Sensors in the hydrogen industry
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Title

State of the art for sensors in the hydrogen industry (techniques, testing protocols, test rigs, applications, operational condition)

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Abstract

The supply chain for hydrogen comprises the processes necessary to produce, distribute, and dispense the hydrogen. The competitiveness of these processes depends directly on their safety and the safety of the facilities where they are used. Hydrogen has a very broad flammability range (4 to 74 % in air) therefore keeping air from mixing with hydrogen, mostly in confined spaces, is very important to ensure safety of system, staff and the public. Hydrogen sensors are a crucial enabling technology for the safe use of hydrogen, but they also can be used to assess gas compositions (in mixtures hydrogen/natural gas or for impurities in hydrogen). The main metrological criteria for sensors include trueness, precision, accuracy, response time, stability and drift, selectivity or cross-sensitivity, limit of quantification, sensitivity, and linear range/measuring range/nominal range (saturation), resolution, hysteresis, reversibility, environmental effects and operation conditions (temperature, pressure, relative humidity, vibration). Assessing the performances of a sensor requires both adequate protocols and testing facilities. In this report, we review existing protocols, test rigs or facilities, applications for the hydrogen supply chain and operation conditions.

Key words

sensors, hydrogen, hydrogen-enriched natural gas, gas quality

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Contents

1 - Introduction

Hydrogen is one of the clean, secure and affordable future energy. The number of countries with policies that directly support investment in hydrogen technologies is increasing, along with the number of sectors they target. There are around 50 targets, mandates and policy incentives in place today that directly support hydrogen, with a majority focusing on transport [1]. Over the past few years, global spending on hydrogen energy research, development and demonstration by national governments has significantly risen.

The supply chain for hydrogen comprises the processes necessary to produce, distribute, and dispense the hydrogen. The competitiveness of these processes depends directly on their safety and the safety of the facilities where they are used. Chemical sensors respond to a particular analyte in a selective and reversible way. Chemical sensors exist for a wide variety of components including hydrogen. Hydrogen has a very broad flammability range (4 to 74 % in air) therefore keeping air from mixing with hydrogen, mostly in confined spaces, is very important to ensure safety of system, staff and the public. Therefore, hydrogen sensors are a crucial enabling technology for the safe use of hydrogen. The sensors can be used to trigger alarms and activate ventilation or shut down systems to prevent hydrogen reaching flammable levels. Sensors have other applications; as contributing to ensure the lifetime of fuel cell electrical vehicles [2] or to measure hydrogen in a mixture, such as blending of hydrogen with natural gas [3]. In this case, the sensors serve as a mean to control hydrogen quality.

Considering the future widespread use of hydrogen sensors, it is important to independently and metrologically assess their performance to ensure their reliable and accurate measurement. Different types of sensors already exist, and development of new hydrogen sensors is ongoing. Each sensor has its own advantages and disadvantages in terms of performance and operational conditions. Some sensor types are extremely sensitive whereas others have a wide measuring range. Some sensors will be selective while other may also react to other components. Therefore, sensor needs to be chosen for a specific application depending not only on the ambient working conditions but also on the detection requirements and sensor performance capabilities. In each application, a sensor's ability to perform the measurements must meet the end-user needs which must be identified and documented.

The main metrological criteria for sensors include trueness, precision, accuracy, response time (T90)/recovery time (T10), stability and drift, selectivity or cross-sensitivity, limit of quantification, sensitivity and linear range/measuring range/nominal range (saturation), resolution, hysteresis, reversibility, environmental effects and operation conditions (temperature, pressure, relative humidity, vibration). Testing of sensors require protocols and test rigs (test facilities) to evaluate the performance of sensors uniformly. Protocols define the performance requirements and test methods to assess that the metrics fulfil the requirements.

In this report, we review existing protocols, test rigs or facilities, applications for the hydrogen supply chain and operation conditions (pressure, temperature, presence of dust, vibration…).

2 – Technologies

Sensors are used in many different applications in the hydrogen chain supply. At least three distinct categories of sensors are needed.

