HYDROGEN RELATED RISKS WITHIN A PRIVATE GARAGE: CONCENTRATION MEASUREMENTS IN A REALISTIC FULL SCALE EXPERIMENTAL FACILITY

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ABSTRACT

Next generation of hydrogen energy based vehicles is expected to come into widespread use in the near future. Various topics related to hydrogen including, production, storage, and application of hydrogen as an energy carrier, have become subjects of discussion in the framework of various European and International projects. Safety information is vital to support the successful introduction into mainstream and public acceptance of hydrogen as an energy carrier. One of such issues, which is seeking major attention is related to hydrogen powered vehicles parked inside a confined area (such as in a private garage). It is of utmost importance to predict, if uncontrolled release of hydrogen from a vehicle parked inside a confined area can create an explosive atmosphere. Subsequently, how the preventive measures can be implied to control these explosive atmospheres, if present inside a confined area? There is a little guidance currently developed for confined areas accommodating hydrogen fuelled vehicles. It is essential that mitigation measures for such conditions become established.

Characterization of different scenarios those may arise in a real situation from hydrogen fuelled vehicle parked inside a garage and furthermore, the investigation of an optimal ventilation rate for hydrogen risk mitigation are some of the main objectives described in the framework of the present study. This work is an effort to provide detail experimental information's in view of establishing guidelines for hydrogen powered vehicles parked inside a private garage. The present work is developed in the framework of a European Network of Excellence HySafe and French project DRIVE. Present paper describes a purpose built realistic Garage test facility at CEA to study the dispersion of hydrogen leakage. The studied test cases evaluate the influence of injected volumes of hydrogen and the initial conditions at the leakage source on the dispersion and mixing characteristics inside the free volume of the unventilated garage. The mixing process and build-up of hydrogen concentration is measured for the duration of 24 hours. Due to safety reasons, helium gas is used to simulate the hydrogen dispersion characteristics.

Key words : Garage, Hydrogen safety, Concentration measurements, flow regimes.

1.0 INTRODUCTION

The highly combustible nature of hydrogen poses a great hazard creating a number of problems with its safety and handling. Safety information's are vital to support the successful introduction into mainstream and public acceptance of hydrogen as an energy carrier. These requirements have focused the need to bring experts from research institutes, industries, government bodies, and lawmakers on a common platform to develop the recommendations and guidelines for the safe and efficient use of hydrogen. At European level, numerous research projects have been devoted to hydrogen safety analysis exploring different phases of utilization, such as, production, storage, distribution, demonstration etc. [1].

While exploring the various safety aspects related to the hydrogen use, one important issue is the possible leakage of hydrogen inside a confined geometry that may result into formation of an

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explosive atmosphere if sufficient ventilation is not present. There had been a few experimental or numerical studies to test the dispersion characteristics of hydrogen in confined geometries [2, 3, 4]. However, most of these studied were carried out to validate the safety concept and not to understand the effects of parameters such as, initial flow regimes, source orientation, distance between walls and source, etc. on the hydrogen dispersion characteristics. Moreover, the concentration sensors used were very limited in numbers and thus restricting the quality of data for numerical codes validation purpose.

The present study is an effort to explore the non-catastrophic conditions those may present dangerous situations due to a possible leakage from a hydrogen fuelled vehicle parked inside a private garage. Experiments are performed in the *Laboratoire d'Études des Transferts et de Mécanique des Fluides* (LTMF) at *Commissariat à l'Énergie Atomique(CEA), Saclay*, which has been involved in the studies related to the hydrogen safety analysis for more than a decade, while using helium for simulating hydrogen related risks due to safety reasons. CEA, with its experience in carrying out the large-scale MISTRA programme [5, 6] for the validation of containment codes, also houses academic-style experimental facilities, namely, GAMELAN and GADDIFAN to understand the gas dispersion and mixing characteristics as well as to develop and apply state-of-the-art instrumentation to generate high quality data [7, 8]. These experimental data's are further supports the development of CFD modelling for hydrogen risk assessment and on the elaboration of safety codes and standards [9, 10]. This paper discusses the results of hydrogen leakages (forced plumes) and the resulting accumulation of hazardous gas-air mixture in no-ventilation conditions inside the GARAGE. The dependence of gas build-up on the released volumes and the initial flow conditions is also made subject of the investigation. This paper presents the preliminary results concerning the following two test arrangements:

- Garage fully sealed: This case is considered as a reference case and investigate the sealing efficiency of GARAGE.

- Garage with lower vent open: Four tests are carried out to understand the influence of injected volume of gas (Test 1 & Test 2) and initial flow regimes (Test 3 & Test 4) on the hydrogen dispersion characteristics.

A dense instrumentation mesh (64 measurement points) is used to generate high quality gas concentration data. The present work, that is carried out in the free volume of GARAGE and without any ventilation means, provides a base study to long term objectives defined in the framework of European project HySafe [11] and a French project DRIVE [12]. Part of the study results will also be included in the international project 'Task 19: hydrogen safety' [13]. Various scenarios of hydrogen leakage (ex. source orientation, flow regimes, mass flow rates, etc.) are planned to study in a free volume or with a real vehicle parked inside the test facility GARAGE for simulating the real leakage scenarios. Investigation of mitigation measures (natural or mechanical ventilation systems) to control the formation of explosive atmosphere is also an integral part of this study.

