Experimental study of the concentration build-up regimes in an enclosure without ventilation

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Abstract : We present an experimental investigation of the different concentration build-up regimes encountered during a release of helium/air mixture in an empty enclosure without ventilation. The release is a vertical jet issuing from a nozzle located near the floor. The nozzle diameter, the flow rate and the composition of the injected mixture have been varied such that the injection Richardson number ranges from $6\ 10^{-6}$ to 190. The volume Richardson number, which gives the ability of the release to mix the enclosure content, ranges from $2\ 10^{-3}$ to $2\ 10^{4}$. This wide range allowed reaching three distinct regimes: stratified, stratified with a homogeneous upper layer and homogenous.

1. INTRODUCTION

As part of safety studies related to the use of hydrogen in confined environment, it is of primary importance to have a good knowledge of the dispersion mechanisms of this low density gas in air during a release characteristic of a leak. Such phenomenon have been the subject of several studies for other fluids in different contexts than hydrogen safety such as, geophysics, heat in naturally ventilated buildings or filling the tanks of liquid methane (see *e.g.* [1] [2] and [3]). The use of hydrogen as an energy carrier for widespread public applications had renewed the interest in this phenomenon. In particular, efficient numerical modeling for safety studies is a major issue that leads to constant efforts for its development (see *e.g.* [4], [5], [6] and [7]). This comes with experimental studies in simplified configuration whose main goal is to provide data for model validation. Conducting experiments in simplified situations can also highlight the mechanisms involved in the dispersion (see *e.g.* [8], [9], [10], [11] and [12]). Various configurations are studied, the source may be a jet or plume, the enclosure may include one or more vents, environmental effects can be considered such as wind. This kind of experimental studies can also provide some information about the validity domain of some simple analytical models that may give useful information on hydrogen dispersion.

When dealing with confined spaces, it is often referred to a room that could be an equipment room in which there is a fuel cell system or a garage in which hydrogen based vehicle may be parked. The volumes involved are then tens of cubic meters. The study presented here is part of a project to quantify the effects of a leak within a fuel cell system. The characteristic volumes are significantly lower, *e.i.* of the order of a few cubic meters.

The most realistic situation would be to study the dispersion in a chamber of small volume, crowded with the system parts, in the presence of natural or forced ventilation and for a jet or plume leak of any orientation. But this particularly complicated case is very dependent on the geometry and the considered scenario. The study of very simplified situations is then a useful first step to both identify the phenomena involved and give elementary test cases for numerical models validation.

In this context, we are interested in the various dispersion regime encountered during the release of a buoyant gas in an empty enclosure of size about $1 m^3$ without ventilation. This fundamental situation has already been the subject of some studies. These include in particular the pioneering work of Baines and Turner [1] who performed experiments with saline water solution and develop a theoretical model of filling an enclosure. They focus their study on the case where the dispersion of a plume produces gradual vertical density stratification. They have noticed that under certain geometrical conditions, the plume may lead to a recirculation zone near the sides of the enclosure. This overturning can be responsible for the formation of a layer of constant concentration near the ceiling. Later, Cleaver, Marshall and Linden [13] have studied the dispersion of natural gas due to a buoyant jet source. Based on experimental results conducted on enclosures of tens of cubic meters, they propose a model that takes into account the formation of a homogeneous layer. In these experiments, the phenomenon of overturning may be linked to both the geometric properties of the flow and the momentum flux introduced by the jet source.

As a consequence of these results on the formation of a homogeneous layer due to the injected momentum flux, there must be a limit regime in which overturning extends over the height of the enclosure thus producing a homogeneous atmosphere in the entire volume of the enclosure.

The present experimental work is a first step in the study of the dispersion in an enclosure due to a release ranging from plume to highly energetic jet. The main purposes are to identify the different dispersion regime regarding the injection condition and to find a criterion on these conditions that gives the limit regime of homogenous dispersion over the entire enclosure.

In the next section the related theoretical bases and previous works are reviewed. Section 3 is devoted the description of the experimental setup and test conditions. The results are presented in section 4, and the main conclusions are summarized in section 5.

2. THEORETICAL BASES AND PREVIOUS WORKS

We consider the injection into an enclosure with a fluid of different density of the ambient. This difference in density is associated with a different composition between the fluids initially in the enclosure and that injected. In particular, we treat here the case of helium or helium/air mixture injection into air. The density in the flow depends on the volume fraction of helium. The thermal effects are neglected. The source is vertical and the momentum is injected in the same direction as the buoyant force, *e.i.* upward.

The source is characterized by a density ρ_0, a volume flow rate Q_0 and a cross section $S_0=\pi R_0^2$. These last two parameters are used to calculate the average speed at the source U_0. The regime of the source flow, is essentially dependent on the Richardson number:

$$Ri_0 = g\,\frac{\rho_a-\rho_0}{\rho_0}\frac{R_0}{U_0^2} \qquad (1)$$

where ρ_a is the air density and g is the gravity acceleration.