2.1 – Safety sensors

They are used to monitor the level of hydrogen usually under the Lower Explosive Limit (LEL). Current applications were defined during the project H2Sense [4] and include room/area monitoring for safety where hydrogen leakage may occur e.g., battery, detection of leaked hydrogen, process monitoring and control (petrochemistry industry), stationary and mobile fuel cell applications.

The project H2Sense created a database of safety sensors. It contains 400 different models from 96 different providers [4]. The different principles of measurements used are thermal conductivity, catalytic, electrochemical, resistivity, mechanical, semiconductor, solid state diffusion, optical, acoustic, MOSFET.

EMPIR project 20IND10 “Decarb” has a work package dedicated to leak detection. The goal is to develop metrology infrastructure to support new leak detection requirements for decarbonising the gas grid. This includes traceable monitoring methods for accurately quantifying leaks of hydrogen or hydrogen-enriched natural gas from pipelines at 25 % of the lower explosive limit (for health and safety reasons).

A review of hydrogen sensors has been done in [5] . Catalytic, thermal conductivity, electrochemical, resistance, work function, mechanical, optical and acoustic types of sensors have been reviewed. Characteristic performance parameters of these sensor types, such as measuring range, sensitivity, selectivity, and response time are reviewed and the latest technology developments are reported. Testing and validation of sensor performance are described in relation to standardization and use in potentially explosive atmospheres to identify the requirements on hydrogen sensors for practical applications.

It was concluded that a further work is required in terms of basic research into new materials and sensor principles as well as applied research and development to fully meet the demands of current and emerging technical applications. Testing and validation procedures combined with relevant standards can support the ongoing development of hydrogen sensing technologies [8].

Testing of sensors have been performed in many studies. One example of those is the evaluation of selectivity of few commercial H2 sensors [6]. Five commercial sensors (chemical, thermal conductivity, and metal oxide-based) have been used and their cross-sensitivity to CO_2, CH_4 and CO has been evaluated.

2.2 – Hydrogen purity sensors

A review of sensors that can be used in a hydrogen matrix and can detect a given impurity at relevant detection limits (below the thresholds in ISO14687:2019 [7] and EN17124:2020 [8] was performed during MetroHyVe2 [2]. Only a few sensors with the required specifications have been found, showing there is a need to develop sensors specifically for the hydrogen industry. Several sensors for detecting oxygen and water were identified, and different principles of measurement allow the detection of low µmol/mol for these two species in hydrogen. Sensors for other compounds, such as carbon monoxide, carbon dioxide, methane, hydrogen sulfide, ammonia, formaldehyde, formic acid, and hydrocarbons, seem to not yet be available at the costs under 5000 euros. The different principles of measurements/sensors types used are electrochemical sensors, phosphorus Pentoxide Moisture sensors, aluminium Oxide Moisture Sensors, Chilled-Mirror Hygrometer, Surface Acoustic Wave, Chemical Optical Sensors, Proton exchange membrane type sensors as shown in the table 1 which is taken from [2].

Table 1 – Sensors available for impurities in hydrogen classified by technologies

Technology	Supplier (compound)	Model	Costs
Electrochemical sensor	DSK GmbH (O_2)	OxyTransII or Oxymaster II	+
	Southland Sensing Ltd (O_2)	TO2-133	++
	Systech Illinois (O_2)	EC91	0
Chemical-optical sensor	Presens (O_2)	Oxy-1 SMA-trace-RS232	+
Phosphorus pentoxide moisture sensor	DKS (H_2O)	Aquatrace IV	+
	DSK GmbH (H_2O)	Aquatrace ATT500	+
	Systech Illinois (H_2O)	MM50	n.c.
	MEECO (H_2O)	Uber M-I	+
	Systech Illinois (H_2O)	MM300	+
	Dr. Wernecke (H_2O)	Humitrace II	
Chilled mirror	Vympel (H_2O)	Cong Prima 2M	00
	Vympel (H_2O)	FAS	00
	Vympel (H_2O)	Hygrovision	
	Baker Hughes (H_2O)	Optica	00
Metal oxide dew-point	Vympel (H_2O)	FAS-SW	
	Baker Hughes (H_2O)	HygroPro	+
	Baker Hughes (H_2O) (aluminum oxide)	M Series Probe	n.c.
	Servomex (H_2O)	Aquaxact 1688	n.c.
Surface Acoustic wave	Ball Wave (H_2O)	FT-300WT	0

n.c.: information not available or not communicated
The prices are indicated by ranges; ++ < 1000€; +: 1000-5000€; 0: 5001-10.000€; 00 > 10.000€

