Testing and validation of the hydrogen leakage monitoring tool in emblematic case studies reproduced in a "hydrogen tunnel"

1. Introduction & Overview of Activities

Hydrogen is expected to become an increasingly important part of the energy transition, supporting low-carbon solutions for industry, transport and energy infrastructures. At the same time, its wider use requires a careful approach to safety. Hydrogen is very light, disperses rapidly and can form flammable mixtures under specific conditions; for this reason, early and reliable leakage monitoring is a key enabling element for future hydrogen applications.

Within WP3 of the HYDRA project, AUTOMA is developing a hydrogen leakage monitoring tool intended to support the detection of hydrogen and hydrogen-containing gas mixtures in relevant operating environments. The tool can be described as a monitoring system designed to collect information on the presence of gas at selected points and to support the interpretation of possible leakage events.

POLITO contributed to WP3 by providing an experimental environment where the monitoring tool could be exposed to controlled and representative release conditions.

The tests were carried out at the SEASTAR Wind Tunnel laboratory in Turin, Italy, a facility dedicated to gas dispersion, fluid dynamics and safety studies. The wind tunnel makes it possible to control air flow, reproduce simplified real-world geometries and observe how gas clouds move when they interact with wind, obstacles and confined spaces. This is particularly useful for hydrogen because its behaviour can change significantly depending on the surrounding environment. In an open and ventilated area, a release may be quickly diluted; in a congested area, obstacles can generate turbulence and local accumulation zones; in a tunnel or in another partially enclosed space, hydrogen may preferentially move towards upper regions.

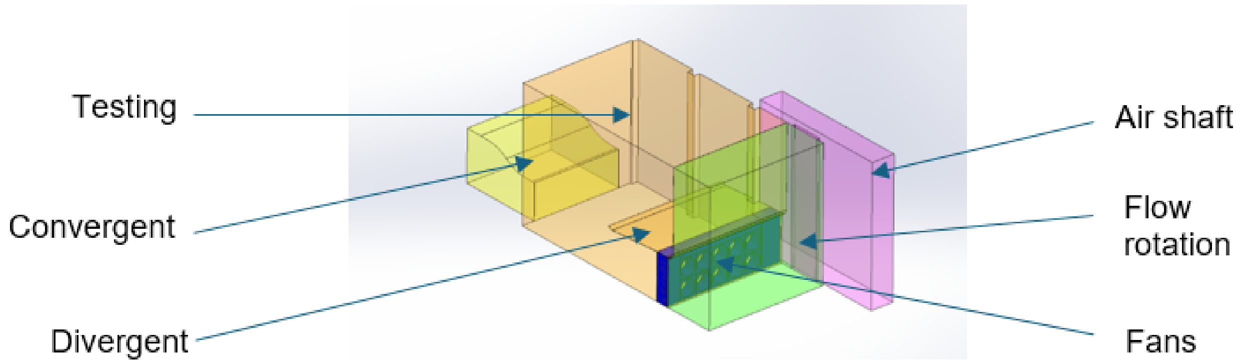

Figure 1: Wind Tunnel Layout

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The SEASTAR WT laboratory is a subsonic open-circuit wind tunnel capable of producing adjustable airflow from 0 to 8 m/s. Its main elements include converging and diverging ducts, a test section, ten independently controlled fans, a flow-rotation chamber, and an air shaft (Figure 1). A honeycomb inlet straightens the airflow, while shutters isolate the system when inactive.

Experiments use a mobile 1:10 scale model of an Adriatic offshore oil and gas platform. The 3 m by 2 m mock-up has three decks, including a sensorized lower deck fitted with simplified equipment shapes and gas sensors. Mounted one meter above the floor and rotatable on a cart, it supports tests under different simulated wind directions.

Gas is supplied from storage through a distribution line to interchangeable 1, 3, or 5 mm nozzles.

In 2024, the laboratory was upgraded for hydrogen experiments (Figure 2). Improvements included ATEX-compliant equipment, enhanced ventilation, gas detection, automated shutdown systems, hazardous-zone classification, updated risk and emergency plans, and staff training.

