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Article

# Domestic Gas Meter Durability in Hydrogen and Natural Gas Mixtures

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**Abstract:** Blending hydrogen into the natural gas infrastructure is becoming a very promising practice to increase the exploitation of renewable energy sources which can be used to produce "green" hydrogen. Several research projects and field experiments are currently aimed at evaluating the risks associated with utilization of the gas blend in end-use devices such as the gas meters. In this paper, the authors present the results of experiments aimed at assessing the effect of hydrogen injection in terms of the durability of domestic gas meters. To this end, 105 gas meters of different measurement capabilities and manufacturers, both brand-new and withdrawn from service, were investigated in terms of accuracy drift after durability cycles of 5000 and 10,000 h with $H_2$NG mixtures and $H_2$ concentrations of 10% and 15%. The obtained results show that there is no metrologically significant or statistically significant influence of hydrogen content on changes in gas meter indication errors after subjecting the meters to durability testing with a maximum of 15% $H_2$ content over 10,000 h. A metrologically significant influence of the long-term operation of the gas meters was confirmed, but it should not be made dependent on the hydrogen content in the gas. No safety problems related to the loss of external tightness were observed for either the new or 10-year-old gas meters.

**Keywords:** hydrogen; natural gas; domestic gas meter; diaphragm; thermal mass; durability; error of indication



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## 1. Introduction

The penetration of renewable energy sources (RESs) in the current energy system is constantly increasing, and recent EU policies encouraging their spread provide that by 2030 at least 32% of final energy consumption will be produced from RESs, with a clause for a possible upward revision by 2023. In today's situation, the percentage of energy from RESs is approaching 20% globally, but there are time windows in which it also exceeds 50%. This causes a continuous increase in stability and regulation problems in the electricity distribution networks. The intermittent and random nature of these supply sources is the main cause of management problems for the electricity grids, such as (i) load balancing, (ii) scheduling of dispatching and (iii) energy losses due to plant disconnection in cases of grid congestion. Since RESs do not have a predictable temporal trend, as they depend on the weather and environmental conditions, they do not allow production that adequately follows demand. Therefore, a decoupling between supply and demand is created. To this end, hydrogen represents chemical storage for renewable electricity when it is produced by water electrolysis, and it is also the key reactant for $CO_2$ methanation (Sabatier reaction). In this latter case, the produced methane is a carbon-neutral gas that fits into existing infrastructure [1].

In particular, power-to-gas (P2G) technology involves the transformation of electrical energy through the process of electrolysis into hydrogen, which can be used both as an energy carrier and as a reactant in the methanation process [2]. By exploiting the natural gas transport and distribution system, as well as the storage facilities, P2G allows temporally decoupling the production and use of energy from RESs, compensating for the intermittent/fluctuating production from renewables and offering balancing and regulation services to the electricity grid. In particular, hydrogen can be injected into the natural gas transportation and distribution networks. Recent research results demonstrate hydrogen production via polymer electrolyte membrane electrolyzer has lower environmental effects than other traditional methods (e.g., coal gasification and reforming, steam methane reforming). On the economical hand, geothermal energy-based systems show the lowest cost of electricity for hydrogen production, unlike the natural gas [3].

In this scenario, the percentage of hydrogen that can be introduced into the network is currently limited by the use of methane in the automotive sector as well as for safety and economic reasons. In fact, it has been tested that hydrogen contents higher than 2 vol% can cause embrittlement damage to the tanks of methane vehicles. As a matter of fact, nowadays hydrogen represents a key energy vector in the medium and long term, thanks to the intrinsic characteristics of flexibility and integrability with alternative technologies for the production and consumption of energy. Therefore, the analysis of the effects of the addition of hydrogen in natural gas networks is a highly debated research topic today due to the benefits that this practice can bring in reducing greenhouse gases and promoting environmental sustainability. In fact, even relatively low concentrations of hydrogen (10–15%) make it possible to store and supply significant quantities of renewable energy without increasing the risks associated with the presence of hydrogen, which shows explosive characteristics certainly higher than those of traditional natural gas mixtures.

On the other hand, the injection of hydrogen into natural gas mixtures directly affects the thermodynamic properties of the gas such as density, calorific value, Wobbe index, speed of sound and specific heat. In particular, for gas type H EN 437 [4] with hydrogen content up to 23%, it was found that (i) the density decreases by 1.7–20.5%, (ii) the specific heat increases by 1.4–16% and (iii) the Wobbe index decreases by 0.49–5.7% [5]. To this end, the effects of hydrogen injection on natural gas infrastructure need to be carefully evaluated. In particular, the injection of hydrogen into a natural gas mixture can affect the metrological performance of gas meters, especially when the measurement principle is influenced by the variation of the thermodynamic properties of the gas (e.g., for ultrasonic and thermal mass meters).

In this regard, one of the most relevant properties of gas meters is their long-term stability. Durability tests are carried out to ensure the required measurement accuracy for the manufacturer, gas meter owner and gas consumers. The purpose is to try to identify weaknesses in the gas meter's structure that may lead to a reduction in the satisfactory properties of the meter during its expected life. Although this property is tested mainly with air, the obtained result should guarantee the correct operation of the gas meter in real conditions, including in natural gas measurement conditions. When gas meters are operated on a gas network distributing natural gas with added hydrogen, the meters must be guaranteed to operate for the long term without deterioration of metrological properties. The measurement technology used in the gas meter may be sensitive to the conditions of use, including the gas composition or variable gas quality. Diaphragm (chamber) gas meters use the volumetric measurement method. The nature of the measurement means that it should not be expected that changes in gas composition will significantly affect the accuracy of the measurement. On the other hand, due to the design solutions used in the measurement unit of these gas meters, there is a real concern that a change in gas quality may cause changes in the degree of tightness between various types of sealing elements and moving parts (e.g., in the seal of the main axis of the diaphragm). Consequently, this may affect the internal tightness of the measuring unit, which may lead to a deterioration of the metrological properties of the gas meter. At the same time, it should be noted that the technologies of ultrasonic and thermal gas meters, due to the nature of the measurement depending on the gas density or the speed of propagation of the sound wave, will be sensitive to changes in gas composition, including in the case of hydrogen added to natural gas. More information about the principle of operation of thermal mass and ultrasonic gas meters is provided in [6–9]. The reliability of the gas meters should be demonstrated under certain critical conditions that may arise in the gas distribution network, including changes in gas quality and the presence of dust and contaminants [10]. For thermal gas meters, the amount of heat transfer depends on the gas mass flow, as well as on the gas composition, which affects its thermophysical properties, such as thermal conductivity and diffusivity [11]. Thermal gas meters are particularly sensitive to the influence of impurities contained in the measured gas and disturbances in the velocity profile, and the significantly variable composition of the measured gas affects their metrological stability [12,13]. The influence of variable gas quality (gas composition) may be acceptable to some extent, taking into account the accuracy class of the gas meters; however, particular attention should be paid to the type of gases declared by the manufacturer, as the gas meters are EU-type tested for those measurements. Reference [14] presents factors that influence the operating conditions of gas meters in more detail, including the influence of hydrogen addition on the durability of diaphragm gas meters.

