EUROPEAN PRE-NORMATIVE RESEARCH PROJECT ON INHERENTLY SAFER USE OF HYDROGEN AND FUEL CELL INDOORS: KNOWLEDGE GAPS AND PRIORITIES

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ABSTRACT

To develop safety strategies for the use of hydrogen indoors, the HyIndoor project is studying the behavior of a hydrogen release, deflagration or non-premixed flame in an enclosed space such as a fuel cell or its cabinet, a room, or a warehouse.

The paper proposes a safety approach based on safety objectives that can be used to take various scenarios of hydrogen leaks into account for the safe design of Hydrogen and Fuel Cell (HFC) early market applications. Knowledge gaps on current engineering models and unknown influence of specific parameters were identified and prioritized, thereby re-focusing the objectives of the project test campaign and numerical simulations. This approach will enable the improvement of the specification of openings and use of hydrogen sensors for enclosed spaces. The results will be disseminated to all stakeholders, including hydrogen industry and RCS bodies.

Keywords: *hydrogen, leak, fire, safety strategy, safety objectives, space, dispersion, vented deflagration, flame, vent*

INTRODUCTION

Hydrogen energy applications often require that systems be used indoors (e.g., industrial trucks for materials handling in a warehouse facility, fuel cells located in a room, or hydrogen stored and distributed from a gas cabinet). It may also be necessary or desirable to locate some hydrogen system components/equipment in indoor or outdoor spaces for security or safety reasons to isolate them from the end-user and the public, or protect from the adverse weather conditions.

Use of hydrogen in confined environments requires detailed assessments of hazards and associated risks, including potential risk reduction measures. The release of hydrogen can potentially lead to its accumulation and the formation of a flammable hydrogen-air mixture.

Safety design guidelines and engineering tools need to be developed for use with specific safety strategies for various HFC applications. Closing knowledge gaps is critical to this effort in several areas: hydrogen release conditions and potential for accumulation, venting of deflagration of localised mixture or entire space deflagration, and indoor fire regimes (e.g., well-ventilated and under-ventilated fire, self-extinction of flame, external flames, etc.). Each phenomenon is influenced by the release position/conditions, the number, size and location of the openings in the room/space of some given size, and the type of ventilation. Nonetheless practical and simple safety strategies need to be defined covering all the potential releases.

HyIndoor is a three year project started in 2012 and gathered key players in the field comprising industry (Air Liquide, HFCS), research organisations (CEA, KIT-G, HSL, JRC, NCSRD), academia (UU), and an actor in RCS development (CCS Global Group).

This paper presents the safety approach that is under development within the project HyIndoor and formulates the project expected results.

- It defines first the different safety objectives and thereafter the safety strategies and means of mitigation that may be used to achieve these objectives.
- It then describes the knowledge gaps and questions to be answered for choosing the optimum safety strategy and designing/sizing the corresponding safety means.
- Then it presents how the project intends to answer these questions and formulates the outstanding issues that will not be covered by the project

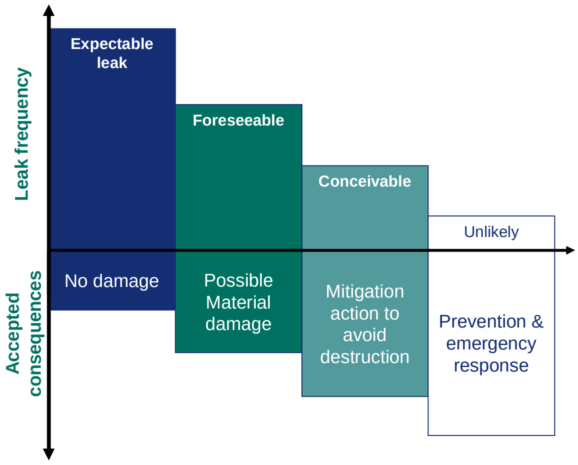
1.0 SAFETY STRATEGIES AND BOUNDARY OF SCENARIOS THAT NEED TO BE ASSESSED

1.1 General safety approach and definition of safety objectives

The proposed safety approach allows us to address all potential leaks of hydrogen by prevention or mitigation measures to achieve a pre-defined specified **safety objective, defined in terms of acceptable consequences**. **These objectives** are defined in function of the **likelihood** of each potential leak to be considered.