Figure 2: Mock-up for hydrogen releases in the wind tunnel

In the wind tunnel, the AUTOMA HYDRA monitoring tool was installed (Figure 3).

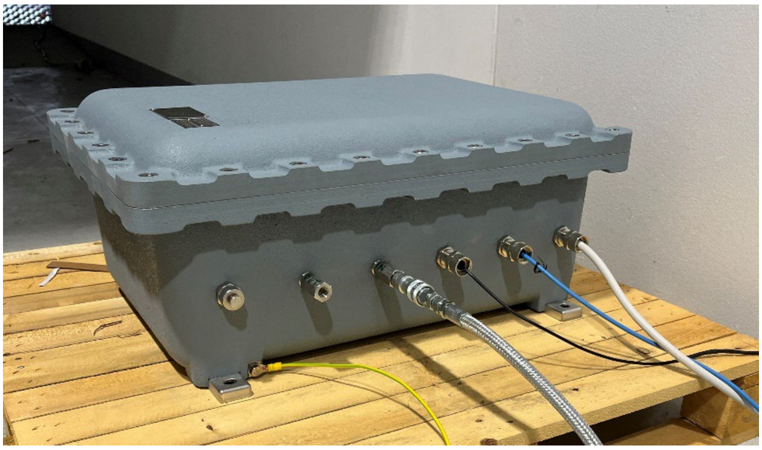

Figure 3: AUTOMA sensor casing and connections

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Detecting and quantifying hydrogen is, in itself, a technical challenge that shaped every design choice. Hydrogen is invisible to common infrared sensors: being a homonuclear diatomic molecule with no dipole moment, it cannot be "seen" by the infrared technologies used as a standard for many other gases. It is also the smallest molecule of all, so it escapes through the tiniest paths and disperses rapidly, demanding fast and reliable detection. In addition, it has a wide flammability range and a very low ignition energy, which means that monitoring must intervene well below the hazard threshold. Finally, in the field hydrogen is almost never present in pure form, but mixed with other gases such as methane, carbon dioxide and nitrogen: selective multi-gas detection is therefore required, rather than a simple single-gas alarm.

To address these constraints, the tool is based on Raman spectroscopy: when laser light is scattered by gas molecules, each species leaves a characteristic spectral "fingerprint". This makes it possible to detect hydrogen — otherwise very hard to identify — and to recognise several gas species at the same time with a single light source, quickly, non-destructively and without any sample preparation or consumables.

The instrument is an integrated system, with hardware and software developed in-house, organised into three functional blocks. The first is the sampling unit, which task is to draw the gas from the environment to be monitored and bring it to the instrument. It consists of a tubing system, designed to collect the sample uniformly from the points where a leak is most likely and to reduce the risk of ignition, and of a pump certified for use in potentially explosive atmospheres, which moves the gas along the line.

The second is the optical unit, that is, the Raman core of the system. Here a laser source illuminates the gas sample; the scattered light is collected and guided, through a probe and a set of focusing optics, into a measuring cell fitted with an optical window that allows the laser beam to pass through the gas. The resulting signal is finally sent to a spectrometer, which breaks it down into its components and extracts the spectral fingerprint of the different species present. The entire optical unit is enclosed in a certified explosion-proof housing, so that it can operate safely even in areas classified as hazardous.

The third is the data-processing unit, consisting of a computer connected to the optical unit and running the proprietary software developed by AUTOMA. The software acquires, analyses and stores the data coming from the sensor, displays concentrations in real time in both numerical and graphical form, and manages an alarm mechanism that is triggered when a predefined safety threshold is exceeded.

The properties of Raman spectroscopy make the measurement intrinsically robust: a single source simultaneously probes all the species present, the linear relationship between concentration and signal intensity allows a one-time calibration, and the relative concentration is measured independently of the laser power and of small misalignments of the optical system. Thanks to a series of tests carried out under controlled and representative conditions, the instrument was progressively optimised for field operation: in particular, a signal-optimisation activity made it possible to obtain a clean and stable baseline in the hydrogen region, making the measurement faster, more repeatable and suitable for continuous, autonomous monitoring, without the need for preliminary reference measurements.