When analyzing the average ultrasonic gas meters available on the market, it should be noted that they are intended for the measurement of gas fuels from the second family of H, L and E according to EN 437 [4]. Thermal gas meters are also intended for the measurement of gas fuels from the second family of H, L and E. The meters with the widest scope of application are diaphragm gas meters, which are designed to measure gas families of first, second and third family according to EN 437. The currently available literature on the effects of hydrogen injection on gas meters substantially demonstrates that with H2 content of up to 10–15%, limited influence occurs on traditional gas meters such as diaphragm, turbine and rotary piston [14–16].

This paper presents the results of Oil and Gas Institute–National Research Institute (INiG-PIB) research on the durability of residential gas meters with natural gas mixtures with different contents of hydrogen, as a second step of the results discussed in [14] which concerned a limited research sample and were treated as preliminary results. The results presented in this publication include all the obtained results together with a discussion of the final conclusions from the entire research work and constitute a complete summary. The novelty of this research should be emphasized, as it covers a large sample (over 100 pieces) of different gas meter types and manufacturers (i.e., the most numerous on the Polish market), as well as thermal gas meters that have not been tested in such a range so far. Tests have been conducted especially for long-term operation up to 15,000 hours and, very importantly, also included gas meters taken out of service (after 10 years of use). What also should be considered innovative is that the research work was not only aimed at proving whether there is an effect of hydrogen on the gas meters, but also aimed at assessing how the hydrogen content in the mixture will have a metrological effect and therefore if it will affect the gas settlement system.

The assumptions for the tests, including the selection of gas meters, test method and the additional hydrogen limits in the tests carried out, are described in detail in [14], which includes the results of durability after 5000 h of gas meter operation with the use of three mixtures of high-methane natural gas, group 2E with 5%, 10% and 15% (V/V) hydrogen. In order to analyze whether the addition of hydrogen to natural gas affects the durability of gas meters, tests were carried out simultaneously on gas meters of the same type with the use of a reference (control) sample, i.e., on gas meters of the same type using high-methane 2E gas without hydrogen.

## 2. Theory and Methods

According to OIML D11 [17], durability is the ability of the measuring instrument to maintain its performance characteristics over a period of use. Thus, the durability error is the difference between the initial error of a measuring instrument and the error after a period of use. In this meaning, a durability test aims to verify whether the measuring instrument is able to maintain its performance characteristics (e.g., measurement error, tightness) over a period of use.

Since the decay of the performance characteristics of a measuring instrument may occur due to a failure, which may happen at an unpredictable moment during its lifetime, or to wear of some components, durability test is aimed at verifying the instrument's capability to operate correctly within the performance criteria over the required period of time. In the specific case of diaphragm gas meters, during and after the completion of a durability test, the following criteria shall be met: (i) the error of indication shall be within the MPE subsequent limits; (ii) the error over the flowrate range between Qt and Qmax shall not differ by more than 2% from the initial one [14]. According to OIML R137 [18], durability test applies to all gas meters with internal moving parts regardless of the flowrate range and to gas meters without internal moving parts and $Q_{max}$ above 25 $m^3/h$. Test gases should be the ones for which the meters are intended to be used and the applied flow rate is at least 0.8 Qmax.

Determination of errors in indications (metrological characteristics) and pressure drop in the gas meters was carried out at the GH54 measuring station of the Flow Metrology Laboratory at INIG-PIB using an accredited method (accreditation certificate No. AB 041 by the Polish Centre for Accreditation (PCA)). The description of the measuring equipment is presented in detail in [14]. The expanded uncertainty (with a coverage factor k = 2 corresponding to about 95% probability level) of the measurement errors of indications is within 0.3% in the range from 0.6 to 6 $m^3/h$ and within 0.5% in the range from 0.04 to 0.6 $m^3/h$. The gas meters grouped into test samples were subjected to a durability test on a test stand with three separate test loops in which the gas meters were operated at the maximum flowrate $Q_{max}$ with mixtures of natural gas and hydrogen of 5%, 10% and 15%. Reference samples of the same types of gas meters were subjected to a similar test with natural gas without hydrogen.

Based on the experience in 2018, the durability tests were continued in 2019 and 2020 for hydrogen additions of 10% and 15%, while testing for the 5% hydrogen concentration was ended after 5000 h. The durability test methodology is based on the EN 1359:1998 [19] standard, which requires gas meters to be operated at maximum flowrate $Q_{max}$ for 5000 hours with natural gas and metrological tests after 250, 2000, 3500 and 5000 h to be carried out with air. The durability tests performed by authors consisted in continuously operating gas meters under test at $Q_{max}$ for growing duration periods and performing error of indication tests after 250, 2000, 3500 and 5000 hours. Furthermore, unlike the common requirement of performing durability tests in air, the authors carried out the entire test program by using directly natural gas mixtures with different hydrogen contents. The durability period was also extended with tests after 8500 and 10,000 h (for all types of gas meters), and finally, four gas meters were additionally tested at 15,000 h.

In this work, the durability test was carried out with the use of various gas mixtures, and additional tests at durations of 8500, 10,000 and for some gas meters even 15,000 h were performed. The research project was completed in 2020 with the results of the durability test for all tested diaphragm gas meters after 10,000 h (with intermediate tests after 250, 2000, 3500, 5000 and 8500 h) and for thermal gas meters after 7500 h (with intermediate tests after 1300, 2900 and 5300 h). Additionally, for some gas meters (4 types), for which the tests were started in 2018, durability test results were also obtained after 15,000 h. For these 4 types of gas meters, test results for 5% hydrogen concentration were obtained after 5000 h.

Most of the test samples, both those tested with natural gas (2E/H0) and natural gas with the addition of 10% hydrogen (2E/H10) and 15% hydrogen (2E/H15), consisted of 6 gas meters. Four types of new diaphragm gas meters, one type of new thermal gas meters and three types of diaphragm gas meters disassembled from the gas network (hereinafter referred to as "in-service") after 10 years of operation were tested. The list of the investigated gas meters is presented in Table 1.