2. EXPERIMENTAL APPROACH

2.1 The Experimental Set-Up: GARAGE

The test set-up GARAGE is representative of a realistic single vehicle private garage. It is of rectangular shape with interior dimensions of 5.76 m (Length) x 2.96 m (Width) x 2.42 m (Height). The internal volume of GARAGE is 40.92 m^3. The maximum uncertainty in GARAGE volume calculation is of the order of ± 0.5 %.The garage is equipped with a door for technical access in the back, and a tilting door on the front side. Figure 1 illustrates the GARAGE test facility at CEA. Concerning the GARAGE design, the choice is made of a stainless steel skeleton, in order to obtain a great modularity of the walls (figures 1a). The material chosen for the panels is Styrodur$^®$ (2500 C), green colored extruded rigid polystyrene foam (figure 1b). In order to investigate the time scales related to the permeation and restitution of helium gas through Styrodur$^®$, tests are performed on a small-scale test facility [8]. Results clearly put in evidence the suitability of Styrodur$^®$ sheets as a

construction material for the purpose of dispersion tests while using helium gas as working fluid. It is then possible to change opaque panels with transparent ones for planned laser measurements.

The reference point of the GARAGE is situated near the front door (at the cross section of the side wall and the floor level) as shown in figure 1a.
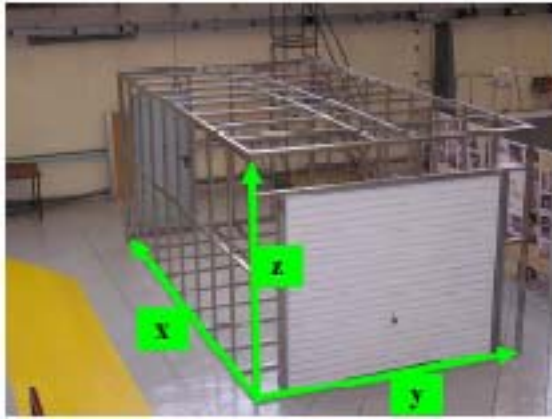
| (a) GARAGE structure showing front and service door | (b) GARAGE structure equipped with Styrodur® sheets |

Figure 1 : Description of GARAGE set-up

2.2 Instrumentation

Flow rates at nozzle exit are measured and controlled with two mass flow controllers (BROOKS Inc). These two controllers can provide precise flow rates in the range of 0 - 700 Nl/min (at standard conditions of 0°C temperature and 1 atmospheric pressure). The maximum uncertainty in measuring the studied flow rates is of the order of 0.9 %. The response time of the flow output signals for controllers is less than 3 seconds.

Helium gas concentrations are measured by using thermal conductivity gauges or mini-katharometers (type 3880Pt). The measurement principle relies on the decrease in effective thermal resistance between the sensitive area of the sensor and the ambient, caused by the thermal conductance of the surrounding gas. An in-house built facility is used to calibrate the mini-katharometers. Calibrated bottles of helium gas with concentrations ranging from 1% to 50 % are used for the calibration purpose. For data analysis, each sensor is assigned with their own constants obtained through the calibration. Figure 2 shows a typical calibration curve of one of the mini-katharometers for air-helium mixture at room temperature.

The output voltage of the mini-katharometer can be approximated by a quadratic formula for helium gas fraction (X_{He}) in air ranging between 0 and 0.5 (Eq. 1):

$$U = U_0 \left\{ 0.9988 - 1.2082 \times X_{He} + 0.5321 \times X_{He}^2 \right\} \tag{1}$$

with, U = output voltage (helium-air mixture)
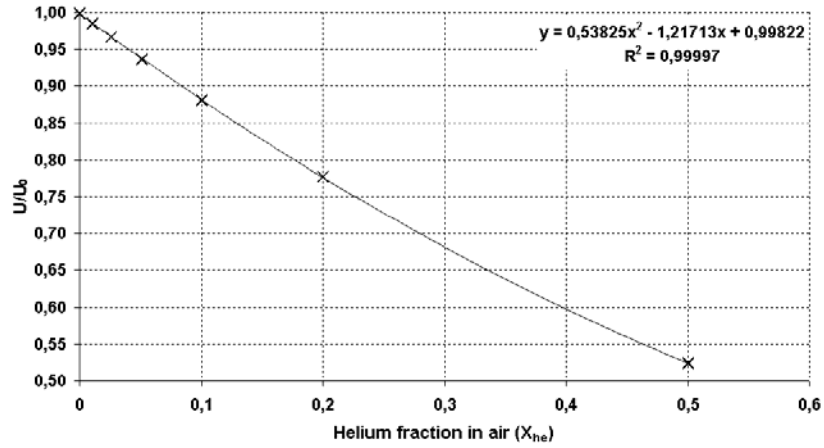
U_0 = output voltage (air)

