EXPERIMENTS ON THE DISTRIBUTION OF CONCENTRATION DUE TO BUOYANT GAS LOW FLOW RATE RELEASE IN AN ENCLOSURE.

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ABSTRACT

Hydrogen energy based vehicles or power generators are expected to come into widespread use in the near future. Safety information is of major importance to support the successful public acceptance of hydrogen as an energy carrier. One of the most important issues in terms of safety is the use of such system in closed area such as a private garage in which a fuel cell car may be parked. This kind of situation leads to the fundamental problem of the dispersion of hydrogen due to a simple vertical source in an enclosure. Many numerical and experimental studies have already been conducted on this problem showing the formation of a stably stratified distribution of concentration. Most of them consider the cases of accidental situation in which the flow rate is relatively important (of the order of 10Nl/min to 100Nl/min). We present a set of experiments conducted on a full scale facility of the size of a typical private garage with helium as a model gas for hydrogen. In this study we focus on the low flow rates that can be characteristic of chronic leaks that may not be detected by security devices of the system (of the order of 0.1Nl/min to 10Nl/min). The facility allows changing natural ventilation conditions and experiments have been conducted from the tightest which is less than 0.01ACH, to that typical of a real garage, say, of the order of 0.1ACH.

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, the position of the source and the ventilation conditions of the enclosure. Different regimes have already been indentified. Without ventilation there are mainly two regimes depending on the ratio of the injected momentum to the potential energy required to mix the entire volume. If the injected momentum is high enough, the entire volume can be mixed resulting in a constant concentration over the space. If not, a vertical stratification takes place. The jet or plume impacts the ceiling and spreads toward the side walls after what a horizontal density front moves downward. Baines and Tuner [1] give an analytical description of the velocity of the first front and the final density profile once the front has reached the floor. Their model is extended by Worster and Hupper [2] to describe the time evolution of the vertical density profile during the first stage of descending front. In some cases, Cleaver, Marshall and Linden [3] show that the vertical density profile exhibits a well defined homogenous layer near the ceiling under which the density increases linearly. If the enclosure has openings, exchanges with the exterior are allowed. Linden, Lane-Serff and Smeed [4], identify two regimes depending on the number and position of openings, a mixing regime in the case of a single opening located near the ceiling and a displacement regime in the case of two openings near the floor and near the ceiling. In the first case, the density should be almost homogenous or weakly stratified. In the later case, a strong stratification stands with two well indentified layers. In the case of a single opening near the floor, fresh air has tendency to occupy the lower part of the enclosure up to the top of the opening. The mixing and displacement regimes have been identified on small scale salt water experiments. In a full scale experiments with gas including wind effects in the configuration with two vents performed by Lowesmith *et. al.* [5] a steady state regime with a well defined two layers vertical structure is clearly indentified.

Most of the experimental studies on the concentration build up in an enclosure are related to some accidental scenarios for which the flow rate of the release is relatively high (see *e.g.* [5] and [6]). Here we are interested in the evolution and distribution of concentration in the enclosure in case of low flow rate release. In particular the focus is on the influence of natural ventilation on the vertical distribution of concentration. In these purposes a set of experiments has been conducted on a full scale facility which dimensions are typical of a room or a private garage. Helium is used as a model gas of hydrogen. In the following section 2 a description of the experimental setup and condition is given. Section 3 is devoted to the results obtained in the limit of no exchange between the enclosure and the exterior. Influences of the weak distributed leaks of the enclosure are presented in section 4. Section 5 deals with the influence of an open vent and its position on the build up. The scaling law for hydrogen releases and properties of the flammable atmosphere are presented in section 6. Finally, main conclusions are drawn in the last section.

2. EXPERIMENTAL SETUP AND CONDITIONS

The experimental set-up is the same than that used for the study of Gupta *et. al.*[6]. It is an indoor 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 and a classical door of 0.81m wide by 2.02m high on the back for human access. One vent of 200mm diameter is located 160mm from the floor at the middle of the back side and another of the same dimension is located 180mm from the ceiling on the front side. Both of these vents link the enclosure to the experimental hall. The enclosure is made of a stainless steel structure and extruded polyester panels. Every joint between the metallic structure and panels is sealed with aluminum tape.

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 the long term absolute error on the volume fraction measurement is about 0.07%. The sensors are located at five levels along six vertical lines (see Fig. 1). Temperature measurements are made with thermocouples at 10 locations in the enclosure near the floor and near the ceiling.

Helium is injected through a 70mm diameter vertical nozzle which exit is 210mm from the floor. The flow rate is controlled with mass flow regulators between 0.1Nl/min and 18Nl/min. A summary of the experimental conditions is given in Table 1. With the diameter D of the nozzle, the density ρ_a of the ambient and ρ_0 of the helium injected, the volume flow rate at the nozzle Q_0 and the gravity acceleration g, the injection Richardson number is defined as (see e.g. [3]):

$$Ri_0 = \frac{\pi^2}{32}\frac{\rho_a - \rho_0}{\rho_0}\frac{gD^5}{Q_0^2} . \quad (1)$$

Its order of magnitude for the tested flow rates varies from 10^2 to 10^7 which indicates that in all cases the flow is highly dominated by buoyancy as soon as the fluid exits the nozzle.

