INFLUENCE OF THE LOCATION OF A BUOYANT GAS RELEASE IN SEVERAL CONFIGURATIONS VARYING THE HEIGHT OF THE RELEASE.

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ABSTRACT

The present work proposes a parametric study on the influence of the height of the release source on the helium dispersion regimes inside a naturally ventilated enclosure. Several configurations were experimentally addressed in order to improve knowledge on dispersion considering conditions close to hydrogen energy systems in terms of operating characteristics and design. Thus the varying parameters of the study were mainly the height of the release, and also the releasing flow rate, the volume and the geometry of the enclosure. Experimental results were compared to existing analytical models and considered through model improvements allowing a better approach of these specific cases for hydrogen systems risk assessment.

1.0 CONTEXT

Experimental and numerical studies on the dispersion of buoyant jet in confined but naturally ventilated environment are carried out in order to better understand implied phenomena and improve predictive methods for risk assessment of hydrogen release in confined volume. Recently experiments on dispersion were performed by several authors (1-5) in large scale enclosure equipped with two ventilation openings. This work aims at studying the natural ventilation through two openings in an enclosure of smaller volume, with a specific geometry close to existing hydrogen energy applications in case of accidental release. The influence of the height of the release source in the enclosure is an important parameter which could be very interesting for risk assessment of these applications. For safety reasons, experiments are performed with helium as releasing source. Based on this information, several points could be improved like analytical models for risk assessment, safety devices (type and performance) for the hydrogen energy systems and design recommendations for future applications.
The first section of this paper presents briefly engineering simple approaches commonly used for maximal concentration assessment at the steady state. In the second section the experimental setup is described. Then in the third part, results are presented and discussed before concluding.

2.0 EXISTING MODELLING APPROACH

Only the steady state is considered in this work. The enclosure is naturally ventilated thanks to two vertical vents localized one near the floor, the other near the ceiling as shown in Figure 1.

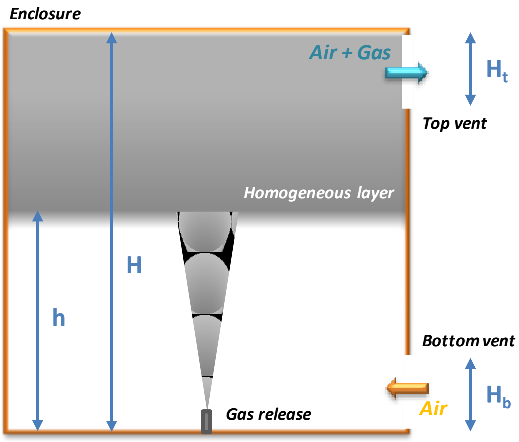


Figure 1. Scheme of the dispersion phenomenon considered in a naturally ventilated enclosure with two openings localized at different altitudes.

Baines and Turner model (6) was extended by Linden to consider an enclosure connected by upper and lower vents to external environment.

Linden showed that a simple stratification develops consisting in two layers separated by a horizontal interface (7, 8). The lower layer is at uniform ambient temperature and the upper layer is also at a uniform but higher temperature that depends on the buoyancy flux from the source.
In a ventilated filling box (see Figure 1), the presence of the upper buoyant layer creates a pressure difference across the vents, which in turn drives a draining flow. A steady state is reached when this draining flow is balanced by the convective plume flow.
A buoyant gas release in an enclosure with two vents leads to a displacement ventilation regime with the formation of an upper homogeneous concentration; and considering zero concentration in the volume below (see scheme in Figure 1).

Linden proposes a methodology to calculate, at steady-state, the concentration of the homogeneous upper layer and the height of the interface.

$$X_f = \frac{1}{C}\left(\frac{Q_o^2 h^{-5}}{g'_o}\right)^{1/3}, \tag{1}$$

where X_f – volume fraction of releasing gas, %, Q_0 – releasing gas flow rate, m^3.s^{-1}, h – height of the interface, m, g'_0 – reduced gravity, m.s^{-2}.

$$C = \frac{6}{5}\alpha\left(\frac{9}{10}\alpha\right)^{1/3}\pi^{2/3}, \tag{2}$$

where C – constant given by the plume theory of Morton *et al.* (9), α – entrainment coefficient (from 0.05 to 0.1 for a pure plume).

The height of the interface, *h*, is given by the following expression:

$$\frac{S^*}{H^2} = C^{3/2}\left(\frac{(h/H)^5}{1-h/H}\right)^{1/2}, \tag{3}$$

$$S^* = \frac{\sqrt{C_t}S_tS_b}{\left(\frac{1}{2}\left(\frac{C_t}{C_b}S_t^2 + S_b^2\right)\right)^{1/2}}, \tag{4}$$

where S^* – effective vent area, m^2, H – height of the enclosure, m, C_t – top vent discharge coefficient, C_b – bottom vent discharge coefficient, S_t – top opening area, m^2, S_b – bottom opening area, m^2.