Figure 2 : Typical calibration curve of mini-katharometer for air-helium mixture

For an extensive concentration measurement, 64 monitoring points are used inside the GARAGE test facility. Figure 3 shows the placement of sensors inside the GARGAE. Measurement sensors are deployed at 27 fixed points attached to the ceiling (PiNj, where I = 1-9, and J=3), 30 mobile points (MiNj, i= 1-6, and j=1-5), and 7 voluntary points (Voli, where i= 1-7). The sensor 'Vol1' is placed in front of the bottom opening, so that it can measure the outgoing helium gas concentration.
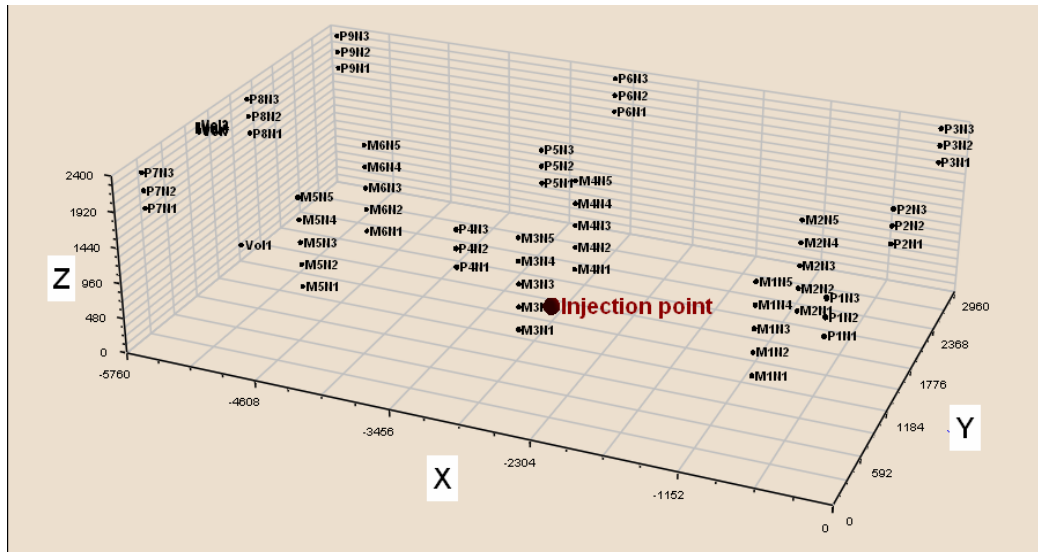

Figure 3 : Monitoring locations inside GARAGE

3. RESULTS AND DISCUSSION

In this phase of the study focus has been put on determining the dispersion characteristics of hydrogen leakage simulated with helium inside a private GARAGE. For similar purpose, feasibility of helium gas to simulate the distribution and concentration of hydrogen gas had already been subjected to various research studies and confirmed the suitability of helium gas for this purpose [2]. The similitude between helium and hydrogen dispersion characteristics is also one of the objectives of the present study. Some preliminary results comparing helium measurements at CEA and hydrogen measurements at INERIS are discussed in [14]. These results also validate the suitability of helium gas to study hydrogen dispersion characteristics inside a confined area.

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3.1 Experimental scenario's and release conditions

Table 1 presents the detail of the studied test cases and concerning parameters. All the four tests are performed in a free volume configuration, i.e. no obstacle in the garage (for example a vehicle), and without ventilation. It should be noted that a vent of 200 mm diameter at the bottom of the garage is kept open. This is done to maintain the test facility at constant atmospheric pressure (figure 4) for the duration of the tests.

| Reference	TEST1	TEST2	TEST3	TEST4
Volumetric flow rate - STP (NL/min)	668,00	668,00	18,00	18,00
He mass flow rate (g/s)	1,99	1,99	0,05	0,05
x release (m)	2,88	2,88	2,88	2,88
y release (m)	1,48	1,48	1,48	1,48
z release (m)	0,22	0,22	0,22	0,22
Exit diameter (mm)	20,70	20,70	5,00	29,70
Garage Temperature Tmoy (°C)	20,00	20,00	20,00	20,00
Exit velocity at 20°C (m/s)	35,50	35,50	16,40	0,5
Release Direction	Upward	Upward	Upward	Upward
Release Type	Continuous	Continuous	Continuous	Continuous
Release duration (s)	121	500	3740	3740
Released volume - STP (Nm3)	1,35	5,57	1,12	1,12
Released volume - Tmoy (m3)	1,45	5,97	1,20	1,20
He released mass (g)	240	994	200	200
Target concentration - Tmoy (%)	3,53%	14,60%	2,94%	2,94%
Re0 at 20°C	6150	6150	686	115
Ri0 at 20°C	9,9E-04	9,9E-04	1,1E-03	8,3E+00
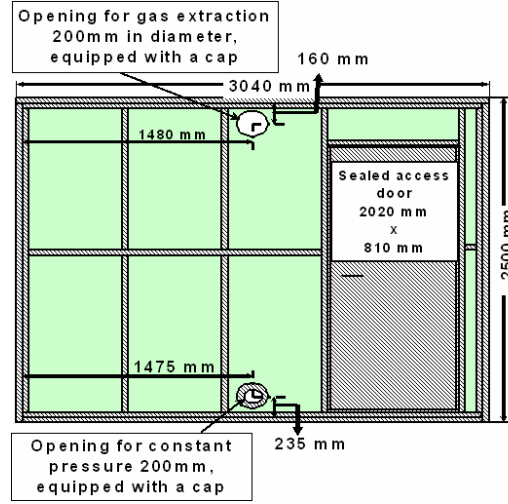
Table 1: Test parameters　　　　　　　Figure 4: Rear wall of GARAGE with openings