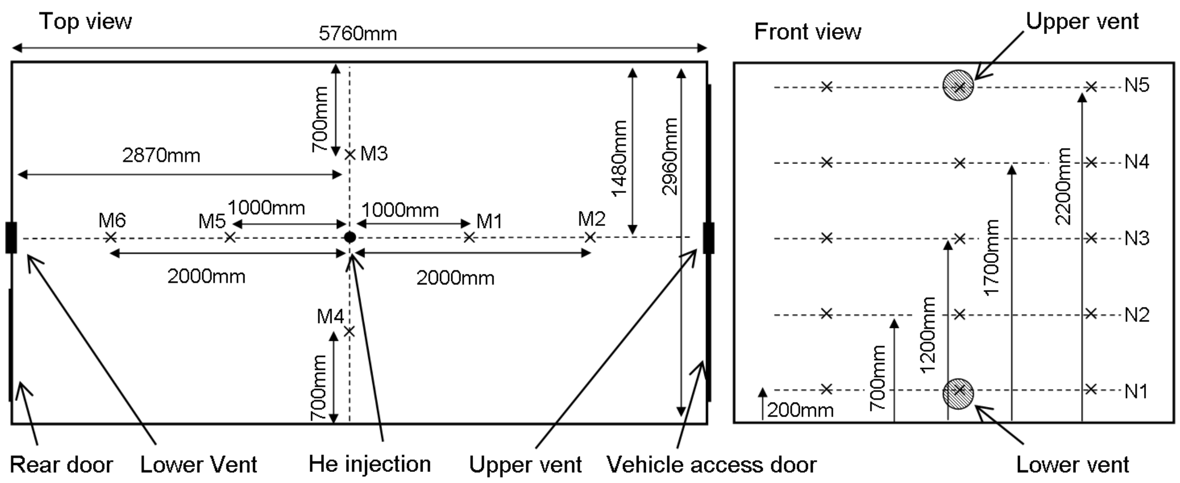


Figure 1: Schematic representation of the experimental set-up with source and volume fraction measurement probes (cross) locations.

Table 1 : Summary of the experimental conditions

Open vent	Q (Nl/min)	T (°C)	Q (10^{-6} m^3/s)	Injection time (h)
No	0.5	18.1	9	23.5
No	1	17.2	18	50.8
No	2	17.7	35	29
No	6	17.2	106	22.4
No	10	17.9	178	8.5
No	14	18.2	249	5.7
No	18	18	320	2.8
Lower	0.1	19.8	2	78.2
Lower	0.5	18.6	9	97.2
Lower	1	18.5	18	76.1
Lower	2	18.5	36	47.2
Lower	3	20.9	54	46.7
Lower	5	19.7	89	28.3
Lower	6	18.1	107	22.6
Lower	10	19.4	179	28.8
Lower	14	19.8	250	21.9
Lower	18	19.3	321	20.4
Upper	0.1	20.1	2	72
Upper	0.5	20	9	95
Upper	1	19.7	18	73.6
Upper	2	20.8	36	43.1
Upper	5	19	89	24.7
Upper	6	20.9	108	22.9
Upper	8	20.5	143	21.9
Upper	10	20.8	179	18.6
Upper	14	19.7	250	14.2
Upper	18	21	323	10.2

The natural ventilation conditions of the enclosure can be varied by any combination of open or close vents, sealed rear door with aluminum tape and obstructed front door. The tightest configuration is obtained when all doors are sealed and vents are closed. For the two other configurations tested here the rear door is left unsealed, the front tilting door is sealed and one of the vent is opened. For these three configurations, the natural ventilation or leakage rate of the enclosure is estimated by the tracer gas decay method. The initial volume fraction for this measurement is 2% in all cases. The air change per hour (ACH) is deduced after exponential fitting of the volume fraction decay. In the tightest case the ACH is less than $0.006h^{-1}$ whereas with one open vent it gives about $0.07h^{-1}$ whether the open vent is near the floor or near the ceiling. For the 40.92 m^3 enclosure, this corresponds to volume flow rates of $0.1\ 10^{-3}m^3/s$ and $10^{-3}m^3/s$ respectively. It is noteworthy that due to the location of the enclosure in an experimental heated hall, one can consider the enclosure in thermal equilibrium with the hall. So that, exchanges between the enclosure and its exterior are more likely to be due to composition gradients than temperature gradients. Hence, the ventilation rates measured with the tracer gas decay method depends on the initial helium volume fraction. The ventilation rates obtained should be interpreted in terms of order of magnitude.

3. CONCENTRATION BUILD UP IN THE LIMIT OF PERFECTLY SEALED ENCLOSURE

The limiting case of perfectly sealed enclosure can be experimentally achieved, provided that the configuration is the tightest and experiments time scale is short enough. The validity of the perfectly sealed assumption is checked by comparison of the evolution of the average volume fraction with what should be expected theoretically. This is shown on Fig. 2a where time is normalized by the theoretical volume fraction increase rate, Q_0/V, with V the enclosure volume. For the considered injection durations, this shows a good accordance with the expected increase of volume fraction.

