

# Quantifying fugitive hydrogen emissions at the component scale: High-flow sampling method

Haydn Barros<sup>1\*</sup>, Hannah Cheales-Norman<sup>1</sup>, Aimee Buck<sup>1</sup>, Jon Helmore<sup>1</sup> and Nigel Yarrow<sup>1</sup>.

<sup>1</sup>National Physical Laboratory, Atmospheric Environmental Science Department, Hampton Road, Teddington, TW11 0LW, UK

**Abstract.** Hydrogen is a key energy vector in the transition to net zero with its industrial use expected to grow significantly in the next decades. At present there are no standard methods specific for hydrogen fugitive emissions quantification, and these are required to inform monitoring schemes and support regulations. On the other hand, the high flow sampling method (HFS) has been successfully used for natural gas leak rate quantification in the industry. So, in this work we present for the first time a performance evaluation of the HFS method for quantifying hydrogen leak rates.

## 1 Introduction

The momentum behind hydrogen is strong. In total, 60 governments (including the European Union) have adopted H<sub>2</sub> strategies [1]. The current H<sub>2</sub> global market is valued at around \$283 billion in 2025, while projections estimate the market could reach \$556 billion by 2034 [2]. Experience in the natural gas industry has found fugitive emissions in different scenarios/scales along the whole production chain. The H<sub>2</sub> leaks could be even more significant, since it is a lighter molecule, is less viscous, and some H<sub>2</sub> storage systems work at higher pressures as compared to natural gas facilities. For those reasons, great efforts are being devoted to better understand the potential H<sub>2</sub> emissions and to identify and develop the reliable methods for monitoring those. There are several international initiatives aiming to fill the existing gaps in the H<sub>2</sub> emissions monitoring [3,4,5,6]. A list of their main topics follows.

- Hydrogen emissions research needs
- Detect and quantify hydrogen emission
- Identify / develop tools and technologies (BAT)
- **Develop methods**, protocols, guidance
- Harmonize existing practices across the value chain
- Accurate hydrogen emissions inventories
- Fill up gaps where little empirical data exist
- Move towards standardisation
- Support regulators and industry
- Better impact assessment (environ., risk, economic)

NPL is actively working on the development of practical methods to reliably quantify industrial hydrogen fugitive emissions [7]. In the present work we test the High-Flow Sampling method (HFS) and assess its feasibility to monitor industrial H<sub>2</sub> leaks at component scale (individual components). The main challenges to quantify H<sub>2</sub> leaks and the found solutions are presented.

## 2 The High-Flow Method

The method consists in sampling at a high flow rate (above hundred litres per minute) using a hover type instrument capable of drawing in a considerable amount of ambient air along with the escaping gas from the leaky component. Then the concentration of the diluted gas is measured, and the leak rate is calculated. The method has been used for many years in the industry to monitor natural gas leaks, so commercial devices incorporate natural gas (CH<sub>4</sub>) sensors internally.

When using a portable (back pack) High-Flow Sampler, the inlet tube is approached to the leak source (~ 1 cm) sucking the leaked gas inside the sampler. The leaked gas will be diluted with ambient air (the sampling flow rate ( $S$ ) is larger than the leak rate). Then, the sampling flow rate and the gas volumetric concentration ( $c$ ) inside the instrument are measured, and the leak rate (volumetric rate,  $Q_V$ ) is calculated as follows:

$$Q_V = S (c - BG) \quad (1)$$

$BG$  represents the background gas concentration corresponding to a far enough point in which the leak source have no effect. Here  $Q_V$  and  $S$  are expressed in L/min while  $c$  and  $BG$  are volumetric fractions. Eq. 1 assumes that the gas is pure ( $c = 1$  or 100%), so the lower concentration measured is caused only by the dilution of the gas with ambient air. In the case of diluted or blended gases Eq. 1 must be corrected accordingly. Eq. 1 also assumes that the whole leaked gas is being sampled during the measurement (in steady state). Great care must be taken to ensure the full capture of the leak, otherwise the actual leak rate could be greatly underestimated.