The leakage sources are experimentally simulated with pipe injectors positioned in the middle of the GARAGE and at a height of 220 mm from the floor. For the three pipe injectors used in this study, the straight length to diameter ratio on the upstream side of the elbow is greater than 25. This ratio is considered to be sufficient enough for ensuring a fully developed flow at the pipe exit [15]. Based on Reynolds number and Richardson number at the pipe exit, flow structures present turbulent as well as laminar flow regimes (See table 1 for details). A vertical buoyant flow with initial momentum behaves like a non-buoyant jet near the nozzle exit, but may behave like a pure plume in the far field. The distance beyond which the jet momentum becomes negligible compared to its buoyancy, L_{jet}, can be estimated from Eq. 2 [16] as given below:

$$L_{jet} = \frac{0.96 \times U_0 \times \sqrt{D}}{\sqrt{\dfrac{g(\rho_{air} - \rho_{He})}{\rho_{air}}}}$$

(2)

Where, U_0, is the initial velocity at the nozzle exit and D represents the nozzle diameter. Cleaver et al [17] also reported a correlation for L_{jet} for horizontal and downward jet releases of natural gas. The correlation was similar to that given by Eq. 1, but with the constant 0.96 replaced by $2.12(\rho_{He}/\rho_{air})^{1/2} = 0.79$. Based on Eq. 2, the distance is calculated as 1.69m for Test 1 and Test 2. This means, for these two test cases, the flow structure is of plume-type in the upper half of the GARAGE near the ceiling (H/2 = 1,21m) and jet-like in the lower-half of the GARAGE. However, in case of Test 3 and Test 4, plume-like flow develops very near to the injector (i.e. 0.38 m for Test 3 and 0.03 m for Test 4).

3.1 Sealing efficiency

Leakage rate from the sealed GARAGE set-up is quantified by using the tracer gas decay method [18]. To interpret data resulting from the tracer gas decay method, mass balance of the helium gas released inside the test volume is employed. Helium gas concentration as a function of time is given by Eq. 3:

$$X_{He}(t) = X_0 \exp(-At) = X_0 \exp(-\frac{Q_L}{V}t) \tag{3}$$

Where, V is the GARAGE volume and X_0 is the initial concentration of helium within the control volume at time t = 0. By measuring the decay rate of X_{He} inside the GARAGE, the determination of the slope of the plot $\ln(X_{He}/X_0) = -(Q_L/V)t$ gives an estimate of the leakage rate Q_L. In Eq. 3, $A = Q_L/V$ denotes the air changes per hour (ACH) within the GARAGE.

Measurements are taken for two test conditions, i.e., X_{He}= 3.05% and X_{He} = 4.04%. The decay of helium gas concentration with time is presented in figure 5a. Details of the parameters tested and concerning results are illustrated in figure 5b. The regression analysis on the logarithm of concentration versus time mentions that the GARAGE set-up is sealed well enough to produce only 0.01 ACH.
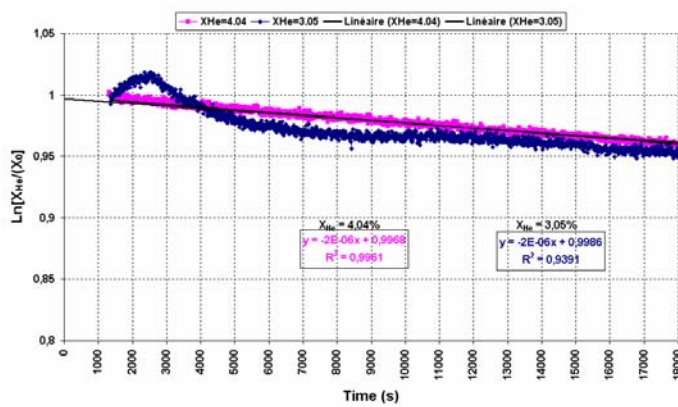
	X_{He}=3.05%	X_{He} = 4.04%
Injector orientation	Horizontal	Vertical
Injector position	Near service door	In the centre of garage
Date	06/12/2006	20/02/2007
ACH (1/h)	0.01	0.01
Leakage rate (Q_L) [m³/h]	0.29	0.29

a) Decay of helium gas concentration with time   b) Tests parameters and results

Figure 5 : Leakage rate calculation inside GARAGE

3.2 Dispersion characteristics

3.2.1 Influence of injected gas volume

In this section, comparison is made between Test 1 and Test 2. These two test cases represent the similar initial conditions, i.e., turbulent flow-regime [19] but different injected volumes of helium gas. Figure 6 shows the evolution of helium concentrations with time inside the GARAGE for both test cases. In the injection phase, helium gas rises immediately upwards due to both buoyancy and diffusive forces and spreads symmetrically across the GARAGE ceiling.

