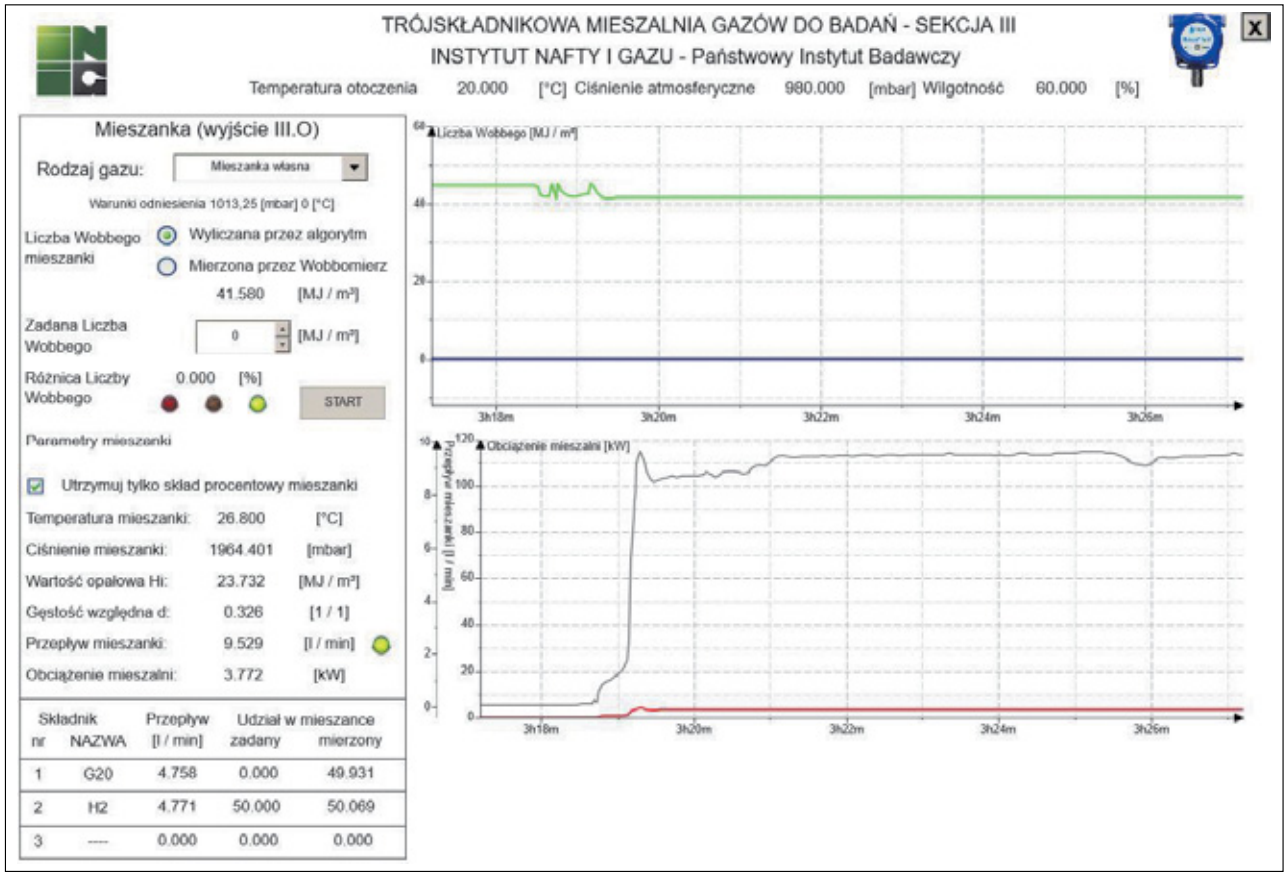


Figure 2. Graphical user interface of the gas mixing system during stabilization of a mixture containing 50% natural gas and 50% hydrogen by volume

Table 4. Reference instruments used at the SG25-G test facility

No.	Reference instrument	Serial number	Manufacturer	Type	Year of manufacture	Measuring range	Communication interface
1.	Drum-type gas meter	10462333	J.B. Rombach	NB2	1994	15 ÷ 2000 [dm³/h]	Voltage pulse output, 1 pulse = 0.005 dm³
2.	Rotary gas meter	E-120834	Common	CGR-01	2013	0.5 ÷ 25 [m³/h]	Voltage pulse output, 1 pulse = 0.064 dm³
3.	Pressure transmitters, 2 units	03213916; 03213917	Aplisens	PC-28 PD Exi	2021	0 ÷ 10 [kPa]	4÷ 20 [mA]
4.	Differential pressure transmitters, 3 units	03213896; 03213897; 03213898	Aplisens	APR-2000G PD Exi	2021	0 ÷ 2.5 [kPa]	4÷ 20 [mA]
5.	Digital barometer	H2340004	VAISALA	PTB330	2012	50.0 ÷ 110.0 [kPa]	RS485
6.	Temperature sensors	–	Termoaparatura Wrocław	Pt100	2021	–50 ÷ +260 [°C]	Resistance measurement

than 600 dm³/h and combusted in a burner. During filling of the facility, the composition and other relevant parameters of the test gas mixtures prepared for testing were monitored using the software interface used to control the gas mixer settings. Figure 2 shows the software window during stabilization of a test mixture (Natural gas blend containing 50% hydrogen).

The indication error was determined as the relative difference between the volume indicated by the meter under test and the reference volume. The reference volume was corrected for the error curve of the reference meter and for differences in thermodynamic conditions. Mean error values were analyzed at each flow point, and the weighted mean error (WME) was calculated for each error curve.

The gas meter indication error was calculated using the following equation (N1):

$$E = \left(\frac{V_G - V_p}{V_p} \right) \cdot 100\%$$

where: V_G – volume indicated by the meter under test, m³,
V_p – reference volume of gas passing through the gas meter, m³.

V_p denotes the gas volume determined by the reference standard and converted to the pressure and temperature conditions corresponding to those at the gas meter under test.

Testing with hydrogen required the implementation of safety measures, including gas detection and alarm signaling. The detection system was configured with two alarm thresholds: 10% of the lower explosive limit (LEL) for the first alarm level and 30% LEL for the second alarm level. The system also enabled control of the safety components of the test facility.

Tests at ambient temperature were carried out at 20°C, with the meter under test installed under normal laboratory conditions. In line with the operating range, tests were also performed at gas temperatures of −25°C and +70°C. The minimum temperature of −25°C was obtained using an HC 4033 climatic chamber and an HT 7020 temperature chamber, both fitted with a heat exchanger, supplemented where necessary by a gas-flow cooler. The meter under test was placed inside the climatic chamber. Stable temperature conditions were maintained over the required flow-rate range. The maximum temperature of +70°C was obtained using the HC 4033 climatic chamber and the HT 7020 temperature chamber, both fitted with a heat exchanger and, where necessary, supplemented by a plate heat exchanger supplied with water heated by a gas-fired boiler. The reference gas meters were operated under laboratory conditions throughout all the tests (20°C). The gas temperature upstream of the reference gas meters was also adjusted to laboratory conditions using a heat exchanger located downstream of the climatic chamber. The indication errors E at flow rates of 0.4 m³/h and 1.25 m³/h were determined using a wet-drum gas meter (RM1), whereas at higher flow rates, a rotary gas meter (RM2) was used. Figure 3 shows a schematic diagram of the gas temperature conditioning system at the SG25-G facility.

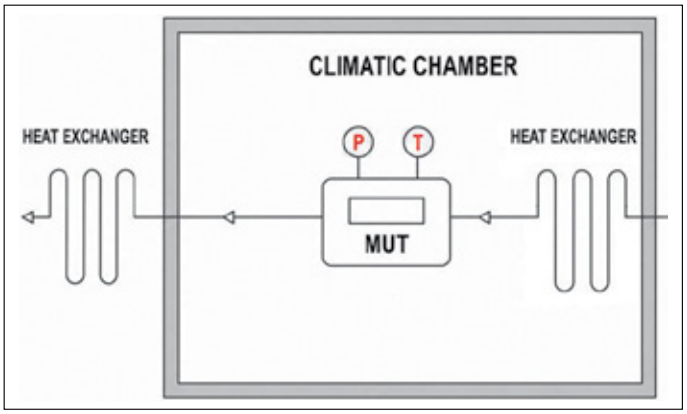


Figure 3. Schematic diagram of the gas temperature conditioning system

Metrological test results

G16 gas meter (Sample 1)

Table 5 lists the mean indication errors ($E_{m\,2E}$, $E_{m\,2E/25\%H2}$, $E_{m\,2E/50\%H2}$, E_{H2}) obtained for the G16 rotary gas meter (Sample 1) at the laboratory ambient temperature (20°C) for natural gas, natural gas mixtures containing 25% and 50% hydrogen, and pure hydrogen (see Table 3); the same data are plotted in Figure 4.

