On the use of hydrogen in confined spaces: Results from the internal project InsHyde

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Abstract

The paper presents an overview of the structure and main results of the internal project InsHyde of the HySafe NoE. The scope of InsHyde was to investigate realistic small-medium indoor hydrogen leaks and provide recommendations for the safe use/storage of indoor hydrogen systems. Additionally, InsHyde served to integrate proposals from HySafe work packages and existing external research projects towards a common effort. Following a state of the art review, InsHyde activities expanded into experimental and simulation work. Dispersion experiments were performed using hydrogen and helium at the INERIS gallery facility to evaluate short and long term dispersion patterns in garage like settings. A new facility (GARAGE) was built at CEA and dispersion experiments were performed there using helium to evaluate hydrogen dispersion under highly controlled conditions. In parallel, combustion experiments were performed by FZK to evaluate the maximum amount of hydrogen that could be safely ignited indoors. The combustion experiments were extended later on by KI at their test site, by considering the ignition of larger amounts of hydrogen in obstructed environments outdoors. An evaluation of the performance of commercial hydrogen detectors as well as inter-lab calibration work was jointly performed by JRC, INERIS and BAM. Simulation work was as intensive as the experimental work with participation from most of the partners. It included pre-test

simulations, validation of the available CFD codes against previously performed experiments with significant CFD code inter-comparisons, as well as CFD application to investigate specific realistic scenarios. Additionally an evaluation of permeation issues was performed by VOLVO, CEA, NCSRD and UU, by combining theoretical, computational and experimental approaches with the results being presented to key automotive regulations and standards groups. Finally, the InsHyde project concluded with a public document providing initial guidance on the use of hydrogen in confined spaces.

1 INTRODUCTION

In the first year of HySafe, a Phenomena Identification and Ranking Table (PIRT) exercise and an expert survey identified that releases (even slow releases, with "small" release rates) of hydrogen in confined or partially confined geometries represent a serious risk, since combustible mixtures may form, which, if ignited, could lead to explosions and even to detonations. Thus, it is necessary to study different configurations of release (position, release rate) and the accompanying sensor equipment and mitigation devices (ventilation or other ways of enhancing mixing, inerting, active ignition or recombination). The InsHyde program [1] was initiated within HySafe to address this need.

The InsHyde project main objectives were:

- To investigate realistic (ATEX related) indoor leaks and ultimately to provide recommendations for the safe use / storage of indoor hydrogen systems
- To pull together work package proposals and existing research projects toward a common goal and a useful contribution to society for the safe implementation of hydrogen technologies.

InsHyde activities were divided into the following 10 subtasks:

- IP1.1 Review (lead, DNV)
- IP1.2 Gas detection experiments (lead JRC)
- IP1.3 Theoretical study of permeation (lead VOLVO)
- IP1.4 Dispersion experiments (lead CEA)
- IP1.5 Explosion experiments (lead FZK)
- IP1.6 Ignition (lead HSL/HSE)
- IP1.7 CFD modelling (lead GEXCON)
- IP1.8 Scaling methodology (lead FZK)
- IP1.9 Recommendations and conclusions (lead INERIS)
- IP1.10 Dissemination (lead INERIS)

2 ACHIEVEMENTS

2.1 Hydrogen detectors performance evaluation and inter-laboratory calibration tests by JRC, INERIS and BAM

The gas detection experiments performed in subtask IP1.2 had the scope to experimentally assess the performance of gas detectors and to prepare their use in the context of dispersion experiments.

Two different experimental programs were performed: an inter-laboratory comparison on calibration-type tests on selected sensor types carried out by JRC and BAM, and a test program based on IEC 61779-1 & 4 for hydrogen sensors, to assess the performance of some commercially available hydrogen detectors, carried out by JRC and INERIS.

Nine different detectors or sensors were tested from different manufacturers. This sample included both electrochemical and catalytic technologies. The basic tests consisted in the acquisition of calibration curves and in measuring the response and recovery time during an instantaneous variation of the hydrogen concentrations. Sensors performance has been assessed by studying the signal response to variation in environmental temperature, humidity and pressure. In addition, sensors' cross-sensitivity has been investigated in the case of carbon monoxide. The experimental facilities used during these tests are described in detail in the public HySafe deliverable D54 [1] and elsewhere [2].

Tests have shown that the electrochemical technology allows to detect hydrogen concentration lower than in the case of catalytic technology, whose detection threshold is more around 500 ppm (between 1 and 2 % of hydrogen LFL).