The more likely the leak, the more stringent the safety objectives have to be and the more reliable the mitigation means have to be.

Figure 1: Safety objectives expressed as accepted consequences related to leak frequency



The choice of a safety objective also depends on the type of space (room where people are located versus a small space where there is only equipment) in function of what are the most practical and acceptable consequences. For instance, in a very small closed area, it may be difficult to avoid a flammable atmosphere in case of a foreseeable leak but this area could be designed to avoid any hazardous effect in case of ignition.

Remark: no objective has been defined concerning ignition source limitation. The reason for this is that in case of electrostatic ignitions, the very low hydrogen ignition energy makes it practically impossible to avoid ignition by a person and/or by uncontrolled static electricity in air. HyIndoor project is focused on the study of the behaviour of hydrogen for FC application in uncontrolled environment so that we suppose that ignition can always occur.

Safety objectives, ranked in order of increasing consequences could be the following:

Objective 1	**no flammable atmosphere** (by design) except in the dilution volume e.g. flammable volume of the plume directly issued from the leak point (effect of ignition of dilution volume considered negligible)
Objective 2	**limited thickness of the flammable layer:** flammable atmosphere may be present but can not cause burning to persons present. In addition, we check that internal overpressure does not exceed a specified limit (case of a large room), (otherwise, see objective 3 or 4).
Objective 3	Flammable atmosphere could be present but **internal overpressure does not exceed a specified amount to avoid destruction of the space** by design. In addition, the vent location and layout will need to be such as to prevent unacceptable effect from flame or overpressure outside of the space (case of a cabinet, or container)
Objective 4	flammable atmosphere could be present but **external overpressure does not exceed a specified amount (to avoid hazardous effect outside the space**). In addition, space designed to resist internal overpressure, and layout such as to prevent unacceptable effect from flame outside of the space (case of a cabinet, or container)

In all above cases the effect of the ignition of the **dilution volume is considered negligible**. If this is not the case, either Objective 3 can be used, or one of the **following objectives needs** to be adopted as well:

Objective 5	**overpressure effect does not exceed a specified amount in the jet**
Objective 6	overpressure effect does not exceed a specified amount **at a certain distance**

If these conditions are not achieved, the installation design has to be improved to reduce leak flow-rate (flow restrictor, …) or the associated scenario frequency (eg. Leak causes mitigation, automatic valve closure …).

In general, the only release parameter that is considered to be defined upfront is the **leak mass flow-rate**. Leak location and velocity are generally not precisely defined. The objective is to define rules which are applicable without knowing the exact location, direction and exact source of the leak. The same applies for wind velocity and direction. In general that means that **the worst conditions with regards to achieving the chosen objective need to be identified**.

Some time, it is relevant to take into account an exact leak location when it has an effect on the choice of the safety strategy and means for achieving the safety objective. In this case, the leak location needs to be categorised with the definition of specific safety measures for each category. For example:

- Leak in the lower part of the room: objective 1
- Leak in the upper part of the room: objective 2

1.2 - Safety strategy to achieve safety objectives

The safety objectives are expressed in terms of technical / quantified objectives which allow designers to size mitigation measures. These technical objectives are related to limiting the concentration, limiting the overpressure, limiting the thermal effect, inside and outside, and increasing the structure resistance. The last mean is not studied in the HyIndoor project.

The safety measures applied to realise this objective need to work for any leak conditions intended to be covered by this objective. This implies that the worst case conditions need to be taken into account and therefore identified for defining the corresponding safety measures e.g. if the objective is to avoid flammable atmosphere, if natural ventilation is chosen as a safety strategy, and if both buoyancy-controlled and momentum-dominated releases are possible. Then we have to know which of the buoyant or momentum release will induce the highest concentration and therefore require the largest opening.