By reproducing urban-like configurations, confined tunnel-like geometries, more open dispersion conditions and selected gas-mixture cases, WP3 provided a first experimental bridge between laboratory development and realistic hydrogen safety applications. The results obtained so far contribute to the HYDRA project by improving the knowledge of hydrogen dispersion detection, supporting the progressive validation of the monitoring approach and identifying practical aspects that should be considered when such systems are installed in real infrastructures.

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2. Methodology

The experimental methodology was designed to expose the HYDRA monitoring tool to different hydrogen release situations while keeping the tests controlled, repeatable and safe. Before starting the campaign, POLITO performed preliminary numerical simulations to support the definition of suitable testing conditions and to identify meaningful positions for the sampling terminal.

These simulations were not used as final quantitative predictions of the experiments; rather, they provided a qualitative guide to understand where the hydrogen cloud was likely to develop, how it could be transported by the air flow and which areas should be avoided for safety reasons. This step was important because hydrogen dispersion can be strongly influenced by wind speed, release direction, surrounding geometry and obstacles.

The tests were then organised around representative scenarios defined within WP3 and realised in specific configuration setups (Figure 4).

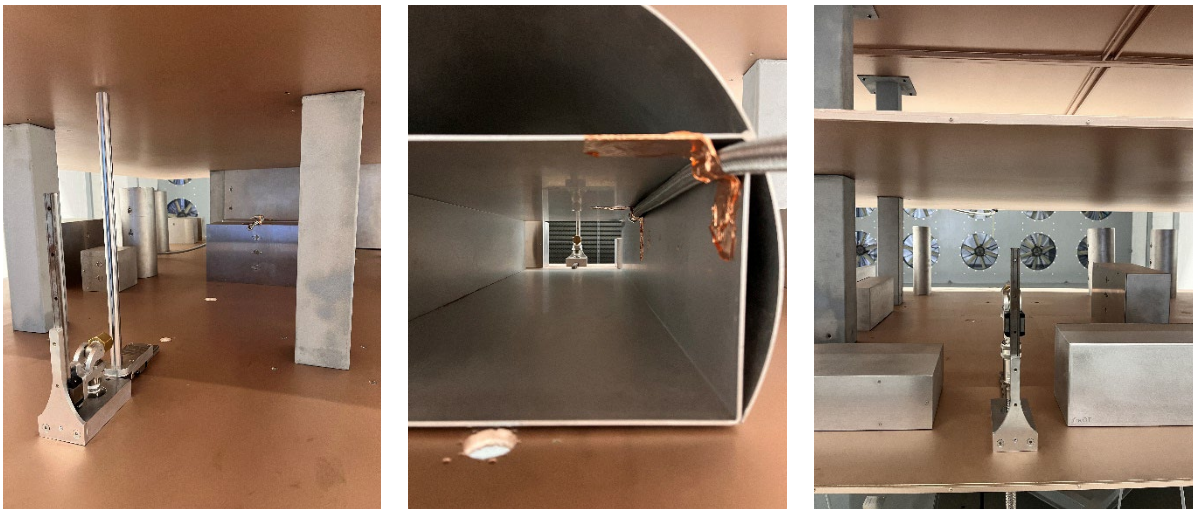

Figure 4: Different configurations for sensor testing: Urban, Tunnel and High Atmosphere

- The first scenario reproduced an urban-like or congested environment. In this configuration, obstacles placed on the mock-up represented the presence of buildings, equipment or other physical barriers. The purpose was to investigate a situation in which the gas cloud does not simply move in a straight path, but interacts with objects that can generate turbulence, recirculation and local concentration differences. This is relevant for streets, industrial sites, energy facilities and other areas where hydrogen equipment may be surrounded by structures.
- The second scenario reproduced a tunnel-like configuration. A scaled tunnel branch was installed on the experimental mock-up in order to study hydrogen behaviour in a confined geometry. This case was selected because confined or semi-confined spaces can be particularly important for safety: hydrogen tends to rise because it is lighter than air, and the upper part of a tunnel or enclosed volume may therefore be a critical location for monitoring.
- The third scenario represented a more open or highly diluted condition, sometimes referred to as a high-atmosphere configuration. In this setup, the release was less affected by nearby obstacles, allowing the cloud to disperse more freely under the action of the wind. The purpose was to evaluate conditions in which the hydrogen reaching the monitoring point is expected to be low and variable, as may occur in well-ventilated environments.

