# COMPARISON OF HELIUM AND HYDROGEN RELEASES IN 1 M$^3$ AND 2 M$^3$ TWO VENTS ENCLOSURES: CONCENTRATION MEASUREMENTS AT DIFFERENT FLOW RATES AND FOR TWO DIAMETERS OF INJECTION NOZZLE.

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**ABSTRACT**

This work presents a parametric study on the similitude between hydrogen and helium distribution when released in the air by a source located inside of a naturally ventilated enclosure with two vents. Several configurations were experimentally addressed in order to improve knowledge on dispersion. Parameters were chosen to mimic operating conditions of hydrogen energy systems. Thus, the varying parameters of the study were mainly the source diameter, the releasing flow rate, the volume and the geometry of the enclosure. Two different experimental set-ups were used in order to vary the enclosure's height between 1 and 2 meters. Experimental results obtained with helium and hydrogen were compared at equivalent flow rates, determined with existing similitude laws. It appears, for the plume release case, that helium can suitably be used for predicting hydrogen dispersion in these operating designs. On the other hand - when the flow turns into a jet - non negligible differences between hydrogen and helium dispersion appear. In this case, helium - used as a direct substitute to hydrogen - will over predict concentrations we would get with hydrogen. Therefore, helium concentration read-outs should be converted to obtain correct predictions for hydrogen. However such a converting law is not available yet.

## 1.0 CONTEXT

Experimental and numerical studies on the dispersion of buoyant jet in confined but naturally ventilated environments are carried out in order to understand better the implied phenomena and to improve predictive methods for risk assessment of hydrogen release within confined volume. Recently experiments on dispersion were performed by several authors (1, 9-11) in large scale enclosures equipped with two ventilation openings. Those recent works aim at studying the natural ventilation through two openings in two enclosures of 1 m$^3$ and 2 m$^3$, with specific geometries close to existing hydrogen energy applications in case of accidental release. Experiments are performed with helium and hydrogen as releasing sources. We compare measurements between hydrogen and helium release from each enclosure and also for the two following diameters of injection pipe:4 mm and 27.2 mm.
The first section of this paper presents briefly engineering simple approaches commonly used for maximal concentration assessment at the steady state. We deduce from those models the similitude law which gives the relationship between hydrogen and helium's flow rates at which helium and hydrogen are expected to produce the same concentration distribution. In the second section, the experimental set-ups are described. Finally in the last part, the results are presented and discussed before concluding.

## 2.0 EXISTING MODELLING APPROACH

Only the steady state will be considered in the following work. The enclosure is naturally ventilated thanks to two vertical vents localized for the first one near the floor and for the second one, near the ceiling as shown in Figure 1. Baines and Turner model (2) was extended by Linden (3, 4) 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 an horizontal interface. The lower layer is set at a uniform ambient temperature as well as the upper layer but with a higher temperature that depends on the buoyancy flux from the source.

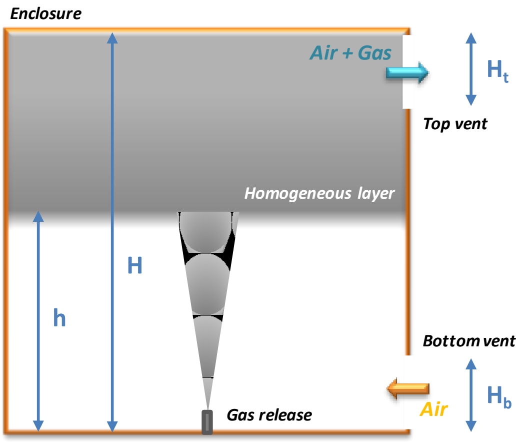



**Figure 1-** Scheme of the dispersion phenomenon considered in a naturally ventilated enclosure with two openings localized at different altitudes.

In a box that can be naturally ventilated as shown in the figure above (see Figure 1), the presence of the upper buoyant layer creates a pressure difference across each vent, provoking consequently 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 composed with two vents leads to a displacement ventilation regime resulting with the formation of an upper homogeneous layer of air and released gas above a lower layer of pure air. Linden suggests a methodology which allows to calculate, at steady-state, the concentration of the homogeneous upper layer and the height of the interface *h*.

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

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, $m.s^{-2}$ and $g'_0$ is the reduced gravity given eq. (6).