Depending on the order of magnitude of the Richardson number, the flow at the exit of the source may either be jet-like or plume-like. But even in the case of $Ri<<1$ for which the exit flow is jet-like, the decrease of the velocity may lead to a transition to a plume-like flow for a given distance from the source. Papanicolaou et List [14] gives a empirical correlation of this transition length defined as :

$$l_m = 3\frac{(U_0Q_0)^{3/4}}{B_0^{1/2}}\,. \qquad (2)$$

B_0 is the buoyancy flux given by :

$$B_0 = g\,\frac{\rho_a-\rho_0}{\rho_a}Q_0 = g_0'Q_0\,, \qquad (3)$$

where g_0' is the reduced gravity at the exit of the source. l_m is also called the jet length.

When this type of flow occurs in an enclosure, the gas disperses in the volume thus leading to an atmosphere of variable density. We then distinguish two main areas in the flow, the forced plume vertical upward and the rest of the volume.

The distribution of density in the enclosure during filling is particularly dependent on injection conditions. When the effects of gravity dominate, the distribution of density is characterized by a stable vertical stratification.

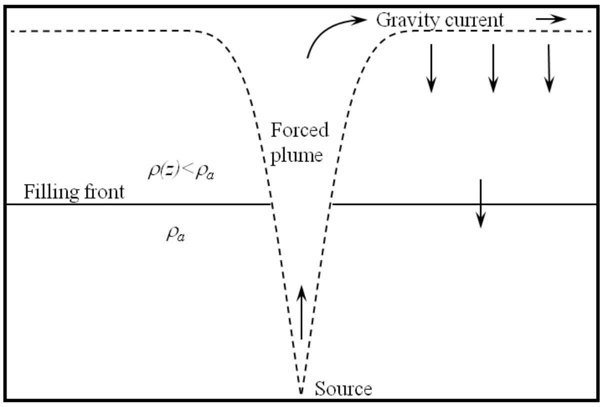

Figure 1: Schematic representation of the flow in an enclosure with a plume source and without overturning.

In this regime, Fig. 1 shows schematically the flow structure during filling. The forced plume develops vertically to the top wall where it is deflected horizontally to the edges of the enclosure. A downward vertical flow occupies the entire horizontal section of the enclosure. A horizontal interface is formed over the section between the upper part of the enclosure where the injected gas accumulates and the lower part where the density remains unchanged. We then call this interface the filling front. In the upper layer, the mixture density decreases from the interface to the ceiling. The filling front moves downward as the gas is injected.

Baines and Turner [1] studied the case of a source producing a pure plume. They propose a model that gives the position of the filling front with time and the density profile when the filling front reached the bottom of the chamber. This model is in good accordance with the experiments conducted in salt water.

To resolve this problem, they introduce a reference time and reduced gravity defined respectively by:

$$t^* = \frac{A}{4\pi^{2/3}\alpha^{4/3}H^{2/3}B_0^{1/3}}\ , \tag{4}$$

and

$$g'^* = \frac{B_0^{2/3}}{4\pi^{2/3}\alpha^{4/3}H^{5/3}}\ , \tag{5}$$

where A is the area of the horizontal section of the enclosure, H is its height and α is the entrainment coefficient of the source flow. For a pure plume, it is about 0.1. The characteristic time t^* is related to the downward propagation velocity of the filling front.

In the absence of thermal and pressure effects, the helium volume fraction is related to the reduced gravity by the relationship:

$$X = \frac{g'}{g'_0} = \frac{\rho_a}{\rho_a - \rho_0}\frac{\rho_a - \rho}{\rho_a}\ , \tag{6}$$

with ρ the mixture density for a helium volume fraction of X. From eq.(5) and (6), the characteristic volume fraction according the normalization scheme of Baines and Turner [1] is given by :

$$X^* = \frac{B_0^{2/3}}{4\pi^{2/3}\alpha^{4/3}H^{5/3}g'_0}\ . \tag{7}$$

The theoretical results of Baines and Turner [1] have been extended by Worster et Huppert [15] who give the time evolution of the density field during the filling process. The hypothesis for this model are, a negligible molecular diffusion of the mass and momentum, the application of the Boussinesq approximation, a negligible volume of the plume upward flow compared to the enclosure volume, a negligible downward velocity out of the plume compared to that in the plume, a constant entrainment coefficient and an instantaneous spread of the injection flow along the ceiling.

Baines and Turner [1] identify that for a pure plume injection flow, the gravity current along the ceiling can lead to overturning as it reaches the side of the enclosure thus producing a homogeneous layer. This occurs only if the ratio of the momentum flux to the buoyancy flux in the horizontal gravity current exceeds 0.1. By taking into account the correlations given by Papanicolaou and List [14] for pure plume, it can be shown that this criterion is only based on geometric properties, *i.e.*, the ratio of the distance from the source to the ceiling and the horizontal length of the enclosure.

Kaye and Hunt [16] show that overturning occurs for aspect ratio z_r/R higher than 0.66, with R the distance from the plume axis to the side wall of the enclosure. The overturning is weak for aspect ratio between 0.66 and 1.5, *i.e.*, there is almost no entrainment. Entrainment in the recirculation flow may be significant only for aspect ratio higher than 1.5. They also conducted some experiments in salt water to validate the theoretical modeling.