This approach, commonly used as engineering tool for build-up assessment, does not allow the height of release to be considered; i.e. release is considered at the floor.

The blocked natural ventilation regime studied by Woods *et al.* (10) was considered and slightly modified to take into account the altitude of the release. Based on this approach, analytical results will be compared to experimental data obtained in this work.

2.0 EXPERIMENTAL SETUP

2.1 Test bench description

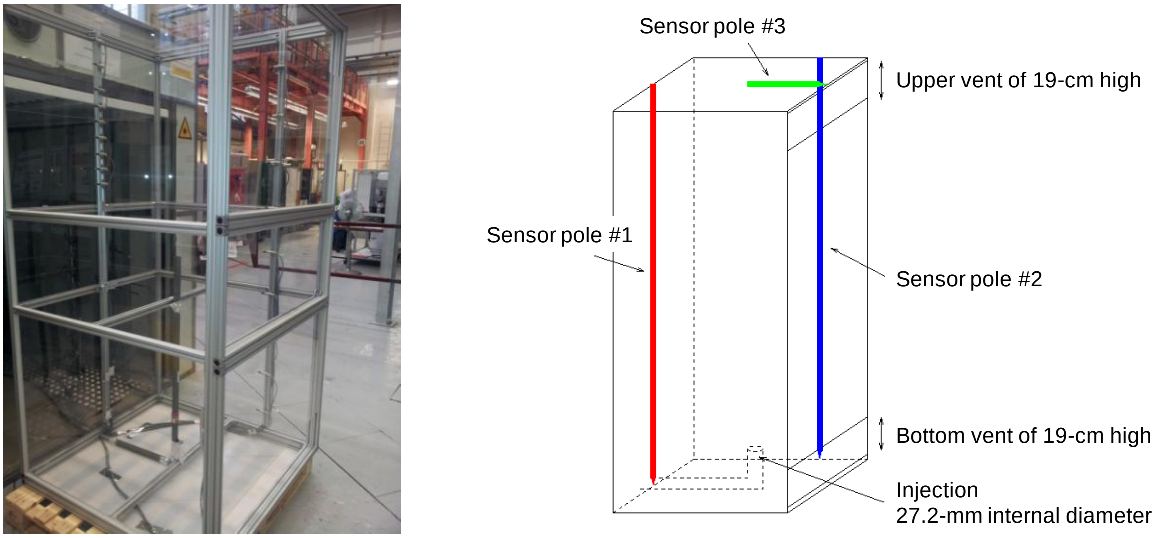
The Plexiglas enclosure is a rectangle parallelepiped with a square horizontal base of an internal volume of 2 m^3 (see Figure 1(A)). Internal size of the enclosure are 96-cm long and wide, for 2.10-m high.

The enclosure has two openings for natural ventilation study: one at the top, and one at the bottom, localized on the same vertical face as shown in Figure 1(B). The bottom opening has a size of h19 x w90 cm, despite the height of the top opening can be changed: 19, 9 and 4.5 cm (the width remaining constant: 90 cm).

The helium injection source is a PVC circular tube of 27.2 mm of internal diameter, centered in the horizontal square section, directed upward. The outlet of the injection tube is localized at several altitudes from the bottom: from 27 cm to 197 cm.

The range of tested flow rates is 1 $NL.min^{-1}$ up to 210 $NL.min^{-1}$. Thus injections were performed with two mass flow controllers chosen according to the desired flow rate. One regulator has a 20 $NL.min^{-1}$ full scale and the other has a 350 $NL.min^{-1}$ full scale. The error on the mass flow rate for the 20 $NL.min^{-1}$ controller is 0.1% of full scale plus 0.5% of the set point. For the 350 $NL.min^{-1}$ controller, the error on the mass flow rate is 0.2% of full scale plus 0.7% of the set point.

Taken into account the release diameter of 27.2 mm, the volume Richardson range studied in this work is from $8.01 \cdot 10^4$ down to 1.82 for respectively 1 and 210 $NL.min^{-1}$.



(A) (B)

Figure 2. Grand-Gamelan 2-m^3 build-up enclosure.
(A) Picture of the enclosure, (B) location of the sensors in the enclosure.