Under PN-EN 12480:2018, the maximum permissible indication errors for rotary gas meters are ±1% for flow rates greater than or equal to Q_t (1.3 m³/h) and ±2% below 1.3 m³/h. Analysis of the indication errors presented in Table 5 and shown in Figure 4 reveals that increasing the hydrogen content of the mixture results in progressively more negative errors at flow rates below Q_t. For pure hydrogen, the indication error at the minimum volumetric flow rate Q_{min} exceeded the MPE, reaching −2.58%. The observed increase in the negative indication errors had no significant effect on the WME.

Table 6 lists the mean indication errors ($E_{m\,2E}$, $E_{m\,2E/25\%H2}$, $E_{m\,2E/50\%H2}$, E_{H2}) obtained for the G16 rotary gas meter (Sample 1) at a gas temperature of −25°C for natural gas, natural gas mixtures containing 25% and 50% hydrogen, and pure hydrogen; the same data are plotted in Figure 5.

Analysis of the indication errors presented in Table 6 and shown in Figure 5 reveals that increasing the hydrogen content of the mixture results in progressively more negative errors at flow rates below Q_t. An exception is the error for a 25% hydrogen content, which is lower than that for natural gas. At the minimum volumetric flow rate, the gas meter errors for the mixture containing 50% hydrogen by volume and for pure hydrogen exceeded the MPE. The largest error, −3.11%, was recorded for pure hydrogen. The increase in negative indication errors was reflected in higher WME values, although the changes were not significant.

Table 7 lists the mean indication errors ($E_{m\,2E}$, $E_{m\,2E/25\%H2}$, $E_{m\,2E/50\%H2}$, E_{H2}) obtained for the G16 rotary gas meter (Sample 1)

Table 5. Mean indication errors of the G16 gas meter (Sample 1) for different gases at the laboratory ambient temperature of 20°C

Gas	Volumetric flow rate [m³/h]							WME
	0.4	1.25	2.5	6.25	10	17.5	25.0	
	Mean indication errors [%]							[%]
2E	−1.50	−0.91	−0.42	−0.04	−0.05	0.21	0.25	0.06
2E/25%H_2	−1.66	−0.83	−0.55	0.10	0.14	0.16	0.22	0.08
2E/50%H_2	−1.72	−0.72	−0.49	0.07	0.07	0.26	0.20	0.10
H_2	−2.58	−0.97	−0.51	0.06	−0.04	0.15	0.39	0.06

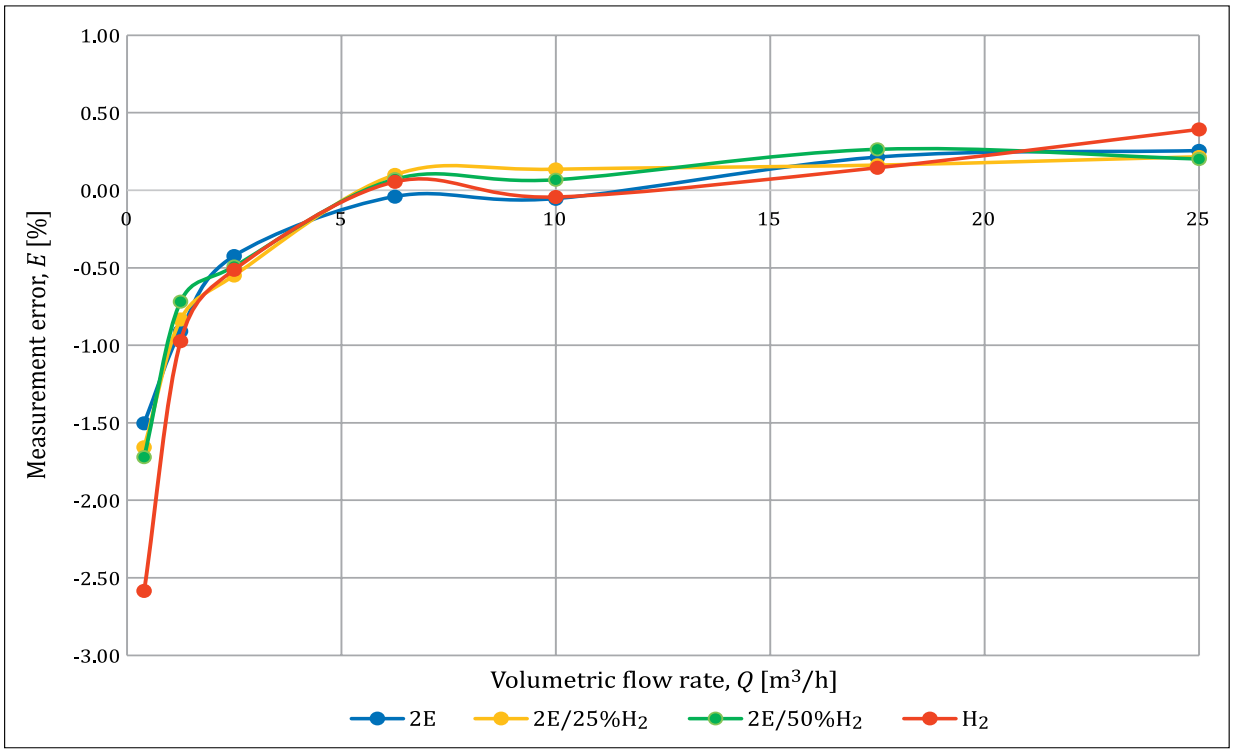


Figure 4. Mean indication errors of the G16 gas meter (Sample 1) at the laboratory ambient temperature of 20°C

at a gas temperature of 70°C for natural gas, natural gas mixtures containing 25% and 50% hydrogen, and pure hydrogen; the same data are plotted in Figure 6.

Analysis of the indication errors presented in Table 7 and shown in Figure 6 reveals that, as in the previous case, increasing the hydrogen content of the mixture results in progressively more negative errors at flow rates below Q_t. At the minimum volumetric flow rate, the gas meter errors for the mixture containing 50% hydrogen by volume and for pure hydrogen exceeded the MPE. The largest error, −2.85%, was recorded for pure hydrogen. Despite the increase in negative indication errors, no deterioration in the WME was observed, except for a minimal deterioration in the case of hydrogen.

Figure 7 shows a comparison of the indication errors of the G16 rotary gas meter (Sample 1) at gas temperatures of 20°C, −25°C and 70°C. To keep the graph legible, only the

Table 6. Mean indication errors of the G16 gas meter (Sample 1) for different gases at a gas temperature of −25°C

Gas	Volumetric flow rate [m³/h]							WME
	0.4	1.25	2.5	6.25	10	17.5	25.0	
	Mean indication errors [%]							[%]
2E	−1.85	−0.61	−0.24	0.03	0.05	0.15	0.22	0.07
2E/25%H_2	−1.36	−0.66	−0.31	0.05	−0.03	0.27	0.24	0.11
2E/50%H_2	−2.02	−0.75	−0.41	−0.05	0.10	0.33	0.29	0.14
H_2	−3.11	−1.32	−0.39	0.10	0.02	0.33	0.56	0.18



Figure 5. Mean indication errors of the G16 gas meter (Sample 1) at a gas temperature of −25°C

Table 7. Mean indication errors of the G16 gas meter (Sample 1) for different gases at a gas temperature of 70°C

Gas	Volumetric flow rate [m³/h]							WME
	0.4	1.25	2.5	6.25	10	17.5	25.0	
	Mean indication errors [%]							[%]
2E	−1.55	−1.03	−0.52	0.06	0.08	0.11	0.13	0.02
2E/25%H_2	−1.80	−1.25	−0.60	−0.11	−0.03	0.10	0.24	−0.01
2E/50%H_2	−2.41	−1.51	−0.75	−0.10	0.11	0.18	0.20	0.02
H_2	−2.85	−1.58	−0.51	−0.13	0.02	0.26	0.43	0.08

results for natural gas and hydrogen have been included. The horizontal axis represents the volumetric flow rate, while the vertical axis represents the relative indication error expressed as a percentage. A pronounced negative indication error, typical of rotary gas meters, is observed at the lower end of the flow range.