A new "continuous calibration" concept has been tested, consisting in the continuous recording of the sensor response upon a progressive increase/decrease of hydrogen content in the test gas. The results compare well with those obtained by the standardised technique.

The response time (t90) of catalytic detectors, with a gas test concentration of 50 % of hydrogen LFL (middle of the scale), was less than 10 seconds. Response time was moderately influenced by temperature.

Humidity had a greater impact on response time. Increased humidity leads to higher response time value.

CO sensitivity was high for catalytic combustion sensors (approximately 1/3 of that to hydrogen). The effect is approximately independent from the presence or the absence of hydrogen in the test atmosphere (tested hydrogen range has been 0 to 1% in air).

Also humidity variations cause a deviation of the sensor reading, though of a more limited amount than in the CO case. Quantitative assessment of the humidity effect is hindered by discrepancies in the results of the two laboratories. The "continuous calibration" concept cannot be used in this case.

In comparison to the humidity and cross-sensitivity effects, temperature and pressure variation induce a more limited signal deviation.

As a result of the InsHyde inter-laboratory hydrogen detector performance evaluation exercise further performance based investigations using different hydrogen sensors and detectors were deemed necessary to cover the many different possible contexts of use. Extensive tests have since been performed to determine the reliability of numerous, commercially available hydrogen sensors for hydrogen detection and the results have been reported in the literature [3, 4].

2.2 Hydrogen dispersion experiments by INERIS

The short and long term evolution of the hydrogen/air mixing of a low momentum release inside an unventilated space at constant pressure has been studied experimentally by Lacome et al. (2007) [5]. The experiments were performed inside a garage like gallery of dimensions 7.2x3.78x2.88 m, using hydrogen and helium for hydrogen mass flow ranging from 0.2 g/s to 1 g/s (vol. flow from 2.3 to 11.5 l/s) for 240 s release time. Diameter of orifice varied from 5 to 20 mm. The release was vertically upwards from the horizontal centre of the facility, 0.265 m above the ground. Hydrogen concentration was measured at 12 positions along the jet axis and laterally displaced to it for a period of 90 min. The experiments showed that a horizontally almost homogenous and vertically stratified layer of hydrogen/air mixture developed fast close to the ceiling. Vertical concentration profiles (see Figure 1) show that hydrogen concentrations are rather homogenous in the formed layer near the ceiling. The higher the layer concentration the more the slope of the profile increases. With increase of the release flow rate the concentration gradient between the hydrogen layer and the ground increases. During the release phase, concentration in the layer is mainly correlated with the flow rate. This layer did not change significantly during the period after the end of release (diffusion phase). For test INERIS-6C (1 g/s and 20 mm orifice) the flammable hydrogen/air mixture occupied approximately half the height of the facility. For the 0.2 g/s release the concentration did not exceed the LFL. Homogeneous conditions were reached four hours after the release. The performed helium tests showed a strong similarity with hydrogen tests.

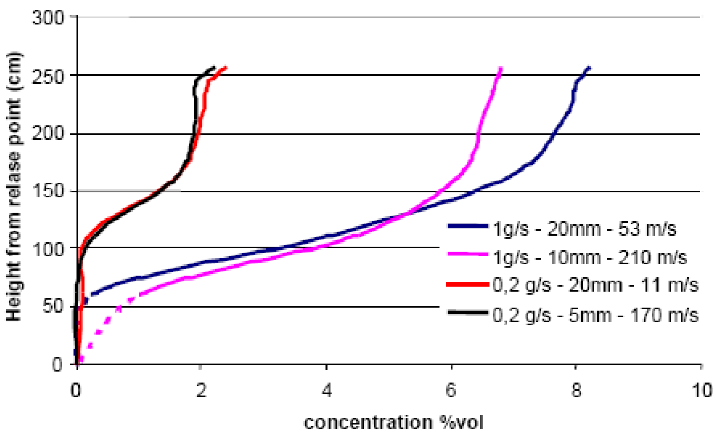

Figure 1: Vertical concentration profile at end of release for various release rates, according to Lacome et al. (2007)

2.3 Helium dispersion experiments by CEA

Helium dispersion experiments were performed by CEA [6] in a full scale newly built realistic GARAGE facility. The work was partly funded by HYSAFE and the French project DRIVE [7, 8, 9]. The GARAGE interior dimensions were 5.76 m (length) x 2.96 m (width) x 2.42 m (height). Results were presented for test cases performed in the free volume of GARAGE without any ventilation. For these tests, all vents were closed and the tracer decay measurements were performed to check the tightness of the GARAGE. Tests 1 and 3 were performed with a flow rate of 688 NL/min (2 g/s helium) using the same nozzle diameter of 20.7 mm and varying the release duration from 121 to 500 s respectively. Test 2 was performed with a flow rate of 66.8 NL/min (0.2 g/s helium) using the same nozzle diameter of 20.7 mm for a duration of 300 s. Tests 4 and 5 were performed with a flow rate of 18 NL/min (0.05 g/s helium) using the same release duration 3740 s and varying the nozzle diameter from 5 to 29.7 mm respectively. In this series helium concentration during and after injection phase was measured at 64 monitoring points.