2.2 Measurement devices and data treatment

Based on the measurement of the thermal conductivity of the ambient gas, twenty one minicatharometers Xen-TCG3880 from Xensor Integration, are used to determine the volume fraction of the helium in the enclosure. Minicatharometers were calibrated before experimental campaign. The absolute accuracy of the minicatharometers was assessed to be around 0.1% of helium volume fraction. Sensors can measure helium fraction fluctuations down to 0.05%. The reactivity of these sensors is assessed to be around 1 s.

Data treatment was automated. According to the fixed parameters for the data selection, the time to reach steady state, the helium volume fraction mean and the corresponding standard deviation are determined (Figure 3).

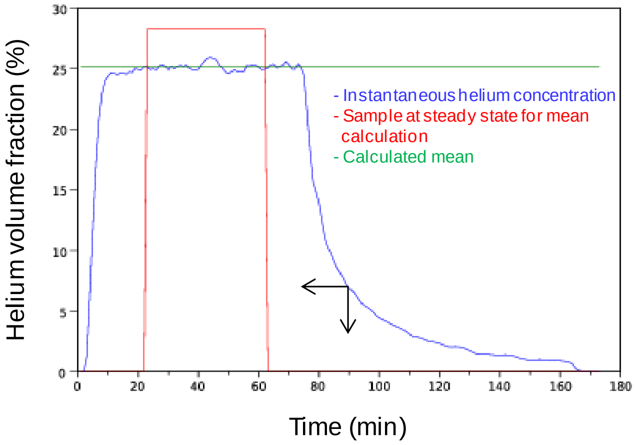


Figure 3. Data treatment for steady state determination
and corresponding measured helium volume fraction.

Pt-100 Ω Platinum probes are integrated inside each helium sensor for temperature measurement inside the enclosure during experiments. The calibration of the platinum probes temperature gives an absolute accuracy of 0.5°C on temperature information. They can measure temperature fluctuations down to 0.1°C.

Sensors are located on three sensor poles: two vertical poles, and one horizontal pole near the ceiling of the enclosure, as shown in Figure 2(B). According to the studied configurations, sensors location can change in order to optimize information on helium distribution in the enclosure (see Figure 4).

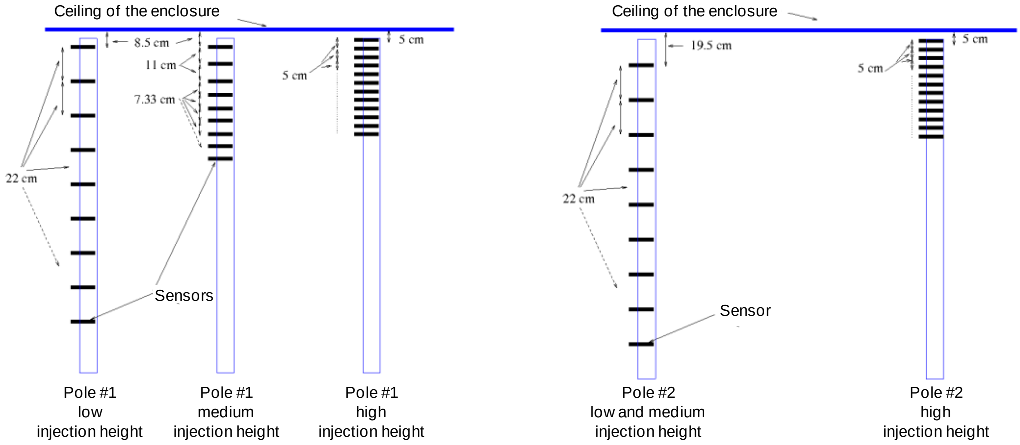


Figure 4. Location of minicatharometers on sensor poles 1 and 2
according to the height of the injection.

2.3 Experimental procedure and studied configurations

Helium is injected at six heights – 27, 107, 138, 158, 168 and 197 cm from the bottom of the enclosure – vertically upwards through a circular nozzle of 27.2-mm internal diameter centered in the horizontal section of the enclosure.

The releasing flow rate is injected in the enclosure when the targeted value is reached and correctly regulated by the mass controller. At this time helium concentrations measured by the minicatharometers as a function of the time and of the height are recorded each 5 s. The injection is stopped after reaching the steady state; i.e. when helium concentrations are stable in the time.

During gas injection, the stability of the pressure and of the temperature inside the enclosure is checked.

The summary of the studied configurations is given in Table 1.

Table 1. Studied configurations.

