RISK ASSESSMENT AND MITIGATION EVALUATION FOR HYDROGEN VEHICLES IN PRIVATE GARAGES. EXPERIMENTS AND MODELLING

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ABSTRACT

Governments and local authorities introduce new incentives and regulations for cleaner mobility, as part of their environmental strategies to address energy challenges. Fuel cell electric vehicles (FCEVs) are becoming increasingly important and will extend beyond captive fleets, reaching private users. Research on hydrogen safety issues is currently led in several projects in order to highlight and manage risks of FCEVs in confined spaces such as tunnels, underground parkings, repair garages, etc. But what about private garages - that involve specific geometries, volumes, congestion, ventilation? This study has been carried out in the framework of PRHyVATE JIP project, which aims at better understanding hydrogen build-up and distribution in a private garage. The investigation went through different rates and modes of ventilation. As first step, an HAZID (Hazard Identification) has been realized for a generic FCEV. This preliminary work allowed to select and prioritize accidental release scenarios to be explored experimentally with helium in a 40-m^3 garage. Several configurations of release, ventilation modes and congestion – in transient regime and at steady state – have been tested. Then, analytical and numerical calculation approaches have been applied and adjusted to develop a simplified methodology. This methodology takes into account natural ventilation for assessment of hydrogen accumulation and mitigation means optimization. Finally, a global risk evaluation – including ignition of a flammable hydrogen-air mixture – has been performed to account for the mostly feared events and to evaluate their consequences in a private garage. Thus preliminary recommendations, good practices and safety features for safely parking FCEVs in private garages can be proposed.

1.0 CONTEXT AND MOTIVATION

Hydrogen fuel cell-based vehicles are brought on the market in order to provide alternatives for ecological and economic transition. This hydrogen alternative for mobility is becoming increasingly important and will reach in a near future more and more private users. For this reason, it was necessary to investigate in detail the consequences of potential accidental scenarios during FCEV parking inside a “closed” private garage in order to be able to define best practice rules and propose mitigation measures if required.

The PRHyVATE project is a Joint Industry Project between Audi AG (Germany), CEA (France) and Air Liquide (France) aiming at better understanding hydrogen build-up and distribution in a private garage taking into account potential release coming from a fuel cell-based electric vehicle.

The first step of the study consisted in analyzing the potential accidental release scenarios regarding the existing design of the FCEV.

Based on the identified scenarios, the experimental facility of the CEA, so-called GARAGE, was used to create the releases of interest and observe the build-up inside the experimental enclosure consequences.

Following the experimental results, the hazardous level of the different studied configurations was evaluated in terms of real consequences.

2.0 DESCRIPTION OF INVESTIGATED CONFIGURATIONS

2.1 Analysis of potential accidental scenarios

Each part of the hydrogen system inside the fuel cell electric vehicle (see Fig. 1) was considered, from the high-pressure reservoir to the fuel cell.

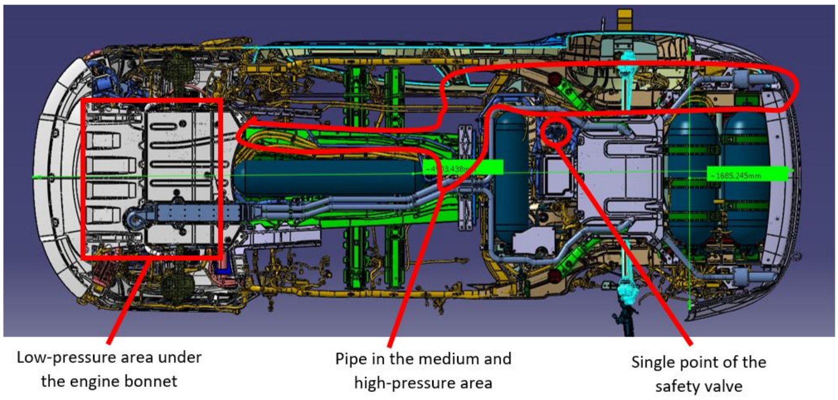


Figure 1. Internal structure of a fuel cell electric vehicle.

Different accidental events leading to a leakage were identified, categorized according to pressure and flowrate, analyzed and commented.