At low volumetric flow rates $Q < Q_t$ the negative indication error for hydrogen is greater than that for natural gas over the entire temperature range. This effect is particularly pronounced at –25°C. In the transitional and nominal flow-rate range $Q_t \leq Q \leq Q_n$, the error curves for both media approach zero. For natural gas, the error curve remains stable and shows only

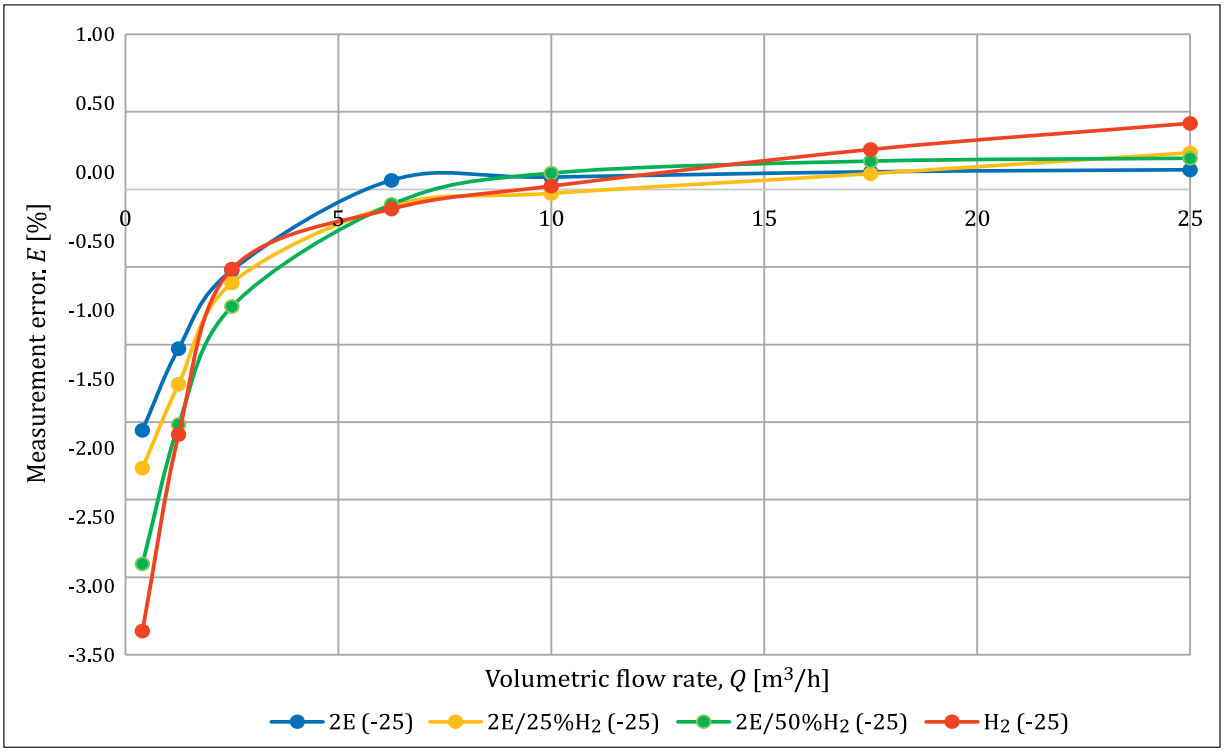


Figure 6. Mean indication errors of the G16 gas meter (Sample 1) at a gas temperature of 70°C

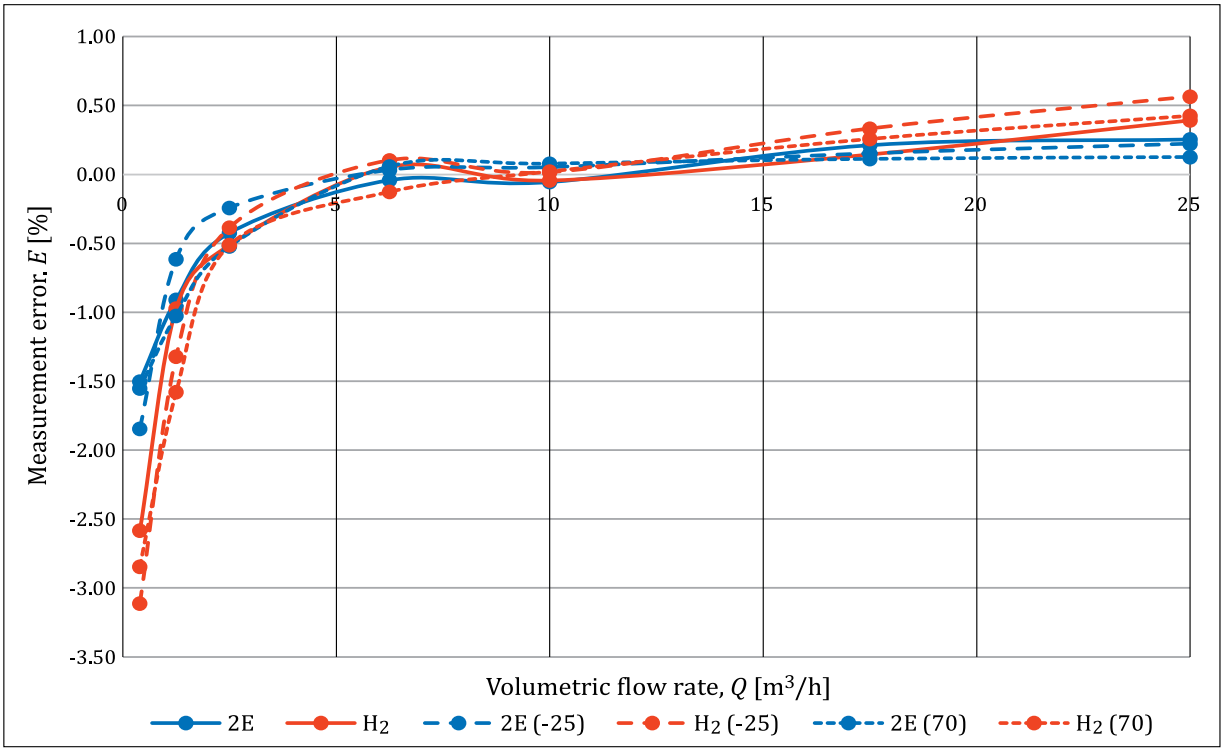


Figure 7. Comparison of the mean indication errors of the G16 gas meter (Sample 1) at gas temperatures of −25°C, 20°C, and 70°C

a weak dependence on temperature. Hydrogen exhibits greater sensitivity to temperature changes, reflected in small upward or downward shifts of the error curves along the error axis.

At the upper end of the flow range, $Q > Q_n$ (16 m^3/h), an increase in the positive indication error is observed, particularly for hydrogen. Gas temperature alters the shape and position of the error curves. At −25°C, the negative errors at the lower end of the flow range become more pronounced. As the temperature rises to 70°C, the error curves shift towards positive error values, particularly at the upper end of the volumetric flow-rate range. This effect is more pronounced for hydrogen than for natural gas, confirming the greater metrological sensitivity of rotary gas meters to temperature when measuring hydrogen.

G16 gas meter (Sample 2)

Table 8 lists the mean indication errors ($E_{m\ 2E}$, $E_{m\ 2E/25\%H2}$, $E_{m\ 2E/50\%H2}$, E_{H2}) obtained for the G16 rotary gas meter (Sample 2) at the laboratory ambient temperature (20°C) for natural gas, natural gas mixtures containing 25% and 50% hydrogen, and pure hydrogen (see Table 3); the same data are plotted in Figure 8. Analysis of the indication errors compiled in Table 8 and shown in Figure 8 reveals that increasing the hydrogen content of the mixture results in progressively more negative errors at the minimum flow rate Q_{min} (0.4 m^3/h). The largest error, −2.55%, was recorded for pure hydrogen and exceeded the MPE limits. The increase in indication errors did not result in an increase in the weighted mean error; instead, the sign of the WME changed.

Table 9 lists the mean indication errors ($E_{m\ 2E}$, $E_{m\ 2E/25\%H2}$, $E_{m\ 2E/50\%H2}$, E_{H2}) obtained for the G16 rotary gas meter (Sample 2) at a gas temperature of −25°C for natural gas, natural gas mixtures containing 25% and 50% hydrogen, and pure hydrogen; the same data are plotted in Figure 9.