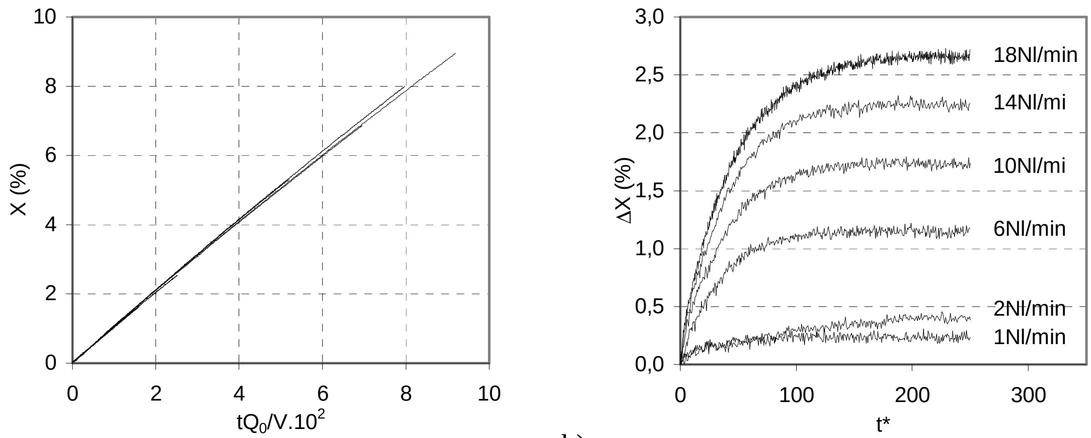
During the injection, setting up of a vertical gradient is measured. Fig. 2b shows the time evolution of the volume fraction difference, ΔX, between the lowest and highest measurement levels (respectively 200mm from the floor and 220mm from the ceiling). Time is normalized after Baines and Turner [1] as :

$$t^* = H^{2/3} A^{-1} B_0^{1/3} t \tag{2}$$

with A the horizontal cross section of the enclosure, H is its height and B_0 the injection buoyancy flux defined as :

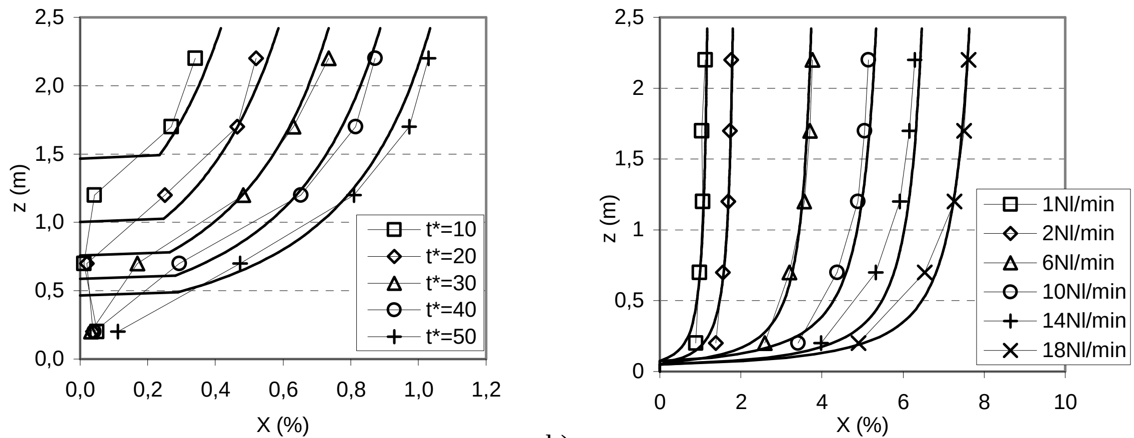
$$B_0 = g \frac{\rho_a - \rho_0}{\rho_a} Q_0 . \tag{3}$$

After a first stage of increase, ΔX reaches a constant value ΔX_s which is what is expected from theoretical work of Baines and Turner [1] and Worster and Huppert [2]. During the first stage the initial front that formed near the ceiling moves downward. The second stage is reached once the initial front has reached the floor. Baines and Turner [1] give the analytical expression for the first front downward velocity and the asymptotic state vertical profiles as time tends toward infinity, whereas Worster and Huppert [2] give the analytic and numerical solutions for the vertical profile during the first stage. Fig. 3 shows the fairly good accordance of the measured profiles with the analytic model derived by Worster and Huppert [2] during the first stage (Fig. 3a) as well as during the second stage (Fig. 3b). In these theoretical works, the authors introduce the entrainment coefficient. The best fit to our data is obtained by varying this coefficient from 0.06 to 0.08. This value compared well with that of 0.1 used by Baines and Turner [1] to fit the model to there experimental data. The variation of ΔX_s with respect to the injection flow rate is compared to the theoretical result on Fig. 4. The best fit to the experimental data is obtained for an entrainment coefficient of 0.078 for all the range of flow rates.



a) b)

Figure 2: Normalized time evolution of the average volume fraction (a) and vertical volume fraction difference (b) for flow rate from 1Nl/min to 18Nl/min.



a) b)

Figure 3: Vertical profiles during the propagation of the initial front for 6Nl/min (a) and once the front has reach the floor (t*=250) for each flow rate (b). Continuous curves represent the model.