\* Corresponding author: [haydn.barros@npl.co.uk](mailto:haydn.barros@npl.co.uk)

In this work we have selected the Hi-Flow Bacharach sampler (BHFS). The concentration of the diluted H<sub>2</sub> inside the HFS was measured by a GS-700-H2 (Gasurveyor - Teledyne) detector. In the lab it was determined that this detector can reliably measure H<sub>2</sub> down to 50 ppm (μmol/mol), which combined with the BHFS capacity to sample 200 L/min allow us to measure hydrogen leaks of 0.01 L/min (if full capture is achieved). On the other hand, although the BHFS is designed to be intrinsically safe for use in hazardous locations (Class I, Division 1, Groups A, B, C & D in North America) is not ATEX rated. For that reason, we tested the instrument for a maximum internal (diluted) concentration below 4% v/v H<sub>2</sub> (100 %LEL), allowing to quantify leaks up to 7-8 L/min.



Fig. 1. High-Flow sampler measuring a leak rate.

Several leak rate tests were performed simulating leak H<sub>2</sub> rates between 0.5 and 7 L/min. When the full capture is guaranteed the method provide high accuracy (deviations < 1%) in all the cases (not shown). It is worth noting that the full capture of the leak is not always possible in real conditions, and this is the most relevant issue in the application of this method.

### 3 High-Flow Sampling rate

The sampling rate of a High-Flow instrument is generally measured with an orifice plate device. The BHFS's orifice plate was calibrated. The main components of the calibration system are: gas supply (air), mass flow controller (MFC), the certified flow meter (Mesa Labs DryCal 1020 flow meter) and the High-Flow Sampler to be calibrated in terms of flow rate. The BHFS flow meter has good linearity (Fig. 2). However, the three lower flow rates are systematically below the actual flow rate (4-7%) and their uncertainties (2σ) cannot explain this difference. For that reason these were excluded for the linear regression fitting. All other seven flow rates overlaps with the actual value within the 2σ interval. The obtained linear fitting is almost the ideal trend (y = x) and no recalibration was required.

The measured sampling rate values are corrected for the effect of temperature on the flow rate (using the ratio of absolute temperatures). It is worth noting that the BHFS maximum flow rate is ~220 L/min, and the minimum accurate value is 150 L/min (as shows Fig. 2). Generally the BHFS sampling rate (produced by an internal fan) is quite stable (σ < 2% in several minutes).

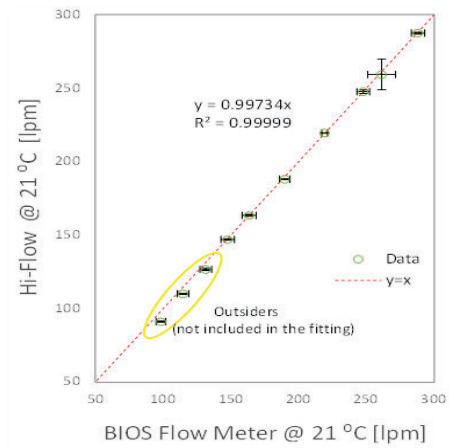


Fig. 2. High-Flow sampling rate calibration.

### 4 Effect of the hydrogen concentration on the sampling rate measurement

The measurement of the sampling flow rate is an essential value to quantify leaks using the High-Flow method. This is usually measured by an orifice and two sensors providing a differential pressure measurement. Generally, this kind of measuring systems are calibrated with dry air, and the read flow rate is depending on the gas passing through the pipe having the orifice and exerting pressure on the sensors. The equation relating the mass flow rate with the differential pressure also considers the gas type, and if we assume that the flow is below the ultrasonic regime (i.e. the differential pressure is not too high), it can be expressed as follows.

$$S_M = \frac{1}{\sqrt{1-\beta^4}} \frac{\pi}{4} d^2 \sqrt{2 \Delta p \rho} \quad (2)$$

$S_M$  is the mass flow rate,  $\Delta p$  is the differential pressure (before - after the orifice),  $\beta$  is the ratio between the orifice diameter ( $d$ ) and the pipe diameters ( $D$ ), and  $\rho$  is the gas density. This expression can be converted in the volumetric flow rate just dividing by the gas density

$$S_V = \frac{1}{\sqrt{1-\beta^4}} \frac{\pi}{4} d^2 \sqrt{2 \frac{\Delta p}{\rho}} \quad (3)$$