Analysis of the indication errors presented in Table 9 and shown in Figure 9 reveals that increasing the hydrogen content of the mixture results in progressively more negative errors at

Table 8. Mean indication errors of the G16 gas meter (Sample 2) for different gases at the laboratory ambient temperature of 20°C

Gas	Volumetric flow rate [m^3/h]							WME
	0.4	1.25	2.5	6.25	10	17.5	25.0	
	Mean indication errors [%]							[%]
2E	−1.24	−0.82	−0.53	−0.21	−0.04	−0.03	0.03	−0.10
2E/25%H_2	−1.44	−0.77	−0.61	−0.12	−0.04	−0.03	0.05	−0.09
2E/50%H_2	−1.45	−0.80	−0.59	−0.19	−0.07	0.08	0.11	−0.05
H_2	−2.55	−0.97	−0.53	−0.08	−0.08	0.19	0.48	0.07

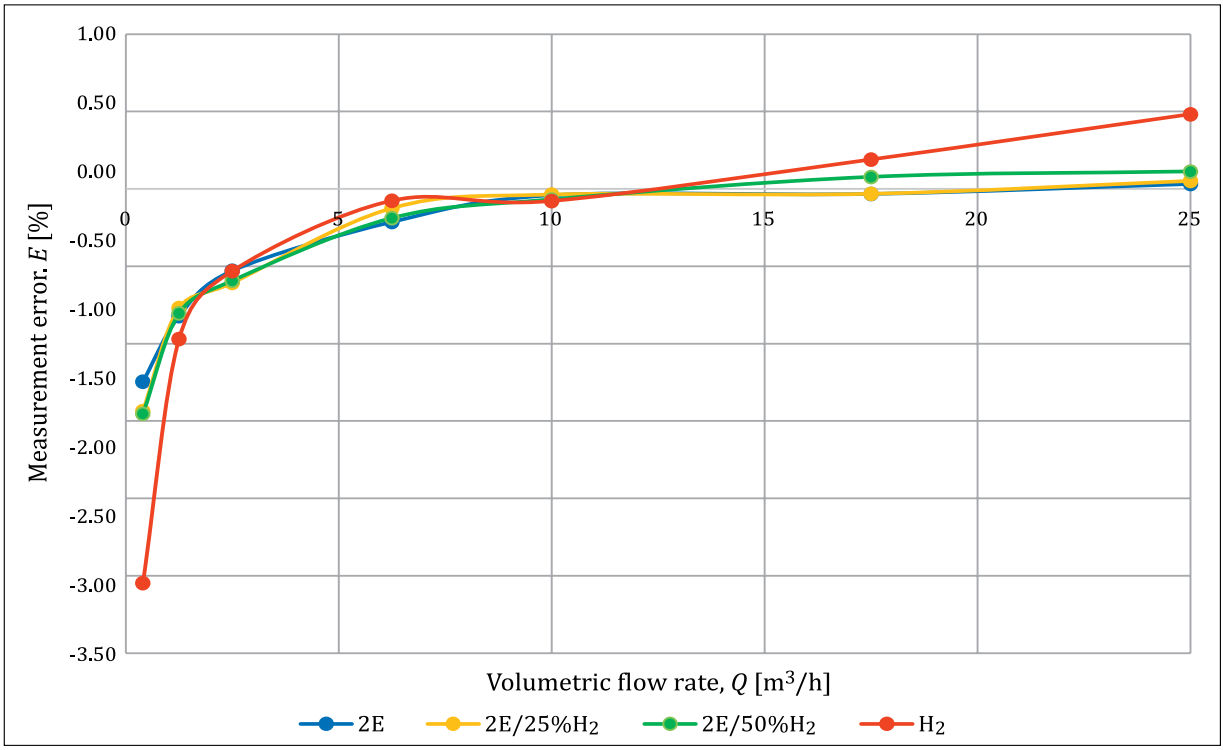


Figure 8. Mean indication errors of the G16 gas meter (Sample 2) at the laboratory ambient temperature of 20°C

Table 9. Mean indication errors of the G16 gas meter (Sample 2) for different gases at a gas temperature of −25°C

Gas	Volumetric flow rate [m³/h]							WME
	0.4	1.25	2.5	6.25	10	17.5	25.0	
	Mean indication errors [%]							[%]
2E	−1.43	−0.81	−0.43	−0.03	0.11	0.22	0.35	0.12
2E/25%H_2	−1.73	−1.03	−0.63	−0.10	0.25	0.25	0.41	0.14
2E/50%H_2	−2.38	−1.43	−0.93	−0.15	0.20	0.14	0.50	0.07
H_2	−3.21	−1.51	−0.81	−0.24	0.09	0.27	0.74	0.13

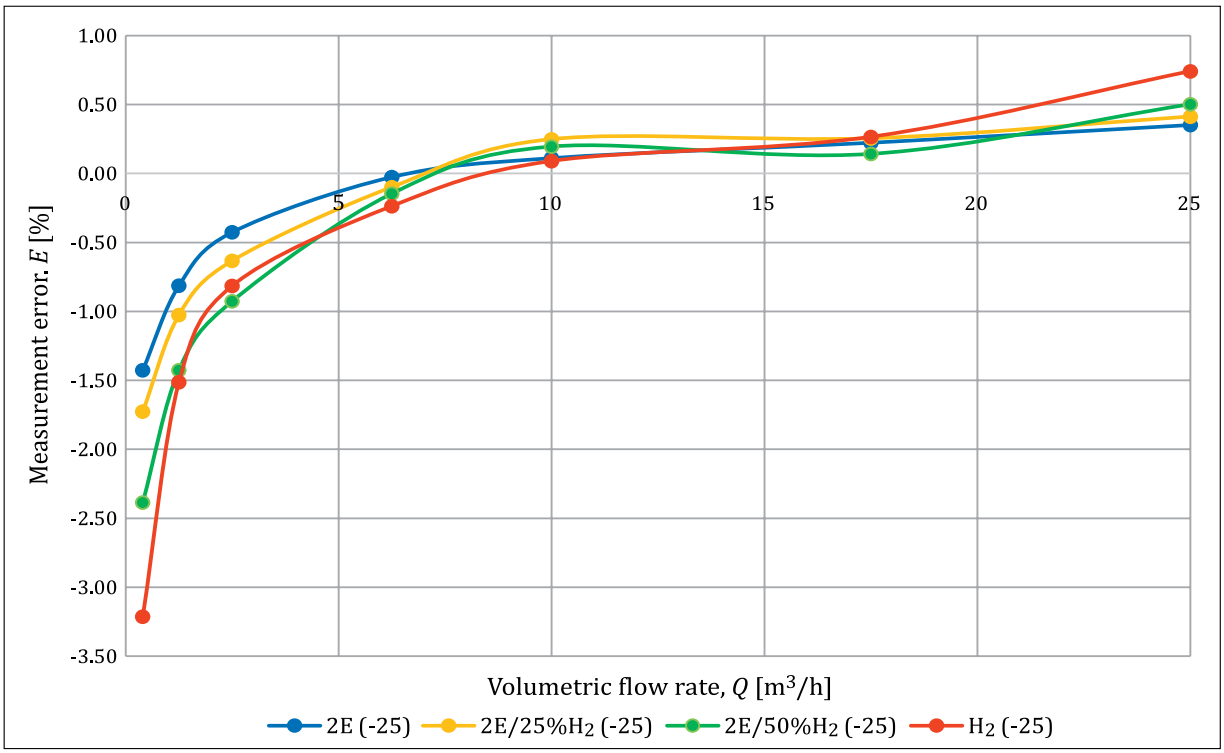


Figure 9. Mean indication errors of the G16 gas meter (Sample 2) at a gas temperature of −25°C

flow rates below Q_t. At the minimum volumetric flow rate, the gas meter errors for the mixture containing 50% hydrogen by volume and for pure hydrogen exceeded the MPE. The largest error, −3.21%, was recorded for pure hydrogen. The increase in indication errors was reflected in higher WME values, although the changes were not significant.

Table 10 lists the mean indication errors ($E_{m\,2E}$, $E_{m\,2E/25\%H2}$, $E_{m\,2E/50\%H2}$, E_{H2}) obtained for the G16 rotary gas meter (Sample 2) at a gas temperature of 70°C for natural gas, natural gas mixtures containing 25% and 50% hydrogen, and pure hydrogen; the same data are plotted in Figure 10.