A critical analysis was performed on more than 20 release scenarios taking into account the relevance of the release, the availability of safety features allowing stopping the release for some cases, the duration of the release, etc. in order to define the main parameters of interest for this study, which will be described later in a dedicated section.

Following the results of this critical analysis, A maximum flowrate of 100 $NL.min^{-1}$ (0.15 $g.s^{-1}$) was chosen to perform experimental releases. This value is a high leak rate and remains thus conservative, as higher leakages would not happen without notice before entering the garage.

Therefore, releases due to a malfunction of a TPRD (Thermally activated Pressure Relief Device) – i.e. TPRD opening without fire – are out of the scope of this study.

2.2 Experimental setup

As previously presented, the objective of this research work is to characterize the dispersion of hydrogen leaks from a fuel cell vehicle in a garage for the different chosen accidental scenarios and understand the influence of real geometries involved as well as transient phenomena. To achieve this safely through experiments, helium is used instead of hydrogen, which has been proven to be a relevant substitute [1].

The experiments were performed in the CEA experimental facility, so-called “GARAGE”, an enclosure of 296-cm width x 575-cm length x 240-cm height (see Fig. 2).

(A) (B)

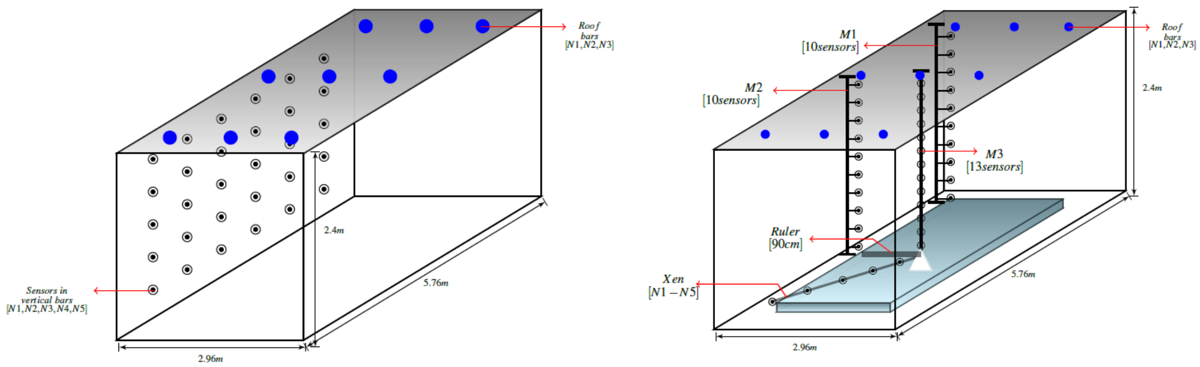
Figure 2. “GARAGE” CEA experimental facility. (A) Inside the enclosure with the chassis in grey close to the roof, (B) outside the enclosure with the sensors monitoring system.

A Brooks 5850 mass flow controller (MFC) was used to measure and control the helium flowrate. The Brooks flow controller has a scale from 7 $NL.min^{-1}$ to 700 $NL.min^{-1}$. Its accuracy is better than 1% and was recalibrated before the test campaign. Helium was injected at a 100% concentration through a circular orifice of 8-mm diameter.

Concentration measurements were performed with up to 70 catharometers located on masts, positioned in the whole volume of the enclosure, according to experience and preparatory trials (see Fig. 3). Location and number of sensors were adjusted depending on the studied configurations and their complexity to capture the maximum concentration gradients.

The main sensors used for this study are minicatharometer Xen-TCG-3880Pt from Xensor, specifically calibrated, with an accuracy assessed to as low as 0.2% of absolute concentration and a response time around 4 s.

For some configurations, a chassis was installed inside the enclosure in order to represent the congestion induced by the car in the garage. This chassis is modular since it is a plate of 1.8-m width x 3.2-m or 4.8-m length, positioned at a height of 18 or 30 cm from the ground, allowing testing the influence of these variable parameters.



(A) (B)

Figure 3. Schematic views of the “GARAGE” with selected locations of the sensors for helium concentration distribution characterization. (A) Enclosure empty, (B) enclosure with the chassis.

In presence of the chassis, the injection point is localized under the chassis.

2.3 Studied configurations

Sensitivity of some parameters on helium concentration distribution was studied and detailed in Table 1.