2.3 – Hydrogen in gas mixtures sensors

The storage and transportation of hydrogen are challenging due to its low density and volumetric energy value [9]. A solution to this issue is to inject hydrogen into the existing natural gas network, where it can be transported to its consumers. The presence of hydrogen in the blend hydrogen/natural gas, or at 100% in the grid might have several impacts associated to gas quality (i.e., end users or billing). Therefore, the amount of injected hydrogen must be controlled so that the hydrogen–natural gas mixture satisfies the gas quality requirements of the pipeline set by legislations and standards [9]. It is foreseen that the injection of hydrogen in the grid will increase significantly in the coming years. A recent project from GERG [3] discussed sensors and measurement devices allowing detection and measurements of varying hydrogen concentration in a gas mixture. A list of sensors already tested in the laboratory or in the field was giving (see table 2 from [3]). The technologies available are based classified in the following categories: catalytic, electrochemical, thermal conductivity, metal-oxide, metal-oxide semi-conductor, optical, coatings/capacitive, tunable filter and chromatography.

Table 2 Sensor models identified [3]

Model	Technology	Hydrogen range (%)		Interference	Tests
		Min	Max		
HY-OPTIMA 2710 (H2SCAN)	Solid-state	0.1	10	Yes	No
HY-OPTIMA 2720 (H2SCAN)	Solid-state	0.5	100	Yes	No
HY-OPTIMA 2730 (H2SCAN)	Solid-state	0.5	100	Yes	No
MGC16 (MECI)	Chromatography	0.002	10	NA	Certification by LNE
700XA H2 (EMERSON)	Chromatography	0.01	20	NA	Certification by LNE and PTB
PGC 9304 (RMG)	Chromatography		20	NA	Certified by PTB
Encal 3000 Quad (Honeywell)	Chromatography		100	NA	Certified up to 20%
PGC 1000 (ABB)	Chromatography		20	NA	Certification in progress
SAM Complete-Advance (Marquis)	Chromatography		12	NA	Certification in progress
MGC^{flex} (MeterQ)	Chromatography		20	NA	Certification in progress
TNO gas sensor (under development)	Responsive coatings with capacitive read-out	0	20	No	Field

3 – Metrics

Many performance characteristics exist to define how a sensor performs: trueness, precision, accuracy, response time (T90)/recovery time (T10), stability and drift, selectivity or cross-sensitivity, limit of quantification, sensitivity and linear range/measuring range/nominal range (saturation), resolution, hysteresis, reversibility, environmental effects and operation conditions (temperature, pressure, relative humidity, vibration). The definition of some of these metrics has been listed in a report done as part of EMPIR project MetroHyVe2 [10]. The definition of the metrics are given below:

3.1 – Trueness

Describes the closeness of agreement between the value (or the mean value of a series of measurements) and an accepted reference value or conventional true value and is a measure of the systematic error (also called bias) of measurement of an instrument. Trueness is often reported **accuracy** when manufacturer list the specifications of sensors/analysers**.** It may be advised to require detailed explanation from instrument manufacturer on the methodology used to determine accuracy and trueness.

3.2 – Precision

The precision describes the closeness of results to one another and is a measure of the standard deviation of results obtained by carrying replicate measurements. The precision can be expressed as **repeatability**.

3.3 – Accuracy

Accuracy is the closeness of agreement between a measured quantity and a true quantity value of a measurand. Measurement accuracy describes how close a single measurement result is to the true quantity value and therefore includes the effect of both precision and trueness.