Analysis of the indication errors presented in Table 10 and shown in Figure 10 reveals that, as in the previous case, increasing the hydrogen content of the mixture results in progressively more negative errors at flow rates below Q_t. The largest error, −2.83%, was recorded for pure hydrogen and exceeded the

Table 10. Mean indication errors of the G16 gas meter (Sample 2) for different gases at a gas temperature of 70°C

Gas	Volumetric flow rate [m³/h]							WME
	0.4	1.25	2.5	6.25	10	17.5	25.0	
	Mean indication errors [%]							[%]
2E	−1.03	−0.59	−0.25	0.10	0.12	0.15	0.30	0.12
2E/25%H_2	−1.25	−0.69	−0.16	0.09	0.19	0.20	0.41	0.17
2E/50%H_2	−1.75	−1.24	−0.65	−0.05	0.09	0.31	0.50	0.15
H_2	−2.83	−1.89	−0.83	−0.15	0.10	0.24	0.52	0.08

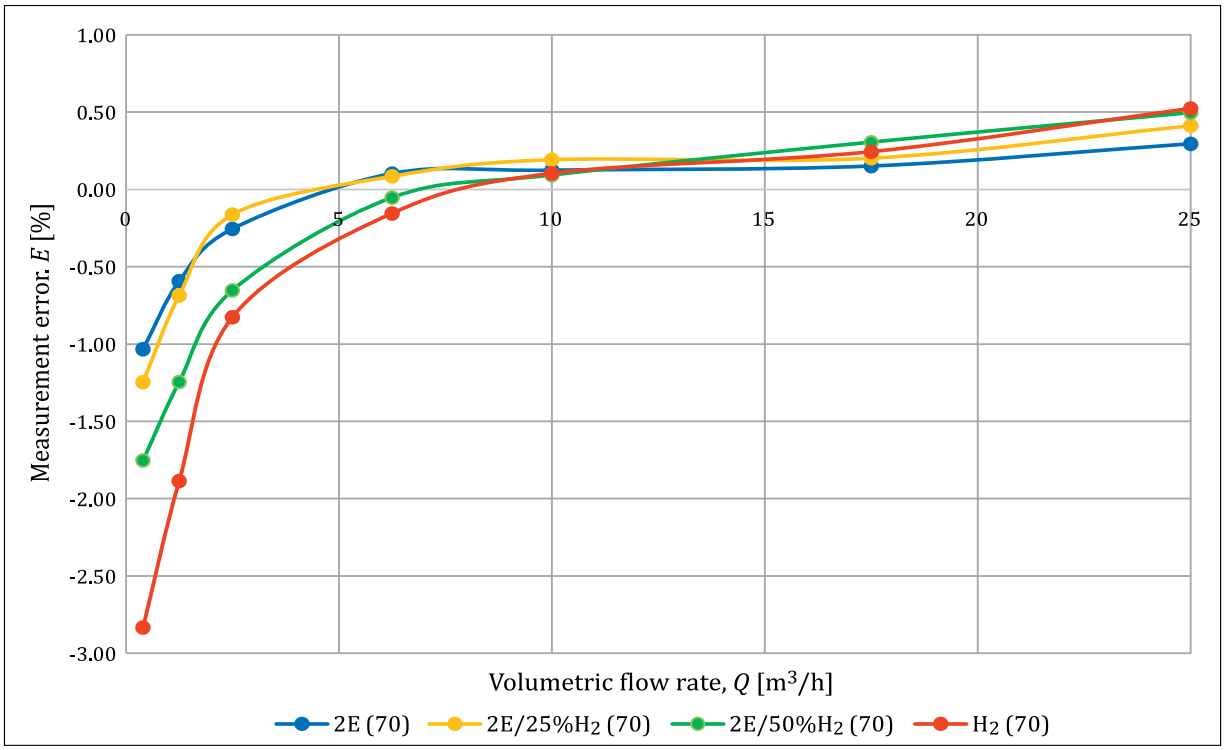


Figure 10. Mean indication errors of the G16 gas meter (Sample 2) at a gas temperature of 70°C

MPE limits. Despite the increase in negative indication errors, no deterioration in the weighted mean error was observed.

Figure 11 shows a comparison of the indication errors of the G16 rotary gas meter (Sample 2) at gas temperatures of 20°C, −25°C and 70°C. At the lower end of the flow range, a pronounced negative indication error, typical of rotary gas meters, is observed. At low volumetric flow rates $Q < Q_t$ the negative indication error for hydrogen is greater than that for natural gas over the entire temperature range. This effect is again particularly pronounced at −25°C. In the transitional and nominal flow-rate range $Q_t \leq Q \leq Q_n$, the error curves for both media approach zero. For natural gas, the error curve remains

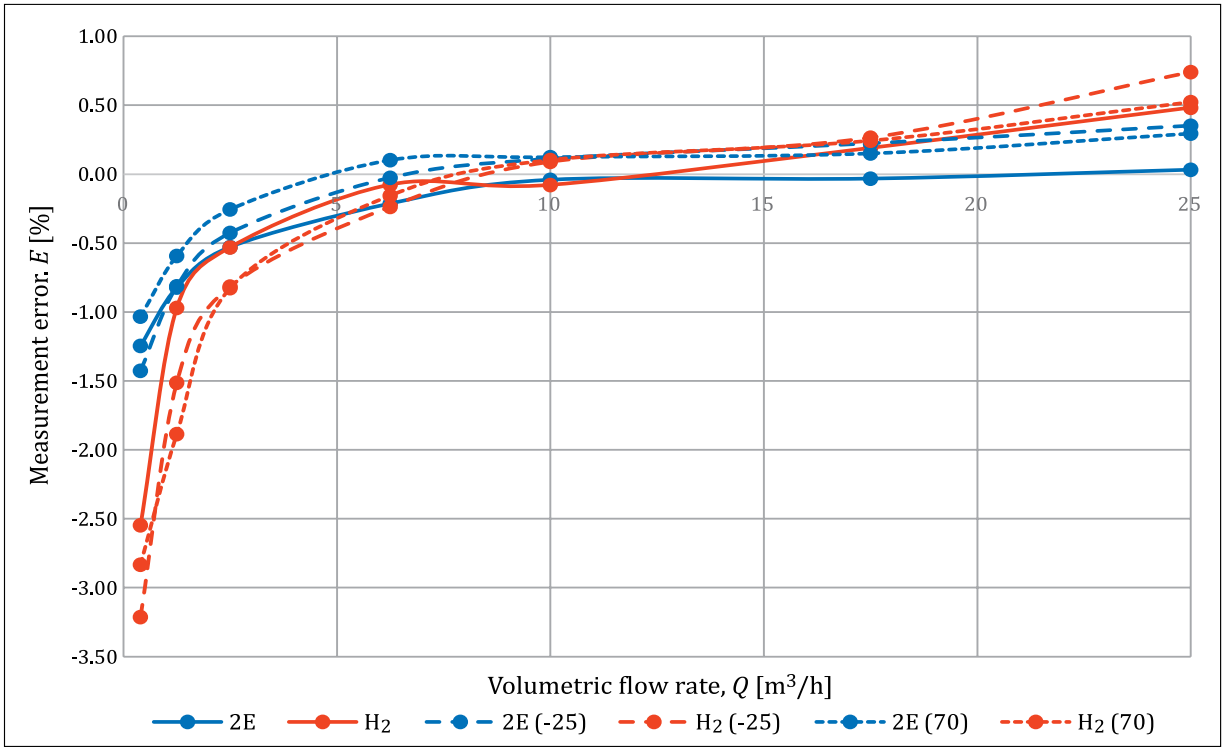


Figure 11. Comparison of the mean indication errors of the G16 gas meter (Sample 2) at gas temperatures of −25°C, 20°C, and 70°C

stable and shows only a weak dependence on temperature. Hydrogen exhibits greater sensitivity to temperature changes, reflected in small upward or downward shifts of the error curves along the error axis.

At the upper end of the flow range, $Q > Q_n$ (16 m^3/h), an increase in the positive indication error is observed, particularly for hydrogen. Gas temperature alters the shape and position of the error curves. At −25°C, the negative errors at the lower end of the flow range become more pronounced. As the temperature rises to 70°C, the error curves shift towards positive error values, particularly at the upper end of the volumetric flow-rate range. This effect is more pronounced for hydrogen than for natural gas, confirming the greater metrological sensitivity of rotary gas meters to temperature when measuring hydrogen.

G40 gas meter (Sample 3)

Table 11 lists the mean indication errors ($E_{m\ 2E}$, $E_{m\ 2E/25\%H2}$, $E_{m\ 2E/50\%H2}$, E_{H2}) obtained for the G40 rotary gas meter (Sample 3) at the laboratory ambient temperature (20°C) for natural gas, natural gas mixtures containing 25% and 50% hydrogen, and pure hydrogen (see Table 3); the same data are plotted in Figure 12.

Analysis of the indication errors presented in Table 11 and shown in Figure 12 reveals that increasing the hydrogen content of the mixture results in progressively more negative errors at the minimum flow rate Q_{min} (0.4 m^3/h). The indication errors for all natural gas–hydrogen mixtures and pure hydrogen exceeded the MPE limits. The largest error, −2.48%, was recorded for pure hydrogen. The increase in indication errors did not result in a higher weighted mean error.

