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Safe hydrogen injection management at network-wide level: towards European gas sector transition

Shimmer

Safe Hydrogen Injection Modelling and Management for European gas network Resilience

D3.5. Summary list of recommended methods along with an assessment of the possibility of their application to mixtures of various compositions and impact on the emission volume, as well as an indication of any gaps, both in access to methods and in the field of standardization

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ABSTRACT

This document presents the results of laboratory tests of four methods for monitoring and detecting gas leaks, i.e. sniffers method, optical gas imaging method, acoustic method, and the laser method. Based on the conducted analysis, it can be concluded that most of the methods used to detect leaks can be applied with the similar effectiveness in networks transporting natural gas and networks transporting NG-H2. However, it should be noted that changes in the transported medium may influence the lower detection limit of the methods.

The conducted tests also showed that it is not possible to indicate a universal method for detecting leaks in gas sector. The sniffer method and the optical gas imaging are complementary methods for leak detection for NG-H2 mixtures. The most commonly used leak detection method (the sniffer method) does not require any changes to the procedure or equipment used. The acoustic method appears to be the least suitable for leak detection for NG-H2 mixtures.

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List of Abbreviations

Table 0-1: List of abbreviations

Term	Explanation
AGI	acoustic gas imaging
dB	decibel
DSO	distribution system operator
EPA	Environmental Protection Agency
LDAR	leak detection and repair
LOD	limit of detection
MCR	mass flow controller
NG	natural gas
OGI	optical gas imaging
SE	sensitivity
TDLAS	tunable diode laser spectroscopy
TSO	transmission system operator
VOC	volatile organic compounds

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Executive Summary

The European Union has set ambitious goals for reducing CO_2 emissions over the coming decades, and the crowning achievement of this effort is to achieve CO_2 neutrality by 2050. Hydrogen is expected to play an important role in this process. Hydrogen transport technologies in pressurized tanks are already well developed, but hydrogen transport via the existing gas network is still the subject of many studies and tests. In order to ensure the safety of transporting natural gas–hydrogen mixtures, gas leakage monitoring and detection in gas networks, as well as methane emission measurement, are of great importance.

This report presents the results of research carried out to evaluate the performance of selected leak detection methods and to determine the most optimal method for detecting gas leaks. As part of the project implementation, measurements were carried out for NG–H_2 mixtures with varying hydrogen content. The tests focused on mixtures with hydrogen concentrations ranging from 0 to 20%, in accordance with the SHIMMER project assumptions. Additionally, measurements were conducted at higher hydrogen concentrations of 50% and 80% to accurately assess the lower detection limit of each method.

The evaluation of leak detection methods was carried out on a laboratory test bench that allows the generation of controlled leaks of methane and its mixtures with hydrogen. Additionally, the test bench is equipped with a set of devices that simulate atmospheric conditions which may interfere with measurements.

Leaks of the NG–H_2 mixture were generated at a nozzle, a threaded connection, and a flange. These elements reflect typical leaking components found in gas networks. The leaks generated at the experimental site ranged from 0.1 to 4.75 l/min, which corresponds to typical small leaks occurring in gas networks. During the tests, four types of measurement methods were evaluated: sniffers, optical gas imaging (OGI), acoustic gas imaging (AGI), and tunable diode laser spectroscopy (TDLAS). The tests were conducted using eight different devices. For each evaluated method, measurements were carried out in series, with each series consisting of 10 independent measurements performed using a given method. Sensitivity and the lower detection limit were evaluated separately for each method and each measurement series.

Three devices were used to evaluate the sniffer method. The first device was equipped with methane sensor, the second with both methane and hydrogen sensors, and the last one with a hydrogen sensor. For the tests, it was assumed that a leak is considered detected if the concentration of the measured gas (methane or hydrogen) in air is at least 50 ppm. Regardless of the type of leaking component and the methane content in the NG–H_2 mixture, sniffers equipped with methane sensors were able to detect all generated leaks with a sensitivity of 100% under the tested conditions, detecting methane present in NG–H_2 mixtures. Sniffers equipped with hydrogen sensors also detected all leaks generated by NG–H_2 mixtures within the tested measurement series. The conducted tests confirmed that sniffer-based leak detection procedures used by TSO and DSO operators are also applicable to NG–H_2 mixtures. With respect to the project assumptions (hydrogen concentrations from 0 to 20%), no changes or replacement of equipment are required when transitioning from natural gas to NG–H_2 mixtures. The tests also showed that existing sniffer-based detection procedures can be applied to NG–H_2 mixtures with higher hydrogen concentrations, without modifications to the equipment. The use of sniffers equipped with two sensors (methane and hydrogen) does not affect the effectiveness of leak detection. During laboratory tests of leak detection using the OGI method, two IR cameras were used. Both tested cameras were able to detect all generated leaks with a sensitivity of 100% for mixtures containing hydrogen from 0 to 50%. Detection performance decreases significantly for 80%

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H_2 mixtures and becomes camera-dependent The OGI method does not require changes in measurement procedures or equipment if the hydrogen content in the NG-H2 mixture does not exceed 20%. Two devices were used to evaluate the acoustic gas imaging method. The lower detection limit of the acoustic method is variable and depends on many parameters, including the shape of the leak and the hydrogen content of the mixture. During testing, differences in the estimated lower detection limits were also observed depending on the type of equipment used. Therefore, it is difficult to clearly indicate in which cases the acoustic method is useful for leak detection.

Finally, one device representing the laser method (TDLAS) was evaluated. Regardless of the type of leaking component and the methane content in the NG–H_2 mixture, TDLAS was able to detect all leaks with satisfactory sensitivity exceeding the assumed 75%.

The report also assessed the tested methods for detecting gas leaks taking into account: (1) lower detection limit, (2) resistance to changes in gas composition, (3) scope of application and possible limitations, (4) availability of measurement devices, (5) availability of measurement standards, (6) cost of purchasing and maintaining devices, (7) personnel qualifications, and (8) other advantages and disadvantages. Each aspect was assessed on a five-point scale from 1 to 5. The sniffer method received the highest score. It is not possible to indicate a universal method within the investigated conditions for detecting leaks in gas networks transporting NG–H_2 mixtures. Each of the methods considered has advantages and disadvantages, as well as an optimal area of application. It should therefore be assumed that, as in the case of leak detection in natural gas networks, monitoring networks transporting NG–H_2 mixtures will require the use of multiple measurement methods. The results show that no single method provides complete coverage of NG–H_2 leak detection requirements. Instead, monitoring of gas networks transporting NG–H_2 mixtures requires the use of a combination of complementary measurement techniques, each with different operational strengths and limitations.

In particular, the sniffer method and optical gas imaging are highly complementary, as sniffers provide precise, point-based detection with high sensitivity, while OGI enables rapid visual identification of gas plumes over wider areas and in hard-to-access locations.

Acoustic gas imaging and tunable diode laser absorption spectroscopy further extend the detection capabilities. AGI may be useful for non-contact detection in accessible above-ground installations, although its performance is strongly influenced by environmental noise and leak geometry. TDLAS, on the other hand, provides high-sensitivity remote detection and is less dependent on direct access to equipment, but its applicability may be limited by installation geometry and line-of-sight requirements.

Therefore, an effective leak detection strategy for NG–H_2 networks should be based on a multi-method approach combining sniffers, OGI, AGI, and TDLAS depending on operational conditions, infrastructure type, and measurement objectives.

About the project: The European natural gas infrastructure provides the opportunity to accept hydrogen (H2), as a means of integrating low-carbon gases, leveraging the existing gas network, and contributing to decarbonisation. However, there are technical and regulatory gaps that should be addressed, along with adaptations and investments, to ensure that multi-gas networks across Europe will be able to operate in a reliable and safe way while providing highly controllable gas quality and required energy demand. Aspects such as the material integrity of pipelines and components, as well as the lack of harmonisation of gas quality requirements at European level, must be resolved to facilitate the injection of H2 in the natural gas network.

In this context, the SHIMMER project (Safe Hydrogen Injection Modelling and Management for European gas network Resilience) was selected for funding as part of the 2023 Clean Hydrogen Partnership programme. SHIMMER aims to enable a higher integration of low-carbon gases and safer H2 injection management in multi-gas networks by strengthening the knowledge base and improving the understanding of risks and opportunities associated with H2 projects.

It will achieve this by:

- Mapping and assessing European gas T&D infrastructure in relation to materials, components, technology, and their readiness for hydrogen blends.
- Defining methods, tools and technologies for multi-gas network management and quality tracking, including simulation, prediction, and safe management of network operation in view of widespread hydrogen injection in a European-wide context.
- Proposing best practice guidelines for ensuring the safety of hydrogen in the natural gas infrastructure and managing associated risks.

The research leading to these results has received funding from Horizon 2020, the European Union's Framework Programme for Research and Innovation (H2020) under grant agreement n° 101111888.

1 Introduction

The ongoing energy transition and the progressive decarbonisation of gas networks are driving increased interest in the integration of hydrogen into existing natural gas infrastructure. The introduction of hydrogen–natural gas (NG–H_2) mixtures presents both opportunities and challenges, particularly in the context of network operation, safety assurance, and emission monitoring. In this regard, reliable detection and quantification of gas leaks remain critical elements of transmission and distribution system operation. As hydrogen differs from methane in its physical and chemical properties, the applicability and performance of existing leak detection and measurement methods require careful reassessment. This document therefore addresses the evaluation of selected techniques used for emission monitoring by transmission system operators (TSOs) and distribution system operators (DSOs) in the context of NG–H_2 gas mixtures.

1.1 Purpose of the document

The introduction of hydrogen into the existing gas network will require network operators, both distribution and transmission, to adapt their leak detection and monitoring methods to the type of the transported medium. Therefore, laboratory evaluation of leak detection methods used by TSO and DSO is crucial to ensuring the safe operation of gas networks transporting natural gas - hydrogen mixtures. These results are therefore crucial to achieving the project's objectives.

1.2 Intended readership

The results presented in this report are relevant for gas network operators, including both transmission system operators (TSOs) and distribution system operators (DSOs), who are responsible for ensuring the safe operation of gas infrastructure.

From this perspective, knowledge of applicable methods for gas leak detection and emission monitoring is essential for operational decision-making, particularly in the context of the planned transition towards hydrogen-enriched gas systems.

1.3 Structure of this document

This document consists of three main parts. The first part describes the research methodology used to evaluate the resistance of leak detection methods to changes in the composition of NG–H_2 mixtures. The second part presents the results of laboratory tests carried out to assess the performance of the selected leak detection methods. The final part provides an evaluation of the tested methods in order to identify the most suitable approach for gas leak detection.

1.4 Stakeholder involvement

This report, presenting the results of laboratory tests of four gas leak monitoring and detection methods (sniffer method, optical gas imaging, acoustic gas imaging, and laser TDLAS), was shared with other project partners for consultation.

Three companies (Technovis Sp. z o.o., NaviGate Sp. z o.o., and EC TEST Systems Sp.z o.o.), cooperating with INIG, provided equipment used in the tests.

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2 Testing methodology

The aim of the tests was to evaluate the resistance of leak detection methods to changes in the composition of the NG-H2 mixture. The most important assessed parameter of leak detection methods was the lower limit of detection (LOD). This parameter determines the effectiveness of a given method, especially for small leaks, which are prevalent in gas networks. The following subsections provide a detailed description of the test setup, measurement conditions, and evaluation procedure applied in this study.

2.1 General assumptions and test bench descriptions

In order to properly evaluate leak detection methods, measurements were carried out for NG-H2 mixtures with varying hydrogen content. The tests focused on mixtures with hydrogen concentrations ranging from 0 to 20%, in accordance with the SHIMMER project assumptions. Additionally, measurements were conducted at higher hydrogen concentrations of 50% and 80% to accurately assess the lower detection limit of each method. The evaluation of leak detection methods was carried out on a laboratory test bench (Figure 2-1) that allows for the generation of controlled leaks of methane and its mixtures with hydrogen.