Parameters	**Values**
Temperature	Ambient temperature, around 20°C
Gas flow rate	From 1 to 210 $NL.min^{-1}$
Injection height	27 | 107 | 138 | 158 | 168 | 197 cm
Internal diameter of the source	27.2 mm
Bottom opening	h19 x w90 cm*
Top opening	h19 x w90 cm h9 x w90 cm h4.5 x w90 cm

* *h the height, w the width*

3.0 RESULTS AND DISCUSSION

3.1 Influence of the injection flow rate

First experiments were carried out on the 2-m^3 enclosure with two identical openings of 19 cm high and 90 cm width each. As previously described one opening is localized near the floor and the other near the ceiling of the enclosure, vertically on the same face. Injection flow rate was the first studied parameter for an injection height of 27 cm from the floor (the lowest injection point of this experimental work).

Thus the distribution profiles – i.e. the helium concentration on the whole height of the enclosure – were obtained at steady state according to the gas flow rate. Figure 5 focuses on results for the extreme flow rates: 1 and 210 NL.min^{-1} of helium. And Figure 6 gives results in terms of helium distribution for intermediate for the whole range of the studied flow rates.

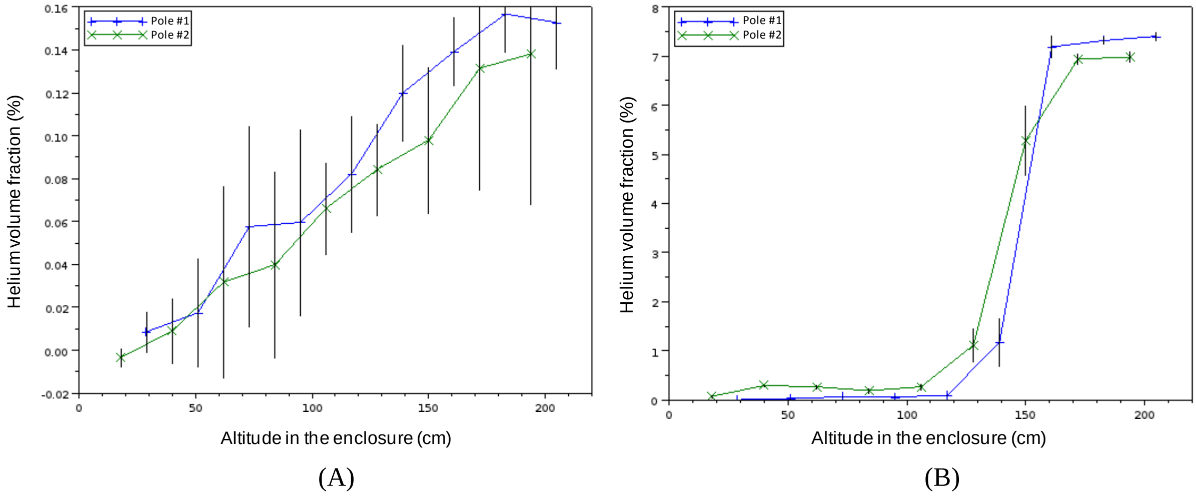
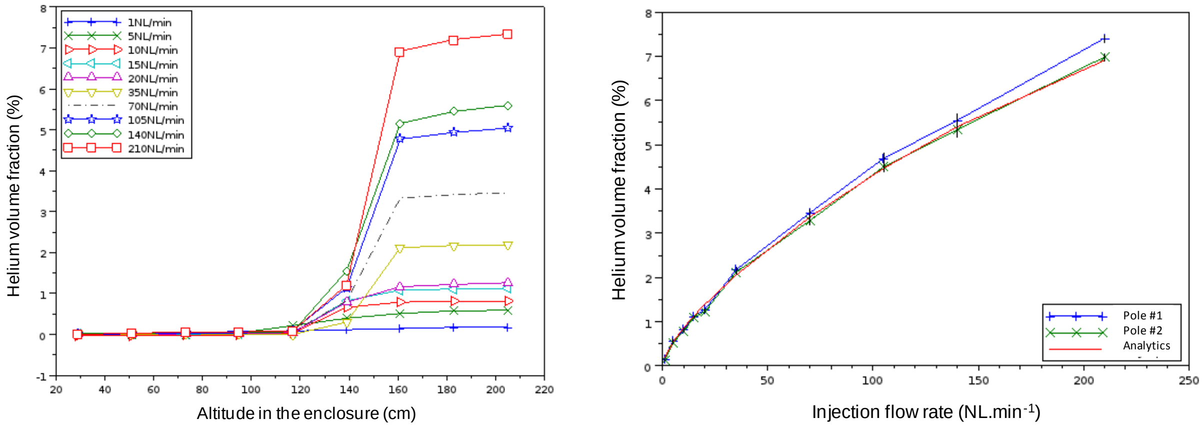


Figure 5. Helium volume fraction as a function of the altitude in the enclosure and at steady state for 1 NL.min^{-1} (A) and 210 NL.min^{-1} (B) injected at 27 cm, with two vents of h19 x w90 cm each (vertical solid line: ± standard deviation).