**Table 1.** Characteristics of the investigated gas meters.

| Type of Gas Meter | Id. | New/ In-Service | Production Year | Cyclic Volume ($dm^3$) | Size | $Q_{min}$ ($m^3$/h) | $Q_{max}$ ($m^3$/h) |
|---|---|---|---|---|---|---|---|
| Diaphragm | Type−1 | New | 2018 and 2019 | 1.2 | G4 | 0.04 | 6 |
| | Type−2 | | 2018 and 2019 | 1.2 | | | |
| | Type−3 | | 2019 | 1.2 | | | |
| | Type−4 | | 2019 | 2.0 | | | |
| | Type−5 | In-service | 2009 | 2.0 | | | |
| | Type−6 | | 2008 | 2.2 | | | |
| | Type−7 | | 2009 | 2.0 | | | |
| Thermal | Type−8 | New | 2019 | - | | | |

New Type−1 and Type−2 diaphragm gas meters, as well as Type−5 and Type−6 in-service diaphragm gas meters, were tested using a mixture with 10% (2E/H10) and 15% (2E/H15) hydrogen addition, while the new diaphragm Type−3 and Type−4 and thermal Type−8 gas meters and in-service Type−7 gas meters were tested with a natural gas mixture with 15% added hydrogen (2E/H15). As part of the durability test, the external tightness of the gas meters was also checked.

Based on the conducted tests, metrological and statistical analyses of the results were developed. To define the metrological criterion necessary to assess the effect of hydrogen content in natural gas on changes in gas meter errors of indication (metrologically significant or metrologically insignificant), the measurement uncertainty was estimated for individual flow rates and individual types of gas meters. Subsequently, a statistical analysis based on a one-way ANOVA was performed. Detailed assumptions for metrological and statistical analysis are presented in [14]. The complete procedure for evaluating the results based on the results of durability tests of the new Type−1 gas meters is presented below, and in the following part of the paper, graphs of the average changes in indication errors ($\Delta E_m$) for other types of gas meters are presented, along with the final conclusions based on all the results of the analyses.

## 3. Results

The error of indication $E$ has been calculated according to the following equation:

$$E = \frac{V_m - V_{ref}}{V_{ref}}$$

where $V_m$ is the volume measured by the gas meter under test ($m^3$) and $V_m$ is the volume measured by the reference gas meter ($m^3$). Furthermore, according to par. 3.2.5 of OIML R137 [19], the weighted mean error of indication (WME) has been calculated by using the Equation (1) as a function of the errors and of the flow rates at which the errors have been measured.

$$WME = \frac{\sum_i k_i\, E_i}{\sum_i k_i} \begin{cases} k_i = \frac{Q_i}{Q_{max}}\, for\ Q_i \leq 0.7Q_{max} \\ k_i = 1.4 - \frac{Q_i}{Q_{max}}\, for\ 0.7Q_{max} < Q < Q_{max} \end{cases}$$

where $E_i$ (%) is the error at the flow rate $Q_i$ and $k_i$ (dimensionless) is the weighting factor at the flow rate $Q_i$.

Table 2 shows the average errors of indications of the gas meters ($E_{m0} \div E_{m6}$) subjected to the durability testing using 2E/H15 mixture, the average drift values ($\Delta E_{m1} \div \Delta E_{m6}$) between errors in subsequent stages of the durability tests (250, 2000, 3500, 5000, 8500 and 10,000 h) and the average initial errors ($E_{m0}$) for new Type−1 gas meters (where $E_{m01}$ are initial errors for meters tested for 250 and 2000 h and $E_{m02}$ are initial errors for 3500, 5000, 8500 and 10,000 h). The results of the average errors of indications and the average drift of errors for all mixtures and all types of gas meters are provided in electronic form as an appendix to this publication.

**Table 2.** Average errors, average drift of errors of indications, WMEs and WME changes of new Type−1 gas meters ($Q_{max}$ = 6 $m^3/h$) tested for durability using the 2E/H15 natural gas mixture with hydrogen.

| | **Flow Rate $Q$** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $Q_{min}$ | 3 $Q_{min}$ | 0.1 $Q_{max}$ | 0.2 $Q_{max}$ | 0.4 $Q_{max}$ | 0.7 $Q_{max}$ | $Q_{max}$ | |
| | Average errors (%) | | | | | | | WME (%) |
| $E_{m01}$ | −1.22 | −0.57 | −0.10 | 0.30 | 0.61 | 0.10 | 0.13 | 0.22 |
| $E_{m02}$ | 0.45 | 0.28 | 0.21 | 0.64 | 0.64 | 0.04 | 0.19 | 0.29 |
| $E_{m1}$ | −2.10 | −1.52 | −0.82 | −0.28 | 0.09 | −0.54 | −0.29 | −0.35 |
| $E_{m2}$ | −3.09 | −1.97 | −1.15 | −0.59 | −0.16 | −0.73 | −0.49 | −0.58 |
| $E_{m3}$ | −2.18 | −1.51 | −0.89 | −0.60 | −0.16 | −0.39 | −0.30 | −0.39 |
| $E_{m4}$ | −2.11 | −1.47 | −0.86 | −0.55 | −0.22 | −0.51 | −0.19 | −0.42 |
| $E_{m5}$ | −3.52 | −1.65 | −1.17 | −0.95 | −0.10 | −0.30 | −0.49 | −0.44 |
| $E_{m6}$ | −3.52 | −1.71 | −1.15 | −1.07 | −0.29 | −0.40 | −0.47 | −0.53 |
| | Average drift of errors (%) | | | | | | | WME changes (%) |
| $\Delta E_{m1}$ | − 0.88 | − 0.96 | − 0.71 | − 0.58 | − 0.52 | − 0.64 | − 0.41 | − 0.57 |
| $\Delta E_{m2}$ | − 1.88 | − 1.40 | − 1.04 | − 0.89 | − 0.78 | − 0.83 | − 0.62 | − 0.80 |
| $\Delta E_{m3}$ | − 2.63 | − 1.79 | − 1.10 | − 1.24 | − 0.80 | − 0.43 | − 0.49 | − 0.67 |
| $\Delta E_{m4}$ | − 2.56 | − 1.75 | − 1.07 | − 1.19 | − 0.86 | − 0.56 | − 0.38 | − 0.70 |
| $\Delta E_{m5}$ | − 3.97 | − 1.93 | − 1.38 | − 1.60 | − 0.75 | − 0.34 | − 0.68 | − 0.73 |
| $\Delta E_{m6}$ | − 3.97 | − 2.00 | − 1.36 | − 1.72 | − 0.94 | − 0.44 | − 0.66 | − 0.82 |

The test results for all types of gas meters with 5%, 10% and 15% hydrogen concentrations are provided in electronic form as an appendix to this publication. Figure 1 shows the average drift of errors of indications of the investigated diaphragm gas meters after the 10,000 h durability test, using a 2E/H10 ($\Delta E_{m6}$,2E/H10) and 2E/H15 ($\Delta E_{m6}$,2E/H15) natural gas mixture with hydrogen, together with the average drift of errors of indications of the gas meters tested using a 2E/H0 natural gas mixture without the addition of hydrogen ($\Delta E_{m6}$,2E/H0). Figure 2, instead, shows the behavior in the same test condition of the new Type−8 static thermal mass gas meters.