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- In addition to pure hydrogen releases, preliminary tests with a hydrogen-methane mixture were performed. This case was included because hydrogen may be blended with natural gas during the transition towards cleaner gas networks, and monitoring systems may need to recognise the presence of more than one gas species.

Across the campaign, the release conditions, wind speed, sensor-terminal position and geometrical configuration were varied in a controlled way. The motivation was to compare different dispersion behaviours rather than to demonstrate a single ideal condition. Repeated measurements were used to assess the consistency of the observed trends, while the different scenarios helped identify the environmental factors that most affect hydrogen detection in practice.

3. Key Results

The experimental campaign produced representative results that are useful both for the development of the HYDRA monitoring tool and for the broader understanding of hydrogen dispersion in realistic environments.

In the urban-like setup, the results showed that the detected hydrogen signal depends strongly on the interaction between the release and the surrounding obstacles. When hydrogen is released in a congested environment, the gas cloud can be diverted, slowed down or locally accumulated depending on the position and shape of nearby objects. The tests confirmed that this type of scenario is more complex than an open release, because the monitoring point may be located in a region where the cloud is either concentrated by the flow pattern or diluted before it arrives. In the urban configuration, increasing wind speed generally diluted the hydrogen cloud, while increasing release pressure raised downstream concentrations. Tests performed during colder weather conditions were associated with higher measured concentrations. This result is important for future installations in urban or industrial areas, where ambient temperature and the presence of equipment, walls, buildings, pipework or protective structures can change the actual gas distribution.

In the tunnel-like configuration, the results were particularly clear from the point of view of dispersion behaviour. Confinement promoted hydrogen accumulation and clearer detection, especially when the sampling terminal was positioned centrally and close to the ceiling. The tests showed that the position of the sampling point is a decisive factor in confined spaces: placing the terminal in an area where the plume develops and accumulates can lead to a clearer response, whereas a position outside the main path of the cloud may lead to lower values.

In the open or high-dilution setup, the measured values were correctly low, indicating that the cloud had already dispersed significantly at the measurement location. This was an expected but important outcome, because it highlights one of the main challenges of hydrogen monitoring in ventilated environments: the gas may be present only in a very diluted and locally fluctuating form. Under these conditions, the sampled signal can be more sensitive to small variations in plume position, turbulence and air flow.

Tests using a 10% H_2–90% CH_4 mixture evaluated the sensor's ability to detect both gases simultaneously under representative urban and tunnel conditions. Releases were conducted at 5 and 7 bar, with airflow speeds of 3 and 4 m/s and compared with pure hydrogen tests. Analysis of the recorded spectral data revealed a clear methane peak and a distinct hydrogen peak (Figure 5 and Figure 6). As expected, the

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hydrogen signal was weaker than in pure hydrogen releases because of its lower concentration. Zoomed spectra confirmed that both gases were successfully identified by the sensor.

In general, the tests showed that sensor performance depends heavily on release geometry, turbulence, obstacles, plume movement, and the relative position of the sampling terminal. Local accumulation zones could significantly influence results. These findings led to the idea of developing a redesigned terminal with multiple suction points distributed over a wider area, reducing dependence on highly localized concentration gradients.

Additionally, operational testing showed that increasing the sampling-pipe length did not affect measurements when the pipe was correctly installed.