Independently of the helium fraction values, Figure 5 shows two different distribution profiles. For 1 NL.min^{-1} the dispersion regime is stratified with an increase of the helium concentration with the altitude in the enclosure. While a bi-layer regime – characterized by a homogeneous upper layer (concentration and thickness) – is observed for 210 NL.min^{-1}, as the displacement ventilation described by Linden *et al.* (7, 8).

Figure 6 allows the transition between stratification and bi-layer regimes to be observed according to the helium injection flow rate. The bi-layer regime appears for flow rates higher than 20 NL.min^{-1}. For lower flow rates the dispersion regime is stratified: there is no homogeneous upper layer.



(A) (B)

Figure 6. Distribution profiles of the helium volume fraction (A) and maximal concentration (B) as a function of the injection flow rate at steady state for an injection height of 27 cm with two vents of h19 x w90 cm each.

Figure 7 presents, for a bi-layer regime, the thickness of the homogeneous upper layer according to the injection flow rate for an injection height of 138 cm. This experimental case was chosen because the bi-layer regime was observed on the whole flow rate range (from 1 to 210 NL.min^{-1}) unlike configurations for lower injection heights. For the lowest flow rates, a decrease of the thickness is first observed when the flow rate increases (up to 20 NL.min^{-1}) during the pure plume-jet transition and after the thickness increases with the flow rate for higher injections. The thickness of the upper layer fluctuates between 7 and 16 cm.

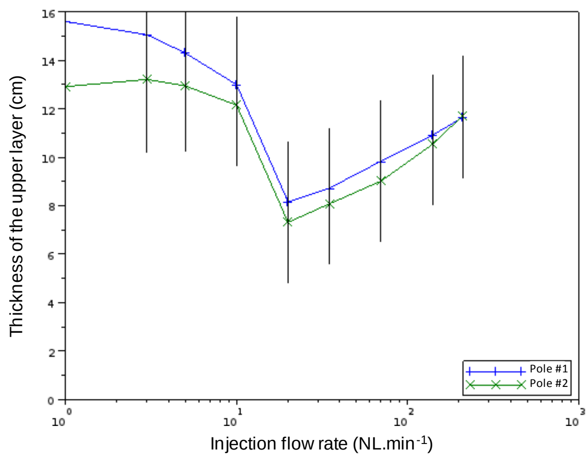


Figure 7. Thickness of the upper homogeneous layer as a function of the injection flow rate at steady state for an injection height of 138 cm (vertical solid line: ± standard deviation), with one upper vent of h4.5 x w90 cm and one bottom vent of h19 x w90 cm.

Thus more than the flow rate value, the release characteristics – which change in this work only through the flow rate – has a significant influence on the thickness prediction (value and evolution) of the homogeneous upper layer for a bi-layer regime.

3.2 Influence of the injection height

In this section experimental results obtained on helium build-up inside the 2-m^3 enclosure according to the height of the injection are presented.

Figure 8 shows for a release flow rate of 210 NL.min^{-1} the influence of the height of the injection on the maximal helium concentration measured inside the enclosure.

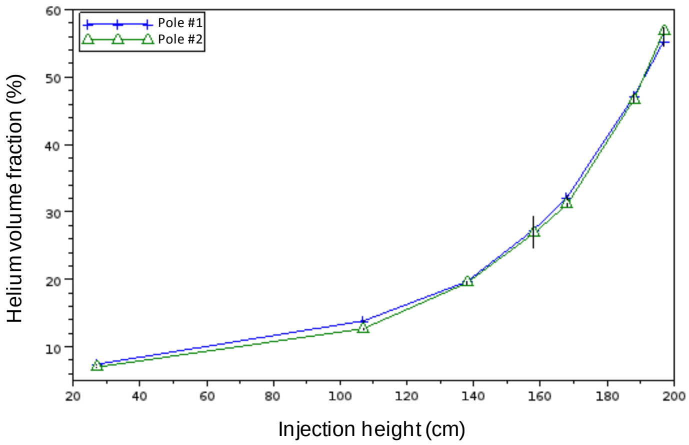
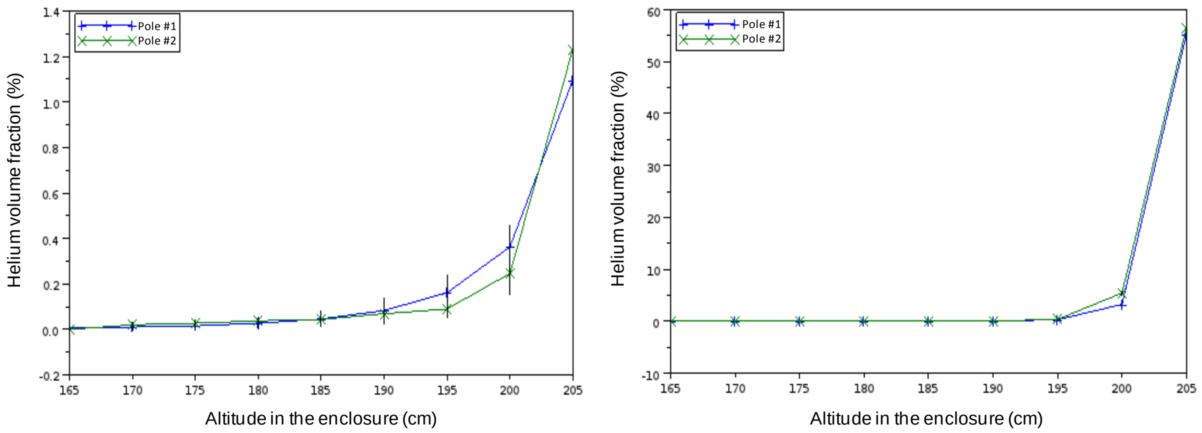