In the more general case of a forced plume, overturning can occur regardless the aspect ratio of the flow. When the injection momentum flux is high enough compared to the buoyancy effects, Cleaver *et. al.* [13] shows that a homogeneous layer can be formed. In order to quantify the balance between the effects of momentum and buoyancy, they introduce the volume Richardson number based on a length scale related to the volume of the enclosure:

$$Ri_v = g\frac{\rho_a - \rho_0}{\rho_0}\frac{V^{1/3}}{U_0^2}, \tag{8}$$

where V is the enclosure volume. For law values of this number compared to unity, overturning occurs and the jet momentum is enough to mix the area near the ceiling and produce a homogenous layer. Cleaver *et. al.* [13] have done experiments with natural gas in enclosures of volumes ranging from 27m^3 to 70m^3 and also in small scale enclosure with saline solution in fresh water as working fluid. They have measured the thickness of the homogenous layer with respect to the volume Richardson number and give the following correlation:

$$\frac{d}{R_0} = \frac{C_i}{\sqrt{Ri_v}}. \tag{9}$$

where d is the thickness of the homogeneous layer, R_0 is the radius of the source and C_i is a constant obtained from measurement. This constant is 25 for ascending jet. This correlation may be used as a criterion for complete homogenization of the enclosure if the extent of the homogeneous layer is equal or larger than the enclosure height.

3. EXPERIMENTAL SET-UP AND MEASUREMENT METHOD

The enclosure used for these tests is a parallelepiped with a square base of 0.93x0.93m^2 and 1.26m high. A 10mm diameter hole located 10mm from the bottom of the enclosure remains open throughout the duration of the tests to avoid pressurization of the chamber during the injection. Helium is injected into the chamber through a 5mm or 20mm diameter vertical tube, directed upward and centered in the horizontal section. The end of the tube is 210mm from the bottom of the enclosure. Injections of pure helium were performed with two mass flow controllers chosen according to the desired rate. One regulator has a 20Nl/min full scale and the other has a 700Nl/min full scale. The error on the mass flow rate for the 20Nl/min controller is 0.1% of full scale plus 0.5% of the set point. For 700Nl/min controller, the error on the mass flow rate is 0.2% of full scale plus 0.7% of the set point. Injections of air/helium mixtures were performed with two mass flow controllers in parallel. The full scale of the regulator for helium is 350Nl/min, the regulator for the air is 50Nl/min. For the latter two flow controllers, the error on the mass flow rate is 0.2% of full scale over 0.7% of the set point.

Tested flow rate ranges from 1Nl/min to 350Nl/min which correspond to volume flow rate from 1.8 10^{-5} to 6.25 10^{-3} m^3/s. Three different compositions of the injected air/helium mixture have been used, 100%, 80% and 60% of helium volume fraction. All these injection conditions give a source Richardson number ranging from 5.6 10^{-6} to 190 and a volume Richardson number ranging from 2.3 10^{-3} to 2 10^4.

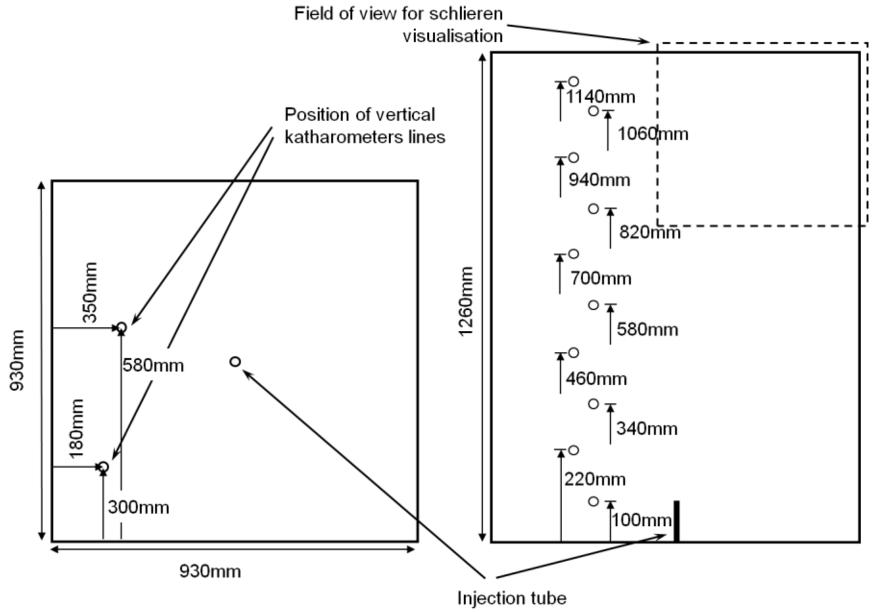

Figure 2: Experimental setup, top view (left) and side view (write).

The temperature in the chamber is measured using a thermocouple. Measurements of volume fraction are made with 10 mini-Katharometers mounted 5 by 5 along two vertical lines as shown in Fig. 2. They are positioned as far as possible from the source to avoid its local influence. The distribution of sensors along the two different vertical lines is designed to check the assumption of a one dimensional concentration build-up away from the source by the coherence of the vertical volume fraction profile. The measurements of 10 sensors are sampled simultaneously with a period of 5s. The measurement absolute error on the helium volume fraction is 0.1%.