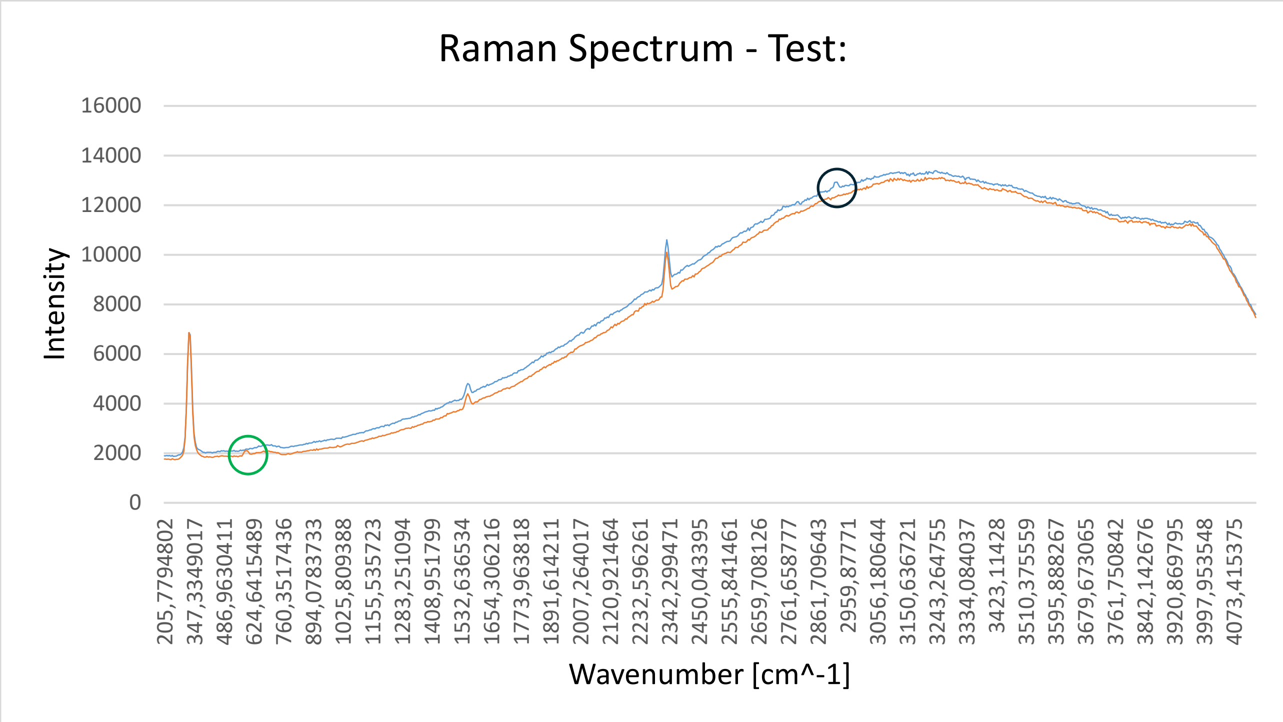

Figure 5: Raman spectrum of the sampling after two releases, one of pure hydrogen (orange line) and one of hydrogen-methane mixture (blue line). In the black circle the methane peak is visible. In the green circle the hydrogen detection is visible.

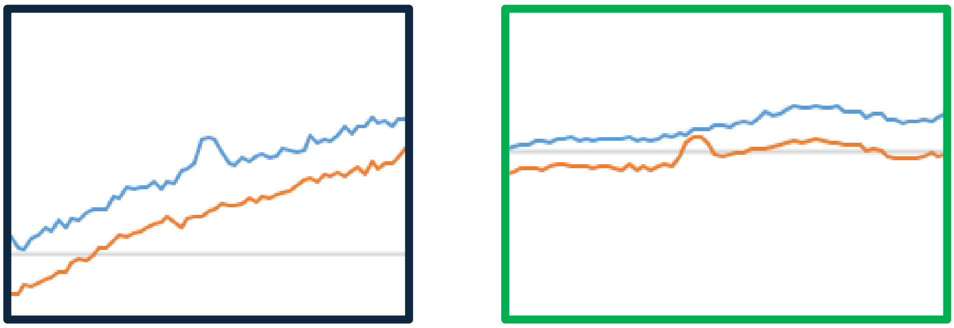

Figure 6: Zoom of the methane (left) and hydrogen (right) detection in the two spectra related to two different releases

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4. Discussion & Interpretation

The results obtained in WP3 show that testing a hydrogen monitoring tool under realistic dispersion conditions is essential before moving towards field deployment.

Hydrogen behaviour is not uniform across environments, and this has direct consequences for how monitoring systems should be interpreted and installed.