Table 1. Overview of the variable parameters of the experimental program.

Parameters	Variation
Release	- Flowrate: up to 100 NL.min^{-1} - Nozzle diameter: 0.8 – 8 mm - Orientation: upward – downward – sideward - Height from the floor: 18 – 22 – 30 cm - Location: centered & decentered
Congestion	- Chassis: with and without chassis - Chassis height from the floor: 18 – 30 cm - Chassis size (L x w): 480 x w 180 cm – 320 x w 180 cm
Ventilation	- Closed/sealed enclosure - Naturally/passively ventilated enclosure – 2 configurations o Openings only located at the top of the enclosure [L120 x H20 cm] o Openings located at the top AND at the bottom of the enclosure [L120 x H20 cm] each

More than 30 trials were performed.

Note that pre-calculations were performed for a preliminary calibration of the studied parameters and the adjustment of the test matrix before launching first trials:

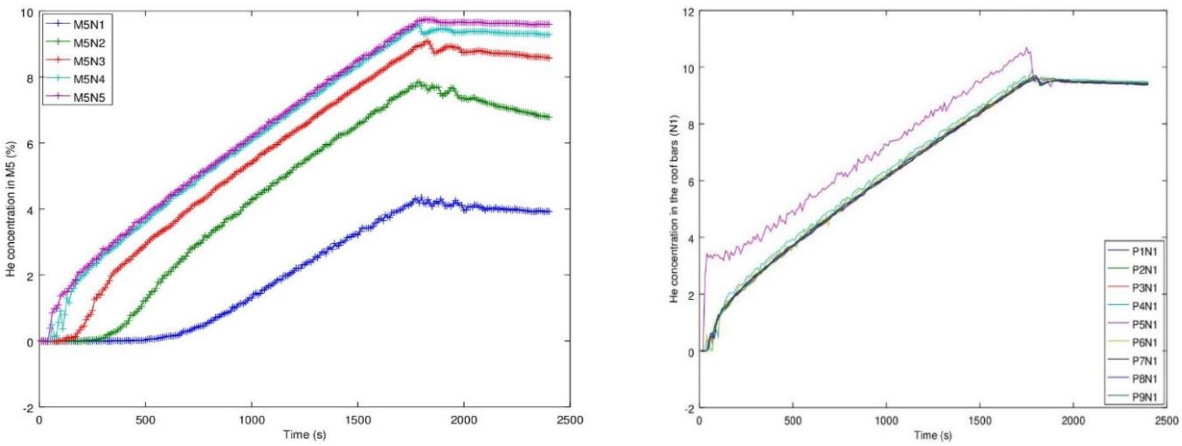
- for closed enclosure without ventilation, with the analytical approach proposed by Worster and Huppert (1983) [2],
- for the pre-sizing of the ventilation openings, with the analytical approach proposed by Linden (1999) [3].

3.0 RESULTS AND DISCUSSION

3.1 Dispersion in closed enclosure

3.1.1 Upward injection

After specific series of tests aiming at evaluating the tightness of the enclosure, trials were launched in confined space.



(A) (B)

Figure 4. Helium concentration distribution in a closed enclosure as a function of release duration for an upward injection. (A) Vertical sensors, (B) Roof sensors.

Characterizing the enclosure tightness is critical to limit side effects and set a relevant reference case. Fig. 4 shows the transient concentration during the helium injection (100 NL.min^{-1} upward injection during 1800 s). Fig. 4(A) gives the concentration of vertical sensors from the ground to the roof, and Fig. 4(B) the concentration of the sensors localized horizontally at the same height close to the roof at different points of the GARAGE.

Note that, in Fig. 4, sensor N1 (in blue) is located at the lowest position and N5 (in purple) at the highest position in the enclosure. It is clearly visible that the highest concentrations are found, as expected from previous experiments and literature, on the M5N4 and M5N5 sensors. Over the duration of the experiment, a global increase in helium concentration is seen until around 1800 s, the moment helium injection stops. We can also notice that the 2 highest sensors M5N4 and M5N5 present almost superposed curves indicating they are located in a homogeneous layer. This is confirmed by all the other sensor masts from 1 to 6 showing a similar pattern. This corresponds to the notion of layer described in the literature and confirmed in this study, as the phenomenon not being only limited to mast 5 and showing a 1 dimensional repartition of the phenomenon. The maximum concentration reached for a 1800-s upward injection at 100 NL.min^{-1} is close to 10% and the thickness of the homogenous layer in the upper part of the GARAGE were assessed to be around 60 cm.