Synthetic schlieren visualizations were performed on a field bounded by the dotted frame in Fig. 2. This method consists of recording a patterned image placed behind the enclosure. This image consists of black squared dots randomly printed on a white paper sheet. It is recorded first before the beginning of the injection thus giving an undisturbed reference image. Then, during the release, changes of refractive index due to air/helium mixing are responsible for an apparent deformation of the pattern. The subtraction of the background image and distorted image allows enhancing the pattern optical displacement. The result is a visualization of density gradient. The images were recorded at a frequency of 63Hz with a resolution of 1280x1024 pixels during the beginning of the injection.

The hypothesis of sealed enclosure has been tested by numerically integrating the vertical variation of the helium volume fraction measured by the 10 sensors during the injection. This gives the average helium volume fraction which can be compared to expected theoretical value given by :

$$\langle X \rangle = 100\frac{t}{\tau}, \tag{10}$$

where <X> is the spatial average of the helium volume fraction expressed in percent and τ is the characteristic time given by the ratio of the enclosure volume to the volume flow rate. The comparison of the measured average volume fraction with this theoretical value is very good for most of the injection flow rates up to 20τ.

The most deviating results from eq. (10) are obtained for the flow rate of 180Nl/min with the smaller source because of the rapid homogenization of the helium volume fraction over the entire volume which leads to a small leak of the helium through the hole near the bottom. For this case, the measured average helium volume fraction at 20τ is 18% instead of 20%. Except for this injection flow rate, the maximum absolute deviation over an injection period up to 20τ is 0.7%.

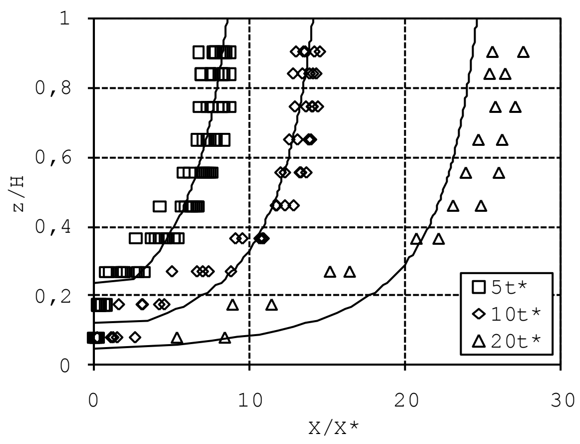

Figure 3: Helium volume fraction vertical variations in the enclosure for flow rates ranging from 1Nl/min to 80Nl/min with the 20mm diameter source. Continuous curves represent Worster and Hupper [15] model.

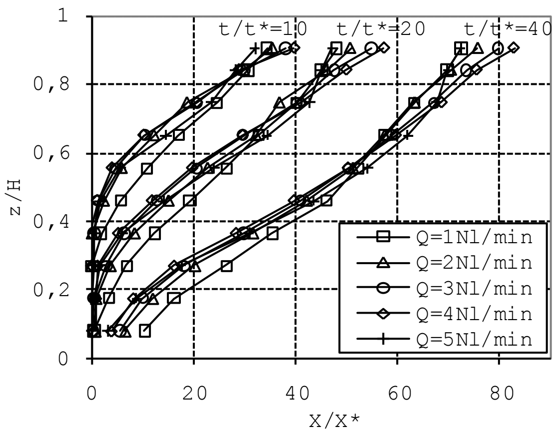

Figure 4: Helium volume fraction vertical variations in the enclosure for flow rates ranging from 1Nl/min to 5Nl/min with the 5mm diameter source.

4. RESULTS

The results are subsequently presented in three sub-sections each corresponding to one of the regimes observed, stratified, stratified with a homogenous layer and homogeneous, for decreasing volume Richardson number.

4.1. The stratified regime

This regime arises when buoyancy dominate the dispersion. However, it is noteworthy that the ratio of the distance from the source to the ceiling and half the horizontal size of the enclosure is 2. This value may be sufficient to produce overturning. Based on the criterion given by Kaye and Hunt [16], 1.5 is the maximum value of this aspect ratio to avoid overturning with significant entrainment.

The results presented in this section only concern injection of pure helium. The injection conditions are chosen such as the volume Richardson number is greater than 3 (*i.e.* for a lower flow rate than 5Nl/min with the nozzle of 5mm diameter and less than 80Nl/min for nozzle 20mm). Thus the injected momentum should not lead to overturning. The injection Richardson number ranges from 0.2 to 0.007 with the 5mm diameter source which leads to a jet length ranging from 0.1m to 0.3m. With the 20mm diameter source, the injection Richardson number ranges from 190 to 0.03 and the jet length from 0.008m to 0.6m.

Normalized profiles according to eq. (4) and (7) shown in Fig. 3 were obtained with the source of 20mm diameter for flow rates ranging from 1Nl/min to 80Nl/min. This corresponds to a volume Richardson number ranging from 20000 to 3, respectively. They are compared with the model of Worster and Huppert [15].

From these measurements, it is difficult to conclude on the formation of a homogenous layer due to overturning promoted by the aspect ratio of the flow. Indeed the three highest sensors give almost a constant volume fraction but, even from the model, the gradient in this region is weak. Thus, the measurements are still in a fairly good accordance with the model.