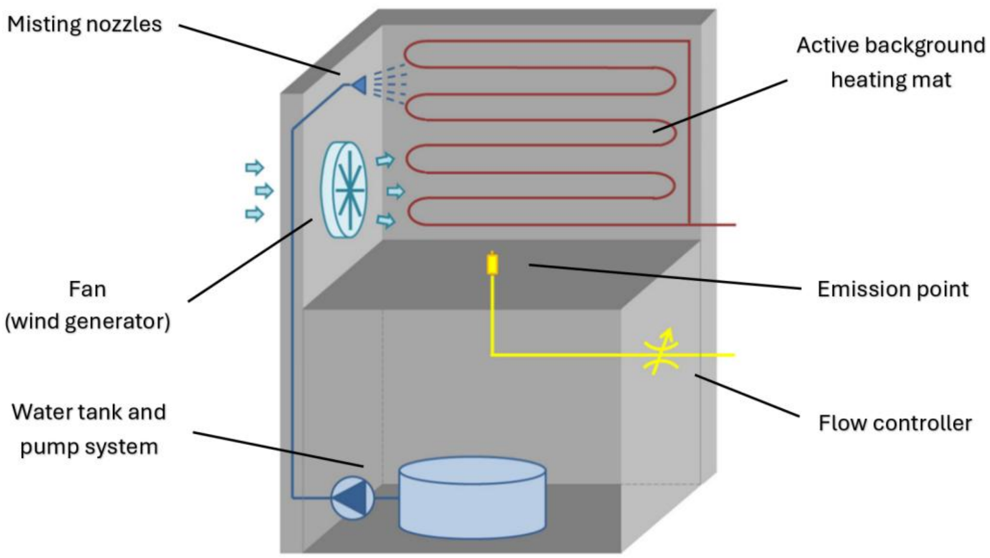

Figure 2-1: Scheme of the INiG test bench GU_84

The primary function of the GU_84 test bench is to generate specified gas volume flow rates. This task is achieved through the MCR flow controller - 50 l/min - D - 5M - 5IN - RS485 MODBUS - HC – GAS. The flow controller enables the generation of prescribed emission levels of methane, carbon dioxide, hydrogen, and their mixtures. Additionally, the test bench is equipped with a set of devices to simulate atmospheric conditions that may interfere with measurements:

- Active background heating mat: Mat allows for heating the background to a temperature 10°C above ambient, simulating conditions where the background temperature is elevated.
- Three Monsoon EXO TERRA misting nozzles: Nozzles enable adjustments to the test bench's operating parameters, including air humidity and misting to simulate varying environmental conditions.

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- Piezoelectric buzzer: Buzzer generates acoustic at a frequency of 3.7 kHz ± 0.5 kHz with a sound pressure level of approximately 82 dB, simulating ambient noise conditions.
- AABCOOLING Super Silent Fan 12 Pro: Fan serves as a wind generator, capable of producing wind speeds of up to 5 m/s to simulate air movement.

The characteristics of the test bench are presented in Table 2-1.

Table 2-1: Characteristics of the INiG test bench GU_84

Equipment	Producer	Type	Range
Flow regulator	Alicat	MCR	0.005-50 l/min
Thermohygrobarometer	Adafruit	BME280	-40 - 85 °C ± 1 °C 10 - 100 % RH ± 3 %RH 300-1100 hPa ± 1 hPa
Spray nozzles	Exo Terra	Monsoon	from air humidity up to 98% in 2% steps
Heating mat	INiG's own design	-	from ambient temperature up to 10°C above ambient temperature in 0.5°C steps
Fan	AABCOOLING	Super Silent Fan 12 Pro	from 0 to 5 m/s in steps of 0.2 m/s

Leaks of the NG-H2 mixture were generated at a nozzle, a threaded connection, and a flange (Figure 2-2). These elements reflect the characteristics of typical leaking components found in gas networks.

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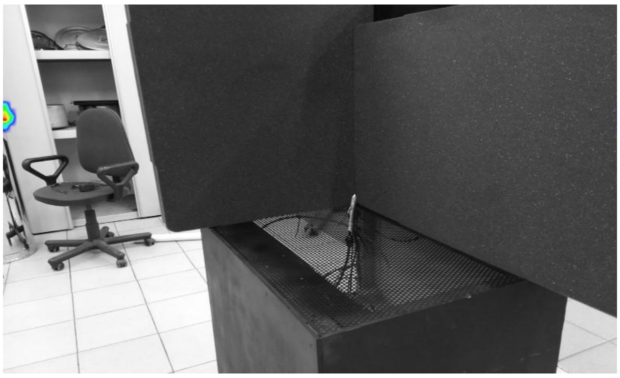

(a)

(b)

(c)

Figure 2-2: Test bench setup with leaky components under test: (a) nozzle; (b) flange; (c) threaded connection

Leaks generated at the experimental site ranged from 0.1 to 4.75 l/min, which corresponds to typical small leaks occurring in gas networks.

2.2 Leak detection methods evaluated

During the tests, four types of measurement methods were evaluated:

- sniffers - handheld portable detectors equipped with methane, hydrogen or both sensors,
- optical gas imaging (OGI),
- acoustic gas imaging (AGI),
- tunable diode laser spectroscopy (TDLAS).

The methods selected for the research were those which, in accordance with deliverable D3.4, are used or planned for use by TSO and DSO operators. The tests omitted computational methods, as tests for this type of methods require a different configuration of the test bench, which simulates the operation of the real gas network not just a single leak.

The tests were conducted using 8 different devices, the characteristics of which are presented below:

1) Sniffers:
    - **Sniffer 1:** GT-44 manufactured by GMI equipped with two methane sensors: semiconductor (1-10,000 ppm) and thermal conductivity (1-100% vol.),

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- **Sniffer 2:** GS 700H manufactured by GMI equipped with infrared methane sensors (1 ppm - 100%) and hydrogen sensors: catalytic (1 ppm – 10,000 ppm) and thermal conductivity (1-100% vol.),
- **Sniffer 3:** GPD 3010 manufactured by SCHUTZ equipped with semiconductor hydrogen sensor (1 ppm-2,5%).

2) Optical gas imaging cameras:
   - **OGI camera 1:** The FLIR GF320 is a camera equipped with an InSb cooled array detector. It has a spectral range of 3.2–3.4 µm and a thermal sensitivity of 15 mK.
   - **OGI camera 2:** Raythink RG630 is OGI handheld camera equipped with a customized band-pass filter and an uncooled VOx infrared detector with high resolution and high sensitivity. Powered by infrared gas thermal imaging technology and AI algorithms, the camera enables the non-contact and visual leakage alarm for dozens of gases including methane (CH_4). Spectral range 7~8.5µm and thermal sensitivity of 15mK.
3) Acoustic gas imaging cameras:
   - **Ultrasonic camera 1:** Distran UltraPro camera enabling the detection of leaks above 1.5 l/h (for nitrogen at 1.5 bar pressure at a distance of 30 cm). The detection limit of the UltraPro camera in typical industrial conditions is 2 l/h.
   - **Ultrasonic camera 2:** The HIKMICRO AI56 acoustic imaging camera is a professional product for gas leak detection. With 64 low-noise MEMS microphones and an adjustable bandwidth range from 0 kHz to 96 kHz, AI56 provides an easy and effective way to locate pressurized gas leaks in industrial environments. Leak rate >0.008 l/min for pressure 6 bar from 0.5 m and >0.013 l/min for pressure 5 bar from 1 m.
4) Tunable diode laser spectroscopy (TDLAS):
   - **Laser 1:** HEQ Laser CH4 Sensor. The sensor operates on the principle of absorption spectroscopy (1650 nm) using a tunable diode laser (TDLAS). The technology used enables the rapid and accurate identification of methane from a distance of up to 300 metres from the source, as well as the detection of low concentrations of the gas, even below 5 ppm.

Measurements using all methods, excluding the TDLAS laser due to device availability, were conducted in parallel.

2.3 Assumptions for evaluating the method

The evaluated methods are qualitative methods intended to determine whether the component being monitored is leaking or not. Validation parameters characterizing the qualitative method that were deemed important include:

- Limit of detection (LOD) – the lowest volumetric flow rate of methane/ hydrogen that can be detected by a given method with a specified probability,
- Sensitivity (SE) – the ability of the method to detect methane/ hydrogen emissions when they actually occur.

From the perspective of assessment gases leak detection methods, the most important validation parameter is method sensitivity, which, in the case of qualitative methods (leak detection), refers to the method's ability to detect actual leaks. Method sensitivity is defined by Equation 1.

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$$SE = \frac{PR}{N} \cdot 100\% \tag{1}$$

where:
SE – method sensitivity [%],
PR – number of positive results, leaks detected by a given method,
N – total number of tests performed by a given method, number of actually occurring leaks.

A parameter closely related to method sensitivity is the lower detection limit. Given that the evaluated methods can be used by TSOs and DSOs to ensure the operational safety of transmission and distribution networks, the lower leak detection limit was assumed to be the one for which the method sensitivity is greater than or equal to 75%. This means that a leak equal to the lower detection limit can be detected with a probability of at least 75% (Equation 2).

$$LOD = SE_{75} \tag{2}$$

where:
LOD – lower detection limit [l/min],
SE_{75} – leak characterized by a methane flow rate that can be detected with 75% probability.

For each evaluated method, tests were carried out in measurement series, with each series consisting of 10 independent measurements performed using a given method. Sensitivity and the lower detection limit were evaluated separately for each method and each measurement series.

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3 Laboratory test results

This section presents the results of laboratory tests carried out to evaluate the performance of the selected leak detection methods. The presented results constitute a detailed description of the obtained measurement data and form the basis for the comparative analysis of the investigated techniques.

The laboratory tests were divided into 111 measurement series, each consisting of 10 independent measurements performed using the methods evaluated within a given series. In series 1 to 66, methods using sniffers, optical and acoustic cameras were evaluated, while in series 67 to 111, the TDLAS method was evaluated. The characteristics of the individual measurement series are presented in Table 3-1.