Additionally, Figures 3 and 4 show the average drift of errors of indications of the gas meters after 15,000 h durability test using the 2E/H10 and 2E/H15 natural gas mixtures with hydrogen ($\Delta E_{m8}$,2E/H10; $\Delta E_{m8}$,2E/H15), together with the average drift of errors of indications of the gas meters tested using a 2E/H0 natural gas mixture without the addition of hydrogen ($\Delta E_{m8}$,2E/H0).

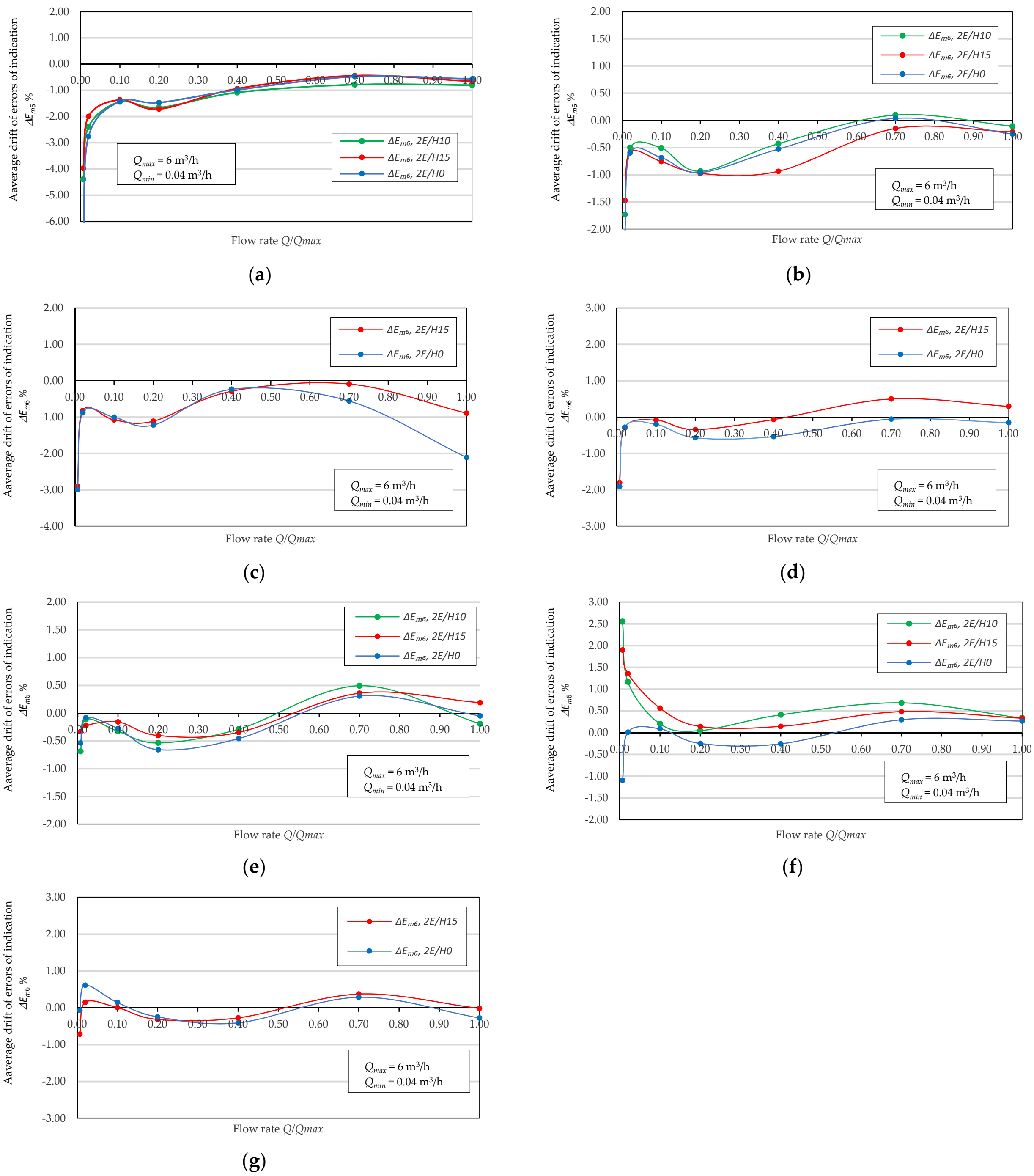



**Figure 1.** Average drift of errors of indications ($\Delta E_{m6}$) after a 10,000 h durability test using 2E/H10 and 2E/H15 natural gas mixtures with hydrogen and 2E/H0 natural gas mixture without hydrogen as a function of flow rate ($Q/Q_{max}$): (**a**) new Type−1; (**b**) new Type−2; (**c**) new Type−3; (**d**) new Type−4; (**e**) in-service Type−5; (**f**) in-service Type−6; (**g**) in-service Type−7.

