EXPERIMENTAL RESULTS ON THE DISPERSION OF BUOYANT GAS IN A FULL SCALE GARAGE FROM A COMPLEX SOURCE.

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ABSTRACT

The lack of experimental data on hydrogen dispersion led to the experimental project DRIVE (Experimental Data for Hydrogen Automotive Risks Assessment, for the validation of numerical tools and for the Edition of guidelines) that involves the CEA (French Atomic Energy Commission), the National Institute of Industrial Environment and Risks (INERIS), the French car manufacturer PSA PEUGEOT CITROËN and the Research Institute on Out of Equilibrium Phenomena (IRPHE). The CEA has developed an experimental setup named GARAGE in order to analyze the condition of formation of an explosive atmosphere in an enclosure. This is a full scale facility in which a real car can be parked. Hydrogen releases were simulated with helium which volume fraction was measured with mini-katharometers. These thermal conductivity probes allow spatial and time volume fraction variations measurements. We present experimental results on the dispersion of helium in the enclosure due to releases in a typical car. The tested parameters are the location of the source (engine, bottom of the car, storage) and the flow rate. Emphasis is put on the influence of these parameters on the time evolution of the volume fraction in the enclosure as well as on the vertical distribution of helium.

1. INTRODUCTION

The problem of concentration build-up in an enclosure during the release of a buoyant fluid finds some applications in various fields of fluid mechanics. It was used as a fundamental model in geophysical fluid mechanics but it is also of practical interest in some industrial process, room natural ventilation or safety. This last item is concerned when the buoyant fluid is a potentially flammable gas mixture. Few decades ago the use of natural gas in private dwellings was one of the motivations for safety studies based on this particular problem. As hydrogen is expected to come into widespread use in the near future, this problem of the concentration distribution in enclosure finds a renewed interest.

The distribution of the buoyant gas in the enclosure depends on the release rate, momentum and buoyancy flux, the volume of the enclosure and the position of the source. Different regimes have already been identified. On one hand, for a highly energetic jet compared to the potential energy required to mix the entire volume of the enclosure the concentration is constant. On the other hand, for plume release with low momentum, Baines and Tuner [1] shows that a stratified layer can grow down from the ceiling. Between these two situations, Cleaver, Marshall and Linden [2] have shown that some releases can lead to a more complex vertical structure with an upper well-mixed layer under which a stratified layer grows down. They also have derived a simple model that takes into account this well-mixed layer. In recent experiments with helium as the buoyant gas, Gupta *et. al.* [3] have obtained similar results. Continuous efforts are made to improve numerical tools in order to give quantitative information for safety studies (see *e.g.*, [4], [5] and [6]).

In most of these studies on the concentration distribution within an enclosure, the experiments are usually based on simple situations with a single axisymmetric source with variable injection directions (see *e.g.* [3] and [7]). Nevertheless, if a nominal or accidental leak occurs in a hydrogen energy based system, the jet or plume is more likely to take place inside the system. The mixture that fills the volume of the enclosure must arise from the system as a pre-diluted plume of complex geometry and variable surface. We present an experimental study on the concentration distribution in an enclosure comparable to a private garage following the release of a buoyant gas in a real car. Helium is used as a model gas for hydrogen. The focus is made on the influence of the source type, location and flow rate on the vertical distribution of concentration in the enclosure.

After the description of the experimental set-up in section 2, results without the vehicle are described in section 3. These results are used as reference cases to compare with the case of releases in the car which is presented in section 4. Conclusions are drawn in section 5.

2. EXPERIMENTAL SETUP

The experimental set-up is the same as the one used by Gupta *et. al.*[3]. It is mainly composed of a parallelepiped enclosure of 5.76m long, 2.96m wide and 2.42m high with a typical garage tilting door of 2.32m wide by 1.99m high on the front for the car access and a classical door of 0.81m wide by 2.02m high on the back for human access. A vent of 200mm diameter is located 160mm above the floor in the middle of the rear side. This vent is opened during gas injection to maintain atmospheric pressure in the enclosure and closed after the release. The enclosure is made of a stainless steel structure and extruded polyester panels. Every joint between the metallic structure and the panels are sealed with aluminum tape. The tilting door and the back door are also sealed with aluminum tape for all experiments. The tracer gas decay method has been used to measure the air change per hour (ACH) with an initial volume fraction of helium of 3% and 4%. In both cases, this gives an ACH of 0.01h^{-1} when the bottom vent is closed and 0.1h^{-1} when it is open.