Table 12 lists the mean indication errors ($E_{m\ 2E}$, $E_{m\ 2E/25\%H2}$, $E_{m\ 2E/50\%H2}$, E_{H2}) obtained for the G40 rotary gas meter (Sample 3) at a gas temperature of −25°C for natural gas, natural gas mixtures containing 25% and 50% hydrogen, and for pure hydrogen; the same data are plotted in Figure 13. The indication errors presented in Table 12 and shown in Figure 13

Table 11. Mean indication errors of the G40 gas meter (Sample 3) for different gases at the laboratory ambient temperature of 20°C

Gas	Volumetric flow rate [m^3/h]					WME
	0.4	3.25	6.5	16.25	25	
	Mean indication errors [%]					[%]
2E	−1.83	−0.58	−0.29	−0.05	0.11	−0.11
2E/25%H_2	−2.02	−0.38	−0.40	−0.25	0.13	−0.20
2E/50%H_2	−2.21	−0.59	−0.30	−0.07	0.13	−0.12
H_2	−2.48	−0.89	−0.38	0.01	0.19	−0.12

* The weighted mean error was determined over an incomplete measuring range of the gas meter.

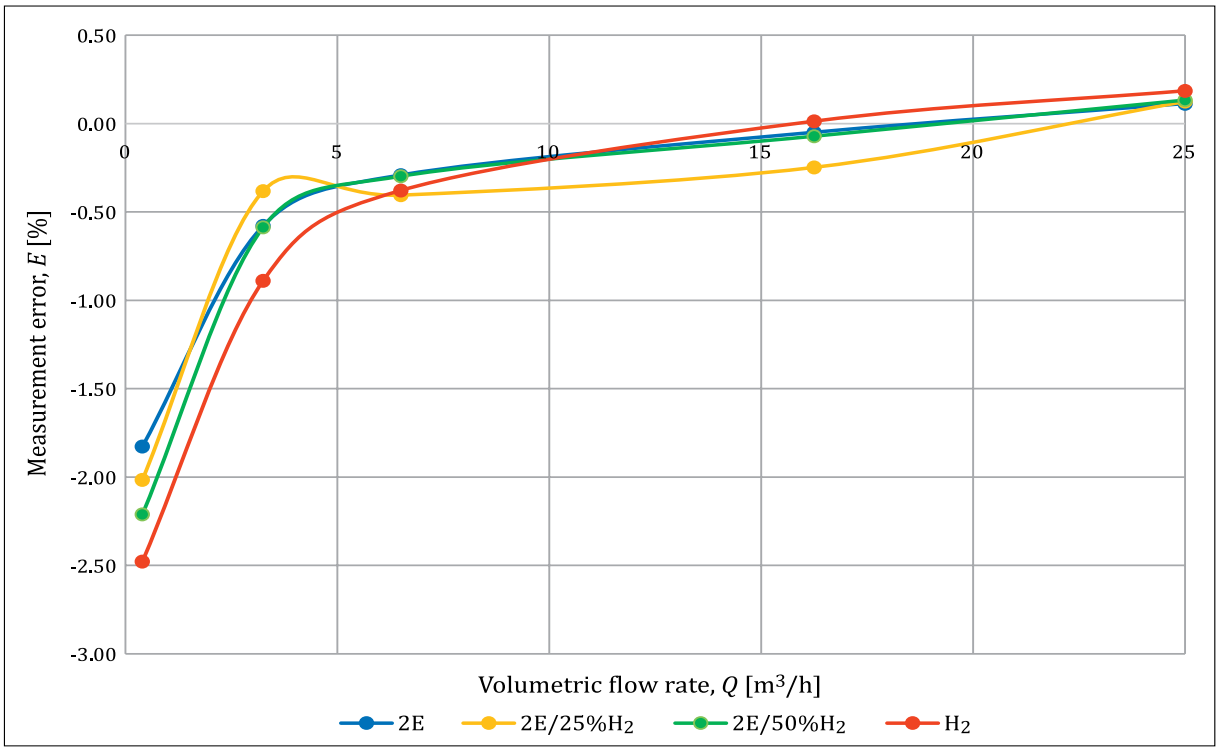


Figure 12. Mean indication errors of the G40 gas meter (Sample 3) at the laboratory ambient temperature of 20°C

reveal that increasing the hydrogen content of the mixture results in progressively more negative errors at flow rates below Q_t. At the minimum volumetric flow rate, the meter errors for all gases tested exceeded the MPE limits. The largest error, −3.54%, was recorded for pure hydrogen. The increase in indication errors was reflected in higher WME values, although the changes were not significant.

Table 13 lists the mean indication errors ($E_{m\,2E}$, $E_{m\,2E/25\%H2}$, $E_{m\,2E/50\%H2}$, E_{H2}) obtained for the G40 rotary gas meter (Sample 3) at a gas temperature of 70°C for natural gas, natural gas mixtures containing 25% and 50% hydrogen, and pure hydrogen; the same data are plotted in Figure 14.

Analysis of the indication errors presented in Table 13 and shown in Figure 14 reveals that, as in the previous case,

Table 12. Mean indication errors of the G40 gas meter (Sample 3) for different gases at a gas temperature of −25°C

Gas	Volumetric flow rate [m³/h]					WME
	0.4	3.25	6.5	16.25	25	
	Mean indication errors [%]					[%]
2E	−2.45	−0.75	−0.35	0.05	0.08	-0.11
2E/25%H_2	−2.59	−1.15	−0.47	−0.13	0.05	−0.25
2E/50%H_2	−3.13	−1.36	−0.12	0.10	0.11	−0.10
H_2	−3.54	−1.59	−0.54	0.13	0.05	−0.21

* * The weighted mean error was determined over the lower measuring range of the gas meter.

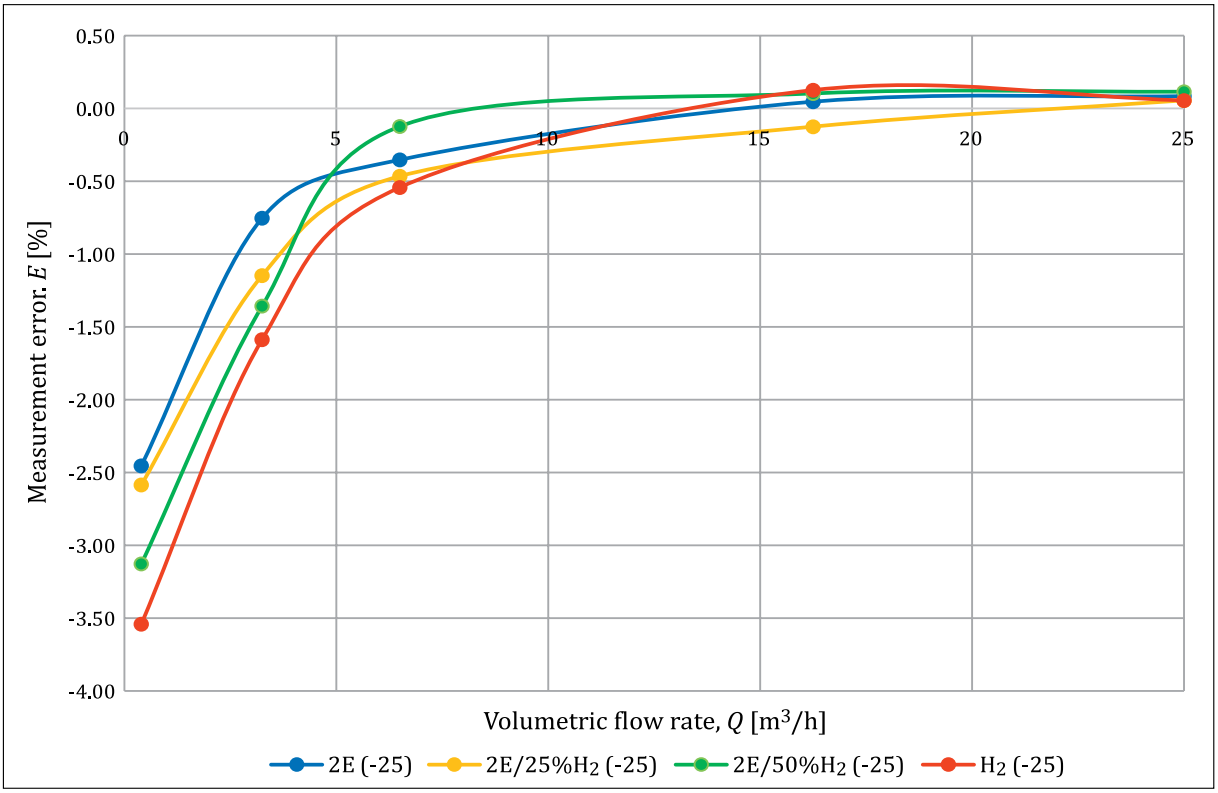


Figure 13. Mean indication errors of the G40 gas meter (Sample 3) at a gas temperature of −25°C

Table 13. Mean indication errors of the G40 gas meter (Sample 3) for different gases at a gas temperature of 70°C

Gas	Volumetric flow rate [m³/h]					WME
	0.4	3.25	6.5	16.25	25	
	Mean indication errors [%]					[%]
2E	−1.58	−0.25	−0.15	0.12	0.13	0.02
2E/25%H_2	−1.52	−0.37	−0.07	0.10	0.10	0.01
2E/50%H_2	−2.33	−0.95	−0.15	0.09	0.18	−0.05
H_2	-2.98	−1.32	−0.25	0.01	0.15	−0.15

* The weighted mean error was determined over the lower measuring range of the gas meter.

increasing the hydrogen content of the mixture results in progressively more negative errors at flow rates below Q_t. At the minimum volumetric flow rate, the gas meter errors for the mixture containing 50% hydrogen by volume and for pure hydrogen exceeded the MPE. The largest error, −2.98%, was recorded for pure hydrogen. Despite the increase in indication errors, no deterioration in the weighted mean error was observed.