For the given aspect ratio of the GARAGE and test conditions stratified layers are formed inside the geometry, see Figure 2. The analysis of results clearly showed that for the leaks inside the unventilated GARAGE, the risk induced is most strongly affected by the total volume of the gas released rather than the flow rate. For the test cases with similar initial conditions peak concentration levels increases with an increase in the injected volume. Test cases with similar injected gas volumes but different initial conditions, show almost identical peak concentration levels at the end of injection phase. However, variations in flow rates influence the mixing behaviour inside the GARAGE that in turn changes the decay rates of gas concentrations. Test cases with higher injected volumes of gas represent the worse condition and take longer time to reduce the concentration levels below lower flammability limit of hydrogen.

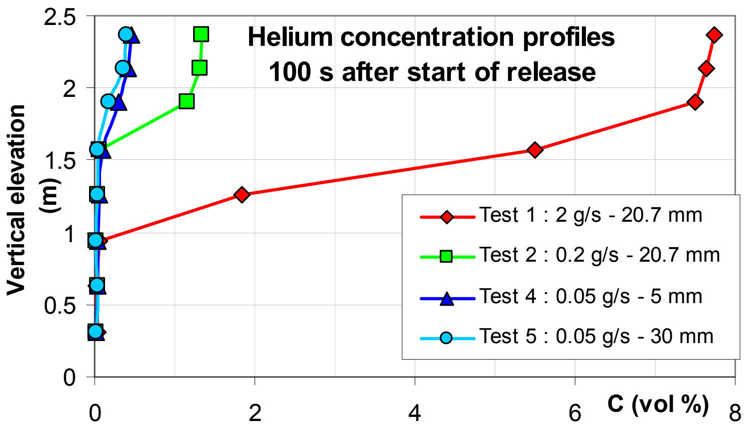

Figure 2: Vertical helium concentration profile in the garage for tests 1, 2, 4 and 5; 100 s after the start of the release

CEA [10] also performed experimental studies on low flow rates that can be characteristic of chronic leaks that may not be detected by security devices in different natural ventilation conditions of the GARAGE ranging from very tight conditions (ACH less than 0.01) to more realistic conditions (ACH of the order of 0.1).

CFD models based on Cast3m code and simplified models [11] were used to analyse the results.

2.4 Hydrogen combustion experiments by FZK/PRO-SCIENCE

Hydrogen distribution and combustion experiments were performed [12] during May 2006 by Pro-Science-FZK. In the scenarios analyzed, a limited amount of hydrogen, possibly enclosed in the pipes and the engine of a faulty hydrogen powered vehicle, is accidentally released. The study investigated the hazard potential of this limited amount of hydrogen when it is released into an almost open geometry with no additional venting, travelling upwards as free jet until it either reaches a horizontal plate, is accumulated in a hood above the release or penetrates a porous system on its way upwards.

Hydrogen release scenarios of up to 10 g hydrogen through one of three different nozzles with release times from 1 to 70 s into a low confined ambience were investigated. In 33 experiments the concentration distribution and the shape of the free jet hydrogen cloud was determined via concentration measurements. The hydrogen concentrations measured in vertical direction along the axis of the jet can be described by mathematical functions, the measured horizontal hydrogen concentration profiles of the jet exhibit the shape of Gaussian distribution functions. Furthermore the possibility of an accumulation of the released hydrogen in a hood above the jet was investigated. Additionally the experiments concerning the hydrogen distribution behaviour were supplemented by Background-Oriented-Schlieren (BOS) photography.