Limiting concentrations

To prevent a concentration threshold being achieved, we can list the following means of mitigation:

- Limiting the leak flow-rate (as the pipe diameter is generally already minimum, it may be achieved by adding a flow restrictor up-stream and, if possible, outside of the space)
- Ventilation
  - Natural (also called passive) ventilation (through openings in the space)
  - Continuous mechanical ventilation
- Leak detection and action
  - Leak detection may be linked to the process (eg. pressure drop detection) or to the environment (eg. hydrogen sensor in the room)
  - Action may be isolation and/or start of the ventilation, which may be natural (opening traps) or mechanical (starting a ventilator)
- the combination of the three strategies above

The choice of one or the other means takes into account:

- Operational constraints (e.g. operating temperature, flow-rate, energy consumption)
- the reliability of the mitigation means, which need to suit the expected leak frequency, in order to achieve safety objective (freedom from unacceptable risk)
- the investment and cost of ownership

Apart from the flow-restrictor, the most reliable and less expensive mitigation mean is **natural ventilation** that is why it is generally the **best and the most cost-effective option,** at least for the most possible leak. For larger but less frequent leaks, more effective means could be added although they may be less reliable.

Limiting the thickness of the flammable layer

With 2 openings located at different height the so-called displacement regime of natural ventilation is realised and hydrogen will accumulate in a layer at the top part of the space. The concentration in the layer and its thickness can be controlled by a proper sizing of the openings. However, in many situations only one vent is available and knowledge on how to provide safety in this case is needed as well.

Limiting the overpressure inside the space

To avoid exceeding a certain overpressure, we can list the following means of mitigation:

- Limit the concentration (see the mitigation means above)
- Add venting areas, which may be
  - Permanent openings in the space
  - Explosion vents which may be a specific device or weak parts of the structure
- Limit the flammable volume (in the concentration decay area) by limiting the leak duration (leak detection and isolation)

It is to be noted that venting areas, by means of **permanent openings** in the space, are also useful to limit the concentration; this is therefore a **very effective mean to limit overpressure inside an space**. However, it may result in significant overpressure outside, which needs to be taken into consideration.

Limiting the overpressure outside the space

To prevent the overpressure outside the space, we can:

- Limit the concentration

- Limit the quantity of un-burnt flammable gases from the enclosure expelled through the vents during combustion

It is noted that venting used to limit overpressure inside could result in significant overpressure outside, which needs to be controlled as well, as specified by the safety objectives.

Limiting the flame extension outside the enclosure

To limit the flame extension outside the enclosure we need to:

- limit the concentration
- possibly act on size and location of vent with regards to likely location of flammable gases

1.3 - Typical industrial configurations and boundary scenarios to be assessed

The following typical industrial HFC applications have been identified and studied within the project:

- Forklift vehicle operation and refuelling in a warehouse
- Operation of a fuel cell in a room where other activities are performed (e.g. providing back-up power to a data centre)
- Storage of hydrogen in a dedicated room (supplying hydrogen to a fuel cell)
- Storage of hydrogen and distribution to a fuel cell in a cabinet or a larger container (located outdoors or indoors)
- Use of a portable fuel cell generator with its hydrogen supply indoors

Table 1 describes typical volumes and order of magnitude of leak rates of interest: from "expectable leak", to be considered for the design of the installation, to "foreseeable leak" that may be considered for design but with a less stringent safety objective, and "conceivable leak" or "unlikely" leaks to be considered for emergency considerations.

Table 1. Typical HFC enclosure types, volumes and leak flow-rates

Enclosure type	Typical volume	Typical leak rates, from expectable to unlikely
Fuel cell (e.g 1.5 kW)	0,1 – 0,5 m^3	10^{-3} g/s – 10^{-2} g/s
Fuel cell cabinet (e.g 5 kW)	1 – 2 m^3	10^{-2} g/s – 10^{-1} g/s
Container with cylinder storage	20 – 30 m^3	10^{-1} g/s – 1 g/s
Container with H2 production (e.g. 50 Nm3/h)	20 – 30 m^3	10^{-1} g/s – 1 g/s
Room	50 - 100 m^3	10^{-1} g/s – 1 g/s
Warehouse	10 000 m^3 – 100 000 m^3	10^{-1} g/s - 25 g/s

It gives the ranges of enclosure volumes and leak flow-rates that need to be addressed within HyIndoor project.

2 - IDENTIFIED QUESTIONS AND KNOWLEDGE GAPS

For choosing the optimum safety strategy and designing/sizing of the corresponding safety means, we need to close a number of knowledge gaps and answer a number of questions. These questions are listed below and classified according to technical objectives. The HyIndoor project aims to answer these questions.