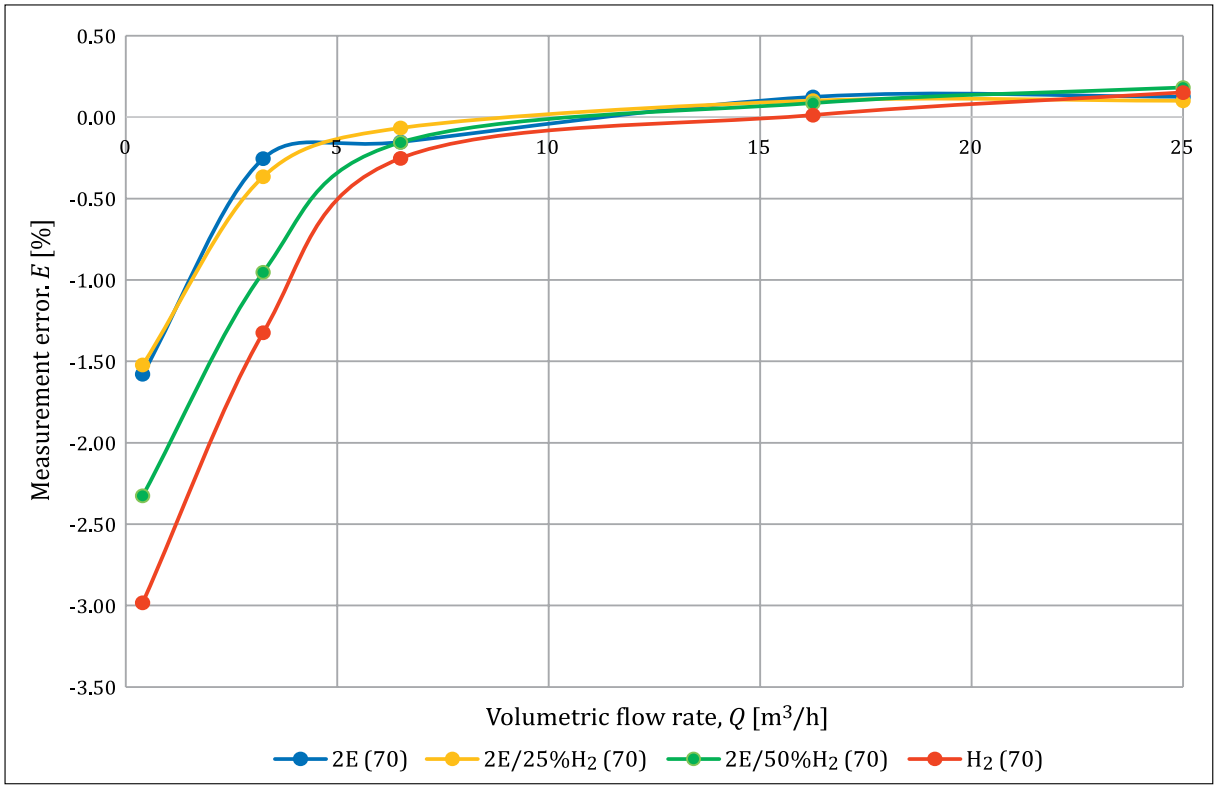


Figure 14. Mean indication errors of the G40 gas meter (Sample 3) at a gas temperature of 70°C

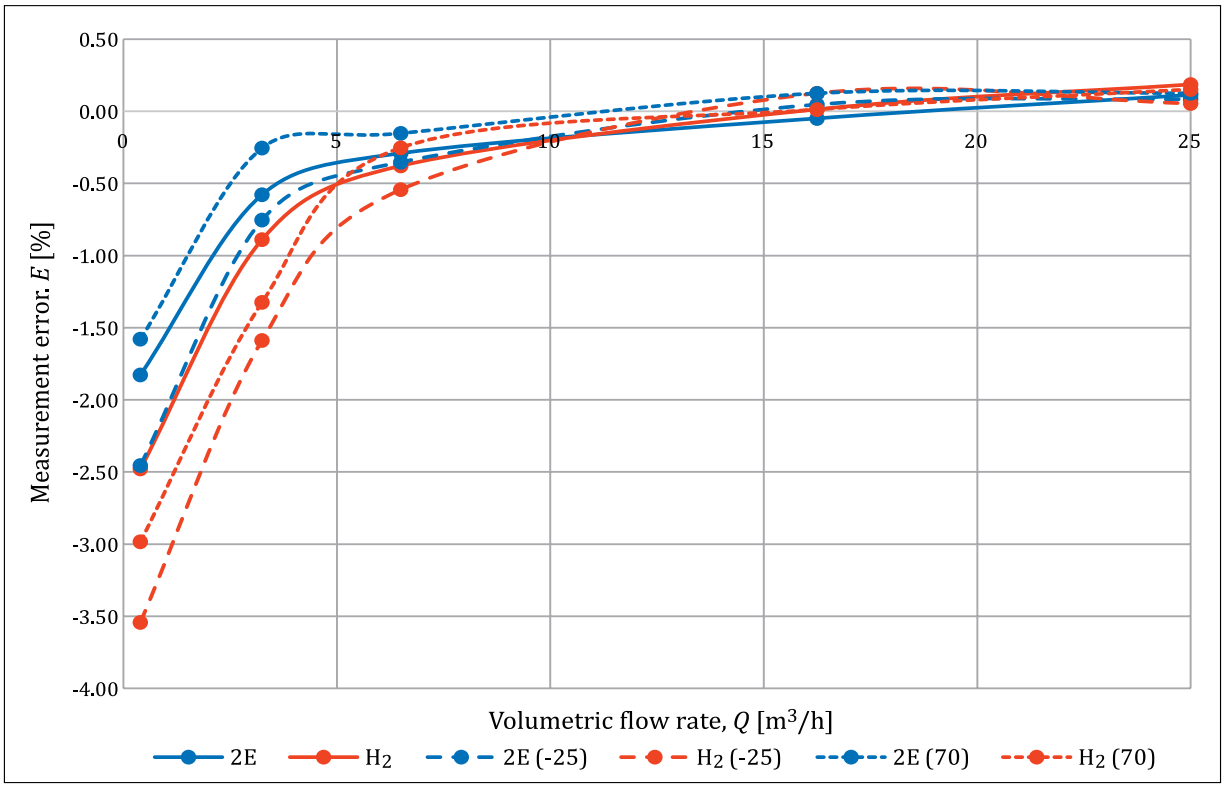


Figure 15. Comparison of the mean indication errors of the G40 gas meter (Sample 3) at gas temperatures of −25°C, 20°C, and 70°C

Figure 15 shows a comparison of the indication errors of the G40 rotary gas meter (Sample 3) at gas temperatures of 20°C, −25°C and 70°C. At the lower end of the flow range, a pronounced negative indication error, typical of rotary gas meters, is observed. At low volumetric flow rates $Q < Q_t$, the negative indication error for hydrogen is greater than that for natural gas over the entire temperature range. This effect is again particularly pronounced at −25°C. In the transitional and nominal flow-rate range $Q_t \leq Q \leq Q_n$, the error curves for both media approach zero. For natural gas, the error curve remains stable and shows only a weak dependence on temperature. Hydrogen exhibits greater sensitivity to temperature changes, reflected in small upward or downward shifts of the error curves along the error axis.

Discussion of results

For all gas meters, the errors at the lower end of the measuring range showed a clear dependence on hydrogen content. At 20°C, increasing the H_2 content resulted in progressively more negative errors at low flow rates. For one of the G16 units (Sample 1), the error at Q_{min} when measuring pure hydrogen reached −2.58%, while for the second meter (Sample 2), it was −2.55%. For the G40 meter (Sample 3) the error reached −2.48%, exceeding the MPE limit of ±2%. Above Q_t, the error curves were considerably more stable. Lowering the temperature to −25 °C made the negative errors at the lower end of the measuring range more pronounced. At higher flow rates, however, the errors remained relatively small, while slight positive indication errors were observed in the upper part of the measuring range. At 70°C, negative errors were again observed at Q_{min} and became larger with increasing hydrogen content. In the upper part of the measuring range, the errors shifted towards positive values.