To get the best agreement of the model with the experimental results, the entrainment coefficient which appears in the normalization scheme has been adjusted from 0.065 to 0.04 for increasing injection velocity. For lower speeds, the injection Richardson number is large (between 5 and 190) and the injection flow regime should be close to a pure plume with an entrainment coefficient between 0.08 and 0.1 (see *e.g.* [14] and [1]). When the injection speed increases, the injection Richardson number decreases down to 0.03 for 80Nl/min. The injection flow regime tends to be a jet. For a pure jet, Papanicolaou and List [14] give an entrainment rate of 0.05.

Fig. 4 shows the normalized vertical profiles of helium volume fraction obtained with the 5mm diameter source for different normalized times. It appears first that there is no homogenous layer thicker than 0.1*H*. The entrainment coefficient used for the normalization is 0.1. This choice of normalization of variables leads to a superposition of the different profiles, showing the auto-similarity of these results. The same entrainment coefficient is applied for all injection flow rate. This suggests that the variation of the jet length for that range of flow rate is weak enough to have no significant effect on the entrainment coefficient.

Comparison with theoretical results of Worster and Huppert [15] and experimental results obtained with the source of 20mm diameter (Fig. 2) shows that the vertical distribution of the volume fraction of helium is very different. The maximum normalized helium volume fraction is much higher than that expected and its decrease with decreasing height is stiffer and close to linear.

The Reynolds number based on the source diameter ranges from 40 to 200 and from 10 to 800, for the source diameters of 5mm and 20mm, respectively. The jet length ranges from 0.06m to 0.3m and from 0.008m to 0.6m for the source diameters of 5mm and 20mm, respectively. Thus, these values are not very useful to clearly distinguish an injection flow regimes dependence on the source diameter that may explain the strong differences observed in the vertical helium volume fraction distribution.

In the theoretical development of Worster and Hupper [15], the vertical distribution shape is obtained with the hypothesis of a constant entrainment coefficient. Despite the transition from jet to plume in the experiments with the 20mm source the shape of the helium volume fraction vertical profile seems to be unaffected. Only a global adjustment of the entrainment coefficient is needed. A possible explanation for the results obtained with the 5mm source is a strong vertical variation of the entrainment coefficient. Also, the mass diffusion of the helium may play an important role. For the later, one can estimate roughly the order of magnitude of the characteristic times involved. For the smallest flow rate (1Nl/min), the front velocity is about 0.002m/s. This gives a characteristic descending time over 0.1m of 50s. The corresponding characteristic diffusion time on the same length is 140s which is not much higher. Thus diffusion may affect the vertical distribution. However, diffusion cannot explain the larger value of the helium volume fraction measured near the ceiling with the 5mm source. This is rather related to a significantly lower entrainment rate in the plume.

Thus, it comes that the source diameter can play a crucial role in the helium vertical dispersion but, a comprehensive understanding of the mechanisms involved needs further investigations on the influence of the role of the helium molecular diffusion and the impact on the entrainment coefficient of the turbulence development in the injection flow.

4.2. Stratified regime with an homogeneous layer

The increase in injection rate leads to an increase in gas velocity and consequently of the jet length. This has the consequence that the injected momentum is sufficiently large near the edges of the enclosure, near the upper wall, to generate overturning, enhance local mixing and form a homogeneous layer. The existence of such a homogeneous layer is visible on the profiles of the helium volume fraction for a flow rate larger than 7Nl/min with the 5mm diameter source (see Fig. 5). The thickness of the mixed layer increases with injection speed in accordance with the observations of Cleaver and. al. [13].

Schlieren visualizations demonstrate clearly a significant change in the flow structure which clearly exhibits strong overturning for the highest flow rates (Fig. 6, 7 and 8). Before the establishment of the filling front, from the start of injection, the jet of helium rises up to the ceiling and then spreads horizontally to the edges of the enclosure. The density front which marks the progression of helium in this phase is called initial front thereafter. It differs from filling front in a much higher speed and a highly turbulent three-dimensional structure.

This initial front is likely to produce overturning if its kinetic energy is high enough when it reaches the edges of the enclosure. The visual test of overturning occurrence that we set is the observation of the spread of initial front downward along the side walls of the enclosure. The differentiation with the filling front is mainly based on its visual appearance, *e.i.* high turbulent mixing.

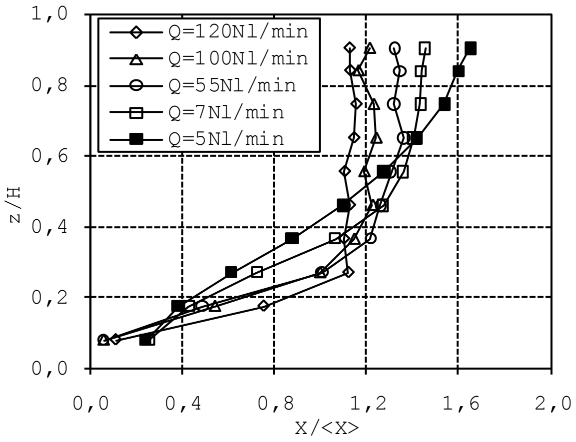

Figure 5: Helium volume fraction vertical variations in the enclosure for flow rates ranging from 5Nl/min to 120Nl/min with the 5mm diameter source at $t/\tau=0.1$.