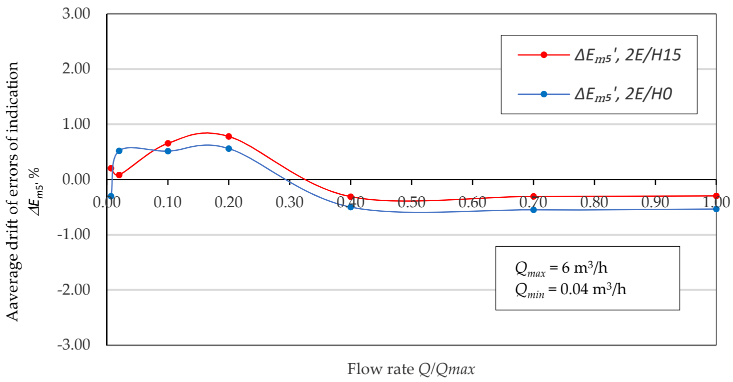
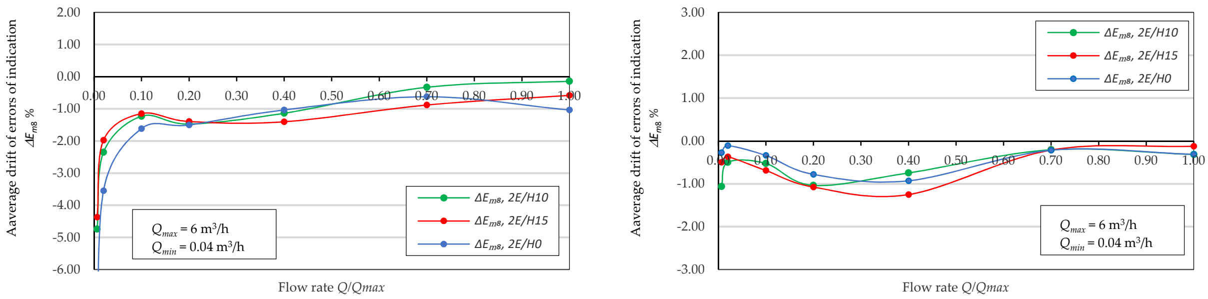
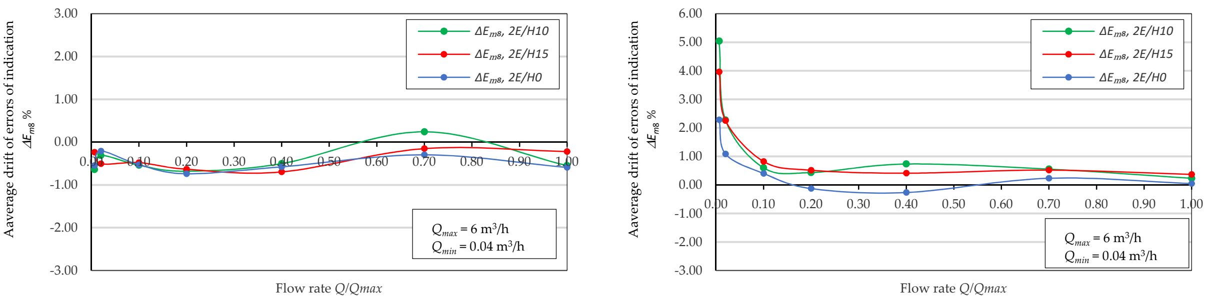



**Figure 2.** Average drift of errors of indications ($\Delta E_{m5'}$) for new Type−8 thermal gas meters after a 7500 h durability test using 2E/H15 natural gas mixture with hydrogen and 2E/H0 natural gas mixture without hydrogen as a function of flow rate ($Q/Q_{max}$).




(**a**) (**b**)

**Figure 3.** Average drift of errors of indications ($\Delta E_{m8}$) for new Type−1 (**a**) and Type−2 (**b**) gas meters after a 15,000 h durability test using 2E/H10 and 2E/H15 natural gas mixtures with hydrogen and 2E/H0 natural gas mixture without hydrogen as a function of flow rate ($Q/Q_{max}$).




(**a**) (**b**)

**Figure 4.** Average drift of errors of indications ($\Delta E_{m8}$) for in-service Type−5 (**a**) and Type−6 (**b**) gas meters after a 15,000 h durability test using 2E/H10 and 2E/H15 natural gas mixtures with hydrogen and 2E/H0 natural gas mixture without hydrogen as a function of flow rate ($Q/Q_{max}$).

## 4. Discussion

The test results obtained were subjected to metrological and statistical assessment. During the metrological assessment, it was assumed that the differences in the average drift of errors during the durability test with different mixtures should not be greater than the total uncertainty of determining the error changes. If the difference in the average drift of errors between the mixtures is greater than the estimated uncertainty, then the significant metrological effect of hydrogen addition to natural gas for the considered hydrogen concentration should be considered.

Table 3 shows the average drift of errors of indications of the new Type−1 gas meters after a 10,000 h durability test for the 2E/H0 gas meter control sample and for the test samples 2E/H15 and the resulting differences in the average drift of errors of indications $\Delta E_{mH\text{-}m2E}$, together with the metrological assessment of the drift. The uncertainty in the average drift of errors, $U(E_m)$, includes the type B uncertainty of the measuring equipment and the type A uncertainty (i.e., the standard deviation of the results of the six tested gas meters with 2E/H0 and 2E/H15 mixtures). On the other hand, the permitted difference in drift, $U(\Delta E_{mH\text{-}m2E})$, is obtained through the quadratic sum of the $U(E_m)$ of the two mixtures. Thus, the metrological assessment returns "insignificant" if the difference in the average drift of errors is below the permitted difference in drift [14].

**Table 3.** Metrological assessment of the average drift of errors of indications of new Type−1 gas meters after the 10,000 h durability test with the use of 2E/H15 and 2E/H0 natural gas mixtures.

| Volume Flow Q | Average Drift of Errors of Indications after the 10,000 h Test for Mixtures (%) | | Differences in Average Drift of Errors (%) | Uncertainty in Average Drift of Errors (%) | | Permitted Difference in Drift (%) | Metrological Assessment |
|---|---|---|---|---|---|---|---|
| | $\Delta E_{m6}$ 2E/H15 | $\Delta E_{m6}$ 2E/H0 | $\Delta E_{mH\text{-}m2E}$ | $U(E_m)$ 2E/H15 | $U(E_m)$ 2E/H0 | $U(\Delta E_{mH\text{-}m2E})$ | |
| $Q_{max}$ | −0.66 | −0.56 | −0.10 | 0.18 | 0.19 | 0.53 | insignificant |
| 0.7 $Q_{max}$ | −0.44 | −0.48 | 0.04 | 0.17 | 0.16 | 0.60 | insignificant |
| 0.4 $Q_{max}$ | −0.94 | −0.99 | 0.05 | 0.18 | 0.19 | 0.52 | insignificant |
| 0.2 $Q_{max}$ | −1.72 | −1.47 | −0.25 | 0.18 | 0.14 | 0.63 | insignificant |
| 0.1 $Q_{max}$ | −1.36 | −1.42 | 0.06 | 0.16 | 0.23 | 0.58 | insignificant |
| 3 $Q_{min}$ | −2.00 | −2.76 | 0.76 | 0.39 | 0.71 | 1.62 | insignificant |
| $Q_{min}$ | −3.97 | −6.55 | 2.58 | 0.92 | 2.45 | 5.23 | insignificant |

When testing the new Type−1 gas meter durability over a period of 10,000 h with the use of 2E/H15 natural gas mixtures with hydrogen, metrologically insignificant differences in the average drift of errors of indications compared to the 2E/H0 control sample were found, in the range of flow rates from $Q_{min}$ to $Q_{max}$. The results of average drift of errors of indications and the resulting differences in the average drift of errors of indications along with metrological assessment for all types of gas meters and different hydrogen concentrations for 10,000 h durability test are provided in electronic form as an appendix to this publication.