Table 3-1: Characteristics of individual measurement series

Series no.	leak flow rate [l/min]	hydrogen content [% mol/mol]	leaky component	**Series no.**	leak flow rate [l/min]	hydrogen content [% mol/mol]	leaky component
001	0.1	0	nozzle	**057**	0.3	5	threaded connection
002	0.2	0	nozzle	**058**	0.7	5	threaded connection
003	0.5	0	nozzle	**059**	0.3	10	threaded connection
004	1.0	0	nozzle	**060**	0.7	10	threaded connection
005	3.0	0	nozzle	**061**	0.4	20	threaded connection
006	4.8	0	nozzle	**062**	0.8	20	threaded connection
007	0.1	5	nozzle	**063**	0.4	50	threaded connection
008	0.2	5	nozzle	**064**	1.0	50	threaded connection
009	0.5	5	nozzle	**065**	0.4	80	threaded connection
010	1.0	5	nozzle	**066**	1.1	80	threaded connection
011	3.0	5	nozzle	**067**	0.1	0	nozzle
012	4.8	5	nozzle	**068**	0.2	0	nozzle
013	0.1	10	nozzle	**069**	0.5	0	nozzle
014	0.2	10	nozzle	**070**	1.0	0	nozzle
015	0.5	10	nozzle	**071**	3.0	0	nozzle
016	1.0	10	nozzle	**072**	5.0	0	nozzle
017	3.0	10	nozzle	**073**	0.1	10	nozzle
018	4.8	10	nozzle	**074**	0.2	10	nozzle
019	0.1	20	nozzle	**075**	0.5	10	nozzle
020	0.2	20	nozzle	**076**	1.0	10	nozzle
021	0.5	20	nozzle	**077**	3.0	10	nozzle
022	1.0	20	nozzle	**078**	5.0	10	nozzle
023	3.0	20	nozzle	**079**	0.1	20	nozzle
024	4.8	20	nozzle	**080**	0.2	20	nozzle

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Series no.	leak flow rate [l/min]	hydrogen content [% mol/mol]	leaky component	Series no.	leak flow rate [l/min]	hydrogen content [% mol/mol]	leaky component
025	0.1	50	nozzle	**081**	0.5	20	nozzle
026	0.2	50	nozzle	**082**	1.0	20	nozzle
027	0.5	50	nozzle	**083**	3.0	20	nozzle
028	1.0	50	nozzle	**084**	5.0	20	nozzle
029	3.0	50	nozzle	**085**	0.1	50	nozzle
030	4.8	50	nozzle	**086**	0.2	50	nozzle
031	0.1	80	nozzle	**087**	0.5	50	nozzle
032	0.2	80	nozzle	**088**	1.0	50	nozzle
033	0.5	80	nozzle	**089**	3.0	50	nozzle
034	1.0	80	nozzle	**090**	5.0	50	nozzle
035	3.0	80	nozzle	**091**	0.1	80	nozzle
036	4.8	80	nozzle	**092**	0.2	80	nozzle
037	0.3	0	flange	**093**	0.5	80	nozzle
038	0.6	0	flange	**094**	1.0	80	nozzle
039	0.8	0	flange	**095**	3.0	80	nozzle
040	0.3	5	flange	**096**	5.0	80	nozzle
041	0.6	5	flange	**097**	0.2	0	flange
042	0.8	5	flange	**098**	0.2	10	flange
043	0.2	10	flange	**099**	0.2	20	flange
044	0.6	10	flange	**100**	0.2	50	flange
045	0.8	10	flange	**101**	0.2	80	flange
046	0.2	20	flange	**102**	0.1	0	threaded connection
047	0.6	20	flange	**103**	0.2	0	threaded connection
048	0.8	20	flange	**104**	0.1	10	threaded connection
049	0.2	50	flange	**105**	0.2	10	threaded connection
050	0.6	50	flange	**106**	0.1	20	threaded connection
051	1.0	50	flange	**107**	0.2	20	threaded connection
052	0.3	80	flange	**108**	0.1	50	threaded connection
053	0.6	80	flange	**109**	0.2	50	threaded connection
054	1.5	80	flange	**110**	0.1	80	threaded connection
055	0.3	0	threaded connection	**111**	0.2	80	threaded connection
056	0.7	0	threaded connection				

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3.1 Sniffers method

This subsection describes the results obtained for the sniffer-based leak detection method. Sniffers are typically battery operated and handheld portable systems that may be used for detect leaks. Devices belonging to this group include both single-gas detection devices and multi-gas detection systems.

Three devices were used to evaluate the sniffer method. The first device (Sniffer 1: GT-44) was equipped with methane sensors, the second device (Sniffer 2: GS700H) was equipped with both methane and hydrogen sensors, and the last one (Sniffer 3: GPD 3010) was equipped with hydrogen sensor. For the tests, it was assumed that a leak is considered detected if the concentration of the measured gas (methane or hydrogen) in the air is at least 50 ppm.

Regardless of the type of leaking component and the methane content in the NG-H2 mixture, sniffers equipped with methane sensors were able to detect all generated leaks with a sensitivity of 100% under the tested conditions (Table 3-2).

Table 3-2: Summary of results for sniffers method equipped with methane sensors

Series no.	leak flow rate [l/min]	hydrogen content [% mol/mol]	Sniffer 1 – methane sensor			Sniffer 2 – methane sensor		
			positive results	negative results	SE	positive results	negative results	SE
001	0.1	0	10	0	100%	10	0	100%
002	0.2	0	10	0	100%	10	0	100%
003	0.5	0	10	0	100%	10	0	100%
004	1.0	0	10	0	100%	10	0	100%
005	3.0	0	10	0	100%	10	0	100%
006	4.8	0	10	0	100%	10	0	100%
007	0.1	5	10	0	100%	10	0	100%
008	0.2	5	10	0	100%	10	0	100%
009	0.5	5	10	0	100%	10	0	100%
010	1.0	5	10	0	100%	10	0	100%
011	3.0	5	10	0	100%	10	0	100%
012	4.8	5	10	0	100%	10	0	100%
013	0.1	10	10	0	100%	10	0	100%
014	0.2	10	10	0	100%	10	0	100%
015	0.5	10	10	0	100%	10	0	100%
016	1.0	10	10	0	100%	10	0	100%
017	3.0	10	10	0	100%	10	0	100%
018	4.8	10	10	0	100%	10	0	100%
019	0.1	20	10	0	100%	10	0	100%
020	0.2	20	10	0	100%	10	0	100%
021	0.5	20	10	0	100%	10	0	100%
022	1.0	20	10	0	100%	10	0	100%
023	3.0	20	10	0	100%	10	0	100%

The research leading to these results has received funding from Horizon 2020, the European Union's Framework Programme for Research and Innovation (H2020) under grant agreement n° 101111888.

Series no.	leak flow rate [l/min]	hydrogen content [% mol/mol]	Sniffer 1 – methane sensor			Sniffer 2 – methane sensor		
			positive results	negative results	SE	positive results	negative results	SE
024	4.8	20	10	0	100%	10	0	100%
025	0.1	50	10	0	100%	10	0	100%
026	0.2	50	10	0	100%	10	0	100%
027	0.5	50	10	0	100%	10	0	100%
028	1.0	50	10	0	100%	10	0	100%
029	3.0	50	10	0	100%	10	0	100%
030	4.8	50	10	0	100%	10	0	100%
031	0.1	80	10	0	100%	10	0	100%
032	0.2	80	10	0	100%	10	0	100%
033	0.5	80	10	0	100%	10	0	100%
034	1.0	80	10	0	100%	10	0	100%
035	3.0	80	10	0	100%	10	0	100%
036	4.8	80	10	0	100%	10	0	100%
037	0.3	0	10	0	100%	10	0	100%
038	0.6	0	10	0	100%	10	0	100%
039	0.8	0	10	0	100%	10	0	100%
040	0.3	5	10	0	100%	10	0	100%
041	0.6	5	10	0	100%	10	0	100%
042	0.8	5	10	0	100%	10	0	100%
043	0.2	10	10	0	100%	10	0	100%
044	0.6	10	10	0	100%	10	0	100%
045	0.8	10	10	0	100%	10	0	100%
046	0.2	20	10	0	100%	10	0	100%
047	0.6	20	10	0	100%	10	0	100%
048	0.8	20	10	0	100%	10	0	100%
049	0.2	50	10	0	100%	10	0	100%
050	0.6	50	10	0	100%	10	0	100%
051	1.0	50	10	0	100%	10	0	100%
052	0.3	80	10	0	100%	10	0	100%
053	0.6	80	10	0	100%	10	0	100%
054	1.5	80	10	0	100%	10	0	100%
055	0.3	0	10	0	100%	10	0	100%
056	0.7	0	10	0	100%	10	0	100%
057	0.3	5	10	0	100%	10	0	100%
058	0.7	5	10	0	100%	10	0	100%
059	0.3	10	10	0	100%	10	0	100%
060	0.7	10	10	0	100%	10	0	100%

The research leading to these results has received funding from Horizon 2020, the European Union's Framework Programme for Research and Innovation (H2020) under grant agreement n° 101111888.

Series no.	leak flow rate [l/min]	hydrogen content [% mol/mol]	Sniffer 1 – methane sensor			Sniffer 2 – methane sensor		
			positive results	negative results	SE	positive results	negative results	SE
061	0.4	20	10	0	100%	10	0	100%
062	0.8	20	10	0	100%	10	0	100%
063	0.4	50	10	0	100%	10	0	100%
064	1.0	50	10	0	100%	10	0	100%
065	0.4	80	10	0	100%	10	0	100%
066	1.1	80	10	0	100%	10	0	100%

The results show consistently high and stable detection performance across the entire tested range of conditions. Both devices achieved 100% sensitivity in all measurement series, regardless of leak size, hydrogen concentration, or type of tested configuration. This includes very small leak rates (0.1–0.2 l/min), indicating a very low detection threshold and high intrinsic sensitivity of the methane-based sniffer method.

Importantly, the presence of hydrogen in the gas mixture (up to 80% H_2) does not affect the detection capability of methane sensors. The results confirm that both devices reliably detect methane leaks independently of the NG–H_2 composition, demonstrating strong robustness of the method with respect to changes in gas mixture properties.

No degradation of performance is observed even at extreme hydrogen concentrations or under low-flow conditions. Likewise, no differences in performance are identified between the two tested devices, indicating high repeatability and consistency of results across repeated measurement series.

The conducted tests confirmed the thesis presented in D3.4 that in the case of NG-H2 mixtures in which hydrogen constitutes up to 20% of the content, it is possible to use sniffers equipped with methane sensors. Laboratory tests have also shown that even when hydrogen constitutes 80% of the NG-H2 mixture, it is possible to effectively detect leaks using sniffers equipped with methane sensors. Analyzing the obtained results, it can be concluded that the lower detection limit for the sniffer method equipped with methane sensors is:

- less than 0.1 l/min of mixture (NG 20% and H2 80%) leakage for the nozzle,
- less than 0.3 l/min of mixture (NG 20% and H2 80%) leakage for the flange,
- less than 0.4 l/min of mixture (NG 20% and H2 80%) leakage for the threaded connection.

This means that it is possible to detect methane leakage at the level of:

- less than 0.020 l/min of methane leakage for the nozzle,
- less than 0.060 l/min of methane leakage for the flange,
- less than 0.080 l/min of methane leakage for the threaded connection.

The presented methane-equivalent (LOD) values are estimated based on volumetric composition and assume ideal mixing conditions.

In all these cases, the recorded methane concentration significantly exceeded the assumed 50 ppm and ranged from 700 ppm for the nozzles to 90,000 ppm for the flanges.

Sniffers equipped with a hydrogen sensors was also used in the tests. This type of sensor detected all leaks generated by NG-H2 mixtures within the tested measurement series. The performance of

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sniffers equipped with hydrogen sensors is presented in Table 3-3. The results show that hydrogen-sensitive devices also achieved full detection capability across all tested NG–H_2 mixtures, including cases with low hydrogen content (5%).