3.1.2 Impact of the injection orientation

The impact of injection orientation on helium distribution was investigated as well. Results obtained for an upward and a downward injection of helium at 100 NL.min^{-1} are shown in Fig. 5 at 2000 s. Helium concentration is represented as a function of the height.

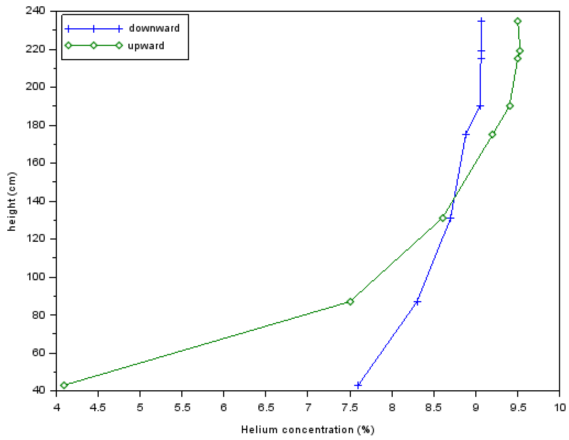


Figure 5. Helium concentration distribution on the height of the closed enclosure for a 2000-s 100 NL.min^{-1} release according to the orientation of the injection.

The main difference is that the concentration variation is much more limited between ground and roof for a downward injection (in blue) compared to an upward injection (in green); the mixture being a lot more homogeneous due to the impingement of the release on the floor of the enclosure. This phenomenon is less accentuated but observed as well for a horizontal injection.

The maximum helium concentrations measured near the roof are slightly lower than for a pure vertical release (in the presented case: 8.75%-He vs 9.5%-He).

3.2 Impact of the presence of a chassis

As previously described, a chassis was set up inside the experimental garage in order to represent a car and investigate the impact of this congestion on helium distribution.

In presence of this chassis, several configurations were studied:

- distribution of helium in the garage
- distribution of helium without and with natural ventilation
- impact of the height of the chassis and of its dimensions
- specific distribution of helium under the chassis

3.2.1 Dispersion in a closed enclosure with a chassis

First experiments with a chassis were performed without ventilation, in a totally closed enclosure, for a downward injection of helium at 100 NL.min^{-1}. Fig. 6 shows the comparison on helium distribution with and without chassis from the previous experiment (30 cm above the ground) for a release time at 2000 s.

The injection point of helium is under the chassis.

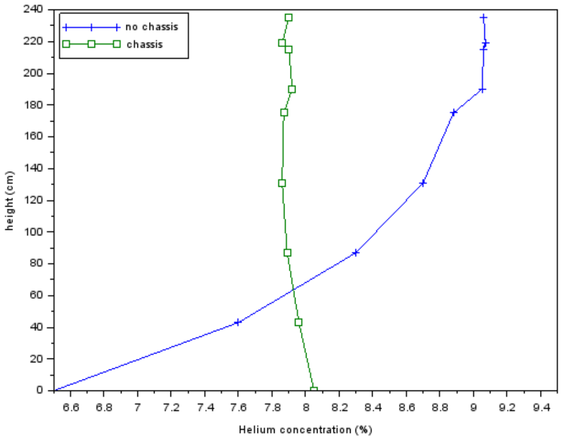
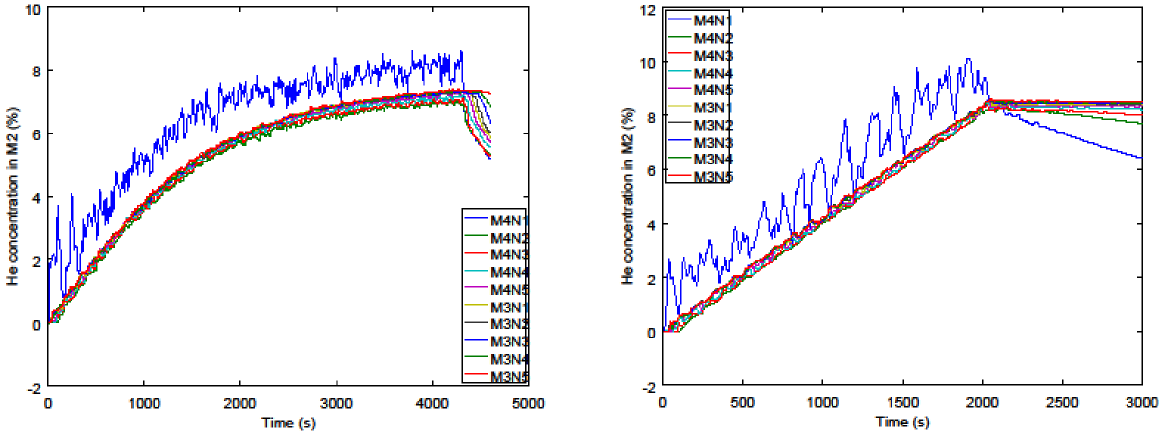