In the initial phase (injection), concentration levels continue increasing that may result due to the presence of the destabilizing buoyancy-induced momentum forces. The peaks in helium concentration levels are detected by the sensors located near the ceiling on the support P5Nj (j= 1, 2 and 3), situated right above the injector. These peak concentration levels in the near ceiling zone depend on the injected volumes and highest concentration levels can be noted for Test 2, which represents the case of

highest injected volume of helium gas (5.97 m³) inside the GARAGE. Once the helium gas injection is stopped, sensors situated on supports P5Nj assume the identical concentration levels as observed with all other PiNj sensors located near the ceiling. The similar tendency is also observed for Test 1.

The intermediate phase (dispersion) that follows the end of the gas injection shows a layer of highest concentrations formed near the ceiling. In this phase, momentum induced forces start to diminish and buoyancy forces start dominating the flow. In the zone near ceiling, the maximum concentration levels measured for two test cases do not show a linear increase with injected volumes of helium gas. Increasing the injected volume about four times for Test 2 (as compared to Test 1) does not increase the maximum concentration levels four times. Well-defined vertically stratified layers can be observed in the GARAGE volume. The formation of ceiling layer depends on the geometry dimensions, release conditions, ratio of momentum and buoyancy forces and also on the ventilation conditions. In case of an unventilated geometry, the possibility of the formation of a ceiling layer can be verified with the criteria proposed by Cleaver et al [17]. A well mixed deep layer forms when the distance between the release point and the ceiling, H_c, is large in comparison to the characteristic dimension $(A_c = L \times W)$ of the ceiling, i.e. $H_c > 0.38\sqrt{A_c}$. In the present study, the distance H_c is equal to 2.22 m, which is large enough from the right hand side ($0.38\sqrt{A_c}$ = 1.57 m²) of the proposed criteria. The momentum generated force need only be about 10 % of the buoyancy force to prevent the formation of stable layers inside a closed geometry of aspect ratio equal to one [20].

Figure 6 shows that the depth of ceiling layer with uniform concentration levels is higher for Test 2 as compared to Test 1. In case of Test 2, sensors located at positions MiN4 show similar concentration levels as for sensors located near ceiling (i.e. PiNj sensors). In contrast, for Test 1, a notable difference can be observed between sensors located near ceiling and at locations MiN4. The sensor supports MiN4 are located just above the middle of the GARAGE at a height of 1.26m from the floor level.

In the last phase (mixing), stabilizing buoyancy forces dominate the flow as compared to momentum induced forces. There is no source of mixing in the unventilated GARAGE, other than forces generated by the momentum or buoyancy fluxes originating due to the jet flow itself. For Test 1 and Test 2, the momentum dominated zone extends to about 1.69 m from the pipe exit and afterwards buoyancy play the dominant role in mixing. Additionally, the momentum forces attenuate after the end of the injection phase. In the buoyancy dominated upper ceiling zone, a displacement flow is thereby established. Due to this, concentration levels in the upper half (i.e., for measurement locations ≥ MiN4) of the GARAGE start to decrease and an increase of concentration levels occur in the lower half (i.e., for measurement locations ≤ MiN4) as the ceiling layer descends with time. Furthermore, the presence of the lower vent adds up in concentration decay that may result due to the vertical density difference between interior of the GARAGE and ambient. After certain time duration when a steady state has been reached, concentration levels start to decrease in both upper-half and lower-half of the GARAGE. Strong stratification occurs for Test 2 as compared to Test 1. Even after 5 hours from the start of helium gas injection, concentration gradients remains on higher side for Test 2 as compared Test 1.