For experiments with the car, a light commercial vehicle which over all width is 1.96m, length is 4.14m and height is 1.81m, is used. The sources were located under the front bonnet, under the engine and under the passenger cell (see Fig. 1). Sources labeled I1 and I3 are diffuse. The helium flows through a foam block at the exit of the tube which makes buoyancy dominant near the exit even for large flow rate. Sources I3b and I5 are downward jets of 6mm and 17mm in diameter respectively. Without the car the source is a jet of 70mm in diameter placed at the center of the enclosure (labeled as source A) or at a location equivalent to that of the I3 source, *i.e.* 1.9m from the tilting door (labeled source B). The height of injection was 210mm.

Local time variations of the volume fraction are measured by Mini-katharometers TCG-3880 from Xensor. These are thermal conductivity gauges sensitive to the surrounding gas composition. From manufacturer fact sensor long term accuracy is about 0.07% and short term accuracy is about 0.007%. Indeed, repeatability test on a typical experiment gives an absolute error on the volume fraction measurement of 0.1%. Measurements in the enclosure are made near the ceiling and along two vertical lines apart of the vehicle (see Fig. 1). The volume fraction was also monitored in areas of the vehicle where injection took place. All signals from the probes were acquired on a computer at a sampling period of 5s. In addition temperature measurements are made with thermocouples at 10 locations in the garage.

Helium flow was controlled using mass flow regulators. Two flow rates were tested, 190±3Nl/min and 569±5Nl/min. For all the experiments the injected volume was 1.09±0.02m^3 which gives an average volume fraction of 2.6%. The injection duration T_{inj} was 316s for 190Nl/min and 105s for 569Nl/min.

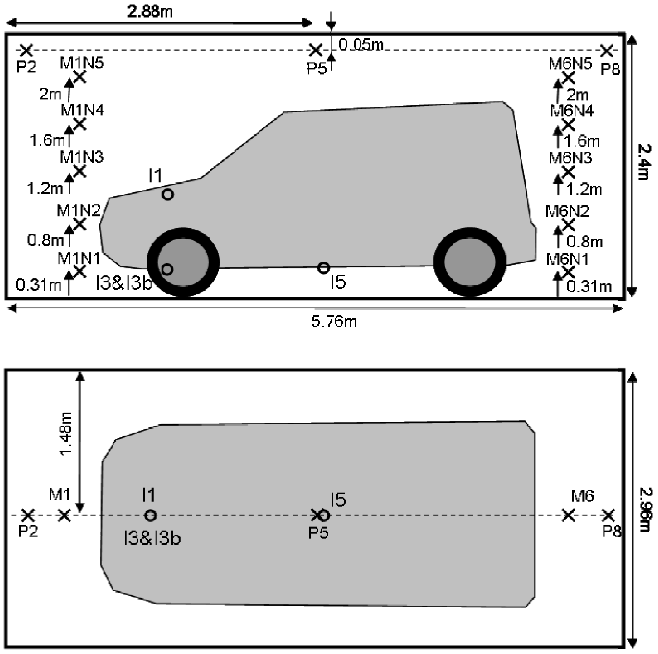


Figure 1: Positions and labels of the volume fraction probes (cross) and sources (circles).

3. DISPERSION IN THE ENCLOSURE WITHOUT THE VEHICLE

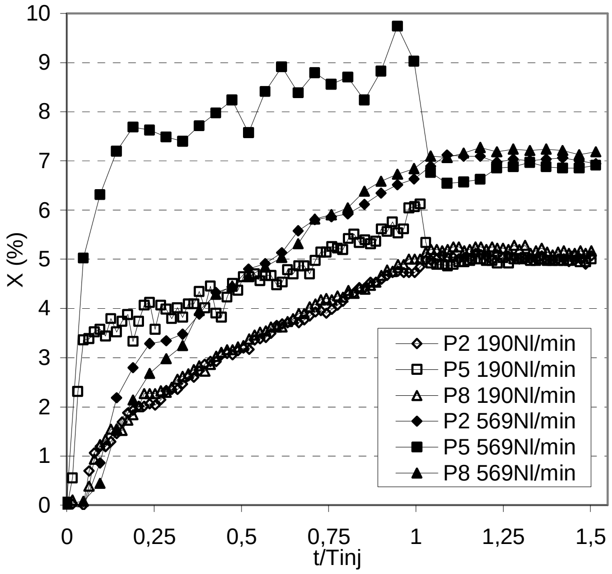
In this section, the results obtained by vertical releases in the enclosure without the vehicle are presented. We first monitored the time variations of the volume fraction near the ceiling during the injection. Then the final vertical distribution of volume fraction measured after the injection is presented.