For the three injection conditions presented in Fig. 6, 7 and 8, time is arbitrarily counted from the first frame of each figure. The first frame has been chosen so that the initial front is approximately at the same height for each injection case. The information provided is essentially an order of magnitude of time scales of these observations.

Fig. 6 presents the results of the visualizations for an injection flow rate of 5Nl/min. The first two images show the initial front that propagates first upward, then horizontally along the ceiling. The third image corresponds to the arrival of the initial front at the edge of the enclosure. After a careful observation of the images it may be possible that overturning occurs. But, the contrast of the images is very low, indicating the weakness of the density gradient, and making it difficult to conclude whether there is overturning or not. As for the results on helium volume fraction measurement, if overturning occurs, it seems to be very weak and unable to mix significantly the upper part of the enclosure to produce a well defined homogenous layer.

The filling front is visible on the fourth image, a little below half the image. Its appearance is clearly different from the initial front. It does not have the characteristic structures of turbulent mixing.

Fig. 7 corresponds to a 20Nl/min injection. For this flow rate, the volume fraction measurements show that a homogeneous layer is formed. Pictures 1 and 2 of Fig. 7 show the upward vertical propagation and horizontal spread of the initial front. It reaches the edge of the enclosure on image 3. The turnover appears on images 4 and 5 in the form of a downward front along the side wall of the enclosure. The main difference with the filling front is its propagation speed. During 0.7τ, it runs approximately the 2/3 of the image which is about a quarter of the height of the enclosure.

The filling front is clearly visible on the last frame. Its structure is far less turbulent than the downward propagating front due to overturning observed on image 4 and 5.

The contribution of the overturning to the mixing and the formation of the homogeneous layer is clearly evidenced by the test performed for an injection flow rate of 70Nl/min (Fig. 8). The spread of the initial front, vertically and horizontally along the ceiling is visible on the first two images. It reaches the edges of the enclosure on the third image. Then, the last three images show a particularly turbulent front reaching the bottom of the image (approximately one third of the height of the enclosure) in only 0.3τ from the moment the initial front has reached the edge of the enclosure. The filling front is not visible in this series because it must be formed below the lower edge of the image.

The thickness of the homogeneous layer has been measured as a function of the volume Richardson number for three injected air/helium mixture with a helium volume fraction of 60%, 80% and 100%.

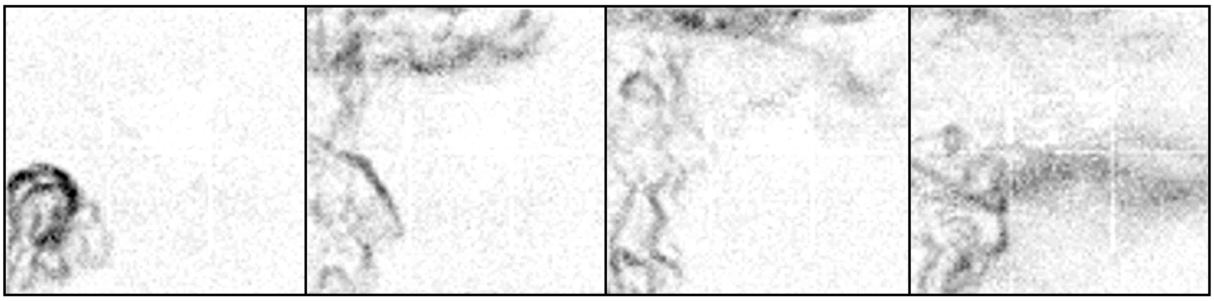

Figure 6: Schlieren visualization of the flow with the 5mm diameter source at a 5Nl/min flow rate. Time increases from left to right and top to bottom. Starting from the first image, the following pictures correspond to 3s, 7s and 22s, *i. e.*, normalized with τ, 0.2 10^{-3}, 0.6 10^{-3} and 1.8 10^{-3}.