In 81 combustion experiments pressure and sound level measurements were performed for the scenarios described. The ignition of the released hydrogen was initiated in positions along the axis of the release, where concentrations of about 30 vol. % hydrogen (almost stoichiometric concentration) were determined in the distribution experiments. Due to the ignition of the undisturbed free jet a maximum overpressure of 11.1 mbar was detected by the pressure gauge in the closest distance (0.403 m) to the ignition source, with a maximum sound level of 121 dB(A) in a distance of three meters from the ignition (experiment PlF03). In the experiments where a hydrogen accumulation in a hood above the release was investigated, a maximum overpressure of 53.2 mbar was measured by the pressure gauge at the highest position inside the hood in a distance of 0.78 m to the ignition, with a maximum sound level that exceeded the measuring range of the sound level meter (130 dB(A)) in a distance of three meters from the ignition (experiment PlF08).

In the experiments, where grid net layer structures were used as flame acceleration devices to simulate porous materials in the vicinity of the hydrogen source, a maximum overpressure of 9176 mbar was recorded by the pressure sensor in the closest distance (0.345 m) to the ignition, while a maximum overpressure of 410 mbar was measured by the pressure sensor in the largest distance of 1.945 m to the ignition (experiment PlC22). In this experiment no sound level measurements were performed to protect the sound level meter.

2.5 Hydrogen combustion experiments by KI

The distribution and combustion of large high pressure jet releases of hydrogen both into free space and into congested area have been experimentally investigated by Kurchatov Institute. More than one hundred experiments were performed at the "Vargos" testing site. Released hydrogen mass varied from 0.1 kg to 1.0 kg with average ejection rate of 200 g/s. Various congestion levels were examined. The influence of additional small congested area was investigated. Different geometrical conditions were modelled and different combustion regimes were obtained. Main conclusions from the experiments are:

Spontaneous autoignition of mixture during ejection was not observed.

For hydrogen release amount more than 400 g in uncongested area no ignition was observed because the hydrogen concentration in a point of ignition is lower than flammability limit.

In a case of congested area (blockage ratios 0.3 and 0.54) ignition and slow combustion took place in all experiments. The maximum overpressure in these experiments was lower than 60 mbar.

In experiments with additional congestion maximum overpressure reaches 400 mbar.

During experiments special geometry was found that results in fast deflagration with overpressure more than 10 atm.

2.6 CFD validation and inter-comparison

Test INERIS-6C mentioned in section 2.2 was used for extensive CFD validation [13]. Blind and post calculations were performed. Participation in the benchmark exercise was large: 12 organizations, two of which were non-HySafe partners, with 10 different CFD codes applying 8 different turbulence models, including an analytical solution. In contrast to earlier CFD validation [14] some partners' blind calculations overestimated the mixing of hydrogen with air and predicted transition to homogeneous conditions in the enclosure much faster than the experimental evidence. This behaviour was attributed to poor discretization accuracy options selected by the CFD users. Improved discretization characteristics (higher order convective schemes, increased vertical grid resolution and smaller time steps) showed to improve the predictions in comparison with the experiments.

Hydrogen dispersion experiments, performed by GEXCON outside of HySafe, in a small scale compartmented naturally ventilated enclosure, were used for CFD validation and inter-comparison [15].

GEXCON performed [16] blind CFD simulations of the release and ignition scenarios of the FZK/PRO-SCIENCE combustion experiments discussed above. Besides CFD validation the simulations aimed at assisting the planning of the experiments. The simulated results were found to correlate reasonably well with experimental data, both in terms of the gas concentrations and overpressures subsequent to ignition. Nevertheless, the experimental set-up can be considered to be small-scale and less severe than many accidents and real-life situations. Future large-scale data of this type will be very valuable to confirm ability to predict large-scale accident scenarios.

NCSRD performed CFD validation for high pressure hydrogen releases in the storage room of a hydrogen refuelling station [17].

2.7 Study of permeation by VOLVO, NCSRD, UU, BRE and CEA

Permeation issues were studied using various approaches, review, theoretical, computational and experimental see public HySafe deliverable D74 in [1] and [18, 19, 20]. The primary goal of the HySafe permeation study has been to assist hydrogen road vehicles to be used safely with the minimum of restrictions for manufacturers and customers by avoiding the restrictions imposed by some countries on alternative fuel vehicles in parking facilities. The HySafe activity was initiated as the rates proposed in the draft ECE compressed gaseous hydrogen regulation and the various versions of ISO/DIS15869 (Gaseous Hydrogen And Hydrogen Blends - Land Vehicle Fuel Tanks) were believed to be overly restrictive. As a result HySafe undertook a scientifically based study to investigate if the existing rates could be relaxed safely. Discussions also took place with the SAE Fuel Cell Safety Working Group. The focus of the work was on providing an allowable permeation rate for the draft EC regulation for type-approval of hydrogen powered motor vehicles and the container requirements in the UN ECE WP29 GTR proposal. The results were presented to key automotive regulations and standards groups.