Table 3-3: Summary of results for sniffers method equipped with hydrogen sensors

Series no.	leak flow rate [l/min]	hydrogen content [% mol/mol]	Sniffer 2 – hydrogen sensor			Sniffer 3 – hydrogen sensor		
			positive results	negative results	SE	positive results	negative results	SE
001	0.1	0	0	10	0%	0	10	0%
002	0.2	0	0	10	0%	0	10	0%
003	0.5	0	0	10	0%	0	10	0%
004	1.0	0	0	10	0%	0	10	0%
005	3.0	0	0	10	0%	0	10	0%
006	4.8	0	0	10	0%	0	10	0%
007	0.1	5	10	0	100%	10	0	100%
008	0.2	5	10	0	100%	10	0	100%
009	0.5	5	10	0	100%	10	0	100%
010	1.0	5	10	0	100%	10	0	100%
011	3.0	5	10	0	100%	10	0	100%
012	4.8	5	10	0	100%	10	0	100%
013	0.1	10	10	0	100%	10	0	100%
014	0.2	10	10	0	100%	10	0	100%
015	0.5	10	10	0	100%	10	0	100%
016	1.0	10	10	0	100%	10	0	100%
017	3.0	10	10	0	100%	10	0	100%
018	4.8	10	10	0	100%	10	0	100%
019	0.1	20	10	0	100%	10	0	100%
020	0.2	20	10	0	100%	10	0	100%
021	0.5	20	10	0	100%	10	0	100%
022	1.0	20	10	0	100%	10	0	100%
023	3.0	20	10	0	100%	10	0	100%
024	4.8	20	10	0	100%	10	0	100%
025	0.1	50	10	0	100%	10	0	100%
026	0.2	50	10	0	100%	10	0	100%
027	0.5	50	10	0	100%	10	0	100%
028	1.0	50	10	0	100%	10	0	100%
029	3.0	50	10	0	100%	10	0	100%
030	4.8	50	10	0	100%	10	0	100%
031	0.1	80	10	0	100%	10	0	100%
032	0.2	80	10	0	100%	10	0	100%
033	0.5	80	10	0	100%	10	0	100%

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Series no.	leak flow rate [l/min]	hydrogen content [% mol/mol]	Sniffer 2 – hydrogen sensor			Sniffer 3 – hydrogen sensor		
			positive results	negative results	SE	positive results	negative results	SE
034	1.0	80	10	0	100%	10	0	100%
035	3.0	80	10	0	100%	10	0	100%
036	4.8	80	10	0	100%	10	0	100%
037	0.3	0	0	10	0%	0	10	0%
038	0.6	0	0	10	0%	0	10	0%
039	0.8	0	0	10	0%	0	10	0%
040	0.3	5	10	0	100%	10	0	100%
041	0.6	5	10	0	100%	10	0	100%
042	0.8	5	10	0	100%	10	0	100%
043	0.2	10	10	0	100%	10	0	100%
044	0.6	10	10	0	100%	10	0	100%
045	0.8	10	10	0	100%	10	0	100%
046	0.2	20	10	0	100%	10	0	100%
047	0.6	20	10	0	100%	10	0	100%
048	0.8	20	10	0	100%	10	0	100%
049	0.2	50	10	0	100%	10	0	100%
050	0.6	50	10	0	100%	10	0	100%
051	1.0	50	10	0	100%	10	0	100%
052	0.3	80	10	0	100%	10	0	100%
053	0.6	80	10	0	100%	10	0	100%
054	1.5	80	10	0	100%	10	0	100%
055	0.3	0	0	10	0%	0	10	0%
056	0.7	0	0	10	0%	0	10	0%
057	0.3	5	10	0	100%	10	0	100%
058	0.7	5	10	0	100%	10	0	100%
059	0.3	10	10	0	100%	10	0	100%
060	0.7	10	10	0	100%	10	0	100%
061	0.4	20	10	0	100%	10	0	100%
062	0.8	20	10	0	100%	10	0	100%
063	0.4	50	10	0	100%	10	0	100%
064	1.0	50	10	0	100%	10	0	100%
065	0.4	80	10	0	100%	10	0	100%
066	1.1	80	10	0	100%	10	0	100%

The results clearly show a strong dependence of detection performance on the presence of hydrogen in the gas mixture. For pure natural gas conditions (0% H_2), both devices consistently failed to detect leaks across all tested flow rates, resulting in 0% sensitivity. This confirms that the hydrogen sensors do not respond to methane-only leaks and are selective to hydrogen presence in the mixture.

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In contrast, for all NG–H_2 mixtures containing hydrogen (5–80%), both sniffer devices achieved consistently high performance, with sensitivity equal to 100% across nearly all tested flow rates and leak configurations. This includes very small leaks (0.1–0.2 l/min), indicating a very low effective detection threshold once hydrogen is present in the mixture.

Only isolated deviations from perfect detection are observed in the dataset (e.g. a single case of 0% detection at 0% H_2 and selected series boundaries), which are related to the absence of hydrogen rather than limitations of the measurement system itself.

Importantly, the results indicate that detection performance is largely insensitive to hydrogen concentration within the tested range (5–80% H_2), as long as hydrogen is present. No significant degradation in sensitivity is observed at higher hydrogen contents, suggesting stable sensor response across varying mixture compositions.

Repeatability of measurements is excellent, with identical results obtained across both devices and all repeated series for a given test condition. This confirms high stability and robustness of the sniffer-based hydrogen detection approach under laboratory conditions.

Analyzing the obtained results, it can be concluded that the lower detection limit for the sniffer method equipped with hydrogen sensors is:

- less than 0.1 l/min of mixture (NG 95% and H2 5%) leakage for the nozzle,
- less than 0.3 l/min of mixture (NG 95% and H2 5%) leakage for the flange,
- less than 0.3 l/min of mixture (NG 95% and H2 5%) leakage for the threaded connection.

This corresponds to hydrogen leakage levels of:

- less than 0.005 l/min of hydrogen leakage for the nozzle,
- less than 0.015 l/min of hydrogen leakage for the flange,
- less than 0.015 l/min of hydrogen leakage for the threaded connection.

The presented hydrogen-equivalent (LOD) values are estimated based on volumetric composition and assume ideal mixing conditions.

In all cases, the recorded hydrogen concentration significantly exceeded the assumed 50 ppm and ranged from 90 ppm for the flanges to 2,000 ppm for the threaded connections.

The conducted tests confirmed that the use of leak detection procedures using sniffers by TSO and DSO operators is also possible in the case of NG-H2 mixtures. With respect to the project assumptions, i.e. in the case of mixtures with hydrogen concentration from 0 to 20%, these procedures do not require any changes or replacement of equipment when switching from natural gas to the NG-H2 mixture. The tests also showed that the existing sniffer-based detection procedures can be applied to NG–H_2 mixtures with higher concentration of hydrogen (without modifications to the equipment). The use of sniffers equipped with two sensors (methane and hydrogen) does not affect the effectiveness of leak detection.

3.2 Optical gas imaging

The following subsection presents the results of optical gas imaging measurements. Optical gas imaging is widely used leak detection technique, e.g. as part of LDAR programmes. The popularity of OGI techniques results from the savings in inspection time compared to the use of sniffers, and also the ability to perform inspections from a distance, which makes it easier to inspect hard-to-reach places. An OGI camera uses infrared radiation to detect gases. This technique can only detect leaks that emit infrared-active gases. Hydrogen, unlike methane, is not an infrared-active gas, therefore the

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OGI technique cannot be used directly to detect leaks in gas networks transporting pure hydrogen. Due to the fact that hydrogen is an infrared inactive gas, its presence in the NG-H2 mixture may make leak detection more difficult compared to pure natural gas. During the laboratory tests of leak detection using the OGI method, two IR cameras were used: Camera 1: FLIR GF320 and Camera 2: Raythink RG630. During testing Camera 1 detected all generated leaks with 100% accuracy. On the base of the obtained results, it can be concluded that the lower detection limit for the OGI method equipped is:

- less than 0.1 l/min of mixture leakage for the nozzle,
- less than 0.2 l/min of mixture leakage for the flange,
- less than 0.3 l/min of mixture leakage for the threaded connection.

The lower detection limit values correspond to the smallest leaks generated during testing for each component type. Example images of leaks detected using the OGI method with the GF 320 camera are shown in Figure 3-1.

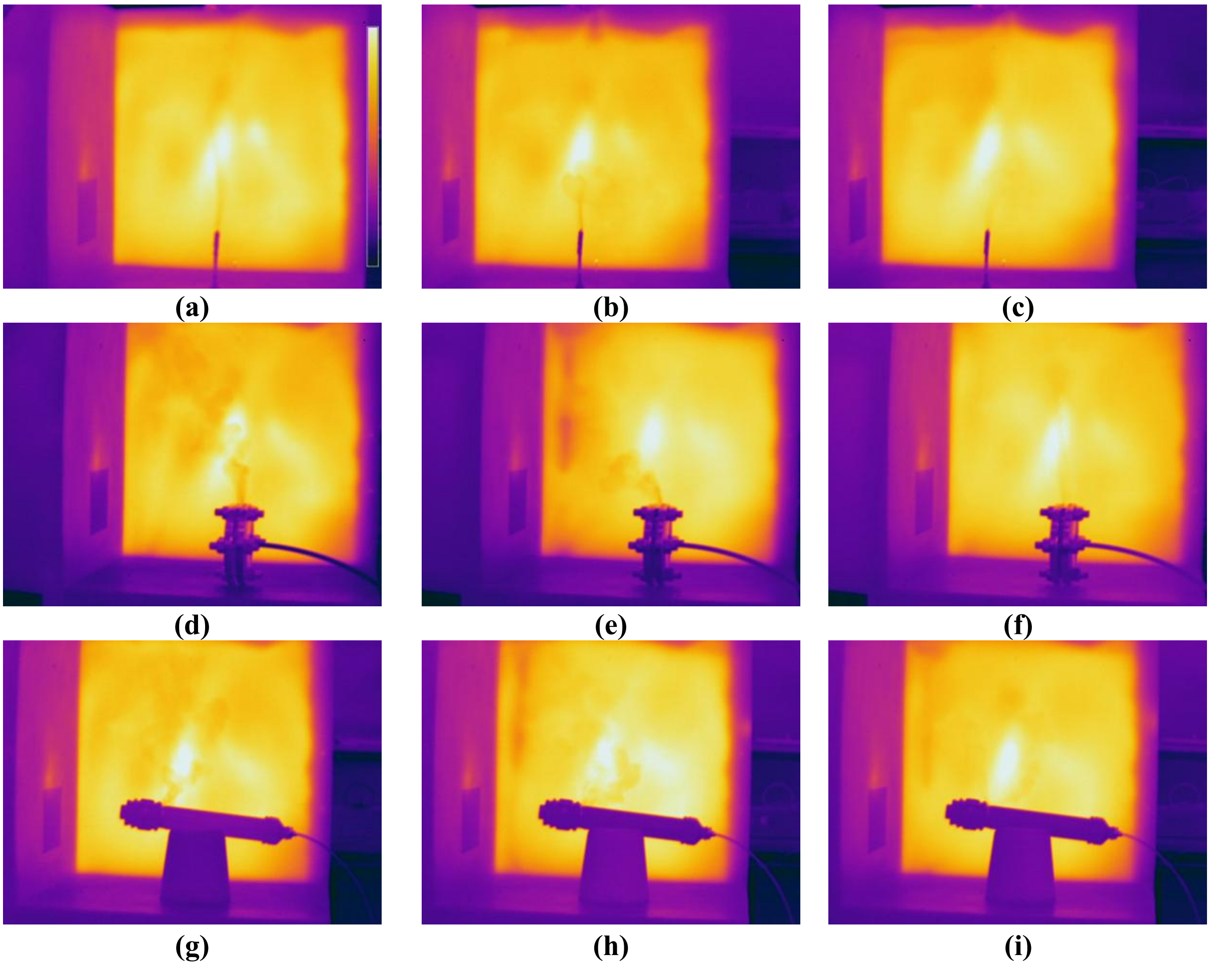

Figure 3-1: Leaks detection using the OGI method with the GF 320 camera; (a) nozzle 0.1 l/min, natural gas; (b) nozzle 0.1 l/min, natural gas and 20% hydrogen; (c) nozzle 0.1 l/min, natural gas and 80% hydrogen; (d) flange 0.3 l/min, natural gas; (e) flange 0.2 l/min, natural gas and 20% hydrogen; (f) flange 0.3 l/min, natural gas and 80% hydrogen; (g) threaded connection 0.3 l/min, natural gas; (h) threaded connection 0.4 l/min, natural gas and 20% hydrogen; (i) threaded connection 0.4 l/min, natural gas and 80% hydrogen

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The photos shown in Figure 3-1 indicate that adding 20% hydrogen to natural gas does not significantly affect the detection of even small leaks. In both the case of natural gas and its mixture with 20% hydrogen, the plume of escaping gas is clearly visible. Only the addition of hydrogen at the level of 80% makes it difficult to identify the plume of the escaping gas, but it is still noticeable.