3.4 - Response time

The response time is defined as the speed of response to an input signal change and is often expressed in seconds. The response time is often also dependent upon test conditions, such as calibration gas flow rate and ambient temperature. Typically, the response time can be measured by changing the gas concentration and monitoring the sensor output as change of concentrations (increase and decrease) are introduced. The response time **T90** is commonly used by the sensors industry and corresponds to the time taken to reach 90% of the applied target gas concentration or its stable reading. The recovery Time **T10** is defined as the time for a sensor to return to baseline value after the step removal of the measured variable, usually specified as time to fall to 10% of final value after step removal of measured variable.

3.5 - Stability and Drift

Drift is a temporal change in the response of an instrument to a constant concentration. Most instrument show drift over long period of time. It is generally due to sensor´s aging, but it can also be caused by dust and variations of measurement conditions (i.e., pressure, temperature, humidity). Drift implies that the performance of a measuring instrument changes, and re-calibration must be performed. The manufacturer should provide guidance on the frequency of recalibration (or replacement) in correlation with instrument drift over time.

3.6 - Selectivity or cross-sensitivity

Sensors are designed to be selective to a compound or to specific classes of compounds. However, in the presence of some non-targeted compounds, a signal may be produced leading to errors in the measurement of the target compound; this is called cross-sensitivity. The manufacturer can sometimes provide a list containing common gases and the typical effect they would have at a given concentration on the signal of sensors.

3.7 – Limit of quantification

According to UIPAC [11], the limit of detection is derived from the smallest measure that can be detected with reasonable certainty. The limit of quantification (LOQ) is derived from the smallest measure that can be quantified with reasonable certainty for a given analytical procedure.

3.8 – Sensitivity, nominal range, saturation

Sensitivity refers to the sensor output signal per µmol/mol of the target gas. The **nominal range** is also often a specification for sensor and corresponds to the range where the gas sensor outputs show the best linearity. This can be measured by successively increasing the concentration from the lowest detectable level and recording the outputs.

Saturation is a state in which the signal that needs to be measured is larger than the dynamic range of the sensor. In that case, the output of the sensor becomes the limiting value of the sensor range. This induces error between the true and estimated values.

3.9 – Resolution

This resolution is the smallest detectable incremental change of input parameter that can be detected in the output signal. Resolution can be expressed either as a proportion of the reading (or the full-scale reading) or in absolute terms.

3.10 - Hysteresis

A sensor should be capable of following the changes of the concentration regardless of which direction it increases or decreases; hysteresis is the measure of this property.

3.11 - Reversibility

Reversibility is the ability of a sensor to recover, or return to its original background/baseline condition, after exposure to an analyte.

3.12 – Environmental effects and operational conditions

The sensor response and/or the interpretation of the sensor response may depend on many environmental parameters, such as temperature, flow rate and pressure. Moreover, sensors only work effectively under specific conditions of temperature, pressure, and flow rate.

3.12.1 – Temperature

It is the normal operating temperature or temperatures range. Operating gas sensors in a lower and higher temperature environment than the operational temperatures may result in slower (or faster) response time. It also may damage the sensors permanently. Some gas sensors may have a transient response to sudden temperature changes, and it may result in false alarming for a short time on the instrument using such sensors.
In between this range, the sensor output can be dependent upon the temperature. In this case, the signal is corrected for the average temperature dependence.

3.12.2 – Pressure

It is the normal operating pressure or pressures range for the gas sensors. Some gas sensors may have a transient response to sudden pressure changes, and it may result in false alarming for a short time on the instrument using such sensors. In addition, there are few sensors which are sensitive to pressure change (typically working at ambient pressure). Any changes cause pressure elevation will lead to wrong value in impurity measurement. Therefore, it is crucial to control and monitor the pressure in sensor performance evaluation.

3.12.3 – Flow range

The flow rate should be low enough to avoid damaging the sensor without being so low as to extend the system response time to an unacceptable level. To ensure that the conditions are in the correct ranges, sensors can be completed with so called sample system.