Figure 8. Steady state maximal helium volume fraction as a function of the injection altitude for a 210 NL.min^{-1} release with two vents of h19 x w90 cm each (vertical solid line: ± standard deviation).

The maximal concentration of helium significantly increases with the height of injection. This experimental information highlights the importance of considering release height when known. Using a simple model like Linden approach for example for risk assessment – which does not allow this parameter to be taken into account – can generate deviations for risk assessment.

The same observations are made for the other studied flow rates (i.e. lower than 210 NL.min^{-1}).

The height of the injection has also an influence on the vertical distribution regimes. Actually, in this 2-m3 enclosure, two regimes – stratification and bi-layer regimes – were identified according to the flow rate. By studying the height of the injection, a third regime appears for injection located at an altitude higher than 168 cm. For these cases, stratified and bi-layer regime disappears, as illustrated by the Figure 9 with an injection point at 197 cm; an impinging regime is observed even for very low flow rates.



(A) (B)

Figure 9. Distribution profiles of the helium volume fraction as a function of the altitude in the enclosure and at steady state for an injection height of 197 cm at 1 NL.min^{-1} (A) and 210 NL.min^{-1} (B) (vertical solid line: ± standard deviation) with two vents of h19 x w90 cm each.

Thus for this impinging regime and therefore for height of release close to ceiling, it seems to be not appropriate to use a model based on the displacement ventilation approach described by Linden *et al.* for helium build-up behaviour assessment in confined enclosure.

3.3 Influence of the thickness of the upper vent

Some experiments were carried out on the thickness of the upper opening (19, 9 and 4.5 cm).

As described in the literature, the maximal concentration measured in the enclosure increases when the thickness of the vent is decreased.

Concerning vertical distribution profiles, for low enough injection point (lower than 168 cm), lower is the thickness of the upper vent, more the bi-layer formation is promoted.

For high injection point differences on maximal concentration are very low for the studied vent thicknesses.

3.4 Modeling preliminary results

In this section comparisons are performed between experimental data and theoretical predictions for build-up assessment in case of buoyant gas release in a naturally two-openings naturally ventilated volume.

Figure 10 presents theoretical predictions of the helium maximal concentrations calculated with the Linden *et al.* methodology (7) and the experimental data obtained for a 27-cm injection point, the lowest studied height of injection in this work. The injection flow rates are from 1 to 210 NL.min^{-1}. The Linden *et al.* model was used with an entrainment coefficient of 0.1 and a discharge coefficient of 0.5 for the two openings.

For release flow rates higher than 20 NL.min^{-1}, the predicted values are significantly lower than the experimental data.

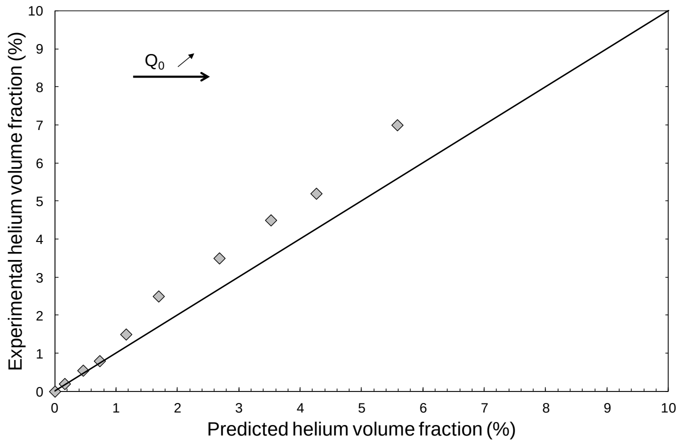


Figure 10. Comparison of the experimental maximal helium volume fraction obtained for an injection height of 27 cm and the predicted values calculated from the Linden approach for a release at the floor at steady state, with two vents of h19 x w90 cm each.