However, it is necessary to introduce a discharge coefficient  $C$  accounting for geometrical effects, it determines the relation between the real flow through a device and the theoretical flow. With a fixed geometry,  $C$  only depends on the Reynolds number of the gas and  $C$  can be seen as a calibration constant for the device. As a first approximation we will consider that the behaviour of air and H<sub>2</sub> near normal temperature and pressure (NTP, i.e. 20C and 101.325 kPa) are close enough to consider  $C$  to be the same for both gases. This is based on the observation that Reynolds numbers for gas flowing through pipes are usually ~10<sup>4</sup> to 10<sup>7</sup>, then the effect on the parameter  $C$  is low. In fact, there are parametrizations of  $C$  showing that when the Reynolds number tends to infinity then the so-called  $C_\infty$  depends only on the geometry [8]. This approximation could introduce discrepancies ≤ 0.01% when changing from air to H<sub>2</sub> (at NTP). In second place, we use an expansion coefficient  $\epsilon$  describing the behaviour of the

compressible media (gas). Using the same approximation (Reynolds number tends to infinity) the Soltz equation can be used to approximate the expansion coefficient, and it can be shown that it depends on geometrical factors, the differential pressure, the pressure before the orifice and the isentropic coefficient  $\kappa$  ( $C_p/C_v$ ) for the gas flowing through the orifice [8]. At NPT most diatomic gases has a  $\kappa$  value of approximately 1.4, so also the expansion coefficient can be considered the same constant in the case of comparing air (mainly  $N_2$  and  $O_2$ ) and hydrogen ( $H_2$ ) flows. This can be simplified using a single factor ( $F$ ) for all the constant parameters (for a given device).

$$S_V = \frac{c}{\sqrt{1-\beta^4}} \varepsilon \frac{\pi}{4} d^2 \sqrt{2 \frac{\Delta p}{\rho}} = F \sqrt{\frac{\Delta p}{\rho}} \quad (4)$$

Different gases density will affect the measurement. For a given flow measurement (reading), there is a given  $\Delta p$ . This differential pressure will take place during the calibration (dry air) and when the gas is measured.

$$S_{V-air} = F \sqrt{\frac{\Delta p}{\rho_{air}}} \quad \text{or} \quad S_{V-gas} = F \sqrt{\frac{\Delta p}{\rho_{gas}}} \quad (5)$$

Combining both equations of equal  $\Delta p$ , we obtain

$$S_{V-gas} = S_{V-air} \sqrt{\frac{\rho_{air}}{\rho_{gas}}} \quad (6)$$

The gas being measured is a combination between the leaked gas (in this case pure  $H_2$ ) and the ambient air (which we will suppose dry air), then the density of the flowing gas can be expressed as follows

$$\rho_{gas} = \rho_{H_2} c + \rho_{air}(1 - c) \quad (7)$$

Where  $c$  is the measured concentration of the leaked gas (in this case  $H_2$ ), as in Eq. 1. Any correct reading (measured sampling rate) must correspond to the calibration gas, which is generally air ( $S_{V-read} = S_{V-air}$ ). Then, combining Eq. 6 and 7, we obtain a corrected sampling flow rate measurement in terms of the direct read flow rate and the gas concentration measured internally where the orifice is located.

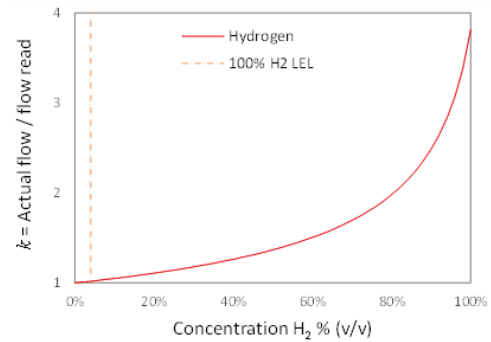
$$S_{V.gas} = \frac{S_{V.read}}{\sqrt{1 + c \left( \frac{\rho_{H_2}}{\rho_{air}} - 1 \right)}} \quad (8)$$

The quantification of the hydrogen volumetric leak rate can be done combining Eq. 1 and 8, the result here is simplified for cases with negligible background.

$$Q_{V.H_2} = \frac{S_{V.read} c}{\sqrt{1 + c \left( \frac{\rho_{H_2}}{\rho_{air}} - 1 \right)}} \quad (9)$$