3.12.4 – Vibration

Sensors shall be constructed to withstand the vibrations expected in its use.

3.13 – Compliance to ATEX requirements

Additional parameters such as compliance to ATEX requirements for H_2 specific applications need to be taken into consideration. However, this is not a metric of the sensor.

General: Non-ATEX areas installations preferable

If there is no possibility to install the sensors in non-ATEX designated areas then the sensors has to comply to a certain ATEX -related requirements.

4 - Protocols

Before implementing any sensor, it is crucial to ensure its performance has fully been validated. To identify sensor technologies that would be best suited for each application, and to understand the performance of the sensor technologies, sensors must be tested according to testing protocols, preferably standardized. Protocols define performance requirements and test methods to assess that the metrics fulfil the requirements. Without protocols, uncertainties arise regarding how well sensors perform, how to operate (e.g., calibrate) them, and how well they need to perform to be fit for a given purpose.

A recent work [12] from EPA underlines the lack of standard testing protocols, metrics, or targets to evaluate the performance of sensors for air matrix uniformly. Logically, the same applies to sensors for hydrogen quality control, which are not yet as commonly used as air sensors. To remediate this issue for air sensors, EPA just produces a technical report containing testing protocols, metrics, and target value for ozone air sensors which contains two parts: a base testing (in the field) and enhanced testing (in the laboratory). The enhanced testing consists of operating and examining at least three replicate ozone air sensors in controlled laboratory conditions to understand the effect of interferents, temperature, and relative humidity in addition to drift and accuracy at higher concentration levels [12]. The testing is performed in an exposure chamber that can control environmental conditions and requires the use of calibration cylinders (preferably reference materials) containing known amount of interferents.

ATSM WK64899 "New Practice for Performance Evaluation of Ambient Air Quality Sensors and Other Sensor-Based Instruments" [13]is under development within this ASTM Committee D22 (Air Quality). This standard intends to establish standardized tests and assessment criteria for the performance evaluation of sensor-based continuous instruments for ambient air quality measurements. A similar approach needs to be undertaken before chemical sensors for hydrogen quality control can be implemented at HRS.

Some studies and protocols are available for sensors measuring concentrations of hydrogen.

ISO standard 26142:2010 [14] defines the performance requirements and test methods of hydrogen detection apparatus that is designed to measure and monitor hydrogen concentrations in stationary applications. It is intended to cover situations where the user desires the ability to detect hydrogen leaks and monitor hydrogen concentrations relevant to safety, primarily for hydrogen detection apparatus at vehicle refueling stations but also to other stationary installations. The standard is intended to be used for certification purposes. It contains general requirements about construction, labelling and marking, instruction manual and vibration. Finally, the standard describes the tests to perform to control the performance requirements. The tests are performed using a standard test gas per one order of magnitude in the measuring range with a hydrogen volume fraction at the midpoint of that order. The tests to assess the measuring range and calibration, the stability and the alarm set point(s) are performed under normal constant conditions (pressure 0.8 to 1.08 bar, temperature 15 to 25 ºC, humidity 20 to 80%). Tests to assess the influence of temperature (-20, 20 and 50 ºC), pressure (0.8, 1, 1.1 bar), humidity (20, 50 and 80%), vibration, orientation, flow (50 to 130 % of the nominal flow rate), air velocity, time of response and time of recovery, selectivity, poisoning are also described.

The National Renewable Energy Laboratory (NREL) has developed a variety of test protocols to quantitatively assess the performance specifications for hydrogen sensors [15] which is similar to ISO 26142 but more rigorous. Specific protocols were developed for linear range, short-term stability and the impact of fluctuations in temperature (-20, 0, 25, 50 and 85 ºC), pressure (0.8 to 1.2 bar), relative humidity (25, 50 and 85%) and chemical environment (CO, NO_2, H_2S, CH_4, NH_3, CO_2). The test gases are generated from blending certified gas mixtures with synthetic air. Typical range is 0 to 2 % hydrogen in air. that is not relevant either for H_2 utilization as a fuel (gas grids or motors) or as a component in various power-to-X (PtX) applications.