During testing, Camera 2 detected all generated leaks within the tested conditions, with a sensitivity of 100%, for mixtures with hydrogen content ranging from 0 to 50%.

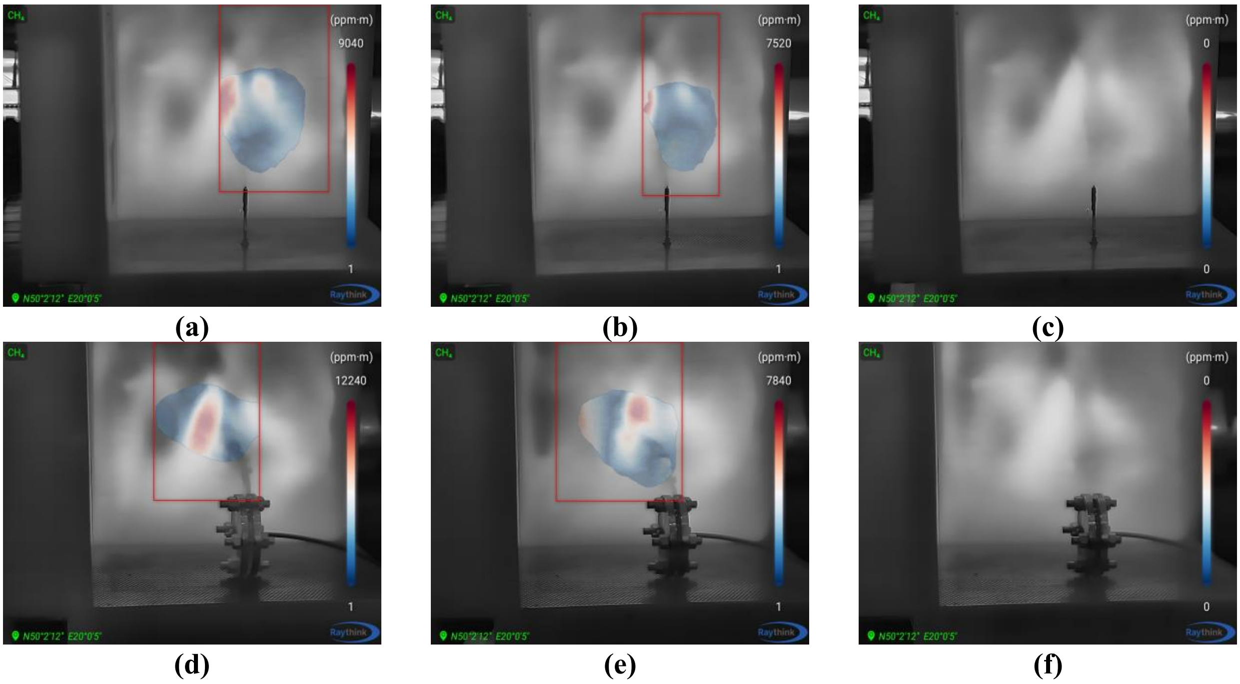
The obtained results indicate that, within the experimental conditions investigated and in line with the SHIMMER project assumption of hydrogen content not exceeding 20%, the lower detection limit for NG–H_2 mixtures is:

- less than 0.1 l/min of mixture leakage for the nozzle,
- less than 0.2 l/min of mixture leakage for the flange,
- less than 0.4 l/min of mixture leakage for the threaded connection.

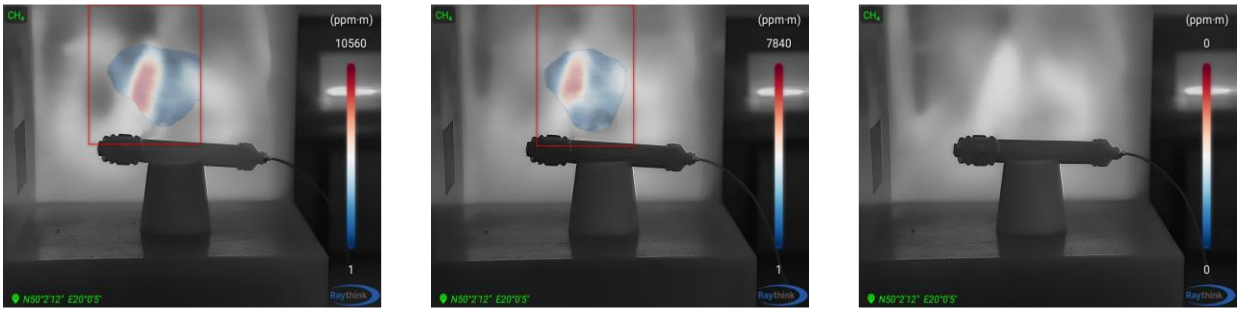
The lower detection limit values correspond to the smallest leaks generated during testing for each component type for a mixture of natural gas and 20% hydrogen.

It should be noted that the presented results are based on laboratory-scale experiments and controlled leak scenarios; therefore, their direct transferability to field conditions may require further validation.

Example images of leaks detected using the OGI method with the Raythink RG630 camera are shown in Figure 3-2.



The research leading to these results has received funding from Horizon 2020, the European Union's Framework Programme for Research and Innovation (H2020) under grant agreement n° 101111888.



(g) (h) (i)

Figure 3-2: Leak detection using the OGI method with the Raythink RG630 camera; (a) nozzle 0.1 l/min, natural gas; (b) nozzle 0.1 l/min, natural gas and 20% hydrogen; (c) nozzle 0.1 l/min, natural gas and 80% hydrogen; (d) flange 0.3 l/min, natural gas; (e) flange 0.2 l/min, natural gas and 20% hydrogen; (f) flange 0.3 l/min, natural gas and 80% hydrogen; (g) threaded connection 0.3 l/min, natural gas; (h) threaded connection 0.4 l/min, natural gas and 20% hydrogen; (i) threaded connection 0.4 l/min, natural gas and 80% hydrogen

In addition to its gas imaging function, the Raythink RG630 camera also has the ability to measure methane concentration around the leaking element. This makes it easier for the camera operator to clearly determine whether a given component has a leak or not. The measurements shown in Figure 3-2 indicate that adding 20% hydrogen to natural gas reduces the methane content at the highest concentration by an average of 26%.

For mixtures of natural gas and 80% hydrogen, a gas plume is still visible, but the methane content around the leaking element measured by the camera is below the quantification limit of the camera. It is therefore possible to detect a leak at a level of 0.1 - 0.4 l/min for mixtures containing 80% hydrogen, but it is difficult and inconclusive.

3.3 Acoustic gas imaging

This part of the report is dedicated to the analysis of acoustic gas imaging results. Acoustic methods based on ultrasonic cameras for acoustic imaging (AGI) are used to detect leaks in above-ground infrastructure. The surface of acoustic cameras consists of dozens of sensors (microphones) that that capture ultrasonic pressure waves emitted by a selected element or group of elements. Differences in the sound waves received by the device are used to locate the sources of emission and present them as an image. The sensitivity and accuracy of the devices depends on both the number of ultrasonic sensors and their mutual arrangement, as well as the data processing algorithms used. Devices of this type can detect multiple leaks simultaneously, but they are not immune to ambient noise, as well as to ultrasonic reflections from steel elements of the inspected installation, which can cause false signals.

Two devices were used to evaluate the acoustic gas imaging method (**Ultrasonic camera 1**: Distran UltraPro and **Ultrasonic camera 2**: HIKMICRO AI56).

In the case of the acoustic method, the lower limit of detection depends on the type of leaking component, the hydrogen content in the NH-H2 mixture and the measuring device used (Table 3-4).

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Table 3-4: Summary of results for ultrasonic cameras

Series no.	leak flow rate [l/min]	hydrogen content [% mol/mol]	Camera 1 – Distran UltraPro			Camera 2 – HIKMICRO AI56		
			positive results	negative results	SE	positive results	negative results	SE
001	0.1	0	0	10	0%	0	10	0%
002	0.2	0	5	5	50%	0	10	0%
003	0.5	0	10	0	100%	10	0	100%
004	1.0	0	10	0	100%	10	0	100%
005	3.0	0	10	0	100%	10	0	100%
006	4.8	0	10	0	100%	10	0	100%
007	0.1	5	0	10	0%	0	10	0%
008	0.2	5	0	10	0%	0	10	0%
009	0.5	5	10	0	100%	10	0	100%
010	1.0	5	10	0	100%	10	0	100%
011	3.0	5	10	0	100%	10	0	100%
012	4.8	5	10	0	100%	10	0	100%
013	0.1	10	0	10	0%	0	10	0%
014	0.2	10	0	10	0%	0	10	0%
015	0.5	10	8	2	80%	10	0	100%
016	1.0	10	10	0	100%	10	0	100%
017	3.0	10	10	0	100%	10	0	100%
018	4.8	10	10	0	100%	10	0	100%
019	0.1	20	0	10	0%	0	10	0%
020	0.2	20	0	10	0%	10	0	100%
021	0.5	20	10	0	100%	10	0	100%
022	1.0	20	10	0	100%	10	0	100%
023	3.0	20	10	0	100%	10	0	100%
024	4.8	20	10	0	100%	10	0	100%
025	0.1	50	0	10	0%	0	10	0%
026	0.2	50	0	10	0%	10	0	100%
027	0.5	50	10	0	100%	10	0	100%
028	1.0	50	10	0	100%	10	0	100%
029	3.0	50	10	0	100%	10	0	100%
030	4.8	50	10	0	100%	10	0	100%
031	0.1	80	0	10	0%	0	10	0%
032	0.2	80	0	10	0%	5	5	50%
033	0.5	80	0	10	0%	10	0	100%
034	1.0	80	10	0	100%	10	0	100%
035	3.0	80	10	0	100%	10	0	100%
036	4.8	80	10	0	100%	10	0	100%

The research leading to these results has received funding from Horizon 2020, the European Union's Framework Programme for Research and Innovation (H2020) under grant agreement n° 101111888.

Series no.	leak flow rate [l/min]	hydrogen content [% mol/mol]	Camera 1 – Distran UltraPro			Camera 2 – HIKMICRO AI56		
			positive results	negative results	SE	positive results	negative results	SE
037	0.3	0	10	0	100%	10	0	100%
038	0.6	0	10	0	100%	10	0	100%
039	0.8	0	10	0	100%	10	0	100%
040	0.3	5	10	0	100%	10	0	100%
041	0.6	5	10	0	100%	10	0	100%
042	0.8	5	10	0	100%	10	0	100%
043	0.2	10	10	0	100%	10	0	100%
044	0.6	10	10	0	100%	10	0	100%
045	0.8	10	10	0	100%	10	0	100%
046	0.2	20	10	0	100%	5	5	50%
047	0.6	20	10	0	100%	10	0	100%
048	0.8	20	10	0	100%	10	0	100%
049	0.2	50	6	4	60%	5	5	50%
050	0.6	50	10	0	100%	10	0	100%
051	1.0	50	10	0	100%	10	0	100%
052	0.3	80	0	10	0%	0	10	0%
053	0.6	80	8	2	80%	10	0	100%
054	1.5	80	8	2	80%	10	0	100%
055	0.3	0	8	2	80%	10	0	100%
056	0.7	0	10	0	100	10	0	100%
057	0.3	5	8	2	80%	10	0	100%
058	0.7	5	9	1	90%	10	0	100%
059	0.3	10	5	5	50%	7	3	70%
060	0.7	10	8	2	80%	10	0	100%
061	0.4	20	5	5	50%	8	2	80%
062	0.8	20	9	1	90%	8	2	80%
063	0.4	50	0	10	0%	5	5	50%
064	1.0	50	0	10	0%	9	1	90%
065	0.4	80	0	10	0%	0	10	0%
066	1.1	80	0	10	0%	0	10	0%

Overall, both cameras demonstrate high detection performance for medium and large leak rates, particularly for flow rates ≥0.5 l/min, where sensitivity typically reaches 97–100% across most hydrogen concentrations. At these conditions, both devices show stable and repeatable detection behaviour, indicating strong robustness of the AGI method for clearly developed acoustic emission signals.