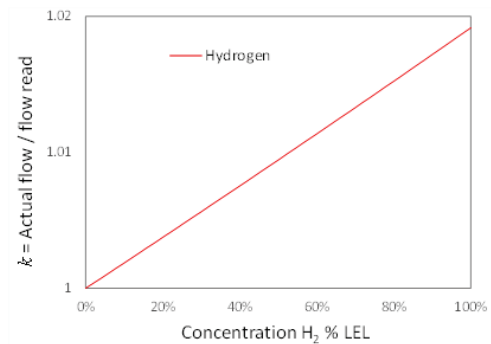
Any gas density is changing with the temperature, but fortunately the ratio of their densities is almost constant (in this case  $\rho_{H_2}/\rho_{air} = 14.56$ ). In most cases, the large dilution caused by the High Flow sampling will produce internal concentration values relatively low and the correction factor in the denominator of Eq. 9 could

be neglected. However, this could not be the case for large leaks of pure hydrogen, and it is worth having a quantitative estimation of this correction. Fig. 3 shows the magnitude of the correction factor ( $k$ ) to be applied as a function of the hydrogen concentration measured in the internal pipe of the system where the measuring orifice is located.



**Fig. 3.** Correction for the leak rate measurement as a function of the measured internal  $H_2$  concentration ( $c$ ).

In the case of common leaks, the concentration inside the sampler is usually below the lower explosivity limit (LEL). Fig.4 shows the details within this range.



**Fig. 4.** Correction for the leak rate measurement for moderate  $H_2$  leaks ( $c \leq 100\% H_2 LEL$ ).

For instance, in the case of measuring 50% LEL, the flow rate must be corrected by a factor of  $\approx 1.01$ , i.e. the flow of the actual gas is  $\approx 1\%$  higher than an air flow producing the same reading (the same differential pressure through the same device). Finally, the emitted leak rate can be quantified as

$$Q_{V.H_2} = k S_{V.read} c \quad (10)$$

Where  $k$  is a function of the measured hydrogen concentration (as shown in Fig. 3). It is often useful to represent the leak rate in terms of mass flow rate ( $Q_M$ ) instead volumetric flow rate, this is important for emissions inventories and other cases where total emissions or balances are relevant. This can be calculated using the ideal gas state equation.

$$Q_M = Q_V \frac{M P}{R T} \quad (11)$$

Where  $M$  is the molar mass of the target gas ( $M = 2$  g/mol in the case of  $H_2$ ),  $P$  and  $T$  are the absolute pressure and temperature where the measurement is done (Pa and K), and  $R$  is the ideal gas constant ( $R \approx$

8,314 L Pa/mol K). Then with a  $Q_V$  (L/min) a mass leak rate  $Q_M$  (g/min) can be calculated.

## 5 High-Flow sampling method for H<sub>2</sub> tested in outdoor windy conditions

Sampling efficiency depends on several parameters associated with the complex aerodynamic features of the leak jet and its capture process due to the drag air stream sucked in by the HFS. There are situations in which turbulence is created at the entrance of the sampling hose, dispersing the H<sub>2</sub> gas randomly.

The leak profile has a region where the gas linear momentum dominates the transport, a transition zone and a diffusional zone. The fast zone features is given by the leak rate, the leak source size and geometry). Depending on the leaked gas speed at the interface, the jet could be difficult to capture (unless the sampling hose is perfectly aligned). It is important to remind that in a real situation it is necessary to detect the leak and determine the source location as accurately as possible, to then approach the leak source without known the jet direction and overcoming any physical restriction (pipework complexity and geometry).

We have simulated hydrogen leaks using open end pipes with different apertures (0.1; 0.3; 0.5; 1 and 4 mm) and leak rates from 0.5 to 5 L/min in outdoor windy conditions. One relevant parameter is the relative orientation of the sampling hose with respect to the leak jet and or the wind direction. This last was tested. Fig. 5 shows one of these configurations.

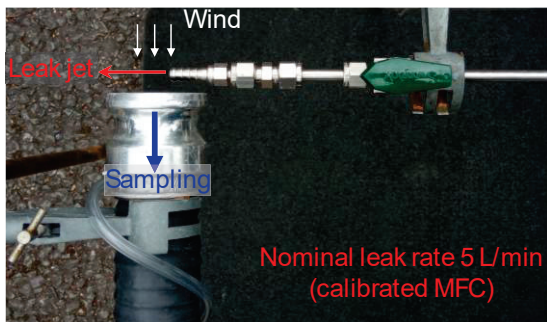


Fig. 5. Simulated hydrogen leak sampled at 90°.