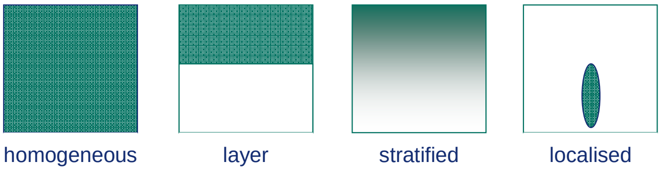
2.1 - Limiting the concentrations

Assuming only natural ventilation is used

For a given leak mass flow-rate and vent openings configuration:

- What are the limits on the release conditions (velocity, direction, distance to ceiling and walls…) that determine the different dispersion regimes?

Figure 2: hydrogen dispersion regimes in a naturally ventilated enclosure



- What is the influence of the leak height on the maximum concentration?
- For sizing the vent, how to consider the influence of:
  - Vent design (grids, wind or weather protecting cover),
  - Wind conditions
  - Obstacles in the enclosure
- What are the limits of application of the answers to the above questions with regard to the characteristics of the enclosure?
  - Size
  - Aspect ratio
  - Location and direction of release

Assuming use of H2 sensor and isolation and natural ventilation

For a given leak mass flow-rate, sensors have to be located on the ceiling:

- How much time do we have to detect and isolate the leak source before exceeding a specified maximum allowable concentration?

- What sensor technology is the most effective for that purpose?

Assuming use of mechanical ventilation

- How to size and locate mechanical ventilation to avoid exceeding a specified concentration in the conditions leading to the highest maximum concentration?

2.2 - Limiting thickness of the flammable layer

Assuming use of vents

- What are the vent location and size to limit the thickness of the flammable layer?

2.3 - Limiting overpressure

Assuming use of vents

- For a given hydrogen dispersion regime, how to size and locate the vents to avoid exceeding a specified overpressure inside or outside enclosure, based on the following parameters?
  - Displacement regime: size of layer and maximum concentration,
  - Stratified regime: maximum concentration and gradient,
  - Fully mixed regime: concentration
  - Combustible mixture in the dilution volume of the leak: combustible mass and release conditions,

- For a given leak size, what is the dispersion regime that requires the largest vents to achieve the overpressure limit?

- For sizing the vent, how to consider the influence of:
  - Equipment volume and piping size and spacing
  - Vent grids
  - Pre-existing turbulence brought by the leak itself (jet release)
  - Pre-existing turbulence brought by mechanical ventilation
  - Inertia of the vent

2.4 - Limiting the flame extension outside the enclosure

- What factors influence the extension of the flame through the vent generated by the combustion of un-burnt mixture outside of the enclosure?

3 – SCIENTIFIC APPROACH AND EXPECTED OUTPUTS

Hyindoor scientific approach is based on:

- Analysis and comparison of existing simple models and CFD models with past experiments
- Providing new experimental results
- Development and validation of new analytical and CFD models.

In the following paragraphs, the analysis of the relevant literature is summarized and the experimental facilities and modelling tools developed to answer the most important knowledge gaps are briefly described.

3.1 – Dispersion of hydrogen in a confined place

A number of simple models predicting hydrogen concentration following a leak in an enclosure have been described in literature. It distinguished 3 main idealized configurations:

- “Closed” enclosure (Cleaver et al.[1], Zhang et al.**[2],** Baines and Turner[3], Worster and Huppert [4], Peterson [5], Kaye and Hunt [6]).

- Naturally ventilated enclosure with 1 vent located near the ceiling or 2 vents located one near the ground, the other near the ceiling. The resulting ventilation is buoyancy driven (Linden, Lowesmith [7] et al, Prasad et al [8]) and will either reach a well mixed regime (1 vent) or a well mixed layer regime (2 vents).

- Opposing wind and buoyancy-driven ventilation (Hunt and Linden [9]), which could be the worst-case scenario and should not be neglected.

Models were either developed only for upward buoyant source localized on the floor or have not been validated for other leak height or direction nor for high momentum release. In addition nearly cubic enclosures are always considered so that an 1D hypothesis has been made on the layer structure. Finally models are based on one adjustable parameter, namely the vent discharge coefficient $C_{D,}$ which has a strong influence on the results but for which no rule is given.