Maximal concentration increasing with the height of injection, this trend is amplified with the height of injection too. Thus, using the Linden modeling approach is not conservative when the source of the release is not located at the floor.

Based on Woods *et al.* works (10), the height of the release can be taken into account for the assessment of the maximal helium concentration in the homogeneous upper layer and for the height of the interface calculation.

Preliminary modeling works on this approach, using experimental data presented herein, show consistent results. Figures 11 and 12 (two different sizes of upper opening) give comparisons on the maximal helium concentration between experiments (blue and green curves) and the fitted analytical approach developed through this work (red curves), from 27 to 168 cm of injection height.

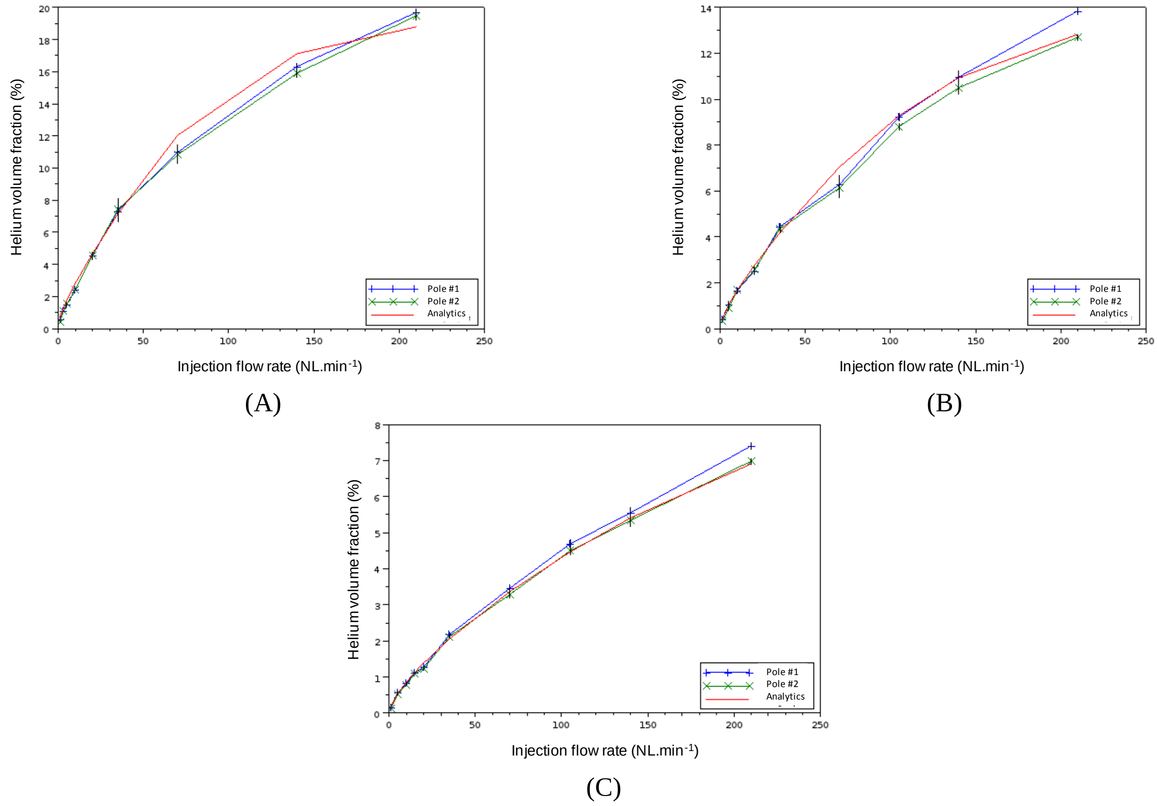


Figure 11. Steady state maximal helium volume fraction as a function of the injection flow rate for several altitudes of release: 138 cm (A), 107 cm (B) and 27 cm (C) from the bottom, with two vents of h19 x w90 cm each (vertical solid line: ± standard deviation).