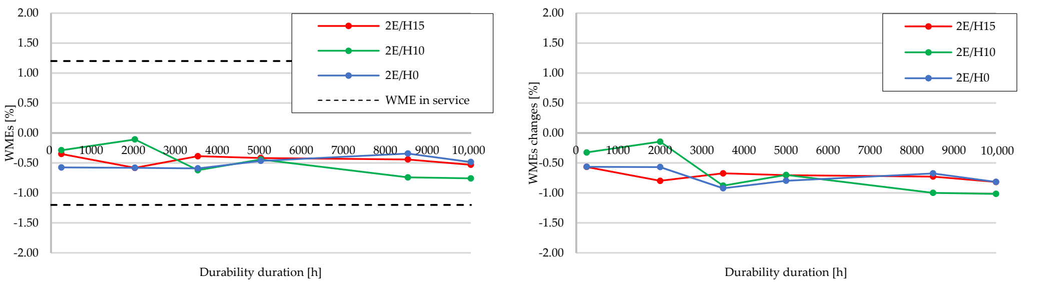
Table 4 shows the results of the one-way analysis of variance for the new Type−1 gas meters after the 10,000 h durability test using different gas mixtures (2E/H10, 2E/H15 and 2E/H0).

**Table 4.** Results of one-way analysis of variance for the new Type−1 gas meters after the 10,000 h durability test using different gas mixtures (2E/H10, 2E/H15 and 2E/H0).

| Volume Flow Q | Brown–Forsythe Variance Homogeneity Test | | Fisher–Snedecor Variance Equality Test | | Tukey Post Hoc Test |
|---|---|---|---|---|---|
| | Statistics | Significance Level | Statistics | Significance Level | |
| $Q_{min}$ | 2.856706 | 0.088879 | 1.546846 | 0.245036 | X |
| 3 $Q_{min}$ | 1.171227 | 0.336787 | 1.361702 | 0.286142 | X |
| 0.1 $Q_{max}$ | 1.110179 | 0.355114 | 0.069812 | 0.932871 | X |
| 0.2 $Q_{max}$ | 0.939051 | 0.412817 | 0.796192 | 0.469211 | X |
| 0.4 $Q_{max}$ | 2.783064 | 0.093765 | 0.162380 | 0.851593 | X |
| 0.7 $Q_{max}$ | 3.172247 | 0.070964 | 0.818781 | 0.459740 | X |
| $Q_{max}$ | 1.650751 | 0.224923 | 0.211673 | 0.811605 | X |

Since for all flow rates the level of significance corresponding to the calculated value of Fisher–Snedecor (FS) statistics for the considered hydrogen concentrations in the gas exceeded the assumed value of 0.05, then the hypothesis H0 of the equality of changes in the average drift of errors of indications for the respective flow rates was assumed. Significance levels corresponding to the calculated Brown–Forsythe statistics were greater than the assumed value of 0.05 for flow rates from $Q_{min}$ to $Q_{max}$; therefore, the hypothesis about the equality of variance in groups was adopted, which confirmed the methodological correctness of the conducted variance analysis. When testing the durability of the new Type−1 gas meters over a period of 10,000 h, the hydrogen content in natural gas at the tested concentrations (10%, 15%) does not affect the average drift of errors of indications in the range of volume flows from $Q_{min}$ to $Q_{max}$.

Weighted mean errors (WMEs) for the obtained test results according to OIML Recommendations R 137 1&2:2012 [19] were also calculated. OIML R 137 1&2:20212 in Section 5.4 only defines for class 1.5 gas meters the maximum permissible WME equal to ±0.6 % during type evaluation and initial verification. No specific WME requirements have been set for gas meters in service, but for the purpose of this research, the authors assumed a double value, i.e., ±1.2%, similarly to the indication errors in service. The detailed tables showing WMEs before and after the durability test, as well as the change in WMEs after 10,000 h for all eight types of tested samples and after 15,000 h for four types of tested gas meters for various gas mixtures with hydrogen, are presented in electronic form as an appendix to this publication. For example, in Figure 5, the WMEs and WME changes for the diaphragm Type−1 gas meter after the 10,000 h durability test are presented.




(**a**) (**b**)

**Figure 5.** Type−1 gas meter after the durability test up to 10,000 h using 2E/H10 and 2E/H15 natural gas mixtures with hydrogen and 2E/H0 natural gas mixture without hydrogen: (**a**) WME; (**b**) WME changes.

From the analysis of Figure 5, it can be pointed out that for the Type−1 gas meter after 10,000 h:

- The maximum WME values are −0.53 %, −0.76 % and −0.48 % for 2E/H15, 2E/H10 and 2E/H0 mixtures, respectively;
- During each stage of the durability test (250, 3500, 5000, 8500 and 10,000 h), the WMEs never exceeded the maximum permissible value of ±1.2%;
- The maximum difference in WME changes was equal to 0.42% after 2000 h, relating to 2E/H10 and 2E/H0 mixtures;
- After 10,000 h the WME changes for the 2E/H15 and 2E/H0 mixtures are both equal to −0.82%.

### 4.1. Metrological Analysis

Based on the obtained test results, a metrological analysis was carried out for all the types of gas meters. As a result of the analysis, it was found that:

- After testing the durability of new diaphragm gas meters Type−1 and Type−2 and in-service gas meters Type−5 and Type−6 over 5000, 10,000 and 15,000 h with the addition of 10% and 15% $H_2$, metrologically insignificant differences in the average drift of errors of indications in relation to the control sample 2E/H0 were found in flow rates from $Q_{min}$ to $Q_{max}$.