At low leak rates (0.1–0.2 l/min), a significant reduction in detection sensitivity is observed, especially for Camera 1 (Distran UltraPro). In several series, no leaks were detected at 0.1–0.2 l/min

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regardless of hydrogen concentration, indicating that these conditions are below or close to the effective detection threshold of the system. Camera 2 (HIKMICRO AI56) shows generally slightly better performance in this range, although detection remains inconsistent and strongly dependent on hydrogen content and test conditions.

Hydrogen concentration has a noticeable but non-linear influence on detection performance. At moderate concentrations (5–20% H_2), both systems maintain high sensitivity for leak rates ≥0.5 l/min. However, at higher hydrogen contents (50–80% H_2), increased variability is observed, particularly for small leaks, where sensitivity may drop significantly (e.g., 0–60% in selected low-flow scenarios). This suggests that gas composition influences acoustic signal characteristics and background noise conditions, affecting detectability of weak leak sources.

Repeatability of results is generally high for medium and high flow rates, where repeated series at identical conditions consistently yield similar sensitivity values (typically 97–100%). This confirms good measurement stability of both devices under well-defined leak conditions.

The lower detection limit of the acoustic method is variable and depends on many parameters, including the shape of the leak and the hydrogen content of the mixture. During testing, differences in the estimated lower detection limits were also observed depending on the type of equipment used.

In the case of leaks located at the nozzle:

- Camera 1 did not detect leaks at the level of 0.1 and 0.2 l/min, regardless of the hydrogen content in the NG-H2 mixture.
- Camera 1 also failed to detect leaks at 0.5 l/min when the hydrogen content in the mixture was 80%.
- Camera 2 did not detect leaks at the level of 0.1 l/min, regardless of the hydrogen content in the NG-H2 mixture.
- Camera 2 also failed to detect leaks at 0.2 l/min when the hydrogen content in the mixture was up to 10%.

If the hydrogen content in the mixture was 80%, camera 2 detected leaks at 0.2 l/min with an insufficient sensitivity of 50%.

Based on the tests performed, it can be concluded that for leaks located on the nozzle, the lower detection limit is:

- 0.5 l/min for both analyzed cameras, when the hydrogen content in the NG-H2 mixture is up to 10%.
- 0.5 l/min for Camera 1, when the hydrogen content in the NG-H2 mixture is 20-50%.
- l/min for Camera 1, when the hydrogen content in the NG-H2 mixture is 80%.
- 0.2 l/min for Camera 2, when the hydrogen content in the NG-H2 mixture is 20-50%.
- 0.5 l/min for Camera 2, when the hydrogen content in the NG-H2 mixture is 80%.

Sample images recorded during acoustic method tests for leakage at the nozzle are shown in Figure 3-3.

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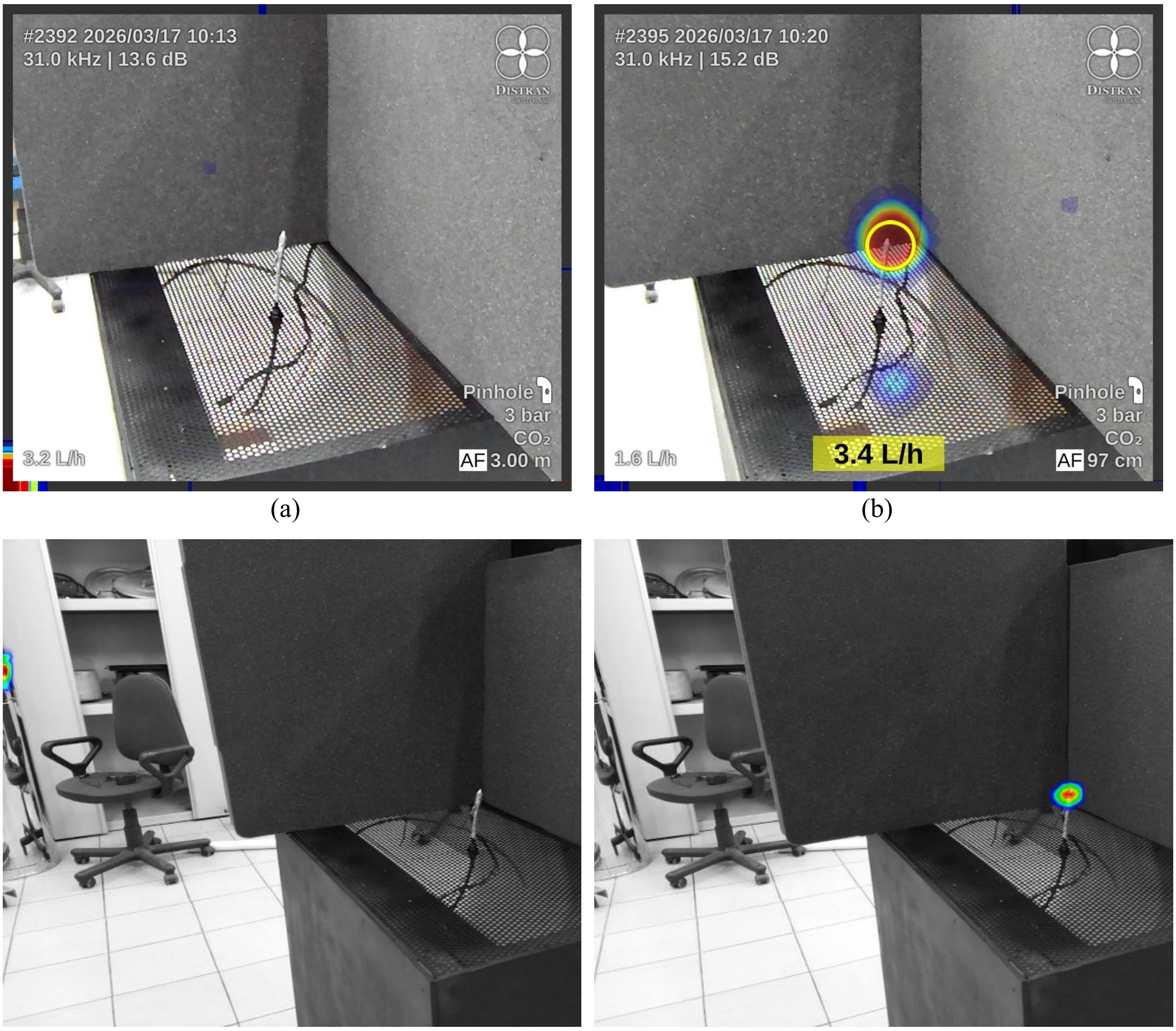

Figure 3-3: Leak detection using acoustic method, leakage at the nozzle measured for a mixture of natural gas with 20% hydrogen; (a) Camera 1: leak 0.2 l/min, no detection; (b) Camera 1: leak 0.5 l/min, detection; (c) Camera 2: leak 0.1 l/min, no detection; (d) Camera 2: leak 0.2 l/min, detection

During the tests, it was also assessed how the detection limit of the acoustic method changes in the case of leaks located on the flange. Also in the case of leaks located on this type of component, the determined detection limit varied depending on the hydrogen content in the gas mixture and the equipment used for measurements. Based on the tests performed, it can be concluded that for leaks located on the flange, the lower detection limit is:

- 0.3 l/min for both analyzed cameras, when the hydrogen content in the NG-H2 mixture is up to 5%.
- 0.2 l/min for both analyzed cameras, when the hydrogen content in the NG-H2 mixture is 10%.
- 0.2 l/min for Camera 1, when the hydrogen content in the NG-H2 mixture is 20%.
- 0.6 l/min for Camera 1, when the hydrogen content in the NG-H2 mixture is 50-80%.

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- 0.6 l/min for Camera 2, when the hydrogen content in the NG-H2 mixture is 20-80%.

These values correspond to the minimum leak rates detected under the applied experimental conditions and measurement configuration. Differences in leak detection ranges for mixtures containing up to 20% hydrogen result from the technical possibilities of generating these leaks and not from the characteristics of the analyzed method.

Sample images recorded during acoustic method tests for leakage at the flange are shown in Figure 3-4.

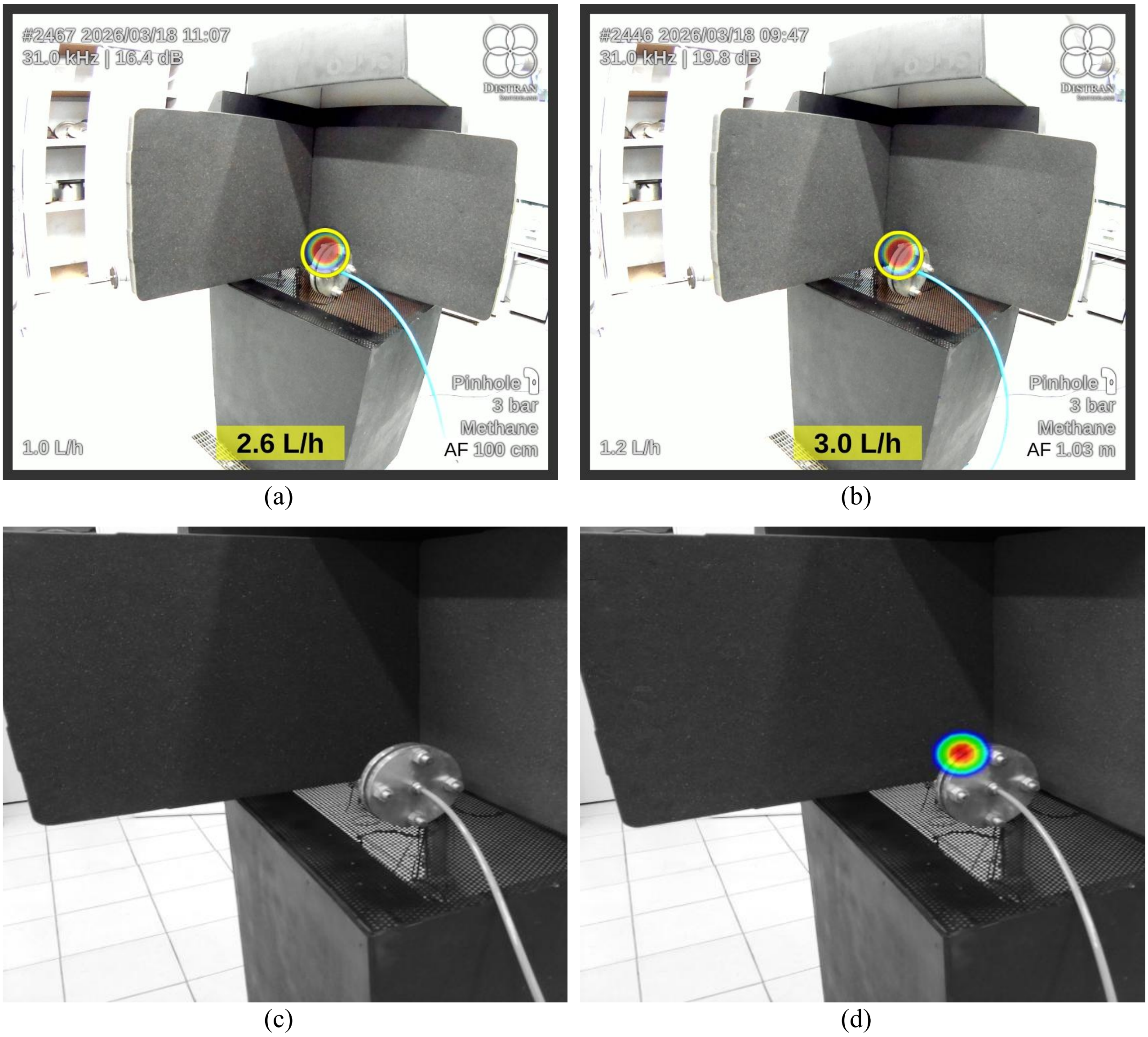

Figure 3-4: Leak detection using acoustic method, leakage at the flange measured for a mixture of natural gas with 20% hydrogen; (a) Camera 1: leak 0.2 l/min, detection; (b) Camera 1: leak 0.6 l/min, detection; (c) Camera 2: leak 0.2 l/min, no detection; (d) Camera 2: leak 0.6 l/min, detection

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The last component that was analyzed that could potentially leak was the threaded connections. They also show noticeable changes in the estimated detection limit, depending on the hydrogen content in the mixture and the type of equipment used.