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

where $C$ – constant given by the plume theory of Morton *et al.* (5), $\alpha$ – entrainment coefficient (from 0.05 to 0.1 for a pure plume). The height of the interface, $h$, is given by the following expression:

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

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

where $S^*$ – effective vent area, m², $H$ – the height of the enclosure, m, $C_t$ – top vent discharge coefficient, $C_b$ – bottom vent discharge coefficient, $S_t$ – top opening area, m², $S_b$ – bottom opening area, m².

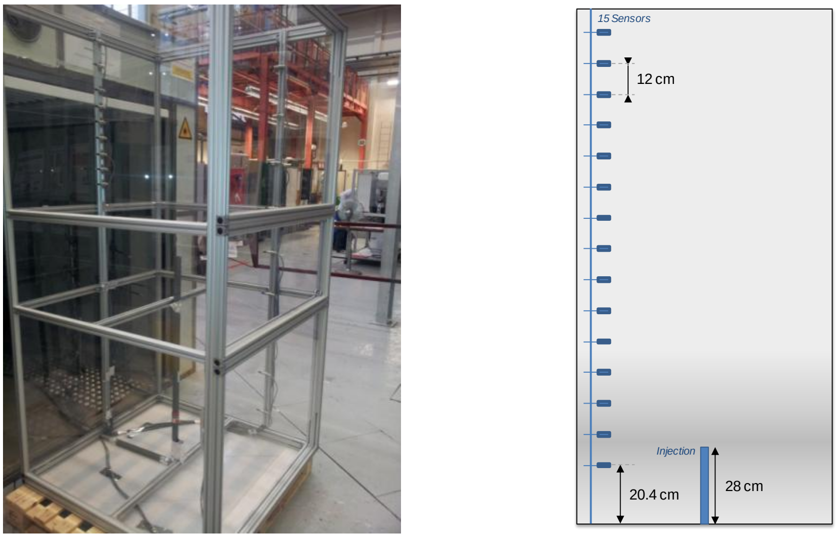
This approach, commonly used as an engineering tool for build-up assessment, does not allow to take into account a height of release located above the ground. It means that the release of gas is considered at the floor.

## 3.0 EXPERIMENTAL SETUP

### 3.1 TEST BENCH DESCRIPTION

#### 3.1.a The 2 m³ enclosure – Grand GAMELAN

The Plexiglas enclosure is a cuboid with a square horizontal base of an internal volume of 2 m³ (see Figure 2 (A)). Internal size of the enclosure is 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. The bottom and top openings have a size of h19 x w90 cm.




(A) (B)

**Figure 2** - Grand-Gamelan 2-m³ build-up enclosure.
(A) Picture of the enclosure, (B) location of the sensors in the enclosure

The gas injection source is a PVC circular tube of 27.2 mm of internal diameter, centered in the horizontal square section, directed upward. A second injection source is a steel circular tube of 4 mm of internal diameter. Both injection sources, used one after another, are located at 28 cm from the bottom of the enclosure. The range of tested flow rates goes from 5 NL.min$^{-1}$ up to 210 NL.min$^{-1}$ for helium and from 5.2 NL.min$^{-1}$ up to 218 NL.min$^{-1}$ for hydrogen, based on the use of the similitude law described below (see Eq. (5) and (6)).

$$Q_{H_2} = \left( \frac{g'_{0,H_2}}{g'_{0,H_e}} \right)^{1/2} \times Q_{He} \tag{5}$$

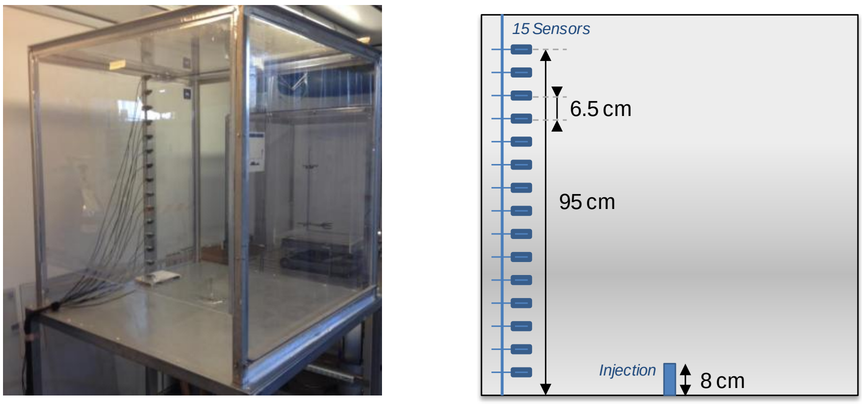
$$g'_{0,gas} = g \frac{\rho_{air} - \rho_{gas}}{\rho_{air}} \tag{6}$$