Both Test 1 and Test 2 create explosive atmosphere inside the GARAGE. For Test 1, only the upper-half volume (i.e., for measurement locations ≥ MiN4) of the GARAGE exceeds the lower flammability limit (LFL) of hydrogen (= 4.1% by volume). This takes approximately 6 hours to reduce the concentration levels below LFL. However, it should be noted that as concentrations are not measured along the jet-axis in the near source zone, the existence of explosive atmosphere can not be denied in this zone for the initial phase of the injection, i.e., when the influence of buoyancy-induced momentum persists. This will be verified in the future tests. In contrast, for Test 2, concentration levels inside the full volume of GARAGE exceed the LFL limit after about 500 seconds and remains above the LFL limit until 22 hours (from the start time of the helium gas injection inside the test facility).
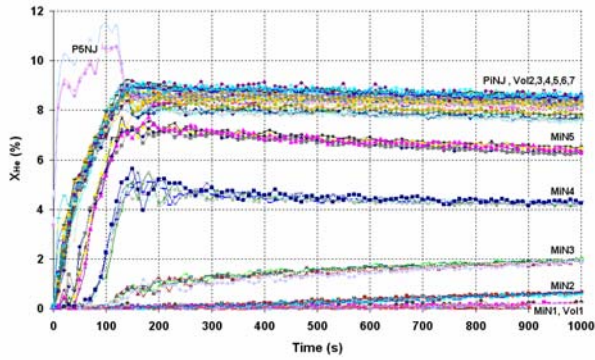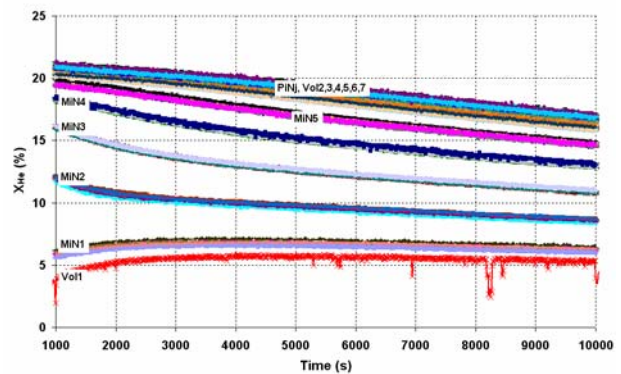
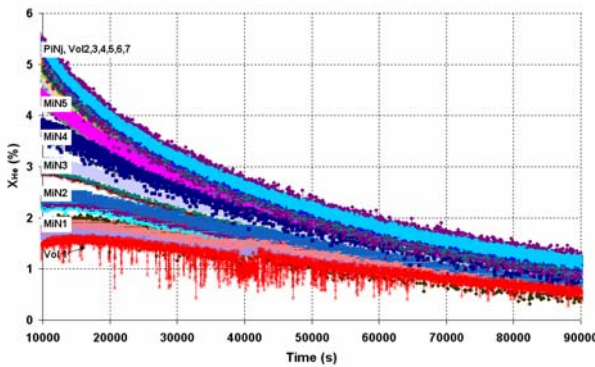Test 1, Q= 668 Nl/min, t = 121 s, D = 20.7mm   Test 2, Q= 668 Nl/min, t = 500 s, D = 20.7mm
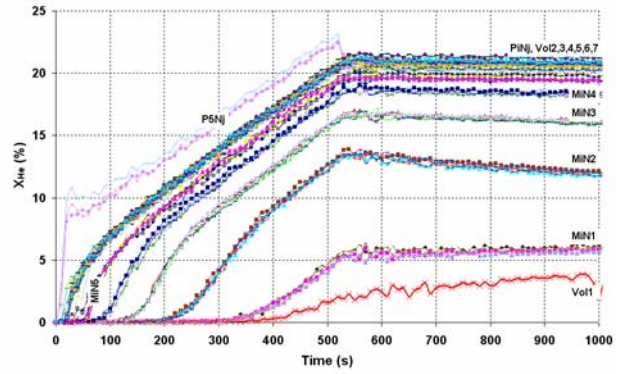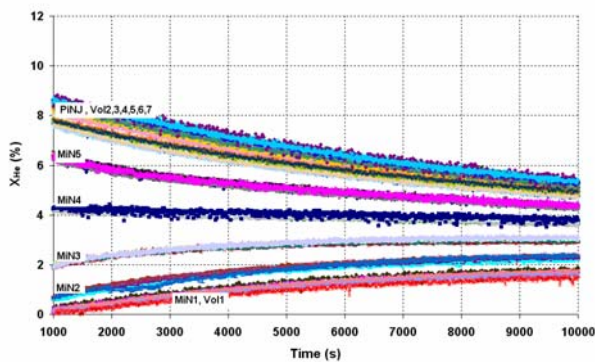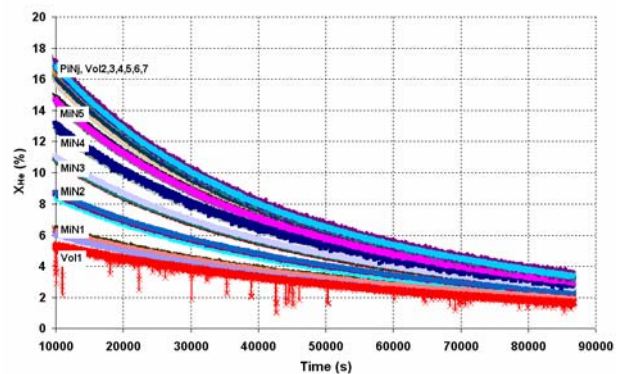

Test 1, Q= 668 Nl/min, t = 121 s, D = 20.7mm   Test 2, Q= 668 Nl/min, t = 500 s, D = 20.7mm

Test 1, Q= 668 Nl/min, t = 121 s, D = 20.7mm   Test 2, Q= 668 Nl/min, t = 500 s, D = 20.7mm

Figure 6 : Evolution of helium concentration (X_{He}) with time inside the GARAGE for Test 1 and Test 2

*3.2.2 Influence of initial flow regimes*

In this section, Test 3 and Test 4 with similar injected gas volumes but different initial flow regimes are compared. These two test cases represent laminar flow regimes at the pipe exit based on the Reynolds numbers [19]. Figure 7 shows the evolution of helium concentrations with time inside the GARAGE for both test cases.