HyIndoor objectives are to identify the conditions and limits of the different regimes that were described (homogeneous (i.e. well-mixed), stratified (displacement regime), or layer regime (displacement regime)), and to assess to what extent and how it will be necessary to take into account the following parameters in the sizing of the vents openings:

- Wind: will be investigated in the HSL experimental programme
- Source momentum (sonic jet): will be investigated in CEA and HSL experiments

- Aspect ratio (elongated box, and very large enclosure, like the one we have in warehouse): will be investigated in CEA experiments

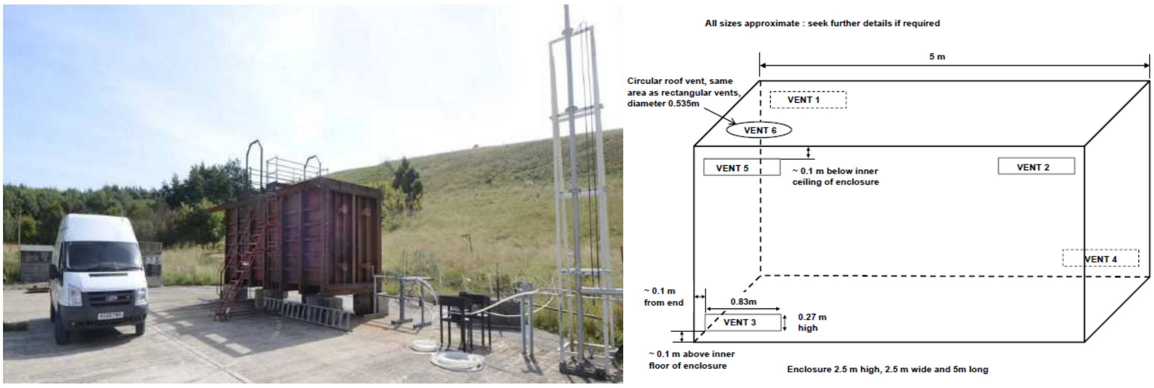
Influence of height of release and vent geometry and position (especially near the top of the ceiling) are currently assessed outside the HyIndoor project [10] but published results will be taken into account in the HyIndoor guidelines.

Influence of obstacles and release direction on the dispersion regimes will not be addressed experimentally. However, if time permits, this will be done with CFD experiments in order to validate a simple way to take these parameters into account within the HyIndoor guidelines.

Experimental set-up and objectives

HSL experimental set-up consists of a 31.25 m^3 enclosure with cross sectional area of 2.5 m by 2.5 m and a length of 5 m. Five similar vents (0.83 m in width and 0.27 m in height) located on the sides of the enclosure and a circular vent of same size located on the roof which can be closed or opened as needed.

Figure 2. Photo and sketch of the HSL 31.25 m^3 test facility



Objectives to address:

- Influence of the wind on the dispersion regimes (mixing versus displacement regime)
- The range of leak flow-rate where a given wind condition could have a negative impact compared to a no-wind ventilation condition.
- How to mitigate a negative effect of wind (i.e. when the wind opposes the flow out of the upper level vent). The use of a vent on the ceiling and the use of the upper level vents fitted on both sides of the enclosure will be investigated.
- How the dispersion/accumulation behaviour of choked flow hydrogen releases differs from that which arises from sub-sonic releases of equivalent mass flow-rate

CEA experimental set-up consists of one enclosure of Plexiglas of 1 m^3 with 1 vent at the top of one side or 2 vents at the top and bottom of one side. In addition to helium concentration and temperature measurements, PIV measurements will allow assessing of:

- Turbulence levels in the enclosure
- Velocities inside the enclosure and at the vents

Mass flow rate will be from $1.5\ 10^{-3}$ to $2.7\ 10^{-1}$ g/s and injection diameter vary from 20 mm to 0.1 mm (180 bar).

Objectives to address:

- How to set the C_D coefficient at the vent

- Provide more exhaustive data for CFD code validation
- How the dispersion/accumulation behaviour of choked flow hydrogen releases differs from that arising from sub-sonic releases of equivalent mass flow-rate

CEA also intends to build new boxes:

- With a fixed height but different widths to address aspect ratio knowledge gap
- Sized down to address the scalability the knowledge gap.

CFD benchmark and objectives

First, a CFD tool benchmark is organized between partners to assess the limits of the validity of the turbulence models such as k-Epsilon, RNG k-Epsilon, SST and LES and laminar models to predict the maximum concentration of helium / hydrogen following a buoyant release in a closed space 1 m^3, then in the same space with 1 and 2 vents.