Figure 6. Helium concentration distribution on the height of the closed enclosure for a 2000-s 100 NL.min^{-1} release with and without chassis inside the enclosure.

A clear and stronger homogenizing effect of the injection is observed with the chassis. The upward injection, without chassis, produces more stratification and higher maximum concentration at the ceiling (as shown in Fig. 5, section 3.1.2). When the injection is downward without chassis, the concentration is well homogenized (please refer to Fig. 5 as well). But that effect is further increased when injection is done under the chassis and this, whatever the height and the size of the chassis tested, as confirmed by the additional tests performs in the study.

3.2.2 Dispersion in a naturally ventilated enclosure

As described in numerous publications [4, 5], natural ventilation can be an efficient way to limit build-up of light gases in case of accidental in confined spaces. Thus the impact of natural ventilation was investigated combined with the effects of a chassis. Fig. 7 presents a comparison with (A) and without (B) natural ventilation for a release rate of 100 NL.min^{-1}.



(A) (B)

Figure 7. Helium concentration distribution according to release duration with a chassis, with (A) and without (B) natural ventilation.

In the presented case, natural ventilation is realized through one single opening (size: [L120 x H20 cm]) located in the upper part of the GARAGE.

Fig. 7 shows that the homogeneous distribution is not modified by natural ventilation since the curves for the sensors located all along the height of the enclosure are almost superimposed. The concentration at 2000 s is much reduced compared to a closed enclosure (Fig. 7(B)), with a drop from around 8.2% to 6% with natural ventilation.

Additionally, a steady state is reached at 4000 s with a maximum concentration around 7%, which is not visible in the tight garage.

3.2.3 Accumulation under the chassis

As shown in the previous sections, the chassis tends to homogenize the concentration distribution inside the enclosure, favoring the reduction of the maximum concentration inside the enclosure.

The natural ventilation contributes, as well, to limit this maximum concentration in the enclosure.

But what about the concentration distribution under the chassis? In order to have better representation of the concentrations, sensors were placed under the chassis in order to observe helium behavior and measure concentrations at this place.

Fig. 8 presents helium concentrations measured under the chassis for an injection flowrate of 100 $NL.min^{-1}$ at different distances from the release (from 15 cm to 78 cm).

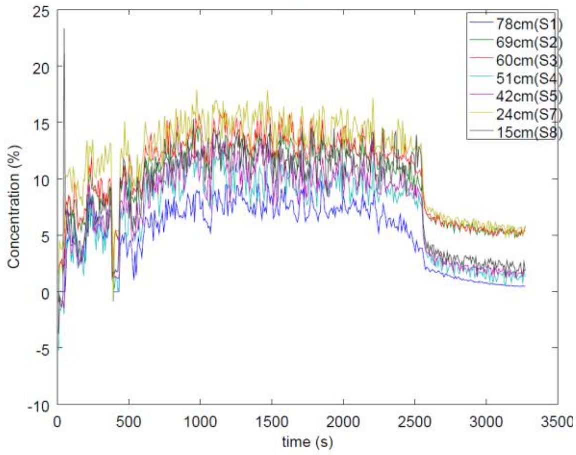


Figure 8. Helium concentration distribution under the chassis
at different distances from the injection point.