4. INFLUENCE OF SMALL DISTRIBUTED LEAKS OF THE ENCLOSURE

Increasing the injection time in the same configuration leads to an increasing influence of the leaks. This is observed by a lower value of the volume fraction than that expected for a perfectly sealed enclosure. We refer here to distributed leaks because there is no identified opening of the enclosure and exchanges with the exterior may take place anywhere. Fig. 5 shows the time evolution of ΔX with normalized time t^* (see eq. 3) and normalized volume fraction difference by ΔX_s. With this normalization all the data collapse on the same curve. The effect of the entering fresh air is to increase ΔX. Although the flow rate of fresh air and its associated characteristic velocity must be very low, this increase suggest that the entering air is flowing downward and dilute the mixture near the floor. The result obtained for 1Nl/min exhibit a homogenous stage for normalized time ranging from 700 to 800. A close look at the variations during the homogenization shows that the characteristic time for this homogenization is very short compared to diffusion time.

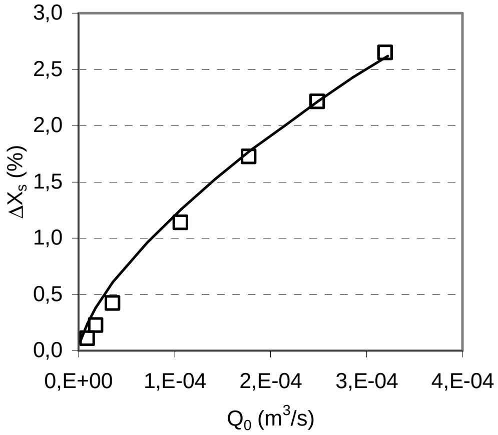


Figure 4: Steady state vertical volume fraction difference as a function of the flow rate, measurement (square) and model (continuous line).

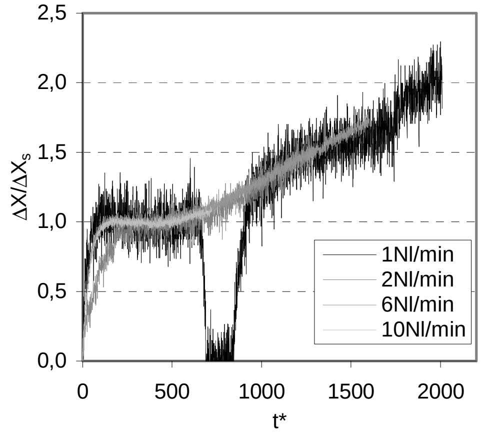


Figure 5: Long term evolution of ΔX normalized with its value ΔX_s during the steady state stage.

Hence, this must be a consequence of convective mixing. Indeed, the monitoring of temperature shows that it is constant over the height of the enclosure during this event while a small stable temperature gradient of about 0.2°C is maintained before and after. The convective mixing may be due to an inversion in the temperature gradient. The vertical density difference over the height of the enclosure associated to the helium volume fraction is of 0.003kg/m^3 before the mixing. Such low density stratification may turn unstable if the enclosure upper part temperature decreases of only 1°C. Yet, during the homogenous stage, the average temperature in the enclosure decreases of slightly more than 1°C. It is interesting to note that once the temperature gradient is again stable, the new volume fraction stratification takes place as if homogenization had not occurred.

Vertical profiles are plotted on Fig. 6 normalized by the average volume fraction in the case of a release at 6Nl/min. The normalized profile significantly changes with time for *t** lower than 500. This is a consequence of the normalization by the average volume fraction because the vertical volume fraction difference is constant while the average increases. In contrast, when the leaks of the enclosure become significant, the normalized vertical profile tends to an auto-similar shape. The shape of the vertical profile is very similar to that of the perfectly sealed enclosure with a decrease of volume fraction mainly located near the bottom along about one third of the total height.

5. OPEN VENT INFLUENCE

In this section we present the results obtained with one open vent. This vent is located either near the floor or near the ceiling. In both cases, the value of the ACH is 0.07h^{-1} which is much higher than in the previous case. Thus one can consider that all exchanges with the exterior will take place at the vent through which the mixture leaves the enclosure while fresh air enters. Thanks to this relatively high value of the ACH it was possible to conduct each experiment until the full steady state is reached.