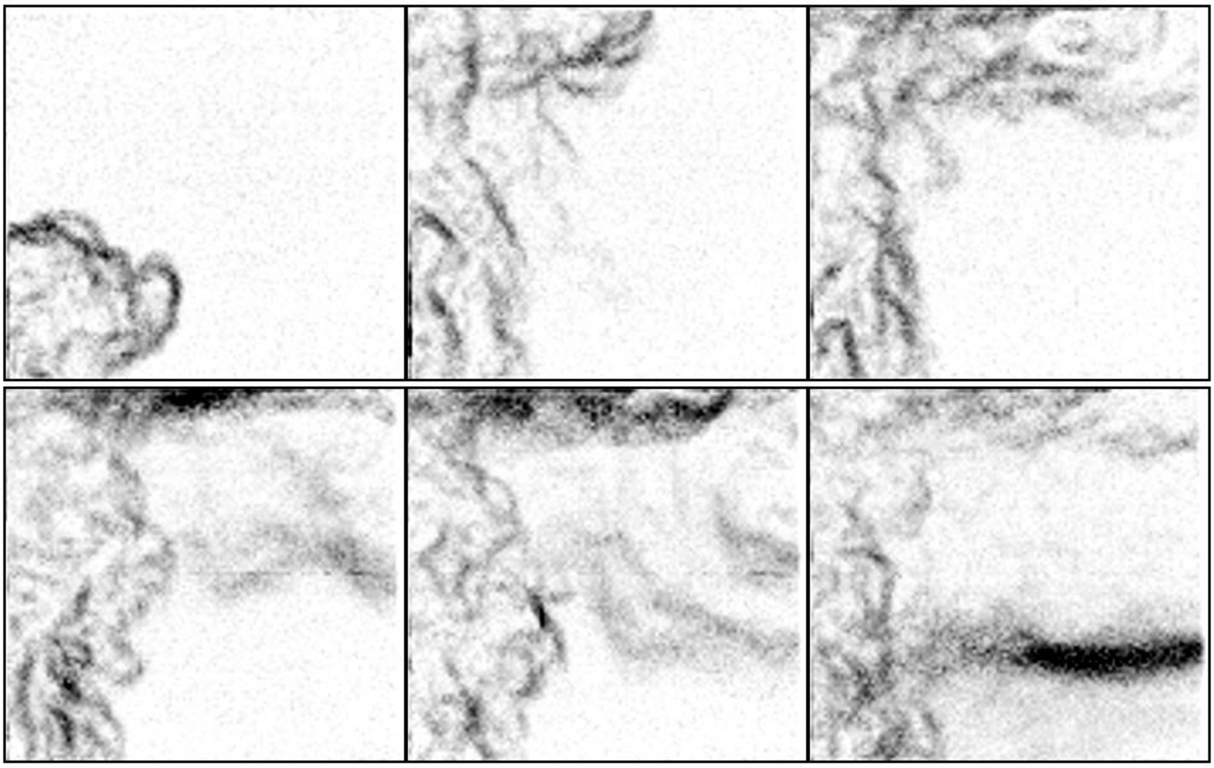

Figure 7: Schlieren visualization of the flow with the 5mm diameter source at a 20Nl/min flow rate. Time increases from left to right and top to bottom. Starting from the first image, the following pictures correspond to 1.5s, 2.7s, 5.1s, 6.7s and 16.5s, *i. e.*, after normalization with τ, 0.5 10^{-3}, 0.9 10^{-3}, 1.7 10^{-3}, 2.2 10^{-3} and 5.4 10^{-3}

The method used for this measurement is based on the non-linear fitting of the helium volume fraction measurement data to a model function given by :

$$X(z) = b_1 \tanh\left(b_2 z^{b_3}\right) \quad (11)$$

where b_1, b_2 and b_3 are the parameters to be adjusted with the non-linear fit. An example of the fitting result is given for three different kinds of profiles on Fig.9. The thickness of the layer is defined as the height from the ceiling where the helium volume fraction has decreased to 99% of the volume fraction measured at $z=H$. The results are plotted on Fig. 10 using the same normalized parameters as Cleaver *et. al*. [13]. The experimental data for each injected mixture composition are compared to the correlation they give. This correlation is in a fairly good accordance with measurements for the values of volume Richardson number less than about 0.01. For larger values of the volume Richardson number, the correlation highly underestimates the actual layer thickness.