Even if the concentrations fluctuate a lot, a maximum value of 15%-He is observed just under the chassis near the injection and decreases down to 6% at the chassis edge (bridging to the homogeneous concentration in the rest of the garage). It shows that a small flammable mixture might form under the chassis, from the pure hydrogen release until the homogeneous area

In a preliminary approach, considering ignition possible for concentrations higher than 10% (for hydrogen) corresponding for this trial to a distance of 51 cm from the release point, and considering the whole height under the chassis (i.e. 30 cm), the flammable volume can be assessed at 245 L.

3.3. Summary of obtained results

Several additional configurations were investigated in the framework of PRHyVATE project in order to assess the impact on helium distribution inside the garage, but are not presented in details in this communication. Nevertheless a few information on results obtained are given in Table 2 hereafter.

Table 2. Impact of studied parameters on helium distribution and maximum concentration inside the garage.

Parameter	Variation	Result	Maximum concentration at 2000 s
Release direction	upward	Layer formation (1D in z)	~ 10.5%
	sideward	Homogeneous mix (1D in z)	~ 9%
	downward	Homogeneous mix (1D in z)	~ 9%
Release diameter	8 mm	No influence on the concentration repartition	~ 9%
	80 mm		
Chassis	18 cm high	Fully homogeneous mix	~ 8%
	30 cm high	No influence on the concentration repartition	~ 8%
	480 x 180 cm vs 300 x 180 cm	No influence on the concentration repartition	~ 8%
Ventilation	1 opening top	No influence on the concentration repartition Reduction of the concentration	~ 6%
	2 openings top / bottom	No influence on the concentration repartition Reduction of the concentration	~ 5.5%

Summarized, the studied variations have no or very low impact on helium distribution. A more extensive presentation and discussion of these results will be done in a follow-up publication.

3.4 Results exploitation and preliminary risk assessment

From the obtained results in this study, two additional critical phenomena are relevant for further discussion in terms of safety:

- the effects of a delayed ignition of the potential flammable cloud under the chassis,
- the pressure peaking phenomena inside the studied garage in case of important release.

These two cases are dealt with in the following sub-sections.

3.4.1 Ignition of the flammable cloud under chassis

Helium dispersion for a broad range of configurations has been experimentally studied. These experiments showed in most of the cases a homogeneous helium-air mixture in the garage volume with acceptable concentrations according to the release conditions under accidental conditions. Nevertheless, it has been highlighted that in presence of a chassis, there is a higher concentration bubble at the release point below the chassis.

For a 100 $NL.min^{-1}$ release, a brief calculation was realized in order to have a first estimation of the potential flammable cloud formed under the chassis, leading to an estimated 245 L volume.

In a conservative approach, by considering this volume homogenous at 15%-H_2 (the maximum concentration measured under the chassis with helium) and by applying a TNO Multi-Energy level of 4 to assess explosion effect distances [6], the threshold of 50 mbar would be felt at a distance lower than 2 m from the release point. Therefore, effects in case of delayed ignition of this flammable cloud are relatively limited, and confined under or close to the chassis. Major damages to the garage or to people are not foreseeable for the considered accidental release flowrate.

3.4.2 Pressure peaking phenomenon

Pressure peaking is the phenomenon observed for very lighter than air gases, which can result in overpressure exceeding enclosure or building structural strength limit in case of high hydrogen release rate. The enclosure can be strongly damaged up to its total destruction.

In order for pressure peaking to occur, the hydrogen release flowrate should be sufficiently high to result in complete displacement of air from the enclosure.

Pressure peaking phenomenon observation is a complex combination of the following parameters:

- high release flowrate,
- small enclosure,
- small vents size

The approach proposed by Brennan and Molkov [7, 8] was applied to the GARAGE in order to assess the relevance of such a phenomenon in the studied conditions.

Calculations were performed considering the dimensions of the GARAGE, the studied opening of 0.24 m^2 (size: [L120 x H20 cm]), and an hypothetic release from a 3-mm TPRD connected to a 700 bar tank of 140 L (corresponding to a peak flowrate of $1.8 \cdot 10^5$ $NL.min^{-1}$); since obviously the flowrate of 100 $NL.min^{-1}$ investigated in this study does not generate pressure peaking.

Fig. 9 shows that the maximum pressure induced by the TPRD-like release is around 3 mbar for the enclosure and opening sizes considered in this study.