Second HSL and CEA experiments will be used to address CFD capacity to assess wind conditions and choked flow hydrogen releases. Finally, each partner will use CFD in its domain of validity to address the remaining knowledge gaps such as:

- Scalability and aspect ratio
- Influence of obstacles

3.2 - Deflagration of hydrogen in a confined place

Only a few simple models dedicated to hydrogen have been developed and validated as of yet to predict overpressure following a deflagration in a confined space: Molkov [11,12] established a correlation for calculating the vent area in an empty space or a space without significant influence of obstacles based on turbulence generated during venting and Bauwens et al [13,14] have developed an engineering vented explosion model allowing the calculation of two pressure peaks generated in a vented explosion process: the first is linked to the external explosion and the second is linked to acoustic effects in the space. This model allows for the consideration of the influence of the ignition location (back, central and front) and the presence of obstacles.

homogeneous

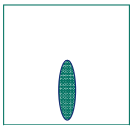
HyIndoor objectives are to continue to validate and improve these correlations for smaller and larger spaces and propose guidelines to size vent openings to fulfill objective 2 or 3, taking into account real situations such as:

layer

stratified

- Low concentration layers and stratification in the space
- Turbulent flammable mixture formed by a high momentum leak
- Typical industrial obstacles created by equipment and piping
- External effects of a vented deflagration such as thermal effect and overpressure decay
- Vent location is not always in the middle of the side but more often on the roof or at the top or bottom of the side
- The inertia of the vent deployment: in the models, the vents are generally open prior to ignition or instantly when appropriate pressure is generated within the space. However when they are dedicated to protection against realistic deflagrations, vent covers start to open at pre-determined static overpressure and it takes time to fully open the vent area

In addition, some of the partners intend to develop a simple model to evaluate the maximum overpressure induced by a localized mixture deflagration, e.g. when the flammable volume is very limited compared to the volume of the enclosure volume



localised

and set the limits of applicability of such a model. This model will be validated against KIT experiments.

The project will also allow to experimentally validate the model for so-called pressure peaking effect proposed by Brennan et al. [15]. This phenomenon seems negligible for the industrial scenarios considered in the HyIndoor project. However it may have to be taken into account in case of catastrophic rupture of an HP line in a space with small vent(s).

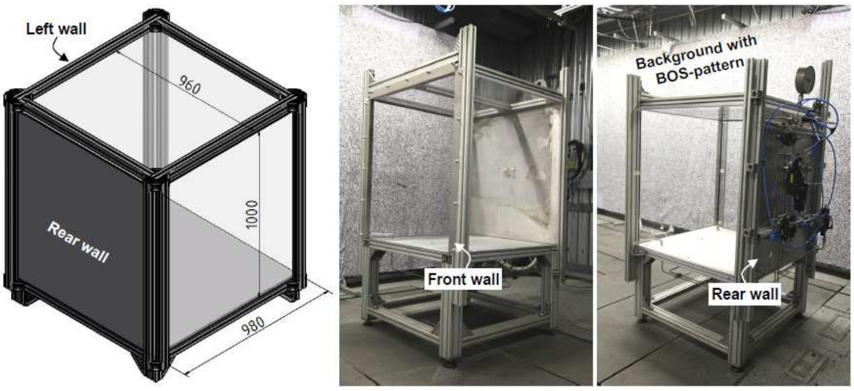
Knowledge gaps such as influence of grids of the opening, e.g. to prevent insect ingress or rain ingress will not be addressed within HyIndoor experiments although it will have to be taken into consideration in Hyindoor guidelines, e.g. through the value of the discharge coefficient and actual venting area.

Experimental facilities and objectives

HSL will use the same test chamber (31.25 m^3) as for dispersion experiments. The weakest part of the space is designed to withstand an internal explosion pressure of 0.2 barg. Hydrogen concentration, distribution, and ignition position will be varied in order to get experimental data for CFD models and the correlation for vent sizing.

KIT facility itself mainly consists of an almost cubic 0.94 m^3enclosure, which is made from aluminum profile rails that are covered with three transparent and three solid plates. The space is designed to withstand an internal explosion pressure of 0.1 barg. A high number of parameters will be studied to fulfil project objectives: H2 concentration and distribution (mixed/layer/stratified/H2 jet), ignition location, vent size, number of vents (1 or 2) and their positions (on one wall or on the ceiling), inertia of vent cover, presence of obstacles. It will allow to measure the main characteristics of vented explosions: position of the flame front with BOS-technique, high-speed-camera and 2 digital photo cameras to record processes inside and outside of the space, overpressure history and pressure decay outside the space will be recorded with 8 pressure transducers (inside and outside) and temperature history with 9 thermocouples located inside the space.