In a recent report on hydrogen measuring sensors for safety applications [16], the authors compared evaluating sensors using "flow through test" methods (which is also mentioned in ISO26142) with the more common "chamber test" methods. The first methods are efficient, cost-effective alternatives for sensor performance assessment as many sensors can be simultaneously tested, in series or in parallel. However, these methods also present challenges associated with the ability to control environmental parameters (humidity, pressure, and temperature) during the test and changes in the test gas composition induced by chemical reactions with upstream sensors. It is important to investigate similar topics to determine the best testing protocols for sensors measuring contaminants in hydrogen.

5 – Test methods

There are at least two distinct methods to test sensors, the "flow-through test" method (more adapted to sensors for purity assessment) and the "chamber test" method (more adapted to fugitive/emission measurement). In a recent study [16], authors have compared testing different sensors using the two methods. The results show that the performance of the sensors was similar but not identical with both methods.

5.1 - Flow through test" methods to monitor process performance

In the flow-through testing method, the interface of the sensors to the gas line is hermetically sealed to assure that the sensors are subjected to the proper gas composition. Therefore, one of the challenges is to maintain a leak proof interface between the sensors and the gas supply line. With this method, several sensors can be tested simultaneously, in parallel or in series (some sensors consume the component they measure). With this method, challenges arise to control the environmental parameters (humidity, pressure, and temperature). According to ISO 26142, flow-through test methods may not properly simulate ambient applications. However, they can be advantageous for testing sensors with very fast responses. Moreover, a fast flushing of the interface line (prior measurements) and additional coatings from a gas intake point to the sensor can further significantly reduce unwanted from the interface line and related process equipment such as MFC and valves.

In the resent years there are developments of new measurement methods when the gas can be taken into the measurement system at a process pressure (e. g. from a pipeline or a gas storage tank) or with a small pressure reduction.

Examples of flow-through test set-up are shown on Figure 1 (ISO 26142) and on Figure 2 [16].