The injection Richardson number is defined as:

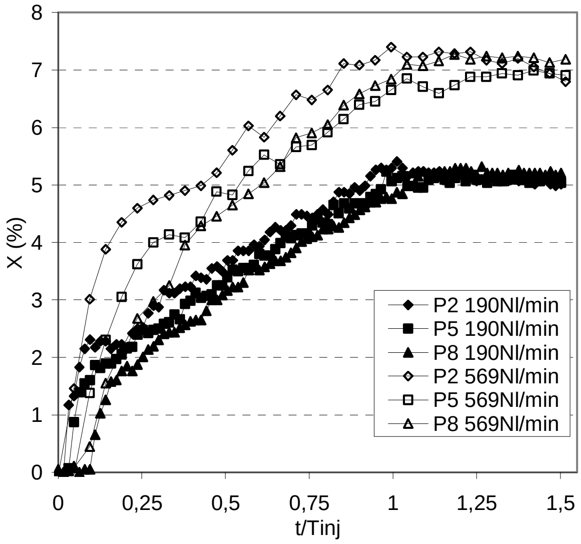
$$Ri_0 = \frac{(\rho_a - \rho_0)gD}{\rho_0 U_0^2},$$

where ρ_a and ρ_0 are the ambient and injected gas density respectively, D is the diameter of the nozzle, U_0 is the average exit velocity and g is the gravity acceleration. Its values are 5 and 0.6 for the flow rates of 190Nl/min and 569Nl/min respectively. For such values of Ri_0 the flow must be buoyancy dominated over most of the height of the enclosure.

The time variations of the volume fraction near the ceiling are monitored by the probes labeled P2, P5 and P8 (see Fig. 2). It is noteworthy that the P5 probe is on the vertical axis of the plume that rises from source A, whereas the plume that rises from source B impacts the ceiling between probes P2 and P5. Except for the P5 probe with the source A, all the records give the same kind of time variations composed of three stages. One first observes a waiting time during which the local volume fraction is zero. This delay of 10s to 20s depends on the considered probe. It corresponds to the sum of two characteristic time scales. The first is the time for the front of the plume to reach the ceiling and the second is the time for the gravity current that propagates along the ceiling to reach the probes. After this delay, the second stage is a rapid volume fraction increase. This is the consequence of the arrival of the front of the gravity current. The third stage is an approximately linear increase of the volume fraction due to the continuous input of helium by the plume and its accumulation in the enclosure.



a)



b)

Figure 2: Time evolution of the volume fraction measured near the ceiling during the injection without the vehicle with the sources A (a) and B (b).

The case of the time variations of volume fraction measured by probe P5 for an injection by the source A is particular due to the position of the probe. The main differences with the records of the other probes are the absence of delay, a high volume fraction increase and its decrease once the injection is stopped. A coarse estimate of the rise time of the starting plume gives less than 2s for it to reach the ceiling (see *e.g.* [8]). Considering the acquisition period of 5s, no delay should be observed. The decrease of volume fraction observed at the end of injection shows that there is a cloud of higher volume fraction in the plume impingement region than in the surrounding. This can be explained by the fact that there is almost no mixing with the surrounding in this region (see [9]). Away from this impingement region the flow becomes a gravity current in which mixing occurs due to entrainment. The resulting horizontal density gradient is maintained by the continuous supply of helium by the plume. Once it is stopped, the gravity acts to remove this horizontal density gradient which causes the decrease of volume fraction in the impingement region. The diameter of the plume at the level of the ceiling can be estimated to be 50cm for both injection flow rates. This value is consistent with the fact that the impingement region is not detected by probes P5 and P2 for the injections and the B source.

After the end of the injection, the volume fraction tends to a constant value of 5% and 7% for flow rates of 190Nl/min and 569Nl/min respectively. These values are the same for both positions of the source. The final volume fraction measured near the ceiling (Fig. 2) clearly shows the existence of a vertical stratification. The expected well-mixed layer from the model of Cleaver *et. al.* [2] does not appear clearly on the vertical volume fraction profiles (Fig. 3). However one can distinguish three regions. On a bottom layer of height 0.5m to 1m there is almost no helium. Then, between 1m to 1.5m there is a high variation of the volume fraction above which, in the third region, the volume fraction increase is smoother. The general characteristics of the volume fraction variations are in relatively good accordance with the model of Cleaver *et. al.* [2]. For a constant injected volume, a higher flow rate gives a higher maximum volume fraction and a lower injection time gives a higher region without helium near the floor.