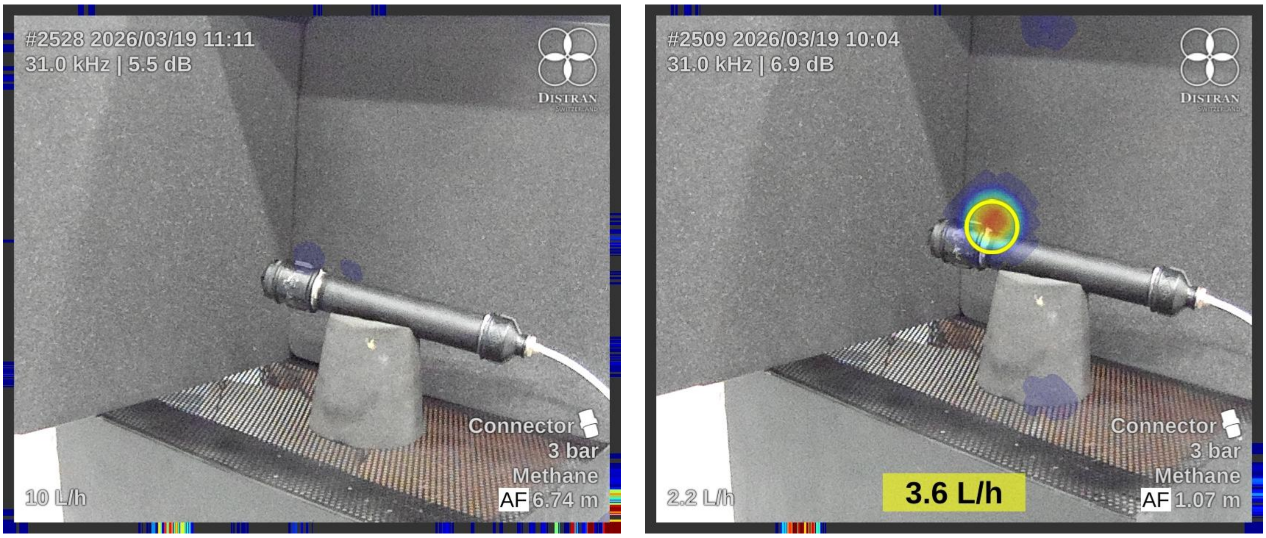
Based on the tests performed, it can be concluded that for leaks located on the threaded connections, the lower detection limit is:

- 0.3 l/min for both analyzed cameras, when the hydrogen content in the NG-H2 mixture is up to 5%.
- 0.7 l/min for both analyzed cameras, when the hydrogen content in the NG-H2 mixture is 10%.
- 0.8 l/min for both analyzed cameras, when the hydrogen content in the NG-H2 mixture is 20%.
- l/min for Camera 2, when the hydrogen content in the NG-H2 mixture is 50%.

Differences in leak detection ranges for mixtures containing from 10 to 20% hydrogen result from the technical possibilities of generating these leaks and not from the characteristics of the analyzed method.

Camera 1 did not detect any leaks generated at the threaded connections in the case of mixtures with a hydrogen content exceeding 50%. A similar situation occurred in the case of camera 2 and mixtures containing 80% hydrogen.

Sample images recorded during acoustic method tests for leakage at the threaded connections are shown in Figure 3-5.



(a) (b)

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(c) (d)

Figure 3-5: Leak detection using acoustic method, leakage at the threaded connections measured for a mixture of natural gas with 20% hydrogen; (a) Camera 1: leak 0.4 l/min, detection; (b) Camera 1: leak 0.8 l/min, detection; (c) Camera 2: leak 0.4 l/min, no detection; (d) Camera 2: leak 0.8 l/min, detection

Changes in the lower detection limit of the acoustic method depending on the type of leaking component and the hydrogen content in the NG-H2 mixture are presented in Table 3-5.

Table 3-5: Lower detection limit of the acoustic method - summary

Hydrogen content [%]	0%		5%		10%		20%		50%		80%	
Leak reates [l/min]	Cam. 1	Cam. 2	Cam. 1	Cam. 2	Cam. 1	Cam. 2	Cam. 1	Cam. 2	Cam. 1	Cam. 2	Cam. 1	Cam. 2
nozzle												
0.1	no	no	no	no	no	no	no	no	no	no	no	no
0.2	no	no	no	no	no	no	no	yes	no	yes	no	no
0.5	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes
1.0	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
3.0	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
4.8	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
flange												
0.2-0.3	yes	yes	yes	yes	yes	yes	yes	no	no	no	no	no
0.6	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
0.8-1.0	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
threaded connection												
0.3-0.4	yes	yes	yes	yes	no	no	no	yes	no	no	no	no
0.7-1.1	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	no	no

Cam. 1 – ultrasonic camera 1: Distran UltraPro; Cam. 2 - ultrasonic camera 2: HIKMICRO AI56

Due to the fact that the detection limit of the acoustic gas imaging method depends not only on the hydrogen content in the natural gas-hydrogen mixture, but also on the type of leaking component, it

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is difficult to clearly indicate in which cases the acoustic method is useful for leak detection. Taking into account that the tests were conducted in laboratory conditions, it can be assumed that in real conditions the lower detection limit will depend mainly on ambient noise, wind conditions and signal reflections from nearby objects.

3.4 Laser TDLAS

This subsection provides an overview of the TDLAS measurement results. Tuned diode laser absorption spectroscopy (TDLAS) is an analytical technique that have been used for many years to detect and measure gas concentrations. Thanks to their versatility, high sensitivity, and selectivity, TDLAS sensors are widely used in industry. Their versatility and compact size have also made them a useful tool for detecting methane in the oil and gas industry.

During laboratory tests, one device was evaluated (Laser 1: HEQ Laser CH4 Sensor). Due to limited time access to the device under evaluation, the tests were conducted in 45 measurement series, including:

- 30 series for the nozzle, in which the hydrogen content varied from 0 to 80% (5 levels), and the generated leaks ranged from 0.1 to 5.0 l/min (6 levels),
- 5 series for flanges in which the hydrogen content varied from 0 to 80% (5 levels) and the generated leakage was 0.2 l/min (1 level),
- 10 series for threaded connections, in which the hydrogen content varied from 0 to 80% (5 levels), and the generated leakage was 0.1 and 0.2 l/min (2 levels).

A single measurement series lasted from less than a minute to about 5 minutes and allowed for the generation of from about 200 to over 2,000 results.

The repeated 0.2 l/min series (e.g. Series 097–101, 103–109, 111) confirms excellent repeatability, with sensitivities mostly at or above 97–100%, regardless of hydrogen concentration.

The results obtained for the TDLAS method are summarized in Table 3-6. The table presents an overview of detection performance across all tested measurement series, including different leak rates and hydrogen concentrations in NG–H_2 mixtures. The results in Table 3-6 indicate that the TDLAS system consistently achieved high detection performance across all tested conditions, with sensitivity values ranging from 77% to 100%. Importantly, all measured configurations exceed the assumed acceptance threshold of 75%, confirming robust leak detection capability.

At lower flow rates (0.1–0.2 l/min), sensitivity shows slightly more variability, particularly at higher hydrogen content (e.g., 77–88% at 80% H_2 in some series). This suggests that very small leaks under high H_2 concentrations represent the most challenging detection scenario. In contrast, moderate to higher flow rates (≥0.5 l/min) consistently yield near-perfect detection (typically 97–100%), indicating improved signal reliability with increasing leak magnitude.

Table 3-6: Summary of results for TDLAS

Series no.	leak flow rate [l/min]	hydrogen content [% mol/mol]	Laser 1		
			positive results	negative results	SE
067	0.1	0	2348	75	97%
068	0.2	0	1531	34	98%
069	0.5	0	2314	77	97%
070	1.0	0	1929	167	92%

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Series no.	leak flow rate [l/min]	hydrogen content [% mol/mol]	Laser 1		
			positive results	negative results	SE
071	3.0	0	1724	24	99%
072	5.0	0	1486	42	97%
073	0.1	10	1350	51	96%
074	0.2	10	878	38	96%
075	0.5	10	1338	3	100%
076	1.0	10	1290	4	100%
077	3.0	10	1950	8	100%
078	5.0	10	357	27	93%
079	0.1	20	708	49	94%
080	0.2	20	961	29	97%
081	0.5	20	1926	8	100%
082	1.0	20	692	0	100%
083	3.0	20	2053	0	100%
084	5.0	20	672	0	100%
085	0.1	50	967	31	97%
086	0.2	50	888	34	96%
087	0.5	50	1050	27	97%
088	1.0	50	1325	3	100%
089	3.0	50	1372	0	100%
090	5.0	50	675	0	100%
091	0.1	80	507	66	88%
092	0.2	80	268	82	77%
093	0.5	80	189	36	84%
094	1.0	80	1371	49	97%
095	3.0	80	477	13	97%
096	5.0	80	485	66	88%
097	0.2	0	1076	18	98%
098	0.2	10	1189	12	99%
099	0.2	20	1281	9	99%
100	0.2	50	1567	36	98%
101	0.2	80	915	32	97%
102	0.1	0	753	46	94%
103	0.2	0	680	51	93%
104	0.1	10	1258	8	99%
105	0.2	10	1010	26	97%
106	0.1	20	1196	13	99%
107	0.2	20	1262	7	99%
108	0.1	50	1257	9	99%

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Series no.	leak flow rate [l/min]	hydrogen content [% mol/mol]	Laser 1		
			positive results	negative results	SE
109	0.2	50	1305	4	100%
110	0.1	80	1149	17	99%
111	0.2	80	1121	18	98%

Sample images recorded during TDLAS method tests are shown in Figure 3-6.

(a)

(b)

(c)

Figure 3-6: Leak detection at 0.2 l/min using the TDLAS method for a natural gas mixture with 20% hydrogen; (a) nozzle; (b) flange; (c) threaded connections

All leaks generated during the tests could be detected with satisfactory sensitivity using the TDLAS method. Therefore, the lower detection limit of the method should be assumed to be equal to the smallest leak generated under the given conditions and is equal to:

- 0.1 l/min for leaks located at the nozzle,
- 0.2 l/min for leaks located at the flange,
- 0.1 l/min for leaks located at the threaded connections,

regardless of the hydrogen content in the NG-H2 mixture.

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4 Recommendations for the use of individual methods

The methods for detecting leaks and measuring hydrogen emissions were assessed taking into account the following aspects:

- Leak detection methods were evaluated based on the following aspects:
- lower detection limit,
- resistance to changes in gas composition
- scope of application and possible application limitations,
- availability of measurement devices,
- availability of measurement standards,
- cost of purchasing and maintaining the devices,
- personnel qualifications,
- other advantages and disadvantages.