where $Q$ – releasing gas flow rate, NL.min$^{-1}$, $g'_0$ – releasing gas reduced gravity, m.s$^{-2}$, $\rho$ – releasing gas density, kg.m$^{-3}$. This similitude law comes directly from equation (1), assuming that the interface height and volume fraction of $H_2$ and $H_e$ would be equal. Indeed, considering equality of concentrations and heights of the interface for both two gases, we write the equality of concentration using equation (1) for each gas, which leads to equation (5). We therefore assume a total similitude of behavior between the two gases since both the concentration levels and the size of the layer would be identical. As we will show further, this similitude won't be possible for high injection flow rates, and the hypothesis to obtain a similitude of behavior should be modified. Indeed a simple modification of the flow rate is not enough to match the behavior of the two gases (for a jet release).

The injections were performed with two mass flow controllers chosen according to the desired flow rate. One controller has a 20 NL.min$^{-1}$ full scale and the other has a 600 NL.min$^{-1}$ full scale. The error on the mass flow rate for the 20 NL.min$^{-1}$ controller is less than 0.5% between 2NL.min$^{-1}$ and the full scale. For the 600 NL.min$^{-1}$ controller, the error on the mass flow rate is 0.2% of full scale plus 0.7% of the set point. Both flow meters were calibrated recently.

### 3.1.b The 1 m$^3$ enclosure

The polycarbonate enclosure is a cuboid shape with a volume capacity of 1m$^3$ (Figure 3), with a square base of 0.995 m and a height of 1 m. The 1-m$^3$ enclosure has two openings: one at the top, and one at the bottom, localized on two opposite vertical face. The bottom and top openings have a size of h18 x w96 cm.




(A) **(B)**

**Figure 3 -** 1-m$^3$ build-up enclosure.
(A) Picture of the enclosure, (B) location of the sensors in the enclosure.

As for the experiments realized within the 2-m$^3$ Grand-Gamelan enclosure, the gas injection source is a circular nozzle, alternatively of 27.2 mm and 4 mm of internal diameter. The release point is centred in the horizontal section of the enclosure and located at an altitude of 8 cm.

The studied releasing flow rates range from 5 NL.min$^{-1}$ up to 210 NL.min$^{-1}$ for helium and from 5.2 NL.min$^{-1}$ up to 218 NL.min$^{-1}$ for hydrogen. Those values correspond to a volume Richardson number range from $5.77 \cdot 10^7$ down to $7.08 \cdot 10^{-4}$. Therefore situations from a plume release up to a jet release are covered.

### 3.2 Measurement devices and data treatment

Based on the measurement of the thermal conductivity of ambient gas, 15 minicatharometers Xen-TCG3880 from Xensor Integration are used to determine the volume fraction of the helium in the enclosure. Minicatharometers were calibrated before the start of the campaign. The absolute accuracy of the minicatharometers was assessed to be around 0.1%$_{vol}$ of helium. The sensors can measure helium and hydrogen fraction fluctuations down to 0.05%. The reactivity of those sensors is assessed to be around 1 s.

The data treatment was automated: calculation of the time range for a steady state, time averaging of the concentrations and standard deviation, as illustrated in Figure 4. A first transient state from the injection's start until the steady state is eliminated. The transient state from the end of the steady state (after the injection is stopped) until the time were the cuboid is filled with air is also eliminated. The red rectangular curve in Figure 4 just shows the boundaries of the data considered at steady state. The calculated mean value is shown by the green line.