Applying the mass conservation in the enclosure in the Boussinesq approximation with the hypothesis of a homogenous mixture and an exchange volume flux across the opening independent of the buoyancy leads to a first estimate of the steady state concentration given by :

$$X = \frac{Q_0}{Q_0 + Q_e}. \tag{7}$$

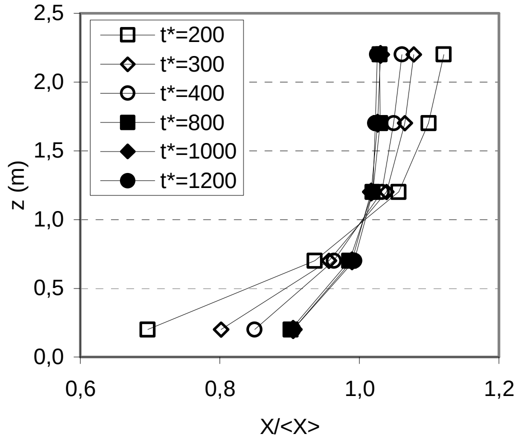


Figure 6: Vertical profiles normalized with the average volume fraction at different normalized time for a release at 6Nl/min. The corresponding average volume fraction are : 0.25%, 0.42%, 0.55%, 1.12%, 1.40%, 1.67%.

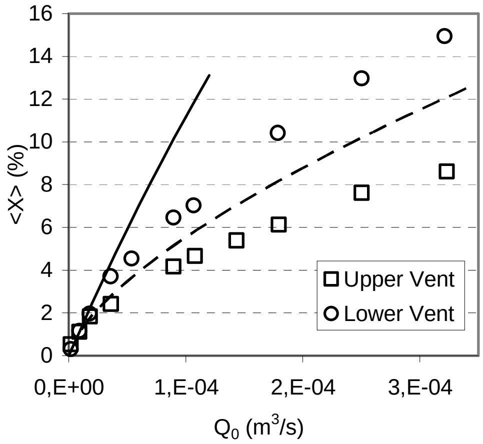


Figure 7: Average volume fraction as a function of the injection flow rate. The continuous curve corresponds of eq. 7 and the dashed curve corresponds to eq. 10.

This raw estimate may be enhanced by considering that the exchange volume flux depend on the density gradient across the opening. Still considering homogeneity in the enclosure and the Boussinesq approximation, the exchange volume flux can be expressed as (see [7]):

$$Q_e = C_D S (g'h)^{1/2} \tag{8}$$

with S and h respectively the surface and height of the opening and C_D is a discharge coefficient that depends on geometrical properties of the opening. The reduced gravity g' is defined as :

$$g' = g\frac{\rho_a - \rho}{\rho_a} = g\frac{\rho_a - \rho_0}{\rho_a}X = g'_0 X \tag{9}$$

Applying mass conservation with this value of the exchange volume flux gives the following expression for the steady state concentration :

$$X = \left[\frac{Q_0}{C_D S (g'_0 h)^{1/2}}\right]^{2/3}. \tag{10}$$

The discharge coefficient has been measured by maintaining homogeneity in the enclosure with fans during the filling until steady state regime is reached. This gives the value of 0.07.

Fig. 7 shows the average volume fraction in the enclosure as a function of the injection flow rate and the position of the opening. The continuous curve corresponds to eq. 7 and the dashed curve corresponds to eq. 10 with the measured discharged coefficient. As expected, the steady state average volume fraction at a given flow rate is always lower if the opening is near the ceiling (see e.g. [8]).

For flow rates lower than 5 10^{-5}m^3/s, both theoretical estimations fit well with measurements independently of the position of the opening. For higher values of the flow rate, the model based on a constant exchange flow rate (eq. 7) always overestimates the average concentration wherever is the opening. This is due to the fact that the exchange flow rate used has been measured for a volume fraction in the enclosure of 2%.

The average volume fraction estimated by eq. 10 gives a more realistic result but the measurements are higher when the opening is near the floor and lower when the opening is near the ceiling. This is due to the formation of a vertical stratification in the enclosure. The actual volume fraction near the ceiling is higher than the average value. The density gradient across the opening at upper level is higher which increases the exchange volume flux with the exterior and decrease the steady state volume fraction. In the same way, the volume fraction near the floor is lower than the average so that density gradient across the low level opening is weaker. The exchange volume flux with the exterior is lower and the steady state volume fraction is increased compared to the homogenous case. However, Fig. 8 shows that the average and local volume fraction are proportional to $Q_0^{2/3}$ deduced from eq. 10.

The vertical volume fraction difference as a function of the injection flow rate is plotted on Fig. 9. It shows that the vertical difference increases with the flow rate and is always lower when the opening is near the ceiling. In both cases, it may be significant for flow rate higher than about 10^{-4} m^3/s with more than 1%.

The comparison of vertical profiles normalized with the average volume fraction (see Fig. 10) shows that the structure of the distribution changes with the position of the opening. In both configurations, there is clearly an upper homogenous layer under which the volume fraction decreases. But, this layer is thicker if the vent is near the floor. The normalized volume fraction near the floor is lower in that case while its maximum value seems to be unaffected by the position of the vent. Fresh air entering the enclosure has the natural tendency to flow downward or to stay near the floor. When fresh air comes from the opening near the ceiling, it produces a downward plume that entrains some helium so that it is no longer fresh when the plume reaches the floor. In contrast, when the opening is near the floor the lower part of the enclosure is mixed with fresh air. The downward fresh air plume promotes mixing over a higher distance whereas mixing is confined to the lower part of the enclosure when fresh air enters near the floor.