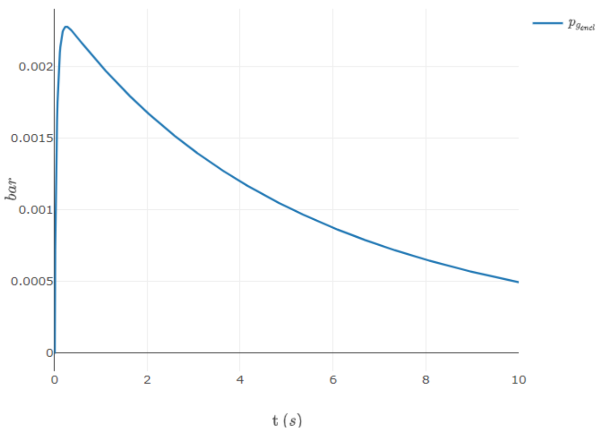


Figure 9. Overpressure dynamics from an unignited release of 3-mm diameter with an initial pressure of 700 bar in the GARAGE with a venting aperture.

Thus, for this configuration considering a ratio of 1.4% of opening area compared to the ground surface of the garage, the pressure peaking is far from leading to significant damages on the enclosure structure. It is important to account for the multiple small openings in a real garage and potential weaker structures that will open in case of overpressure.

4.0 CONCLUSIONS

The study – performed in the framework PRHyVATE JIP project – was led to evaluate potential risks induced by an accidental release of hydrogen coming from a fuel cell electric vehicle parked inside a private garage.

For a relevant definition of the parameters of the study, an HAZID (Hazard Identification) has been performed for a generic FCEV. This preliminary work allowed to select and prioritize accidental release scenarios to be explored experimentally with helium – for safety reasons – in a 40-m^3 garage. Several configurations of release, ventilation modes and congestion – in transient regime and at steady state – have been tested.

Despite a wider investigation range, the experimental work presented made a focus on helium releases through a circular 8-mm diameter orifice and a flowrate of 100 NL.min^{-1}. Note that this release flowrate is significantly high compared to the identified and analyzed foreseeable accidental scenarios.

Closed and naturally ventilated enclosure configurations were studied in order to characterize helium concentration distribution and highlight the efficiency of ventilation apertures to mitigate helium build-up in confined spaces.

In a closed enclosure, a homogenization of the helium concentration in the upper part was shown, and this behavior is accentuated by the orientation of the release, or the presence of the chassis placed inside the enclosure to simulate a car. Therefore, in these configurations, the maximum concentrations measured are reduced and homogeneous in the whole garage space

Natural ventilation configurations showed no change in the homogenization of the helium concentration, with obvious reduction of the maximum concentration.

To complete this study, investigations were performed to determine the helium distribution under the chassis. It has been highlighted than concentrations would be higher than in the upper part of the enclosure, but in a limited volume, since at 50 cm from the injection point, the measured concentration is almost equivalent to the concentration in the enclosure beyond the chassis. Nevertheless, based on this trials, considering a release of hydrogen instead of helium, a flammable mixture can be formed under the chassis, but effects in case of ignition remains relatively limited, and confined under or close to the chassis for the studied flowrate (i.e. 100 NL.min^{-1}).

Additionally, a preliminary calculation demonstrates that pressure peaking phenomenon can be avoided in a private garage of a medium volume thanks to sufficient but realistic venting aperture.

For the next steps, additional configurations will be experimentally studied, and numerical calculations approaches will be tested in order to be validated in a first time, and to enlarge the studied configurations. This work is already launched and illustrated in the Fig. 10.

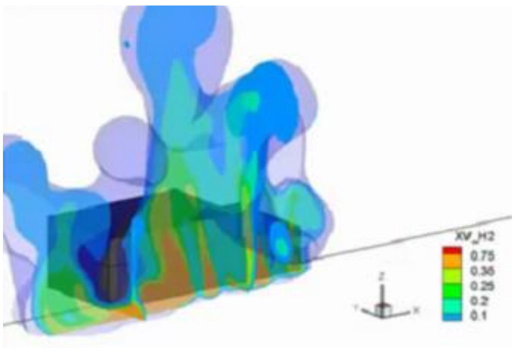


Figure 10. CFD preliminary simulation of the helium dispersion around the FCEV.

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