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As depicted in figure 7, during the injection phase (t < 3740 s) helium gas disperse in the similar manner for both the test cases. As mentioned for Test 1 and Test 2, these two test cases also show the symmetric dispersion of helium gas and subsequent formation of ceiling layer. Afterwards, buoyancy bound ceiling layer descends with time due to engulfing of surrounding air. This results into decrease in the concentration levels in the upper-half of the GARAGE and increase in concentration levels near the floor level. For Test 3 and Test 4, the injected volumes of helium gas are identical and the resulting distributions of concentration levels inside the test facility are similar at the end of injection.

In case of Test 3 and Test 4, if we compare the peak concentration levels detected by sensors on supports P5Nj, it is clear that sensors attain the similar levels as for sensors on supports PiNj only after about 500 seconds. The peak concentration levels detected by sensors on supports P5Ni are lower than concentration levels attained in the ceiling layer that forms just after the end of injection. This trend is in contrast with Test 1, which has nearly same injected volume of helium but represents the turbulent flow regime at the pipe exit. For this case (Test 1), concentration levels detected by sensors on supports P5Nj are higher than concentration levels in the stabilized ceiling layer just after the end of the injection phase. Test 3 and Test 4, represents initial laminar flow regimes and plume-like flow develops very near to the source as compared to Test 1 (for which plume-like flow develops in the upper half of the GARAGE). Thus, for Test 1 during the injection phase, helium-rich mixture reaches near the ceiling faster due to the momentum dominated forces. However, at the end of injection, formation of a stabilized ceiling layer occurs, that may result due to the development of buoyancy dominated forces. Thereafter concentration levels decrease due to the air fed from lower part of the GARAGE. In contrast, for Test 3 and Test 4, as penetration height (momentum dominated) is very near to source (i.e. 0.38 m for Test 3 and 0.03 m for Test 4) and flow rises towards the ceiling due to the buoyancy dominated momentum forces during the injection phase. Therefore, helium rich mixture entrains the surrounding air at the earlier stage even before the end of injection phase and depicts identical concentration levels at all PiNj supports.

Apart from similar trends depicted by Test 3 and Test 4 in the initial phase, the decay of concentration levels varies in the later stage. After the end of injection, when initial momentum diminishes and buoyancy forces become dominant, mixing may occur mainly due to the molecular diffusion resulting into homogeneous stable layers inside the GARAGE for both test cases. Test 3 shows a faster decay as compared to Test 4. This may occur due to the fact that the ratio of initial momentum and buoyancy fluxes changes with time and with axial distance. An approximate expression for the variation of this ratio with downstream distance has been derived by Pitts [21]. The analysis shows that values of this ratio are directly proportional to U_0^2 and inversely proportional to z^2. The initial buoyancy flux is quite similar for both cases but initial velocity is higher for Test 3 as compared to Test 4 and that is why enhanced engulfing of surrounding air may occurs due to the higher energy input from the flow acceleration in the injection phase for Test 3 then Test 4. However, as mentioned in section 3.2.1, no flow overturning occurs and concentration decay occurs only because the higher concentration layers descends with time and increase the concentration levels in the zone near the floor level due to the entrainment of surrounding air.