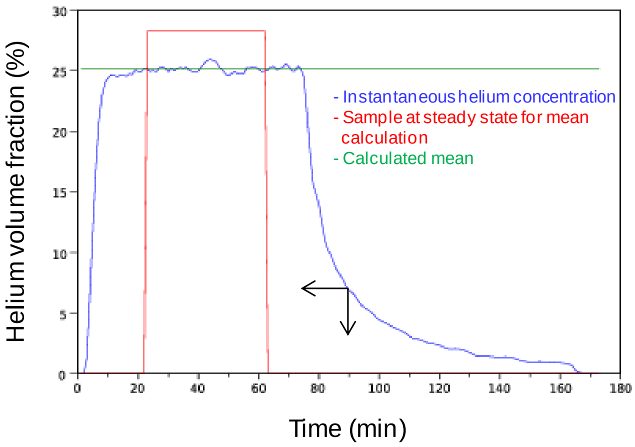



**Figure 4 -** Data treatment for steady state determination based on time-measured helium volume fraction.

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

### 3.2.a Sensors location inside the 2 m$^3$ enclosure

Fifteen sensors are located on one vertical pole. From 20.4 cm from the floor of the enclosure, the fifteen sensors are installed each 12 cm alongside the mast (see Figure 2(B)), with a single exception: no sensor was placed at height 32.4 cm. The sensors are located on a single mast since it has been established in the Linden model that the concentration distribution is only dependent on the height and therefore one dimensional, except in the jet. This distribution has also been verified experimentally by Linden (3, 4) and Bernard-Michel (8).

### 3.2.b Sensors location inside the 1 m$^3$ enclosure

In the same way as with the 2 m$^3$ enclosure experiments, fifteen sensors are also placed alongside a single pole, at intervals of 6.5 cm; the highest sensor being localized at 95 cm from the bottom of the enclosure (see Figure 3(B)).

## 3.3 Experimental procedure and studied configurations

### 3.3.a The test facility

The experiments have been carried out at INERIS, center of Verneuil-en-Halatte. The facility is a gallery of approximately 3 meters high, 3 meters wide and 50 meters long. The top of the gallery is located 5 meters under the ground. Using a smoke generator, we have established that the wind velocity in the facility is far lower than 10 cm/s (probably around 1 cm/s). Two plastic covers have been also placed near the enclosure to reduce any wind influence.

Safety rules allow us to carry out experiments where a maximum concentration of hydrogen is around 10 $\%_{vol}$.

Temperature in the gallery is very steady. A maximum drift of 2 K is observed during a day. This drift is a very slow process connected to outside temperature variations. During the longest experiments (1 hour), the temperature variation is not measurable therefore negligible.

On the contrary, humidity in the gallery is quite high. According to Xensor's specifications for the sensor, the influence on the measurements is expected to be less than 1% of relative error.

### 3.3.b Reproducibility of the experiments

First, CEA has used the facility Grand Gamelan in its experimental warehouse. Tests were performed with helium. The experimental results were then compared with those obtained with the very same experimental set-up at INERIS. These Grand-Gamelan results were also compared with previous experiments performed on the same Grand Gamelan facility at the CEA with CEA's own Xensor sensors (8). The results were reproducible with discrepancies lower than 0.2 $\%_{vol}$ for the concentrations of gas. This value corresponds to the absolute error of CEA calibration of the Xensor sensors. Therefore the reproducibility tests were conclusive. More details are given in the results section.

Air Liquide performed the same kind of reproducibility tests, indeed experiments have been performed in its facility with the 1 cubic meter box and the same sensors used at INERIS. The results after comparison were found to be ranged within the sensors calibration's accuracy. Those tests validate the fact that INERIS surroundings have no significant influence on the measurements.

Lastly, some chosen experiments were repeated up to five times on different configurations (change of diameter, enclosure or of flow meter), in order to assess the quality of the reproducibility. This part will be discussed in the results section.

### 3.3.c Injection

The influence of flow meters on the measurements was also checked. 4 flow meters of 20, 100, 600 and 700 $NL.min^{-1}$ have been used and all of them were recalibrated with an accuracy greater than 1% one month before the experimentation. Only the 100 $NL.min^{-1}$ failed our reproducibility test, due to a problem of condensation of the humid compressed air at an early stage, during the experimental set-up preparation. This flow meter has been put aside and only the functional flow meters were used.

Then some helium or hydrogen is injected vertically upwards through a circular nozzle of 27.2 mm or 4 mm internal diameter centred in the horizontal section of the enclosure. The releasing flow rate is injected in the enclosure only when the targeted value is reached and correctly regulated by the mass controller. In order to achieve this, a solenoid valve is employed and redirects the flow outside of the enclosure at the initial time of the injection process. When the correct flow is attained (a delay is due to the head loss in the long pipes from outside of the gallery), the solenoid valve is switched on to inject the flow in the enclosure. The pipe length from the solenoid valve to the enclosure is less than 2 meters long.