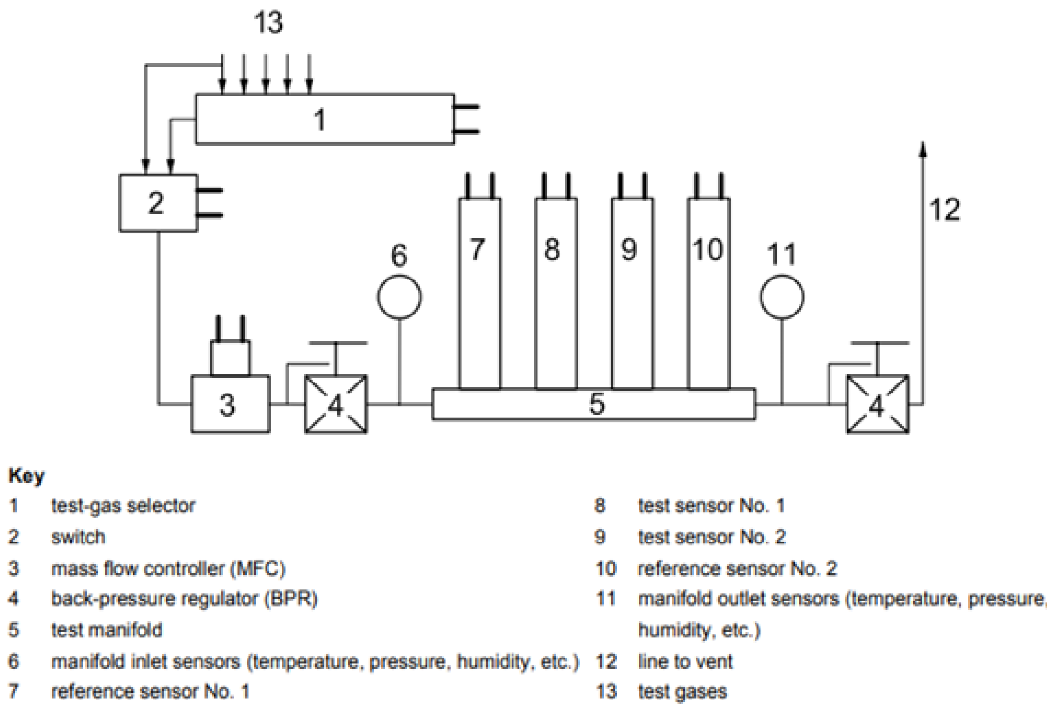

Figure 1 - Set-up for a flow-through test according to ISO26142

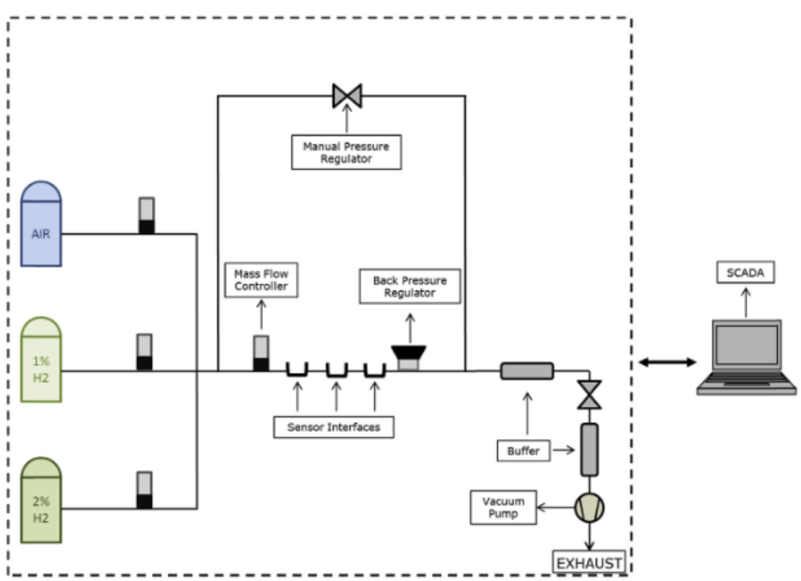

Figure 2 - Set-up for a flow-through test according to [16]

5.2 - "chamber test" methods

In the "chamber test" method, the sensors are placed in a micro-chamber where flow-through conditions are simulated. The environmental parameters can be easily controlled. The pressure inside the chamber can be regulated with a back pressure regulator and a vacuum pump. In this method, gas transport to the sensor is dominated by diffusion which can be viewed as mimicking deployment in rooms or other confined spaces [16]. The number of sensors that can be tested simultaneously depends upon the size of the chamber (30 liter or larger is the internal volume mentioned in ISO 26142).

An example of chamber test set-up is shown on Figure 3 [16].

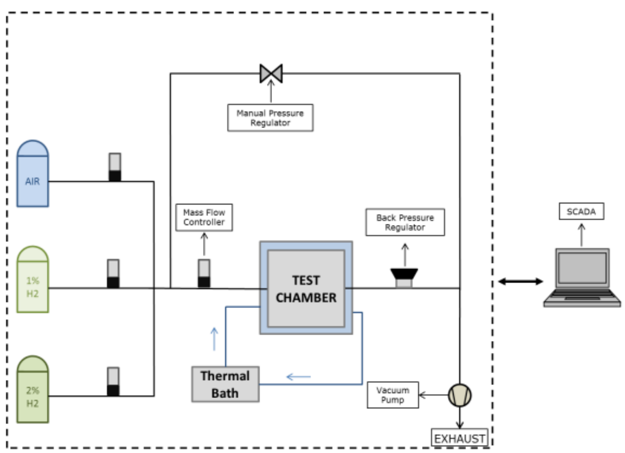

Figure 3 - Set-up for a chamber test according to [16]

6 – Testing facilities

Some testing facilities already exist, and they often are built to test safety sensors.