Since the build-up of concentration in the enclosure can be considered one dimensional, it is possible to estimate the time variations of the average volume fraction and the equivalent mass of hydrogen as soon as an explosive atmosphere is created (Fig. 4). As expected, the highest flow rate gives rise to an explosive atmosphere in shorter time than the lowest flow rate. The average volume fraction and total equivalent hydrogen mass are also higher. In contrast the plots of the equivalent hydrogen mass evolution show a lower rate of increase for the highest flow rate, once time is normalized by the injection time. The final explosive atmosphere volumes are 17m^3 and 16m^3 for 190Nl/min and 569Nl/min respectively.

4. DISPERSION IN THE ENCLOSURE WITH THE VEHICLE

During injection from sources I1, I3 and I3b, helium is mainly dispersed in the engine compartment. After a transient increase of volume fraction of 10s to 30s, it reaches a steady state until the end of injection. Depending on the dispersion in the enclosure it has been observed that the steady state regime can be disturbed and the volume fraction slowly increases during all the injection. For injections from source I1, helium accumulates under the bonnet and leaves the engine compartment mainly through its perimeter. Injection with the source I3 leads to more dispersion of the helium in the engine compartment and part of it may exit by the grille and the wing valances. In the case of the injection from I3b the impinging jet can lead to a radial flow on the floor. The radius over which the flow spreads depends on the injection conditions and the distance between the source and the floor. Application of the experimental correlation obtained by Cooper and Hunt [10] leads to a spreading radius larger than 1m for the present injection conditions. Hence, part of the helium is dispersed outside the engine compartment directly in the enclosure whereas the other part remains under the vehicle bonnet and behaves as for the diffuse source I3.

The larger radius of the source I5 leads to a smaller radius of the spreading flow on the floor. This radius is not high enough to eject helium directly in the enclosure but it flows as a gravity current along the passenger cell floor and leaves the vehicle by its sides and rear. In addition to that a significant amount of helium flows through the central tunnel toward the engine compartment as it was observed by Maeda *et. al.* [11]. A steady state regime is reach under the car after about 20s and in the engine compartment after about 50s. In that case helium leaves the vehicle by its sides and also by the engine compartment.

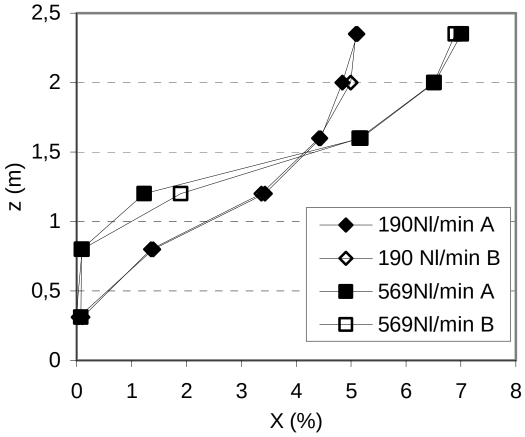
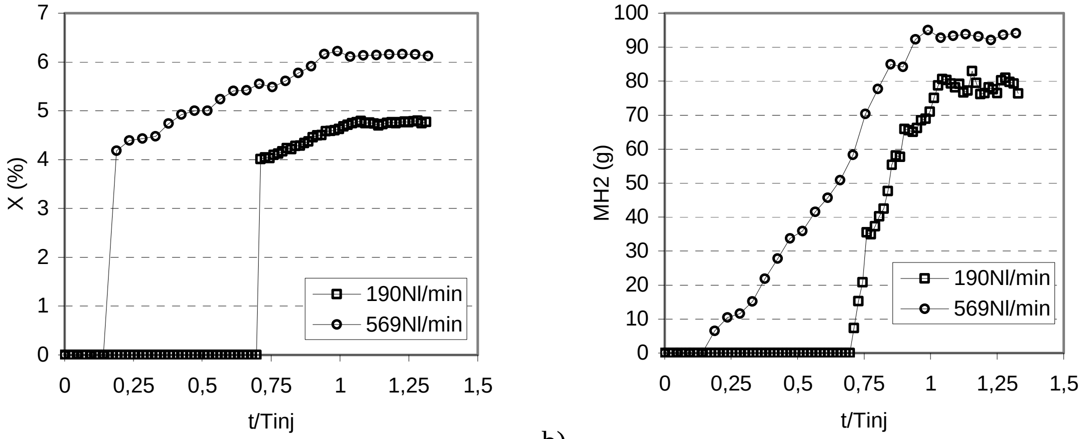


Figure 3: Vertical variations of the volume fraction for both flow rates and locations after the release at



a) b)

Figure 4: Explosive atmosphere properties evolution with time for injection with source A, average volume fraction (a) and equivalent hydrogen mass (b).