Each aspect was assessed on a five-point scale of 1-5, where 1 represents the lowest score, 3 represents a medium (acceptable) level, and 5 represents the highest score. The assessment was based on experimental results obtained under laboratory conditions within the SHIMMER project framework.

The results of the evaluation of individual methods formed the basis for developing recommendations regarding their use for natural gas-hydrogen mixtures.

Table 4-1 presents a comparative evaluation of the investigated leak detection methods, including their performance across selected assessment criteria together with the corresponding justification of the assigned ratings.

Table 4-1: Leak detection methods – ranking list

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Aspect	Description	Rating
Sniffers		
Lower detection limit	• regardless of the sensor used (methane or hydrogen), all leaks generated during the tests for NG-H2 mixtures were detected with 100% sensitivity, • the lower detection limit in terms of methane is from 0.1 l/min for the nozzle to 0.4 l/min for the threaded connection.	5
Resistance to changes in gas composition	• resistant to changes in hydrogen content from 0 to 80% • requires no changes to measurement equipment or procedures	5
Scope of application	• both the distribution and transmission networks • only elements that can be accessed directly • only above-ground elements	4
Devices availability	• high availability, • there are dozens of device manufacturers, • different device configurations are available	5
Standards availability	• EN 15446:2008 [1] developed for VOC can also be used for leak detection for NG-H2 mixtures	5
Costs for purchasing device and implementing method	• low purchase cost (up to 5,000 Euro) • low operating costs related to periodic calibration, filter and battery replacement,	5
Staff qualifications	• easy to use, • typical device used by operational services	5
Other	+ mostly devices intended for explosion hazard zones + light and small - leak detection is time consuming - leak detection only possible for accessible components	3
Optical gas imaging		
Lower detection limit	• all leaks generated for NG-H2 mixtures with hydrogen content up to 50% were detected with 100% sensitivity, • leak detection may be difficult for NG-H2 mixtures containing 80% hydrogen	4
Resistance to changes in gas composition	• resistant to changes in hydrogen content from 0 to 50% • requires no changes to measurement equipment or procedures	4
Scope of application	• both the distribution and transmission networks • above ground elements • can be used for hard-to-reach places	5
Devices availability	• there are several devices available from different manufacturers • not all devices are intended for use in explosion hazard zones	3

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Standards availability	• the only available standard NTA 8399 [2] does not directly concern LDAR procedures, however, there are technical guidelines for the use of this method developed, among others, by the EPA	4
Costs for purchasing device and implementing method	• expensive (purchase cost approx. 75-100 k€)	2
Staff qualifications	• requires specialized staff • staff experience improves the quality of the inspection and shortens its duration	4
Other	+ short inspection time + possibility of using one device for leak detection and emission measurement	5
Acoustic gas imaging		
Lower detection limit	• depends on the hydrogen content in the mixture and the type of leaking component • it can be as high as 0.7 l/min for mixtures containing 20% hydrogen • the detection limit is affected by ambient noise.	2
Resistance to changes in gas composition	• as the hydrogen content increases, the detection limit increases	3
Scope of application	• both the distribution and transmission networks • above ground elements • can be used for hard-to-reach places • should not be used in places where there is noise	4
Devices availability	• there are several devices available from different manufacturers • not all devices are intended for use in explosion hazard zones	3
Standards availability	• there are no dedicated standards for leak detection using acoustic imaging methods • only descriptions of same applications and the results obtained are available in the literature	2
Costs for purchasing device and implementing method	• quite expensive (purchase cost below 50 k€)	3
Staff qualifications	• requires specialized staff • staff experience improves the quality of the inspection and shortens its duration	4

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Other	+ short inspection time + possibility of simultaneous leak detection and emission measurement - not resistant to ambient noise	4
TDLAS		
Lower detection limit	• all leaks generated during the tests for NG-H2 mixtures were detected with satisfactory sensitivity, • the lower detection limit in terms of methane is from 0.1 l/min for the nozzle to 0.4 l/min for the threaded connection,	5
Resistance to changes in gas composition	• resistant to changes in hydrogen content from 0 to 80% • requires no changes to measurement equipment or procedures	5
Scope of application	• both the distribution and transmission networks • above ground elements • can be used for hard-to-reach places	5
Devices availability	• there are several devices available from different manufacturers • measurement performed remotely, no requirements for the device to be placed in explosion-hazard zones	4
Standards availability	• there are no dedicated standards for leak detection using TDLAS • only descriptions of same applications and the results obtained are available in the literature	2
Costs for purchasing device and implementing method	• quite expensive (purchase cost below 30-40 k€)	4
Staff qualifications	• requires specialized staff • the measurement is often carried out using a drone, therefore the ability to operate it is required	3
Other	+ short inspection time + possibility of remote measurement - sensitivity to optical alignment / weather conditions	5

The method using sniffers received the highest score, obtaining a total of 37 points, the remaining methods received:

- 33 points – TDLAS method,
- 31 points – optical method,
- 25 points – acoustic method.

What is important, however, is that in different aspects, individual methods were rated with different numbers of points (Figure 4-1).

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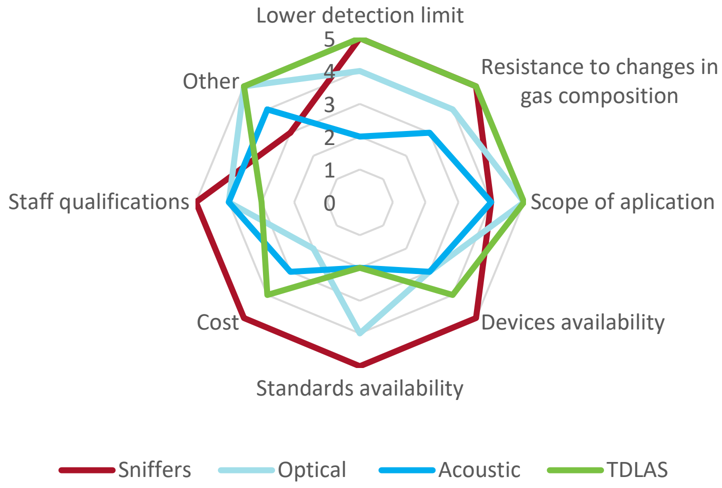

Figure 4-1: Evaluation of leak detection methods in various aspects

Taking into account the data presented in Figure 4-1, it is not possible to indicate a universal method within the investigated conditions for detecting leaks in gas networks transporting NG-H2 mixtures. Each of the methods considered has advantages and disadvantages, as well as the optimal area of application of a given method.

The most commonly used leak detection method by TSO and DSO operators, using sniffers, was rated the highest in 6 out of 8 aspects. This method is resistant to changes in gas composition being tested, and its use by operators does not require changes to LDAR procedures or equipment. This method is recognized for leak detection, and therefore fully standardized measurement procedures or guidelines are available. The only limitations to its use are the lack of access to potential leak locations and the time-consuming nature of the measurements.

The TDLAS laser method is relatively rarely used by TSO and DSO operators in LDAR procedures. This is due to the fact that TDLAS devices operate in conjunction with drones, requiring additional skills from the personnel conducting the inspection. This method, similarly to the sniffers method, is resistant to changes in the hydrogen content in the NG-H2 mixture, which means that it does not require changes in either the measurement procedures or the equipment used. The advantages of the TDLAS method include the ability to conduct measurements remotely, without exposing personnel to explosion-hazard zones. However, in the case of installations with complex geometry or installations partially placed in containers, the TDLAS method will not allow for effective leak detection.

It should be assumed that the most complementary method to the sniffers method, which allows for the detection of leaks in hard-to-reach places, is optical gas imaging method. This method, like the sniffers method, is well known and often used by TSO and DSO operators. For this reason, there are a number of technical guidelines for conducting measurements using this method. This method is resistant to changes in the composition of the NG-H2 mixture, in which the hydrogen content is up to 50%, and in this respect does not require changes in the LDAR procedures and/or equipment used. Higher hydrogen contents in the NG-H2 mixture may make leak detection more difficult, therefore the use of the OGI method for this type of mixtures requires additional validation.

Tests have shown that the acoustic gas imaging method is the least resistant to changes in measurement conditions. The lower detection limit for this method is influenced by both the hydrogen

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content in the NG-H2 mixture and the type of leaking component. Furthermore, this method is not resistant to ambient noise, making it difficult to assess its effectiveness in real-world conditions in a laboratory testing. The advantage of the acoustic method is that leak detection does not require direct access to potentially leaking components. However, the same effect can be achieved using the OGI method.

It should be assumed that, as in the case of leak detection monitoring of natural gas networks, monitoring networks transporting NG-H2 mixtures will require the use of various measurement methods. The tests carried out have shown that the sniffer method and the optical gas imaging method are complementary methods for leak detection for NG-H2 mixtures.

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5 Conclusions

The conducted tests confirmed that currently available leak detection methods can be effectively applied to gas networks transporting natural gas–hydrogen (NG–H_2) mixtures, particularly within the hydrogen concentration range assumed in the SHIMMER project (0–20% H_2). The results demonstrate that the transition from natural gas to NG–H_2 mixtures does not necessarily require fundamental modifications to existing leak detection procedures or replacement of commonly used measurement equipment.

Among the evaluated methods, the sniffer method proved to be the most reliable and versatile under the investigated conditions. Sniffers equipped with methane and/or hydrogen sensors achieved 100% sensitivity for all tested leak scenarios, regardless of leak geometry or hydrogen concentration. The study confirmed that existing sniffer-based procedures currently used by TSOs and DSOs remain applicable for NG–H_2 mixtures, including mixtures with significantly higher hydrogen concentrations than those assumed in the project.

Optical Gas Imaging (OGI) also demonstrated very high effectiveness for NG–H_2 mixtures containing up to 50% hydrogen, achieving satisfactory leak detection sensitivity under laboratory conditions. However, the detection performance decreased significantly for mixtures with very high hydrogen content (80% H_2), confirming that hydrogen presence negatively affects infrared-based detection due to the infrared inactivity of hydrogen. Consequently, OGI may not be suitable as a standalone technique for future pure hydrogen networks.

The Acoustic Gas Imaging (AGI) method showed variable performance depending on leak geometry, hydrogen concentration, environmental conditions, and the type of measurement equipment used. Although AGI may provide useful non-contact detection capabilities in selected applications, its practical applicability requires further investigation and careful consideration of operational limitations.

The Tunable Diode Laser Absorption Spectroscopy (TDLAS) method demonstrated satisfactory sensitivity exceeding the assumed 75% threshold for all investigated leak scenarios. The method offers valuable remote detection capabilities and may complement conventional techniques, particularly in installations where direct access is difficult.

The performed comparative assessment confirmed that no single leak detection method can fully satisfy all operational requirements for monitoring NG–H_2 transmission and distribution networks. Each evaluated technique has specific strengths, limitations, and optimal areas of application. Therefore, effective monitoring of future NG–H_2 infrastructure should be based on a complementary multi-method approach combining sniffers, OGI, AGI, and TDLAS depending on infrastructure type, operational conditions, and measurement objectives.

Overall, the results indicate that existing gas network leak detection practices can be successfully adapted to NG–H_2 mixtures, supporting the safe integration of hydrogen into gas infrastructure and contributing to the European Union’s long-term decarbonization and climate neutrality goals.

The research leading to these results has received funding from Horizon 2020, the European Union's Framework Programme for Research and Innovation (H2020) under grant agreement n° 101111888.

6 References

[1] EN 15446:2008 Fugitive and diffuse emissions of common concern to industry sectors. Measurement of fugitive emission of vapours generating from equipment and piping leaks

[2] NTA 8399:2015 Air quality - Guidelines for detection of diffuse VOC emissions with optical gas imaging

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