6. SCALING ON HYDROGEN RELEASE AND FLAMMABLE ATMOSPHERE PROPERTIES

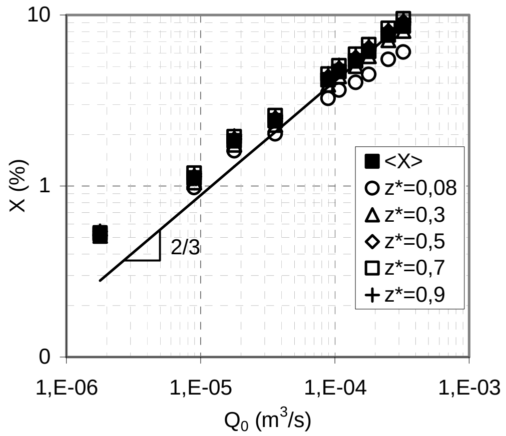
In these experiments helium is used instead of hydrogen. The suitable scaling law has to be applied to recover the expected results in the case of hydrogen. The eq. 10 can be applied to derive the relationship between the hydrogen volume flow rate Q_{H2} and the helium volume flow rate Q_{He} that is supposed to give the same volume fraction. This gives the following scaling law which is consistent with the dimensional analysis by Linden [8] :

$$Q_{H_2} = \left(\frac{g'_{H_2}}{g'_{He}} \right)^{1/2} Q_{He} \tag{11}$$

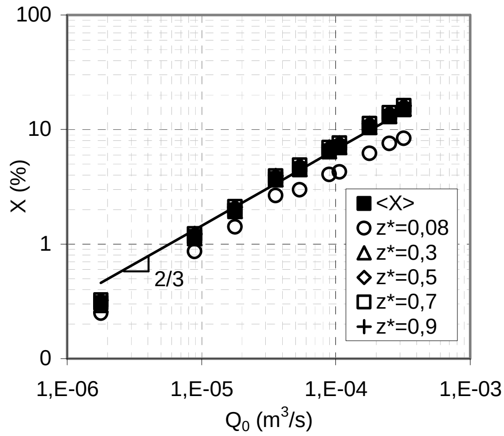
where g'_0 with 0 the considered gas index, is the reduced gravity at the source :

$$g'_0 = g \frac{\rho_a - \rho_0}{\rho_a} . \tag{12}$$

This definition implies the Boussinesq approximation. Considering transient stages, time has to be rescaled with the same law. The rescaling applies both on the perfectly sealed enclosure and on the enclosure with opening cases. In this section we focus only on the results obtained with one opening.



a)



b)

Figure 8: Variations of the steady state volume fraction as a function of the injection buoyancy flux in the case of the upper vent (a) and the lower vent (b).

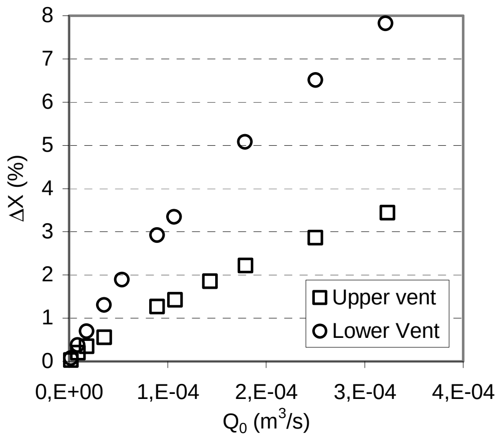


Figure 9: Variations volume fraction vertical difference as a function of the injected flow rate.

Application of the rescaling on the maximum flow rate for which the volume fraction will stay below 4% is 4.38 $10^{-5}m^3/s$ for the vent near the floor and 8.8 $10^{-5}m^3/s$ for the vent near the ceiling. At 18°C this gives 2.5Nl/min and 4.9Nl/min respectively. For flow rates that give rise to a flammable atmosphere, data on the time and vertical variations of the volume fraction can be used to estimate its properties. Linear interpolation is used to estimate the vertical position at which the volume fraction reaches 4%.

Trapezoidal integration is used to compute the average volume fraction from that height to the ceiling. The volume fraction at the ceiling is supposed to be equal to the one measured at the highest level. At the floor level, linear extrapolation is used.