Whatever the source, an increase in the flow rates leads to an increase of the volume fraction in steady state in the area concerned.

As for the case of free volume injection, the time variations of the volume fraction are monitored at the same locations near the ceiling during the injection (Fig. 5).The general behavior is almost the same as in the free volume case. In particular the stages are the same. The first delay is longer since the paths of the flow are longer before it reaches any probes. The rapid increase of volume fraction is observed in all cases. It indicates that the build-up of the volume fraction in the enclosure starts with a gravity current flowing along the ceiling as in the free volume case. Once this initial gravity current reaches the sides of the enclosure, the volume fraction increase is approximately linear.

Some of the measurements seem to exhibit the behavior typically observed in the impingement region of the plume. This is the case of probes P2 and P5 for source I1 at 569Nl/min, P5 for source I3 at both flow rates, P2 for source I3b at both flow rates, P8 and P5 for source I5 at 569Nl/min and only P5 at 190Nl/min. These results suggest that the impingement region extends over a large area.

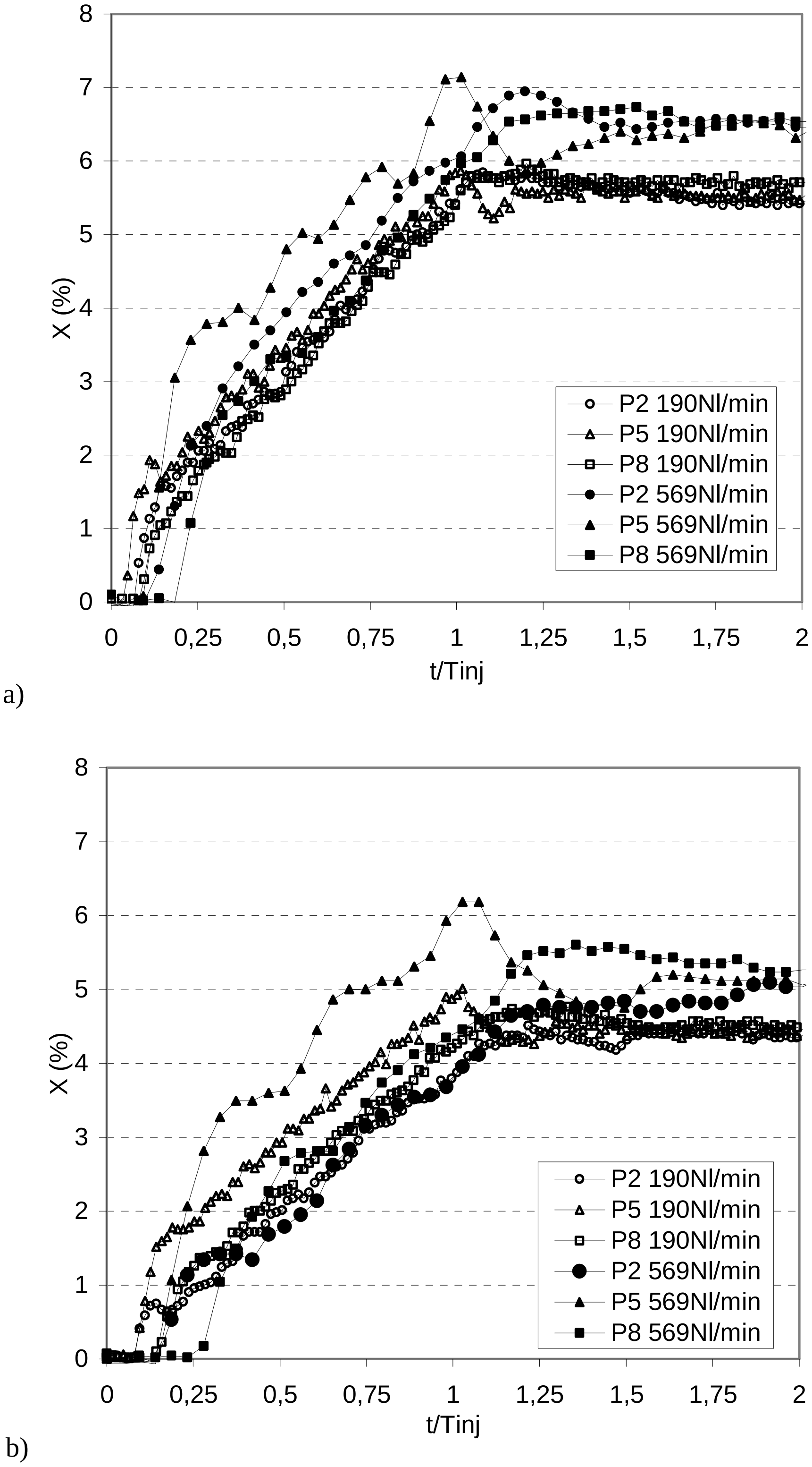
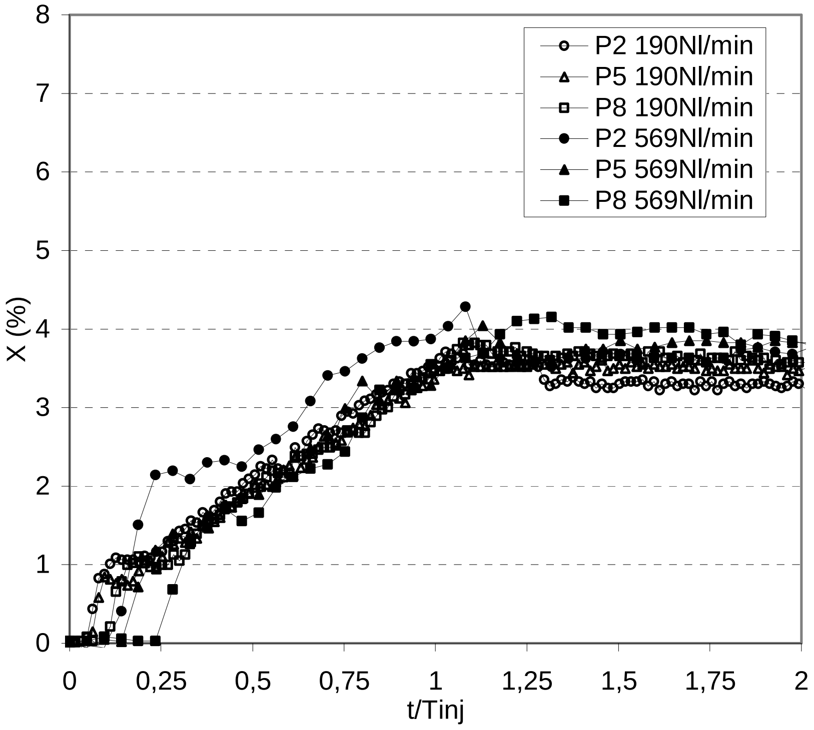
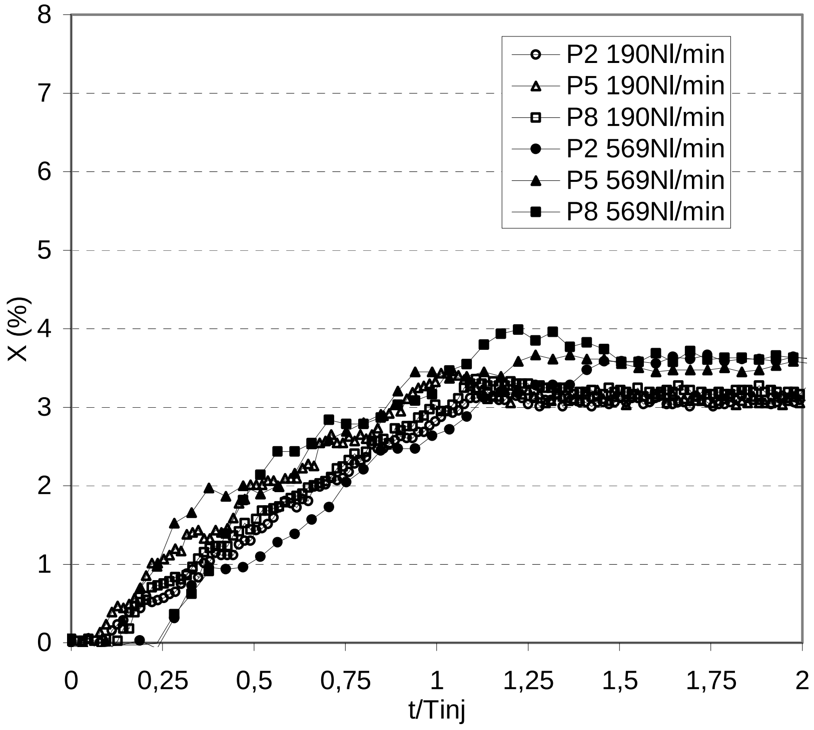