In case of Test 3 and Test 4, an explosive atmosphere develops only in the ceiling zone (sensors located on supports $\geq$ PiNJ) for both the test cases and prevails for about 2 hours ($X_{He} > 4.1$ %). However, as mentioned before, concentrations are not measured along the jet-axis in the near source zone and therefore the existence of explosive atmosphere can not be denied in this zone for the initial phase of the injection. Further measurements in the near source zone will be needed to confirm this possibility.
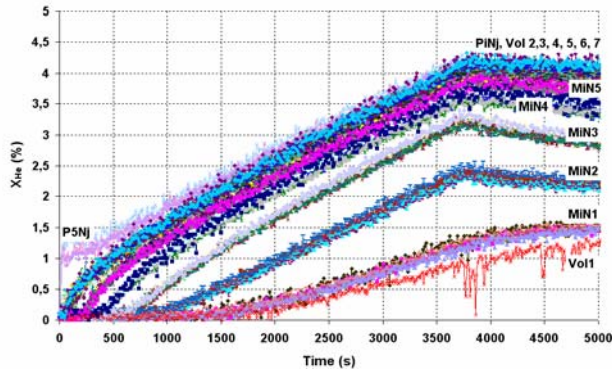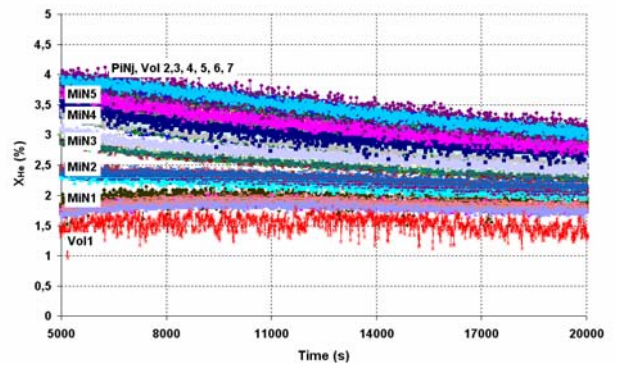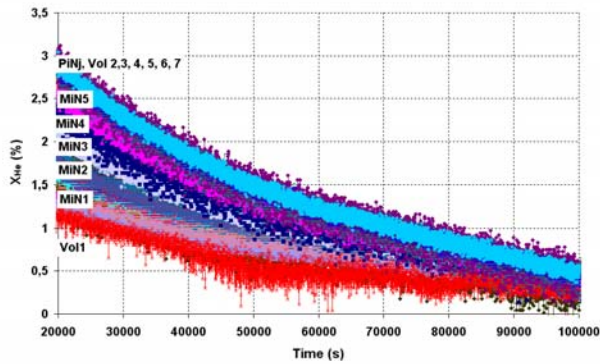
Test 3, Q= 18 Nl/min, t = 3740 s, D = 5mm
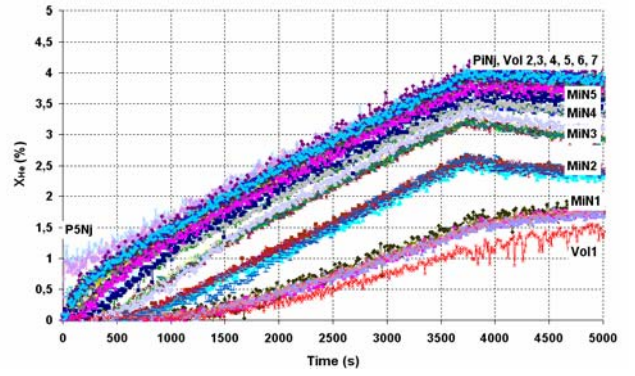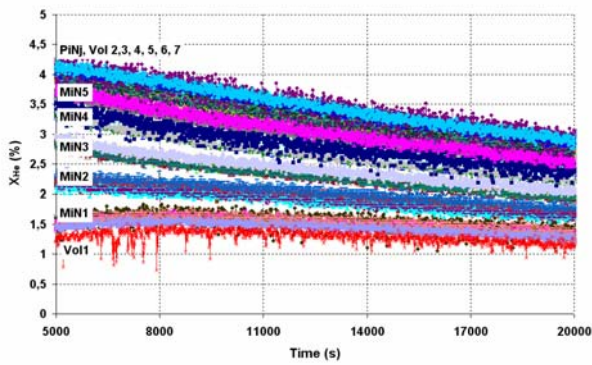
Test 4, Q= 18 Nl/min, t = 3740 s, D = 29.7mm

Test 3, Q= 18 Nl/min, t = 3740 s, D = 5mm

Test 4, Q= 18 Nl/min, t = 3740 s, D = 29.7mm

Test 3, Q= 18 Nl/min, t = 3740 s, D = 5mm
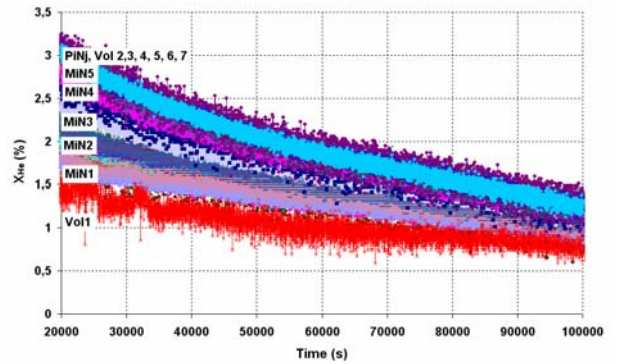
Test 4, Q= 18 Nl/min, t = 3740 s, D = 29.7mm

Figure 7 : Evolution of helium concentration (X_{He}) with time inside the GARAGE for Test 3 and Test 4

4. CONCLUSIONS AND PERSPECTIVES

Helium dispersion experiments are performed in a full scale realistic GARAGE facility. Results are presented for the test cases performed in the free volume of GARAGE without any ventilation. For the given aspect ratio of the GARAGE and test conditions, no overturning of flow takes place and stratified layers are formed inside the test facility.

The analysis of results clearly show that for the leakages 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 (Test 1 and Test 2), peak concentration levels increases with an increase in the injected volume. The peak concentration levels reached at the end of injection phase for injected volumes of 5.97 m^3, 1.45 m^3, and 1.20 m^3 are 23.08 %, 9.22 %, and 4.39 % respectively.

Test cases with similar injected gas volumes (Test 3 and test 4) but different initial conditions, show almost identical peak concentration levels at the end of injection phase. However, variations in flow rates influence the mixing behavior inside the GARAGE that in turn changes the decay rates of gas concentrations.

Test cases with higher injected volumes represent the worse condition and takes longer time to reduce the concentration levels below lower flammability limit of hydrogen. Test 1 with injected volume of 5.93 m^3 takes about 22 hours as compared to 2 hours for Test 3 with injected gas volume of 1.20 m^3.

This work will be extended with additional test cases in order to take into account the effects of leakage orientations in free volume or with an obstacle (a model or real vehicle) inside GARAGE. In addition to concentration measurements, velocity and turbulence measurements will also be carried out with laser based techniques (Particle Image Velocimetry and Laser Doppler Velocimtry) for the precise definition of explosive atmosphere. The emphasis will also be given to investigate the mitigation measures using ventilation to reduce the risks lie in using hydrogen fuelled vehicles parked inside a garage.

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