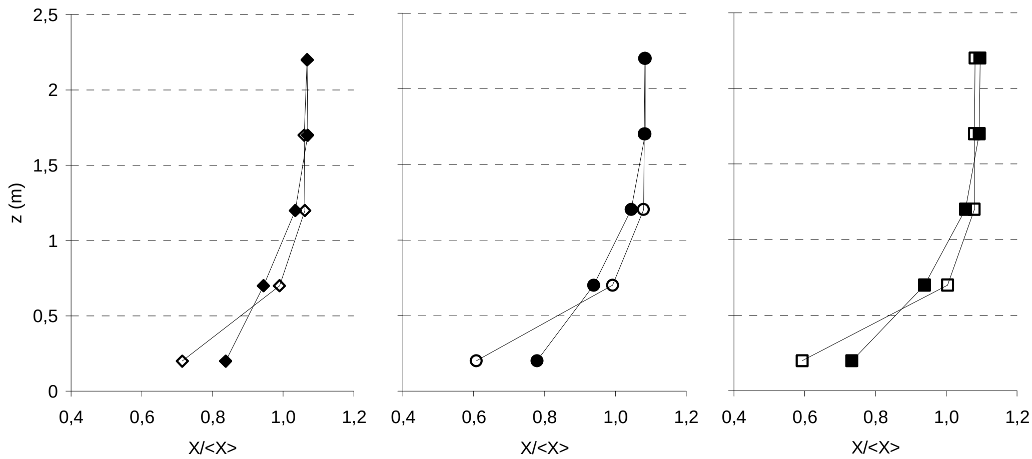
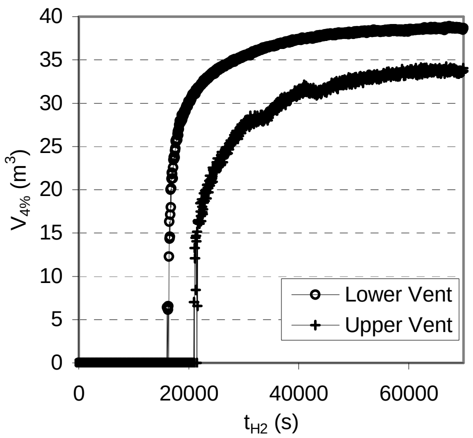
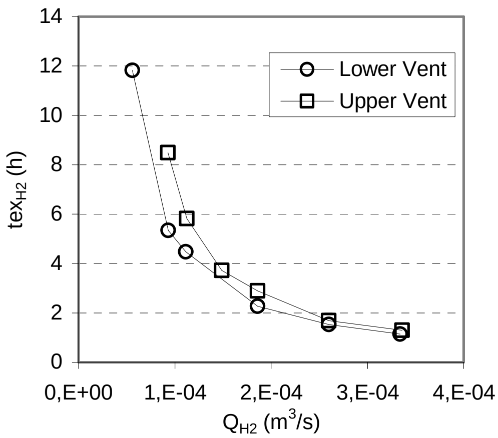


Figure 10: Steady state vertical profiles normalized with the average volume fraction for the vent near the floor (empty symbols) and near the ceiling (filled symbols)



a)

Figure 11: Time variations of flammable atmosphere volume for a release at 6Nl/min. Time is rescaled for hydrogen release case.



b)

Figure 12: Time needed to produce a flammable atmosphere as a function of the volume flow rate. Time and flow rate are rescaled for the hydrogen release case.

Plots on Fig. 11 show the typical time evolution of the flammable atmosphere volume in both configurations for an injection flow rate of 6Nl/min. For this plot cubic spline interpolation is used to determine the height at which the volume fraction reaches 4%. Due to the nearly homogenous layer near the ceiling the volume increase is very stiff at the beginning. Since this homogenous layer is thicker in the case of the lower opening, the first jump of the volume is higher with about $20m^3$ whereas it jumps at about $15m^3$ in the case of the upper opening. After this first jump the growth rate of the volume decreases to tend to a constant value once steady state is reached. The injection time necessary to form a flammable atmosphere is significantly higher if the opening is near the ceiling in the case of low injection flow rate (Fig. 12). For increasing flow rate, this time tends to be very similar in both configurations.

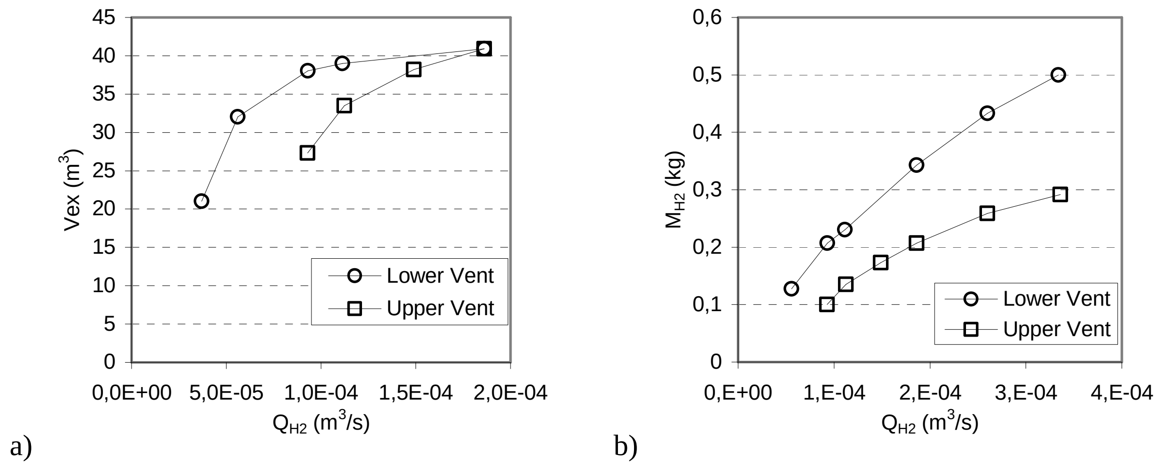


Figure 13: Variations of the flammable atmosphere volume (a) and equivalent hydrogen mass (b) as a function of the injection volume flux rescale for hydrogen release.