Figure 3: sketch and two views of the KIT test space (0.94 m^3) inside the 160 m^3 test chamber.



CFD benchmark and objectives

All the codes which are intended to be used within HyIndoor project e.g. FLACS V.10 (AL), COM3D V4.5 (KIT), ADREA (NCSRD), FLUENT, ANSYS v14.5 (UU), REACFLOW (JRC), RDEM (CEA) have limited verification and validation status against vented combustion and explosions. Therefore, as a first step, it is proposed to perform a benchmark against available literature data, e.g. on uniform lean H2/air deflagration in 64 m^3 space experiments carried out by FM Global, Kumar Experiments (120 m^3), and H2E Experiments on 0.01 m^3 small scale 30% H2 experiment.

Expected improvement within HyIndoor will include:

- Scaling capabilities (space volume from 0.01 m^3 to 120 m^3)

- Ability to predict maximum overpressure inside and extent of effects (flame /overpressure) outside space
- Ability to adequately predict the potential for flame acceleration depending on mixture composition and distribution, initial level of turbulence, vent parameters and obstacle configuration

3.3 – Well-ventilated and under-ventilated hydrogen indoor fires

The non-premixed combustion of hydrogen in a space has not been specifically studied to the partners' knowledge. As a consequence, the corresponding phenomena have not been taken into account in the described above safety objectives as:

- We need to better know the phenomena and associated hazards/risks to be able to set accurate objectives to protect life and property.
- A priori, for a given leak flow-rate, avoiding flame extinction will be less stringent on vent sizing than limiting the concentration or overpressure phenomena
- These phenomena and induced hazards may take time to develop: if persons are not directly injured by the flame, they may have time to evacuate but HyIndoor results may be used to define the right emergency procedures and recommendations for fire brigades

As a result, within the HyIndoor project, the goal is to quantify the phenomena that might happen for a given leak rate, space volume and vent(s) characteristics. It may confirm the defined safety objective (which did not consider these phenomena) or necessitate taking the risk of flame extinguishment and re-ignition into account in specific leak versus volume cases.

Different regimes need to be described and their limits defined:

- Well ventilated jet fire (complete combustion of hydrogen within the space) or plume with similar associated effects (temperature and heat flux) as outdoor but with the potential of flame impingement on the ceiling and in any case hot combustion products rising and forming a hot layer: depending on the size and location of the vents this hot layer could propagate downwards and present thermal and asphyxiation hazards

- Under-ventilated fire: in this regime not all released hydrogen will burn inside the space and an external flame can be established under specific conditions

- Self-extinguishment is possible for under-ventilated fire due to oxygen depletion and water vapour produced by the initial flame. The space would be filled in with hydrogen and once the leak is stopped, gravity current of air into the space would create a flammable mixture with the potential re-ignition and create potentially dangerous deflagration

Experimental set-up and objectives

KIT and HSL facilities described above will be reused to test fire phenomena:

- in the 0.94 m^3 KIT facility: the conditions required for jet-fires to become under-ventilated and for self-extinction in the 1 vent and 2 vents spaces (following pre-test simulations carried out by UU partner)

- in the 31.25 m^3 HSL facility: the radiative effects of a well-ventilated jet fire, particularly the characterization of the thermal effects of the hot layer at floor level (to predict flashover phenomenon)

CONCLUSION

The HyIndoor pre-normative research project identified and ranked the knowledge gaps on hazards related to hydrogen behaviour in naturally ventilated spaces. It is focused on **industrial needs to**

design inherent safer installations and will generate new knowledge about hydrogen accumulation regimes, vented deflagrations, and hydrogen fires in confined spaces through complementarities and synergies of experimental, analytical and numerical studies. The outcome of the HyIndoor project will be **guidelines, engineering tools** and recommendations for RCS improvements allowing for the development of safety strategies and practical engineering solutions that will comprehensively address all potential hydrogen leaks and associated hazards for any hydrogen and/or fuel cell system, in order to provide expected level of life and property protection.

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