During the measurement the sampling rate was stable, however, in some rare cases, the measured H<sub>2</sub> concentration was variable, due to turbulent flow in the entrance of the hose. Fig. 6 shows the case exhibiting more variability in the measured concentration. In this example the measurement does not stabilise but fluctuates, and only the maximum concentration values produce the right (nominal) leak rate calculation. For that reason, the measurement needs to be verified for stability, it shall be a steady state process. If this is not possible, then it might be advisable to choose only the maximum values (spiking) to avoid underestimating the actual leakage rate. The physical explanation is that only in brief occasions the leaked gas is fully captured by the sample in the conditions of this specific test.

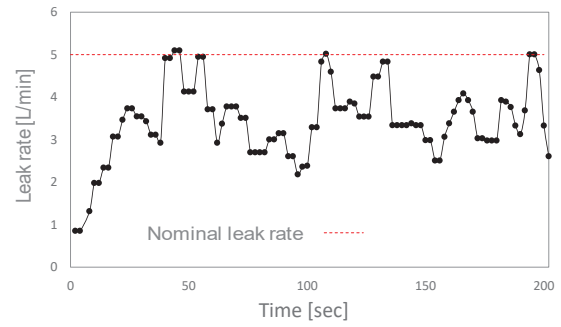


Fig. 6. Measured leak rate in extreme windy conditions.

In another test series the leak jet was facing upwards (vertical) and the sampler was placed in different orientations respect to the wind (Fig. 7). The full capture condition was checked (inserting the pipe end in the sampler hose), several inlet attachments were tested (cone, hose), and the sampling distance was varied (0, 1 and 5 cm from the interface) simulating not knowing the precise location of the leak source.

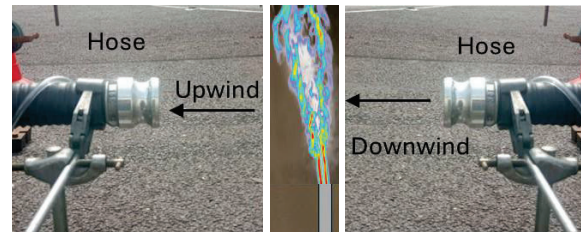


Fig. 7. Different High-Flow sampling configurations.

All the measurement performed at the full capture condition coincides with the nominal simulated leak rate. Also, in several simple cases the measured values are close to the actual leak rates. However, in many cases there are large discrepancies, mainly underestimating the leak rate due to a lack of sampling efficiency. For a sake of brevity, here it is shown only one case, which is depicted in Fig. 8. In that case, the measurement from *Above* (sampling hose aligned with the leak jet) works well in close proximity (0 cm) or at 1 cm of the leaky orifice, but at a distance of 5 cm the values are more dispersed and underestimate the leak rate in half or more. At 0 cm also the *Downwind* sampling provides a good estimate of the leak rate. The other measurement conditions systematically underestimate the actual leak rate and produce values with a larger dispersion.

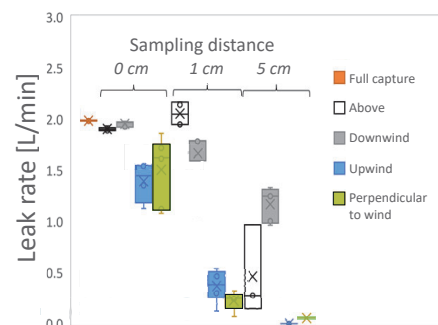
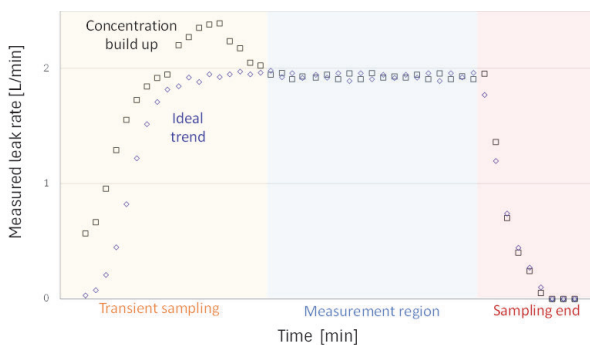


Fig. 8. Test leaking 2 L/min of H<sub>2</sub> through a 1 mm orifice.