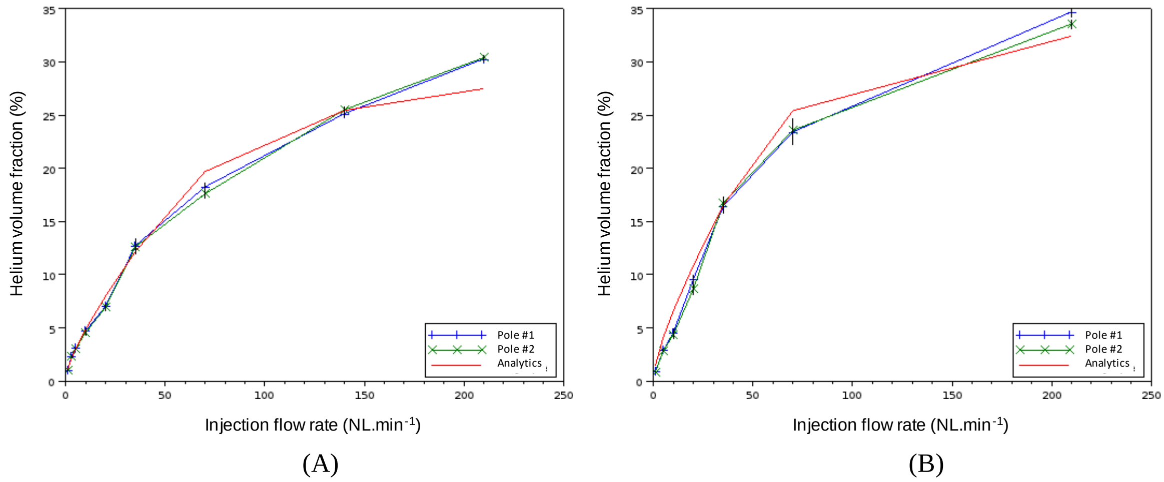


Figure 12. Steady state maximal helium volume fraction as a function of the injection flow rate for several altitudes of release: 158 cm (A) and 168 cm (B) from the bottom with one upper vent of h4.5 x w90 cm and one bottom vent of h19 x w90 cm (vertical solid line: ± standard deviation).

These preliminary results are very satisfying and hopeful since a good agreement is obtained whatever the release flow rate, whatever the injection point and whatever the size of the upper opening.

However a strong dependence on entrainment coefficient was observed and has significant effects on analytical results for maximal concentration in homogeneous layer assessment and more for the height of the interface calculation.

The maximal concentration seems to be a function of α^5. The interface height modeling appeared more difficult.

Thus more developments on the analytical model are needed in order to obtain the complete description of the two-openings natural ventilation. This work of optimization is now in progress.

4.0 CONCLUSIONS

Experiments on the dispersion of a helium release in a 2-m^3 rectangle parallelepiped with a square horizontal base enclosure equipped with two openings for natural ventilation were performed to assess the effects of the injection flow rate and of the height of the release source on the helium volume fraction and on the distribution profile. Injection flow rates, corresponding to volume Richardson numbers higher than 1, cover the [1 - 210] $NL.min^{-1}$ range.

According to the experimental works, at steady state, it is shown that the flow rate has an influence on the maximal concentration in the enclosure, and the vertical distribution profile. Two main distribution profiles were observed: a stratified regime for the lowest flow rates and a bi-layer regime characterized by a homogenous upper layer for high enough flow rates.
The study of the height of the injection point allowed the observation of several phenomena.
A low injection point promotes a bi-layer regime. But when the height of the injection is significantly increased, the bi-layer structure disappears; a third regime is observed: an impinging regime without homogeneous layer.
The maximal concentration measured inside the enclosure increases with the height of the injection.
The influence of the thickness of the upper opening was studied too and the experiments show that lower the thickness of the vent is, more the bi-layer distribution structure is favoured.

To complete this experimental work, two theoretical approaches were studied: first the Linden *et al.* methodology commonly used, and then the Woods *et al.* approach which allows the height of the injection to be considered.
Results show that the Linden approach is not conservative for the helium maximal concentration assessment when the injection point is not at the bottom of the enclosure for flow rates higher than 20 $NL.min^{-1}$.
Then Woods *et al.* methodology was considered and the model was adjusted on experimental data through the entrainment coefficient parameter. Satisfying and hopeful results were obtained with this approach.

For next steps, works on analytical approach of Woods *et al.* will be completed for a better assessment of the build-up behavior of the releasing buoyant gas. An important study on the influence of the entrainment coefficient and on the predictive strength of this approach fitted on our experimental data is in progress. Other approaches will be studied too (e.g. Carazzo *et al.* (11)), and more experimental data will be taken into account to test the availability of our analytical approach on a large number of cases, configurations and scenarios.

ACKNOWLEDGMENTS

The results presented in this paper have been obtained within the frame of the Horizon Hydrogène Energie (H2E) program. The authors acknowledge the French agency for innovation support OSEO, and CEA for technical, experimental and scientific support.

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