Figure 5: See the caption next page

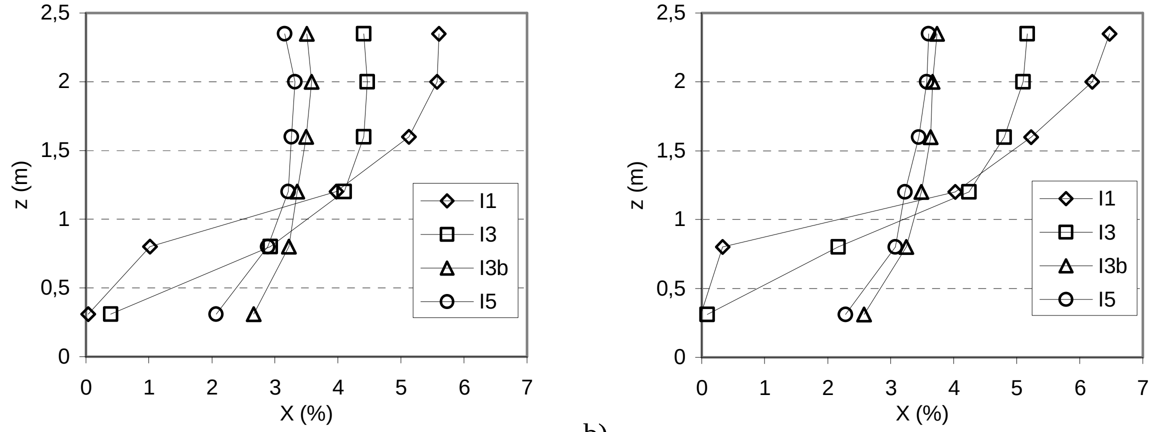


c)



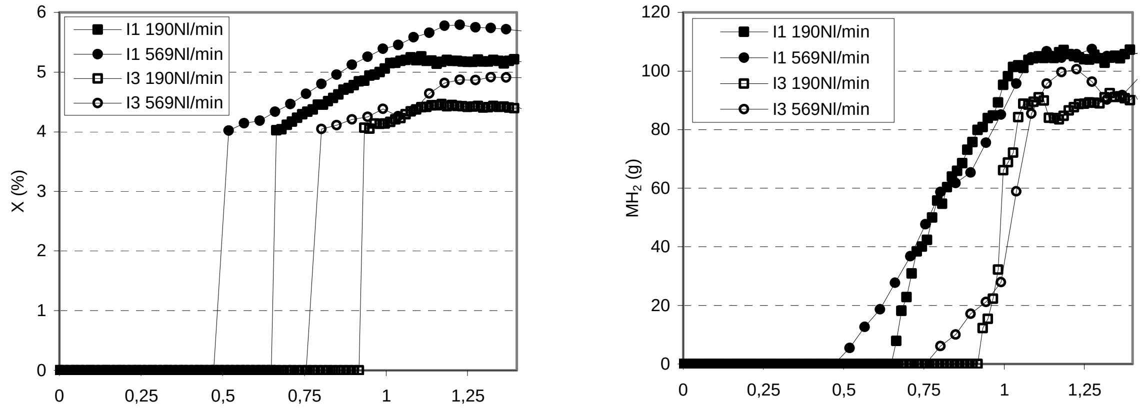
d)

Figure 5: Time variations of the volume fraction measured near the ceiling during injections through sources I1 (a), I3 (b), I3b (c) and I5 (d).



a) b)

Figure 6: Vertical profiles of volume fraction in the garage as a function of the source for 190Nl/min (a) and 569Nl/min (b), after the end of injection at $2T_{inj}$.



a) b)

Figure 7: Explosive atmosphere properties evolution with time for injection with source I1 and I3 in the vehicle, average volume fraction (a) and equivalent hydrogen mass (b).

At the end of injection some probes show a still-increasing volume fraction. This is due to the time needed for the helium to completely leave the vehicle. Then it tends to stabilized to a value strongly dependent on the source location between 4.5% and 6.5% for sources I1 and I3 and around 3.5% for sources I3b and I5. The influence of the flow rate during the increase of volume fraction and at the end is significantly weaker compared to the free volume case.