In real cases it is not possible to know the sampling efficiency beforehand, therefore it is recommend performing two measurements, one at the highest sampling rate and another one at a lower rate (60-80% of the highest sampling rate). If in both cases the obtained results are close enough (< 5 or 10%) they can be regarded as efficient samplings, otherwise it will imply a lack of gas collection. In those cases, it is advisable to use a different sampling strategy, as using the High-Flow sampling through a bag type enclosure (antistatic) to trap the escaping gas and repeat the measurements at two different rates. In the case of flanges, it is better to use a plastic strap (also antistatic) with inlet and outlet apertures to drag the leaking gas.

## 6 High-Flow Sampling using bags or other encapsulations

Generally, when measuring with a HFS, the readings grow continuously (transient sampling) until a plateau is reached, in this steady state (ideal) condition all the gas being leaked is trapped by the HFS at a constant sampling rate, and the valid measurements shall be taken in this situation. In the case of using bags or other kind of encapsulation to constrain the leaked gas plume, for a short period of time the encapsulation could built up a certain amount of gas, causing a peak before the plateau. Fig. 11 gives an example of these situations.



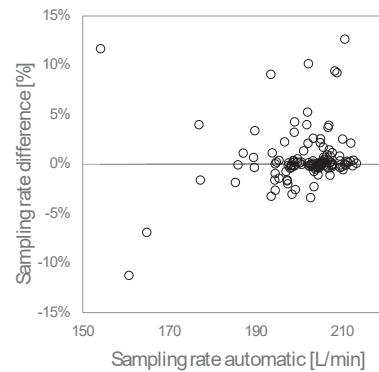
**Fig. 9.** Measured leak rate, ideal case and transient build up.

In these cases, it is of paramount importance waiting until the readings reach a plateau to avoid leak rate overestimations. Measurements shall be taken only from the plateau (measurement region), discarding the readings from the transient and end sampling regions. The values in the plateau should correspond to the actual leak rate, unless a sub-optimal sampling condition resulted from limitations in the positioning of the sampling tip (hose, cone, etc.), as shown in Fig. 8.

For a sampling rate ~200 L/min it is advised to wait at least 1 minute until the readings stabilises to an approximate steady state value (plateau), which should be within  $\pm 10\%$ . The measurement region should take some 1-2 minutes. In general, at least three readings shall be taken reporting the average value and an expanded uncertainty with a coverage factor  $k=2$  (2 x standard deviations).

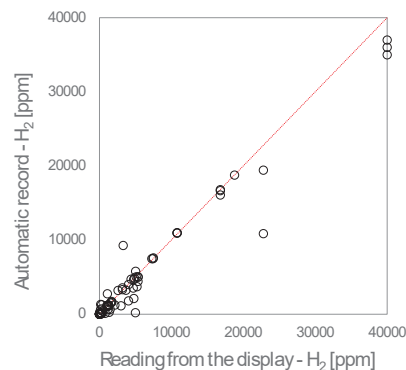
## 7 Integration of HFS and H<sub>2</sub> gas detectors for leak rate quantification

Nowadays there are no available HFS for the quantification of hydrogen fugitive emissions. Fortunately, the two selected instruments (BHFS and GS-700-H2) can record and store data automatically during the measurement. The operator has then two options, use the read values in the devices display, or record the two set of data separately. On the other hand, it is clear that the method (Eq. 1) relies on measuring sampling flow rates and diluted H<sub>2</sub> concentrations simultaneously. In order to evaluate the impact of the data acquisition method we have recorded the data manually and automatically, to be able to compare both. Figure 10 shows the relative differences between the automatic and the manually recorded sampling rates for a set of measurements.



**Fig. 10.** Relative difference between manual and automatic High-Flos sampling rate measurements.

The differences observed in Fig. 5 are generally below  $\pm 5\%$ , with some outliers reaching up to  $\pm 12\%$ . Fig. 11 compares the H<sub>2</sub> concentration measurements recorded automatically vs the values recorded manually from the display.