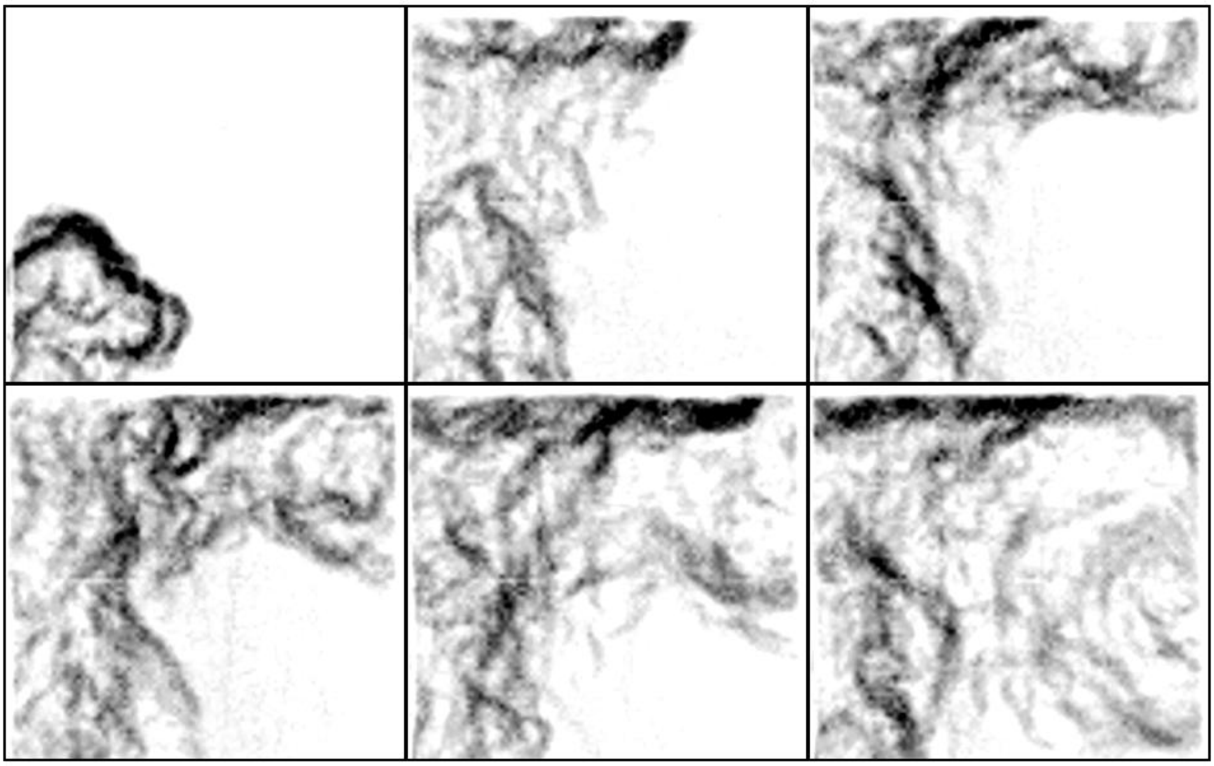

Figure 8: Schlieren visualization of the flow with the 5mm diameter source at a 70Nl/min flow rate. Time increases from left to right and top to bottom. Starting from the first image, the following pictures correspond to 0.8s, 1.2s, 1.9s, 2.3s and 3.5s, *i. e.*, normalized with τ, 0.9 10^{-3}, 1.4 10^{-3}, 2.2 10^{-3}, 2.6 10^{-3} and 4 10^{-3}.

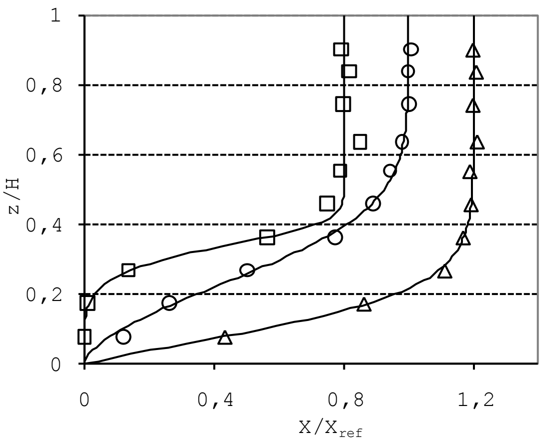

Figure 9 : Example of data fitting with function defined be eq. (11). The reference volume fraction is arbitrary and chosen for plotting convenience.

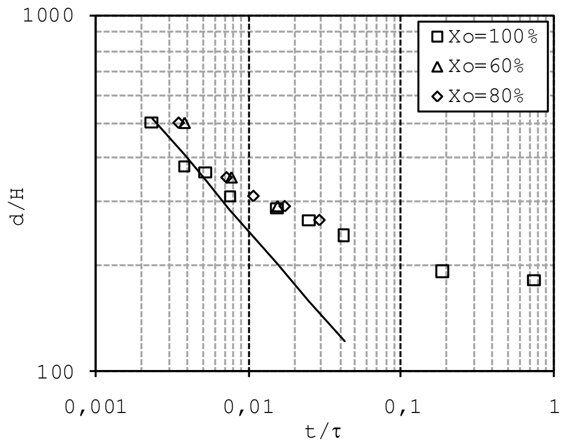

Figure 10: Homogenous layer thickness variations with respect to the volume Richardson number for three different composition of the injected air/helium mixture.

4.3. The homogeneous regime

The homogeneous regime is a limit case of the previous regime when the injection conditions lead to the formation of a homogeneous layer of height equal to the height of the enclosure. This regime has been reached for the three volume fractions of helium injection tested, 60%, 80% and 100%. The critical volume Richardson number that leads to a homogeneous distribution is 0.0038, 0.0035 and 0.0023, respectively. On average, this gives a value of 0.0032. This value is quite close to that given by the correlation and Cleaver *et. al.* [13] which is 0.0025. But one can notice that this critical value seems to increase for decreasing helium volume fraction at the injection.

5. CONCLUSION

The results of these experiments in an enclosure of small volume give a clear identification of the three filling regimes: stratified, stratified with a homogeneous layer and homogeneous. The parameter that differentiates these regimes is the volume Richardson number based on the volume of the chamber.

For values greater than unity, the vertical profile of the volume fraction has a regular stratification similar to that provided by the one-dimensional model of Worster and Huppert [15]. A good agreement with this model is obtained for a source diameter of 20mm. Nevertheless, an adjustment of the entrainment coefficient is necessary to fit the model on the experimental data. This adjustment is justified by the change in the injection flow regime from plume to jet as source velocity increases. The results obtained with the 5mm diameter source are very different from the model. In this case, the filling front descends more slowly, the concentration in the layer increases approximately linearly and the maximum helium volume fraction is significantly higher than that given by the model. The most likely hypothesis to explain such a difference with the model of Worster and Huppert [15] is that the entrainment coefficient may change significantly with distance from the source. Nevertheless further investigations on the detailed properties of the injection flow are needed to conclude on these results.

The transition to the regime with a homogeneous layer arises for volume Richardson number less than unity. The correlation proposed by Cleaver and. al. [13] underestimates the layer thickness for volume Richardson number higher than 0.01. For lower values the accordance with measurements is fairly good.

As a consequence, this correlation gives a good criterion for the transition to the homogeneous regime. This has been verified here for different injection air/helium mixture although an increase of the critical volume Richardson number is observed for decreasing helium volume fraction at the injection.

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