The urban-like tests demonstrated that obstacles and local air movements can strongly affect the shape and position of the cloud. In practical terms, this means that a sensor or sampling terminal installed in a real facility should not be considered as an isolated object: its response depends on the surrounding geometry, ventilation conditions and likely release points. A monitoring strategy should therefore be planned together with an understanding of the facility layout and of the possible gas paths.

The tunnel tests confirmed the relevance of confined spaces. Since hydrogen is lighter than air, the upper part of a tunnel or enclosed volume can become particularly important, especially when the geometry favours accumulation or when ventilation is not sufficient to rapidly remove the gas. This does not mean that every confined environment behaves in the same way, but it confirms the need for careful placement and for scenario-based validation.

The high-dilution tests highlighted a different challenge. In open or well-ventilated environments, hydrogen may disperse quickly, which is positive from a safety perspective but more demanding from a monitoring perspective. The gas cloud can become patchy and variable, so a measurement taken at a single point may depend strongly on local fluctuations. This suggests that future developments should consider how to make sampling more representative, especially in areas where the cloud is expected to be diluted or unstable.

The mixture tests also point to an important direction for future work: the ability to collect information on more than one gas species could be valuable in transitional energy systems, including hydrogen-enriched natural gas applications.

From the AUTOMA perspective, the next steps will focus on continuing the development of the monitoring tool while maintaining the appropriate level of confidentiality for technical details and performance parameters. Within HYDRA, activities will move progressively from controlled laboratory tests towards more realistic case-study conditions. This will include further validation of the system in relevant environments, refinement of the software interface for the interpretation of gas information and continued development of advanced data-analysis capabilities. The results also suggest possible system-level improvements, such as optimising the sampling configuration to reduce the influence of very local concentration gradients and improving robustness in complex flow conditions.

From the POLITO perspective, the campaign provided a valuable experimental basis for interpreting hydrogen dispersion and for identifying practical lessons for safe installation. The next phase should therefore combine field-oriented validation, operational feedback and continued cooperation between technology developers and testing partners. In this way, WP3 can support the gradual transition from prototype testing to monitoring solutions that are better adapted to real hydrogen infrastructures.

The main remaining aspects for further development can be divided between activities to be carried out within the HYDRA project and those foreseen for subsequent system optimization.

Within HYDRA, efforts have focused on the validation of the system through dedicated test campaigns under progressively more realistic field conditions, as well as on the initial integration of additional gas

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quantification functionalities into the software interface, limited to selected target species and preliminary visualization features. A redesign of the sampling terminal geometry has already been developed to improve gas capture efficiency and reduce sensitivity to plume position and flow variability observed during the experimental campaigns; its physical implementation may be carried out within the project, subject to a specific assessment, should it prove necessary for the validation campaign at CERTH. In parallel, the development of an AI module has been initiated within the Software Area. At this stage, the activity is focused on data collection and dataset structuring, which are necessary to enable future model training. Due to the current limited availability of representative datasets, the AI module is not yet sufficiently mature to provide reliable outputs, and its implementation remains at an early development stage. In addition, the regulatory framework (including AI Act compliance) is being assessed to ensure future integration aligns with requirements on safety, transparency, and cybersecurity. Furthermore, the patent application process has been formally initiated, with the support of a specialized consultancy. The activity includes ongoing patentability assessment and technical documentation preparation, with submission of the patent application expected within the HYDRA project timeframe.

Other aspects are considered part of future developments beyond HYDRA, aimed at advancing the TRL and further optimizing the sensor based on the results obtained during the project. These include the adoption of a more powerful sampling pump, which will be evaluated in future prototypes, taking into account operational constraints such as ATEX compliance, power consumption, and system integration limits. The integration of additional gas quantification functionalities will also be further extended beyond the initial implementation developed within HYDRA, with the objective of enabling multi-species detection and supporting broader air quality monitoring applications. This will require both hardware optimization and advanced signal processing strategies to ensure selectivity and measurement reliability across different gaseous compounds. Finally, further validation campaigns will be carried out using more advanced prototypes under fully realistic operating conditions, including long-term stability tests, deployment in representative industrial environments, and performance assessment under varying environmental and interference conditions (e.g., temperature, humidity, and background gases). These activities will support the progressive transition of the system toward higher TRL levels and market deployment.

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