**Fig. 11.** Automatic vs manual records of H<sub>2</sub> concentrations.

Again, in most cases both automatic and manual recorded values are in close agreement, however, there differences become more important for concentrations below ~5.000 ppm, and even at higher concentration it can be found several outliers. This emphasise the need to automatically register the data and process it statistically to enhance its reliability.

When both measurements are combined, the resultant uncertainty could increase due to a sub-optimal data processing. This evidence the need to integrate both instruments, a HFS and a H<sub>2</sub> gas detector to allow accurate hydrogen leak rate quantifications.

The High Flow Sampling method can be used during walkover surveys to quantify industrial hydrogen fugitive emissions, gathering data on the magnitude of these emissions at component scale, identify common leaky components and their leak distribution, identify concerning leaks and inform LDAR schemes. Also, it is a useful tool to contribute to calculate estimated emission levels (e.g. considering the non scanned components) and could be used as a tool for regulatory compliance.

## 8 Conclusions

Emission rates can be accurately quantified by high flow sampling if full capture of the hydrogen leaks is achieved. Sufficiently good estimations of the actual hydrogen leak rates can be done in most cases, but it requires to be verified by measuring at two different sampling rates.

The used High Flow system is not ATEX rated for H<sub>2</sub>, then the max. measurable H<sub>2</sub> leak rate is  $\approx$  7-8 L/min. With the used instruments, the lower measurable H<sub>2</sub> leak rate is  $\approx$  0.01 L/min.

Challenging conditions, as windy scenarios or complex pipe geometries preventing a close approximation to the leak source (even at the 1 cm scale) may cause measurements underestimations

Selecting the appropriate sampling accessory (hose, cone, etc.) is relevant, while in some cases sampling requires full encapsulation (capture bag or flange straps)

In case of variable sampling (due to wind or gas build up) a method refinement in the data analysis and data quality control are both needed: Select only the maximum values in case of large variations caused by wind and select plateau region in case of buildup caused by encapsulation.

Sampling rates and H<sub>2</sub> concentrations records shows differences in the manual and automatic records. Full integration of the two devices is required.

Produced quantitative data is relevant for identifying common leaky components and leak distributions, inform LDAR schemes, estimate emission levels originated from leaky components and as a tool for regulatory compliance.

Acknowledgements: This work was partially funded by the UK Department for Energy Security and Net Zero and the NHyRA project (co-funded by the European Union).

Authors contributions. H. Barros: Theoretical development, experimental design, testing leader, data analysis and charts, work conception and writing. H. Cheales-Norman and A. Buck: logistics, calibrations, testing, data acquisition. J. Helmore and N. Yarrow NPL leaders of projects that partially funded the work.

## References

1. IEA, 2025. <https://www.iea.org/energy-system/low-emission-fuels/hydrogen>.
2. PE&PE, 2025. Precedence Energy and Power Experts. Hydrogen Market Driving the Clean Energy Transition with Innovation and Global Expansion. Report Code 5195. <https://www.precedenceresearch.com/hydrogen-market>.
3. NHyRA Project. pre-Normative Hydrogen Releases Assessment <https://nhyra.eu/>
4. UK-HyRES. UK Hub for Research Challenges in Hydrogen & Alternative Liquid Fuels. <https://ukhyres.ac.uk/>
5. Decarb Project. Metrology for decarbonising the gas grid <https://www.decarbgrid.eu/>
6. Environmental Defense Fund. Measuring hydrogen emissions: A global research collaboration. <https://www.edf.org/measuring-hydrogen-emissions-global-research-collaboration>
7. A. Connor\*, H. Barros, R. Robinson, A. Guzzini, M. Pellegrini, C. Saccani, J. Holewa-Rataj, T. Kuchta, H. Wigger, T. Vogt, V. Bescos Roy, V. Krohl. Methods for detecting and quantifying hydrogen emissions over a wide range of temporal and spatial scales: a state-of-the-art review. *Measurement: Energy*. **8**. 100069, 19 p (2025). <https://doi.org/10.1016/j.meane.2025.100069>.
8. Y. Pistun. L. Lesovoy. Calculation of expansibility factor of gas at its flow through an orifice plate with flange pressure tapings. *JEECS*. **2**(2), 80 p. (2016) <https://doi.org/10.23939/jeeecs2016.02.033A>