- After testing the durability of new diaphragm gas meters Type−3 and Type−4 and in-service gas meter Type−7 over 5000 and 10,000 h with the addition of 10% and 15% $H_2$, metrologically insignificant differences in the average drift of errors of indications in relation to the control sample 2E/H0 were found in flow rates from $Q_{min}$ to $Q_{max}$.
- After testing the durability of new Type−8 thermal gas meters over 6000 and 7500 h with the addition of 15% $H_2$, metrologically insignificant differences in the average drift of errors of indications in relation to the control sample 2E/H0 were found in flow rates from $Q_{min}$ to $Q_{max}$.
- After testing the durability of diaphragm and thermal gas meters over 10,000 and 15,000 h with the addition of 10% and 15% $H_2$, there was no significant difference in WME changes in relation to the control sample 2E/H0. The maximum difference in WME changes after the durability test with the use of the 2E/H15 mixture in relation to the 2E/H0 mixture was 0.45% for the Type−6 gas meter, and after 15,000 h it was 0.44% for the Type−4 gas meter.

Based on the results of the durability tests, the general conclusion can be drawn that no metrologically significant influence of the addition of 10% and 15% hydrogen on the long-term operation of the tested gas meters was found.

### *4.2. Statistical Analysis*

Based on the performed statistical analysis, it was found that of the majority of the analyzed results, no statistically significant influence was found for hydrogen content in the gas on the change of the gas meter errors of indications after the durability tests. In several cases, it was found that the hydrogen content in natural gas had a statistically significant impact on the values of changes in the mean errors; however, when analyzing the values of these changes and their uncertainties, these differences were considered to be metrologically insignificant. Detailed comments are provided below:

- For the new Type−1, Type−2, and Type−3 gas meters, as well as in-service Type−5 and Type−6 gas meters, after a durability test of 10,000 h, no statistically significant influence of the 15% hydrogen content in natural gas on the change in errors of indications was found.
- For the new Type−4 gas meters, after a durability test of 10,000 h, a statistically significant influence of 15% hydrogen content in natural gas was found for the flow rates at $0.4Q_{max}$ and $0.7Q_{max}$; however, when analyzing the values of these changes and their uncertainties, these differences were considered to be metrologically insignificant.
- For in-service gas meters of Type−7, after a durability test of 10,000 h, a statistically significant influence of the 15% hydrogen content in natural gas was found for the flow rates at $3Q_{min}$ and $Q_{max}$; however, the difference in the average drift of the errors of indications is within the total measurement uncertainty and thus is metrologically insignificant.
- For Type−8 thermal gas meters, after the 7500 h durability test, no statistically significant influence of 15% hydrogen content in natural gas on the change of errors of indications was found.

### *4.3. Leakage Test*

No problems related to the loss of external tightness were observed for either the new gas meters or gas meters with 10 years in operation. This indicates that gas meters subjected to durability testing for the period of 10,000 h with a natural gas mixture with a maximum 15% hydrogen addition remain safe for use.

## 5. Conclusions

The research included performing durability tests on diaphragm and thermal gas meters for various mixtures of high-methane natural gas with added hydrogen. The tests were carried out for the 2E natural gas and 2E natural gas mixtures with hydrogen additions of 5%, 10% and 15% ($v/v$) for 5000 and 10,000 h. Some of the diaphragm gas meters were tested for even 15,000 h, and the tests of the thermal gas meters were completed after 7500 h. The general conclusions resulting from the obtained results are as follows:

- For the test samples subjected to the durability tests, regardless of whether they were gas meters in service (after 10 years of operation) or new gas meters, no significant metrological influence of added hydrogen was found on the obtained average drift of errors of indications after the durability tests. Apart from single Type−1 gas meters tested in sample 2E/H0 (without hydrogen addition), in which most likely internal leakage occurred, the gas meters meet the metrological requirements for a durability test according to EN 1359 [18].
- For the majority of diaphragm gas meters and for thermal gas meters, no statistically significant influence of the hydrogen content in the gas was found on the change in gas meter errors of indications after they were subjected to the durability tests. For the new Type−4 diaphragm gas meters and in-service Type−7 gas meters, after the 10,000 h durability test, statistically significant differences were found in the average drift of the errors of indications of gas meters subjected to the durability test with a 2E natural gas mixture with 15% hydrogen addition and 2E natural gas without hydrogen at flow rates $0.4Q_{max}$ and $0.7Q_{max}$ and $3Q_{min}$ and $Q_{max}$, respectively. Analyzing the average drift of errors of indications for the control sample 2E/H0 and the test sample 2E/H15, it can be concluded that the differences between these changes are smaller than the uncertainty of determining the difference, and therefore these should be considered metrologically insignificant.
- For all types of gas meters subjected to the durability test after 10,000 h, no significant differences were found between the average weighted mean error (WME) changes for the tested gas mixtures, and almost all gas meter errors were within ±1.2%, except for single gas meters (four meters).
- During the durability tests, no damage was found that would compromise operational safety. All gas meters—diaphragm or thermal—remained tight after the durability tests.
- The tests carried out with the use of diaphragm gas meters, both new and after 10 years of operation, as well as thermal gas meters, indicate that they can be used for the settlement purposes of natural gas with the addition of hydrogen up to 15% concentration. Nevertheless, it should be noted that research in the field of flow metrology should still be carried out because the discussed results concern only a certain group of gas meters, which is not representative of all types of gas meters used.