The evaluation of permeation issues was performed by VOLVO, CEA, NCSRD and UU. BRE performed a review of regulations and guidelines regarding ventilation rates and ventilation areas for garage facilities. Volvo led the work, developed scenarios and presented the results to the regulations and standards groups. The work undertaken by CEA, NCSRD and UU was focussed on the subject of hydrogen dispersion at very low flow rates with input from the modelling (NCSRD, UU) and experimental side (CEA).

Due to its small molecular size, hydrogen permeates through the containment materials found in compressed gaseous hydrogen storage systems. Permeation increases with increasing storage pressure, material temperature and the number of pressure cycles that the container is exposed to. For metallic containers or containers with metallic liners the permeation rate is considered to be negligible. However, hydrogen permeation is an issue for containers with non-metallic liners (commonly known as Type 4) which are constructed from a non-load bearing polymer liner over wrapped with structural fibres set in a resin matrix. Proposals for vehicle regulations and standards for hydrogen systems give limits on the allowable permeation rate from Type 4 containers during type approval tests. The work involved the development of a methodology, assumptions and scenarios on which to base a proposal for an allowable permeation rate and compares the HySafe proposal with earlier proposals. The conclusion from the activities of CEA, NCSRD and UU was that while some degree of stratification was observed in the experimental and modelling activities, it was so small in practical terms that it can be neglected. For the purposes of estimating an allowable permeation rate, the studies concluded that it would be valid to assume homogeneous distribution of hydrogen at the flow rates and ventilation rates considered.

The HySafe methodology and proposals were presented to key automotive regulatory groups at the following meetings: UN ECE WP29 HFCV-IG SGS working group on 21 January 2009, EC Hydrogen Working group on 27 January 2009, EC Hydrogen Working group on 10 March 2009.

2.8 Initial guidance for using hydrogen in confined spaces. Results from InsHyde

A report was prepared by InsHyde partners entitled "Initial guidance for using hydrogen in confined spaces. Results from InsHyde", see public deliverable D113 in [1]. This report aims at gathering the knowledge learned during the InsHyde project, as well on a theoretical point of view as on a practical point of view.

This report focuses on the use of hydrogen in confined spaces and the necessary safety measures to be taken. It does not aim at gathering all the documents issued by InsHyde and HySafe on this subject but to give an overview of each topic. References to detailed documents, available via HySafe, are made in each chapter so that the reader may deepen the subject of interest for him or her. To be fully complete, this report makes references to existing standards and best practices.

In the first chapter, the physical properties of hydrogen are briefly summarized. In the second chapter, focus is given on the risk control measures to be applied for a safe use of hydrogen indoor. This chapter aims at improving the safety of existing systems and at designing a safe system in an integrated way. In chapter 3 focus is given on the behaviour of hydrogen in potentially accidental situations and this means release, dispersion and of course ignition and explosion. In the fourth chapter a short overview of risk assessment methodology is given and some examples of what have been done amongst HySafe partners to design safe experiments with hydrogen. At last, all the procedures followed by HySafe partners to design and perform safe experiments with hydrogen (dispersion, ignition, explosion, etc…) are gathered in the annex.

3 SUGGESTIONS FOR FURTHER RESEARCH

The consortium strongly suggests funding of further pre-normative work in order to:

- Formulate the requirements for permitting the use of hydrogen systems (vehicles, hydrogen storage and delivery systems, fuel cells) in confined spaces both from the perspective of the hydrogen systems and the buildings.

- Increase our understanding on hydrogen behaviour in confined spaces

This work should include:

- Further evaluation and investigation of existing and emerging hydrogen detecting technologies to identify and assist development of safer and more reliable detection systems tailored for specific end use applications

- Investigations (experimental and/or computational) to formulate recommendations for the correct use, location and number of hydrogen detection devices required for rapid and effective detection of leaked hydrogen in confined spaces.

- Risk assessment studies examining realistic scenarios for a wide range of confined environments using validated CFD tools

- Further hydrogen/helium dispersion experiments to test a wider range of conditions (release location, strength, direction, ventilation, obstructions, inclined roofs) including the effect of temperature gradients between confined space and outside environment.

- Further combustion experiments …
- Further analysis of permeation.

The work should be jointly undertaken by research + industry + regulatory bodies

4 ACKNOWLEDGEMENTS

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