Measurements of the vertical volume fraction profiles for each source and flow rates show strong variations of the typical distribution depending on the source location (Fig. 6). With a release from source I1, the profile is very similar to the free volume case. The upper well-mixed layer is more visible and of comparable thickness. Under this layer the volume fraction rapidly decreases to zero at a comparable level. For this particular injection case, the most striking result is that the maximum volume fraction near the ceiling is very close to the free volume result and even higher for 190Nl/min. This may be a consequence of the small size of the rising plumes from the bonnet perimeter.

With a release from source I3, the rising plume must be larger. The consequences on the vertical volume fraction profile are a thicker well-mixed layer near the ceiling and an associated lower maximum volume fraction. As a confirmation of the influence of the horizontal extent of the rising plume from the vehicle, results for sources I3b and I5 show near homogenous vertical distributions of volume fraction. It is clear that both sources lead to very large plumes.

As for the time evolution, the vertical distribution is weakly influenced by the flow rate. Although the model from Cleaver *et. al.* [2] is not directly applicable in this complex geometry it can be used to help for the interpretation of these results. In this model, the vertical extent of the well-mixed layer depends mainly on the ratio of the distance between the source and the ceiling and the horizontal area of the enclosure. The presence of the vehicle increases the horizontal extent of the plume thus moving a virtual point source away from the ceiling. In Cleaver *et. al.* [2] model, moving the source away from the ceiling increases the thickness of the well-mixed layer. This is consistent with what we observed here.

The time evolution of the explosive atmosphere properties are deduced from the vertical variations of volume fraction (see Fig. 7). However, the approximation of a one dimensional build-up is less good in these cases because of the large extent of the plume. Obviously, only the cases of injections with sources I1 and I3 are plotted because the other two did not lead to the formation of an explosive atmosphere. As it is observed on Fig. 5 and Fig. 6, the flow rate has a weak influence on the equivalent hydrogen mass evolution and final value. In contrast, the influence of the flow rate appears clearly on the average volume fraction. This influence is the same as in the case of free volume injection, i.e., the average volume fraction increases with the flow rate. Although the time to achieve an explosive atmosphere is still lower for the highest flow rate, it is longer than in free volume injection. Source I3 injections give the longer time to achieve the explosive atmosphere. Also, one can notice that the increase rate of the equivalent hydrogen mass is much higher for this source. These two characteristics are consequences of the vertical volume fraction profile that exhibit a well defined homogenous layer near the ceiling. In all cases the total equivalent mass of hydrogen in the explosive atmosphere is higher than in the free volume cases. The final volume of the explosive atmosphere varies weakly for the different cases from 19m^3 to 21m^3.

5. CONCLUSIONS

In this set of experiments the build-up of concentration during injection of helium in an enclosure with a vehicle has been studied. The focus is the influence of the release flow rate, the source type and location in the car on the vertical structure of the volume fraction distribution. Reference experiments without the vehicle have also been conducted in similar conditions.

The flow rate has a weaker influence for releases in the vehicle than in the free volume case. In contrast, the results show a strong variability in the vertical distribution of volume fraction depending on the type and position of the source in the vehicle. Very confined diffuse sources give rise to stratified environment whereas impinging jets on the floor lead to a near homogenous mixture. The path of the gas to exit from the vehicle and the subsequent characteristic dimension of the plume that fills the enclosure seems to be the key parameter that controls the vertical distribution of volume fraction. The underlying mechanism may be the overturning of the flow when it reaches the sides of the enclosure after impinging the ceiling. The control parameter of this flow is mainly the ratio of the plume momentum flux at the ceiling to the buoyancy flux through the horizontal section of the enclosure as in the case of a single vertical axisymmetric plume (see [1]).

As a consequence of the large dispersion induced by impinging jets in case of sources I3b and I5, the lower flammability limit is not reached for the injected volume tested. Diffuse sources in the engine area give a stratification that leads to the formation of an explosive atmosphere as in the case of free volume injections. The results on the properties of this explosive atmosphere show that injection in the vehicle can lead to an increase of the equivalent hydrogen mass. Also, in some cases the formation of the explosive atmosphere is delayed by injection in the engine area. More generally, it is clear that the vertical distribution of volume fraction plays a major role on properties of the explosive atmosphere and there time variations.

ACKNOWLEDGEMENTS

The authors are grateful to M. Cazanou, J.-L. Widloecher and J.-L. Lejeune for technical assistance in the development of the GARAGE facility. This work has been supported by French Research National Agency (A.N.R.) through *Plan d'Action National sur l'Hydrogène et les piles à combustible* program (project DRIVE ANR05 PANH022).

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