The Shared Sensor Technology User Facility (SSTUF)

SSTUF was built by the Sensor Research Group of the International Center for Sensor Science and Engineering [17] is one of the most known facilities designed to test chemical sensors. The SSTUF has a gas-mixing system that provides different concentrations of targeted analytes in different matrices. It operates from sub-ambient temperature up to 450 ºC and from sub-atmospheric pressures to several bar. The test chamber is cylindric (10 cm diameter, 25 cm long). Nitrogen, hydrogen, carbon dioxide and carbon monoxide can be introduced in any proportion.

NREL has developed a rig to test sensors for safety applications (Figure 4). The facility is fully automated with controlled and monitored environmental parameters (temperature, pressure, and relative humidity) and gas parameters (flow and composition).

Figure 4: NREL test rig

JRC-IET (Figure 5) has a testing facility dedicated to the independent characterization of hydrogen sensor performance and reliability [18]. Up to six sensors can be mounted in an environmental chamber in which temperature (40 to 130 ºC, held constant with ±2 ºC), pressure (0.5 to 2.5 bar), humidity and gas composition can be varied. A total of four gases can be mixed to produce the desired composition. A gas chromatograph can independently confirm the composition. The facility allows the evaluation of the cross-sensitivity to species such as carbon monoxide, hydrocarbons, ammonia, and sulphur containing compounds.

Figure 5 - JRC-IET facility

Air Liquide developed a simple testing setup (Figure 2) for chemical sensors detecting impurities in hydrogen during MetroHyVe project [19]. This testing facility was designed to work with varying compositions. For this purpose, a Gasmix dilutor was used to mix gas standards with hydrogen or nitrogen. The outlet of the dilutor was set at 500 mL/min. The sensors were mounted in series using ¼ inch stainless steel tubing. The sensor assembly was enclosed in a plastic chamber continuously flushed with 5 L/min of nitrogen for safety purposes due to the presence of electronics in combination with a potential explosive mixture of hydrogen and oxygen from air. A new testing rig was developed by Air Liquide during MetroHyVe2 project [20]. With this rig, several sensors mounted in parallel can be tested simultaneous under varying compositions and at different flow rates as shown in Figure 6. The parallel arrangement is beneficial compared to early series used because the gas entering a particular analyzer does not affect by the previous analyzer.

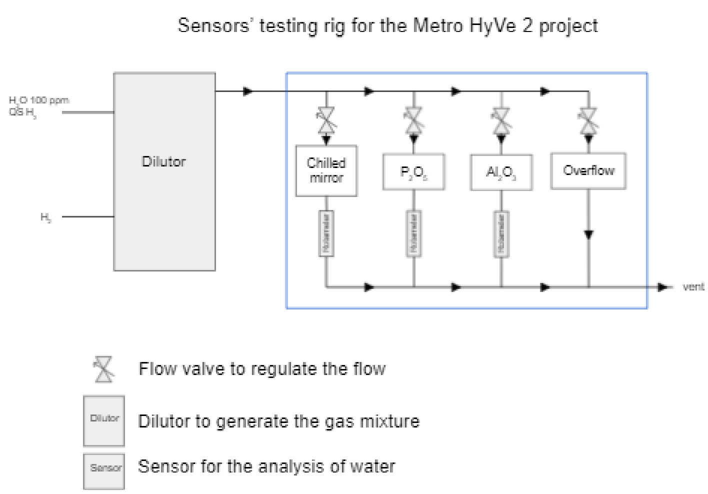

Figure 6 – Air Liquide Test rig

7 – Conclusions and recommendations

For each individual sensors´ applications, different metrics may be more relevant than others. For instance, in some cases, a short response time is crucial while in other cases, the environmental effects will be of higher importance (for example, resistance to vibration). The selection of sensors must then be made on a case-by-case basis by metrologically evaluate the performance of the sensors. This requires both adequate protocols and testing facilities.

Based on the outcomes of this state-of-the-art review, a protocol to test sensors will be developed including a description of methods to measure the metrological metrics described here. Two rigs capable of testing the different types of sensors will also be built at RISE and NPL and will include equipment to monitor different parameters (e.g., flow, pressure, humidity, composition of gas).

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