Fig. 13 shows the main characteristics of the flammable atmosphere in steady state regime. As it can be expected, the position of the opening has a strong influence on both the volume and the hydrogen mass in the flammable atmosphere. Its volume extends to the entire enclosure for equivalent hydrogen flow rate higher than 1.8 $10^{-4}m^3/s$.

7. CONCLUSION

Experiments on the build up of concentration in an enclosure due to a helium plume have been conducted. The enclosure size is typical of a private garage. The volume fraction vertical distribution has been studied for three different ventilation conditions. First, the perfectly sealed enclosure limit is reached if the injection time is short enough while there is no opening to the exterior. Still without opening, the second ventilation condition corresponds to the influence of small distributed leak with the exterior for long term injections. The third case studied is the influence of an opening on one of the vertical wall of the enclosure. In this last configuration the exchange flow rate with the exterior is much higher than in the distributed leak case. Steady state regime has been reached and the opening vertical location influence has been investigated. The helium flow rate was varied from 2 $10^{-6}m^3/s$ to 320 $10^{-6}m^3/s$ which corresponds to 0.1Nl/min to 18Nl/min at 18°C.

In the limit of perfectly sealed enclosure, the vertical volume fraction difference between the ceiling and the floor tends to be time independent. Its value depends on the height of the enclosure, the injected buoyancy flux and the entrainment coefficient. Spatial and time variations of the volume fraction are in good accordance with the theoretical model of Worster and Huppert [2] provided that the entrainment coefficient of the plume is tuned between 0.06 and 0.08 depending on the injection flow rate.

When small leaks of the enclosure begin to be significant the vertical volume fraction difference begin to increase with time. Volume fraction vertical profiles are auto-similar when normalized by the average value. This differs from the normalization scheme appropriate to obtain auto-similar profiles in the perfectly sealed enclosure case. A vertical stratification develops for all tested flow rates. However, it is very weak for flow rates below 3.5 $10^{-5}m^3/s$ (2Nl/min at 18°C) which makes it very sensitive to thermal conditions.

Steady state volume fraction field has been studied when there is one opening to the exterior. Stratification is found to occur over a wide range of flow rates independently of the opening position. The opening near the ceiling promotes mixing but not enough to produce a homogenous mixture. However, for the lowest flow rates, below 5 $10^{-5}m^3/s$ (2.8Nl/min at 18°C), the stratification is almost negligible an the average volume fraction for both opening positions is closed to that given by the homogenous models whether or not the exchange volume flux with the exterior is considered constant. For flow rates higher than 5 $10^{-5} m^3/s$ the homogenous model based on an exchange flow rate dependent on the density difference with the exterior is more realistic. Due to the vertical stratification this homogenous model only gives that both the average and local volume fraction follow the power law $X \propto Q_0^{2/3}$. It tends to overestimate the average concentration when the opening is near the ceiling and to underestimate it when the opening is near the ceiling.

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REFERENCES

1. Baines W. D. and Turner J. S., Turbulent buoyant convection from a source in a confined region, *J. Fluid Mech.,* vol. 37, 1967, p.51-80

2. Worster M. G. and Huppert H. E., Time dependent density profiles in a filling box, *J. Fluid Mech.,* vol. 132, 1983, p.457-466.

3. Cleaver R. P., Marshall M. R. and Linden P. F., The build-up of concentration within a single enclosed volume following a release of natural gas, *J. Hazardous Mater*., 36, 1994, p. 209-226.

4. Linden P. F., Lane-Serff G. F. And Smeed D. A., Emptying filling boxes : the fluid mechanics of natural ventilation, *J. Fluid Mech.*, Vol. 212, 1990, p.309-335.

5. Lowesmith B. J., Hankinson G., Spataru C. and Stobbart M., Gas build-up in a domestic property following releases of methane/hydrogen mixtures, *Proceedings of the 3rd International Conference on Hydrogen Safety*, Sep. 2007, San Sebastian, Spain.

6. Gupta S., Brinster J., Studer E. and Tkatschenko I., Hydrogen related risks within a private garage: concentration measurements in a realistic full scale experimental facility, *Proceedings of the 3rd International Conference on Hydrogen Safety*, Sep. 2007, San Sebastian, Spain.

7 Brown W. G. and Solvasons K. R., Natural convection through rectangular openings in partitions-1, *Int. J. Heat Mass Transfer,* Vol.5, 1962, p.859-868.

8. Linden P. F., The fluid mechanics of natural ventilation, *Annu. Rev. Fluid Mech.*, vol. 31, 1999, p.201-238.