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## Nomenclature and Symbols

| | |
|---|---|
| $E$ | error of indications of the gas meter (%) |
| $E_m$ | average errors of indications of the gas meter (%) |
| $E_0$ | initial errors of indications of the gas meter (%) |
| $E_{m01}$ | average initial errors of indications (for sample of three gas meters) (%) |
| $E_{m02}$ | average initial errors of indications (for sample of six gas meters) (%) |
| $E_{m1}$ | average errors of indications of the gas meters after 250 h of work |
| $E_{m2}$ | average errors of indications of the gas meters after 2000 h of work (%) |
| $E_{m3}$ | average errors of indications of the gas meters after 3500 h of work (%) |
| $E_{m4}$ | average errors of indications of the gas meters after 5000 h of work (%) |
| $E_{m5}$ | average errors of indications of the gas meters after 8500 h of work (%) |
| $E_{m5'}$ | average errors of indications of the gas meters after 7500 h of work (%) |
| $E_{m6}$ | average errors of indications of the gas meters after 10,000 h of work (%) |
| $E_{m8}$ | average errors of indications of the gas meters after 15,000 h of work (%) |
| $MPE$ | maximum permissible errors (%) |
| $\Delta E_{m1}$ | average drift of errors of indications of the gas meters after 250 h of work (%) |
| $\Delta E_{m2}$ | average drift of errors of indications of the gas meters after 2000 h of work (%) |
| $\Delta E_{m3}$ | average drift of errors of indications of the gas meters after 3500 h of work (%) |
| $\Delta E_{m4}$ | average drift of errors of indications of the gas meters after 5000 h of work (%) |
| $\Delta E_{m5}$ | average drift of errors of indications of the gas meters after 8500 h of work (%) |
| $\Delta E_{m5'}$ | average drift of errors of indications of the gas meters after 7500 h of work (%) |
| $\Delta E_{m6}$ | average drift of errors of indications of the gas meters after 10,000 h of work (%) |
| $\Delta E_{m8}$ | average drift of errors of indications of the gas meters after 15,000 h of work (%) |
| $\Delta E_{mH\text{-}m2E}$ | difference of the average drifts of errors of indications of the gas meters tested for durability using a 2E/H5, 2E/H10 and 2E/H15 natural gas mixture with hydrogen and a 2E/H0 natural gas mixture without the addition of hydrogen (%) |
| $Q$ | flow rate ($m^3$/h) |
| $U(\Delta E_{mH\text{-}m2E})$ | uncertainty of determining the difference of the average drifts of errors of indications of the gas meters tested for durability using a 2E/H5, 2E/H10 and 2E/H15 natural gas mixture with hydrogen and a 2E/H0 natural gas mixture without the addition of hydrogen (%) |
| $U(E_{mH})$ | uncertainty of determining the average drifts of errors of indications of the gas meters tested for durability using a 2E/H5, 2E/H10 and 2E/H15 natural gas mixture with hydrogen (%) |
| $U(E_{m2E})$ | uncertainty of determining the average drifts of errors of indications of the gas meters tested for durability using a 2E/H0 natural gas mixture without the addition of hydrogen (%) |
| Abbreviations | |
| INiG-PIB | Oil and Gas Institute–National Research Institute |
| 2E | natural gas of group E of the second gas family (high-methane) described in EN 437 |
| 2E/H0 | 2E natural gas mixture without the addition of hydrogen |
| 2E/H5 | 2E natural gas mixture with 5% hydrogen content (V/V) |
| 2E/H10 | 2E natural gas mixture with 10% hydrogen content (V/V) |
| 2E/H15 | 2E natural gas mixture with 15% hydrogen content (V/V) |

## References


1. Castellani, B.; Gambelli, A.M.; Morini, E.; Nastasi, B.; Presciutti, A.; Filipponi, M.; Nicolini, A.; Rossi, F. Experimental Investigation on $CO_2$ Methanation Process for Solar Energy Storage Compared to CO2-Based Methanol Synthesis. *Energies* **2017**, *10*, 855. [CrossRef]
2. Perna, A.; Moretti, L.; Ficco, G.; Spazzafumo, G.; Canale, L.; Dell'Isola, M. SNG Generation via Power to Gas Technology: Plant Design and Annual Performance Assessment. *Appl. Sci.* **2020**, *10*, 8443. [CrossRef]
3. Ozturk, M.; Ibrahim, D. A comprehensive review on power-to-gas with hydrogen options for cleaner applications. *Int. J. Hydrogen Energy* **2021**, *46*, 31511–31522. [CrossRef]
4. European Committee for Standardization. *EN 437:2021 Test Gases—Test Pressures—Appliance Categories*; Technical Committee CEN/TC 238; European Committee for Standardization: Brussels, Belgium, 2018.
5. Stetsenko, A.; Naumenko, V. Exploration of hydrogen influence on physical properties of natural gas and metrological characteristics of its metering systems. In Proceedings of the Flomeko 2019, Lisbon, Portugal, 26–28 June 2019.

6. Buonanno, G. On field characterization of static domestic gas flowmeters. *Measurement* **2000**, *27*, 277–285. [CrossRef]
7. Farzaneh-Gord, M.; Parvizi, S.; Arabkoohsar, A.; Machado, L.; Koury, R.N.N. Potential use of capillary tube thermal mass flow meters to measure residential natural gas consumption. *J. Nat. Gas Sci. Eng.* **2015**, *22*, 540–550. [CrossRef]
8. Parvizi, S.; Arabkoohsar, A.; Farzaneh-Gord, M. Natural gas compositions variation effect on capillary tube thermal mass flow meter performance. *Flow Meas. Instrum.* **2016**, *50*, 229–236. [CrossRef]
9. Huang, L. City Natural Gas Metering. In *Natural Gas—Extraction to End Use*; IntechOpen Ltd: London, UK, 2012; Chapter 9.
10. Ficco, G. Metrological performance of diaphragm gas meter in distribution networks. *Flow Meas. Instrum.* **2014**, *37*, 65–67. [CrossRef]
11. Ficco, G.; Celenza, L.; Dell'Isola, M.; Vigo, P. Experimental evaluation of thermal mass smart meters influence factors. *J. Nat. Gas Sci. Eng.* **2016**, *32*, 1–10. [CrossRef]
12. Kułaga, P.; Jaworski, J.; Gacek, Z. Thermal gas meters in individual settlements. Characteristics and application perspectives. *Gaz Woda Tech. Sanit.* **2018**, *11*, 390–395.
13. Jaworski, J.; Dudek, A. Study of the Effects of Changes in Gas Composition as Well as Ambient and Gas Temperature on Errors of Indications of Thermal Gas Meters. *Energies* **2020**, *13*, 5428. [CrossRef]
14. Jaworski, J.; Kułaga, P.; Blacharski, T. Study of the Effect of Addition of Hydrogen to Natural Gas on Diaphragm Gas Meters. *Energies* **2020**, *13*, 3006. [CrossRef]
15. Polman, E.A.; De Laat, J.C.; Crowther, M. *Reduction of $CO_2$ Emissions by Adding Hydrogen to Natural Gas*; Gastech Tecnology BV: Apeldoorn, The Netherlands, 2003.
16. Dehaeseleer, J. *The Effects of Injecting Hydrogen (Renewable Gases)*; EASEE-Gas GMOM: Budapest, Hungary, 2018.
17. International Organization of Legal Metrology. OIML D11. In *General Requirements for Measuring Instruments—Environmental Conditions*; International Organization of Legal Metrology: Paris, France, 2013.
18. International Organization of Legal Metrology. *OIML R1371&2:2012, Gas Meters Part 1: Metrological and Technical Requirements Part 2: Metrological Controls and Performance Tests*; International Organization of Legal Metrology: Paris, France, 2012.
19. European Committee for Standardization. *EN 1359:2017 Gas Meters. Diaphragm Gas Meters and EN 1359:1998+A1:2006*; European Committee for Standardization: Brussels, Belgium, 2017.