The most critical condition was therefore the combination of a low flow rate and a medium with a high hydrogen content. At intermediate flow rates, the effects of temperature and gas composition were much less pronounced. Higher temperature, however, tended to shift the error curve towards positive values at higher flow rates. The results indicate that metrological suitability is determined particularly by the lower limit of the measuring range, which may need to be increased for a given medium and declared gas meter operating temperature.

When interpreting the results, it should be borne in mind that testing of the G40 gas meter was limited to 25 m^3/h and therefore did not cover its full measuring range up to Q_{max} = 65 m^3/h. The WME for this gas meter therefore refers only to the lower part of the range tested range and cannot be regarded as the WME for the complete error curve. Because the test facility was limited to 25 m^3/h, the behavior of the G40 gas meter in the upper part of its measuring range was not evaluated. Conclusions for this type of gas meter should therefore be confined to the range tested and regarded as a basis for more extensive testing.

The experimental error curves obtained are consistent with the operating mechanism resulting from the design of a rotary gas meter. At low flow rates, the available driving torque is small, so the relative contribution of mechanical resistance and internal leakage increases. Replacing natural gas with gas of lower density and viscosity may further intensify this effect, producing a negative shift in the error curve. During testing, the negative error at Q_{min} increased with increasing hydrogen content. This relationship was observed for all gas meters tested and at different temperatures. It does not, however, imply uniform deterioration of the error curve over the entire measuring range. At intermediate flow rates, the differences between the media were clearly smaller.

The increase in positive error observed at high flow rates, particularly for hydrogen, indicates a shift in the balance of the dominant effects as the gas volumetric flow rate increases. In this region, mechanical resistance becomes less significant, while the effects of flow dynamics and thermal conditions increase. The error curve may therefore change slope, progressing from negative values at Q_{min} to positive values in the upper part of the measuring range. The WME for the G16 meters remained within the adopted limits despite local exceedances of the MPE at Q_{min}.

The error curves obtained for the rotary gas meters indicate that:

- when measuring hydrogen, greater negative indication errors occur at low volumetric flow rates, together with slightly larger positive errors at high flow rates than those observed for natural gas;
- gas temperature affects the indication error curve, with a more pronounced effect observed for hydrogen;
- the indication error curve of a rotary gas meter retains its typical shape, although its position depends on the properties of the medium and the temperature conditions.

In summary, the fundamental differences between hydrogen and natural gas have important metrological consequences:

- when hydrogen is measured, the effects of temperature and mechanical losses become more significant;
- gas meters calibrated using natural gas may exhibit a different error curve when used to measure hydrogen;
- separate calibration and conformity assessment procedures may be required for hydrogen and hydrogen-containing mixtures;
- for hydrogen, it may be necessary to restrict the measuring range of rotary gas meters by increasing the minimum flow rate Q_{min}.

Conclusions

The tests demonstrated that both the hydrogen content of the measurement medium and gas temperature affect the metrological performance of the rotary gas meters investigated. The greatest sensitivity was observed at the lower end of the flow range. As hydrogen content increased, the errors at the minimum flow rate Q_{min} became progressively more negative. For pure hydrogen, the MPE limit of ±2% was exceeded in some tests. This finding indicates that usable measuring range may need to be restricted when measuring media with a high H_2 content.

The characteristic negative error observed in the lower flow range from Q_{min} to Q_t results from the limited driving torque available to the rotors and from internal leakage between the meter body and the rotors. As gas temperature decreased, the negative error in this range became more pronounced because lower gas temperatures increase the mechanical resistance of the rotors (greater frictional forces acting on them). At low flow rates, particularly near Q_{min}, the driving torque generated by the flowing gas may be insufficient to maintain proper rotor rotation, leading to a further increase in the negative indication error.

At intermediate flow rates, the error curves for the different media approached zero, and the differences were considerably smaller than at Q_{min}. At higher flow rates, particularly for hydrogen, the errors tended to shift towards positive values. Lowering the gas temperature to −25°C made the negative errors at the lower end of the measuring range more pronounced. Raising the temperature to 70°C shifted the error curves towards positive values, particularly at higher flow rates. The effect of temperature was more pronounced for hydrogen than for natural gas.

The results suggest that rotary gas meters can potentially be used in practice for natural gas–hydrogen mixtures, but measuring ranges established for natural gas should not be applied directly to hydrogen-containing media. For high hydrogen contents, and particularly for pure H_2, it may be necessary to increase the minimum volumetric flow rate Q_{min}, thereby reducing gas meter rangeability.

The results are preliminary, as only three gas meters were included in the study. Further work should cover a larger number of gas meters, different meter sizes and designs, devices from different manufacturers, and the full flow ranges. It would also be appropriate to determine whether separate calibration procedures or modified minimum flow rates (Q_{min}) are required for hydrogen and mixtures with a high H_2 content.

The article was prepared on the basis of the study entitled *Wpływ zawartości wodoru w paliwie gazowym na dokładność gazomierzy rotorowych (The effect of hydrogen content in gaseous fuel on the accuracy of rotary gas meters)* – work carried out by INiG–PIB; contract no.: 0079/GM/25/01, archive no.: DK-4100-57/25.

References

Altfeld K., Pinchbeck D., 2013. Admissible Hydrogen Concentrations in Natural Gas Systems. *Gas for Energy*, 03/2013.

Bergervoet J.T.M., 2003. Spin-Offs from the development of rotary gas meters. *11th IMEKO TC9 Conference on Flow Measurement (FLOMEKO 2003) Groningen, The Netherlands, 12–14 May 2003*, 472–486.

Gacek Z., 2025. Leakage Testing of Gas Meters Designed for Measuring Hydrogen-Containing Gas Mixtures and Pure Hydrogen. *Energies*, 18, 4207. DOI: 10.3390/en18154207.

Gacek Z., Jaworski J., 2020. Optimisation of measuring system construction in the context of high flow variability. *Journal of Natural Gas Science and Engineering*, 81, DOI: 10.1016/j.jngse.2020.103447.

Jaworski J., Kukulska-Zając E., Kułaga P., 2019. Wybrane zagadnienia dotyczące wpływu dodatku wodoru do gazu ziemnego na elementy systemu gazowniczego. *Nafta-Gaz*, 10, 625–632, DOI: 10.18668/NG.2019.10.04.

Guzzini A., Pellegrini M., Saccani C., Dudek A., Gajec M., Król A., Kulaga P., Gislon P., Cigolotti V., Robino M., Enescu D., Fernicola V.C., Smorgon D, Maury R., Gaiardo A., Valt M., Polak D., Bissig H., 2024. Hydrogen in natural gas grids: prospects and recommendations about gas flow meters. *International Journal of Hydrogen Energy*, 86, 343–362, DOI: 10.1016/j.ijhydene.2024.08.344.

Molkov V., 2012. Hydrogen Safety Engineering: State-of-the-Art and Future Trends. *Springer, Dordrecht*. DOI: 10.1016/B978-0-08-087872-0.00418-2.

Perry R.H., Green D.W., 1999. Perry's Chemical Engineers' Handbook. *McGraw-Hill*.

Szymczyk T. [ed.], 2003. Tablice matematyczne, fizyczne, chemiczne, astronomiczne. *Świat Książki, Warszawa*.

Workamp M., Schakel M., 2021. Effect of hydrogen admixture on the accuracy of a rotary flow meter. *VSL National Metrology Institute*.

Legal acts and normative documents

[N1] PN-EN 12480:2018-06 Gazomierze. Gazomierze rotorowe.

[N2] OIML R137 1&2:2012 International Organization of Legal Metrology, Gas Meters Part 1: Metrological and Technical Requirements, Part 2: Metrological Controls and Performance Tests; International Organization of Legal Metrology: Paris, France, 2012.

[N3] PN-ISO 6976:2003 Gaz ziemny. Obliczanie wartości kalorycznych, gęstości, gęstości względnej i liczby Wobbego na podstawie składu.

[N4] PN-EN 437:2021-09 Gazy do badań. Ciśnienia próbne. Kategorie urządzeń.



Zbigniew GACEK, Ph.D. Eng.
Assistant Professor at the Flow Metrology Department
Oil and Gas Institute – National Research Institute
25A Lubicz St., 31-503 Kraków
E-mail: *zbigniew.gacek@inig.pl*