### 3.3.d Flow rates

The flow rates used in the different performed experiments are summed up in the Table 1.It can be noticed that for some few configurations at INERIS, tests have not been performed with helium whereas they have been performed with hydrogen. This fact is due to a lack of time and thus it has been decided to use instead the experimental results for helium tests performed at Air Liquide with the same 1 m3 enclosure. It is important to recall that reproducibility tests had been performed within

INERIS, Air Liquide and CEA installations. Whenever measurements with helium have not been performed at INERIS, equivalent flow rates measured at Air Liquide are used. When similar data are obtained both at INERIS, at Air Liquide or at CEA, they are used to check the reproducibility of the results.

| Parameters | Flow Values at INERIS $NLmin^{-1}$ | Flow value at AL $NLmin^{-1}$ | Flow value at CEA $NLmin^{-1}$ |
|---|---|---|---|
| **4 mm diameter, 2m$^3$, $H_2$** | 5,2 \| 21 \| 73 \| 218 | None | None |
| **4 mm diameter, 2m$^3$, $H_e$** | 5 \| 20 \| 70 \| 210 | None | None |
| **27 mm diameter, 2m$^3$, $H_2$** | 5,2 \| 21 \| 73 \| 218 | None | None |
| **27 mm diameter, 2m$^3$, $H_e$** | 5 \| 20 \| 70 \|210 | None | 5 \| 20 \| 70 \| 210 |
| **4 mm diameter, 1m$^3$, $H_2$** | 10 \| 21 \| 62 \| 104 \| 218 | None | None |
| **4 mm diameter, 1m$^3$, $H_e$** | None | 10 \| 20 \| 60 \| 100 | None |
| **27 mm diameter, 1m$^3$, $H_2$** | 10 \| 21 \| 62 \| 104 \| 218 | None | None |
| **27 mm diameter, 1m$^3$, $H_e$** | 10 \| 100 | None | None |

**Table 1** – Flow rates used for the different experiments performed.

### 3.3.e Measurements

Gas concentrations measured by the minicatharometers are recorded each second. The injection is stopped after at least 5 times the time needed to reach the steady state; that is when helium concentrations are stable in the time. Approximately 10 minutes of steady state regime were recorded, which is up to 10 times the length of the transient regime. During the gas injection, the stability of pressure and of temperature inside the enclosure is checked.

### 3.3.f Studied configurations

The summary of the studied configurations is given in Table 2 (see below).

| Parameters | Values |
|---|---|
| **Temperature** | Ambient temperature, around 13°C |
| **Gas flow rate** | From 5 to 218 $NL.min^{-1}$ |
| **Injection height** | 27 cm |
| **Gas** | Helium \| Hydrogen |
| **Internal diameter of the source** | 4 \| 27.2 mm |
| **Bottom opening** | h19 x w98 cm* <br> h18xw96 cm** |
| **Top opening** | h19 x w98 cm* <br> h18 x w96 cm** |

** h the height, w the width, Grand GAMELAN 2 m$^3$*
*** h the height, w the width, Air Liquide 1m$^3$*

Table 2 - Studied configurations.

## 4.0 RESULTS AND DISCUSSION

Here the focus will be essentially on the results as a confirmation of the potential use of helium as a substitute for hydrogen in dispersion related experiments. The phenomenology of dispersion in a two vents cavity will be the object of future complementary works.

### 4.1 Reproducibility of the results

The focus will be put upon the reproducibility tests because the experiments were performed in an "outdoor" environment. Working conditions during the first days were difficult due to rainy days resulting in an atmosphere charged with high humidity and even a flooding of the floor. Therefore, it was of prime importance to ensure that electronic devices were normally functioning and that physical phenomena were not altered by these climatic changes.

#### 4.1.a Comparisons for 2-m$^3$ enclosure at CEA and INERIS

For helium injections, we compare the maximum volume concentration of helium measured at CEA and at INERIS for the same enclosure with the same sensors. Only the flow meters are different whereas the sensors are provided by Air Liquide. We also achieve comparisons with the same experiments carried out one year earlier at CEA with CEA's own catharometers, see Figure 5.

| | | Exp. I | Exp. II | Exp. III |
|---|---|---|---|---|
| Diameter | Flow rate | $C_{max}$ | $C_{max}$ | $C_{max}$ |
| mm | NL/min | $\%_{vol}$ | $\%_{vol}$ | $\%_{vol}$ |
| 27 | 210 | 6.6 | 6.5 | 6.7 |
| 27 | 70 | 2.81 | 2.9 | 3.1 |
| 27 | 20 | 1.34 | 1.4 | 1.3 |
| 27 | 5 | 0.68 | 0.55 | 0.6 |

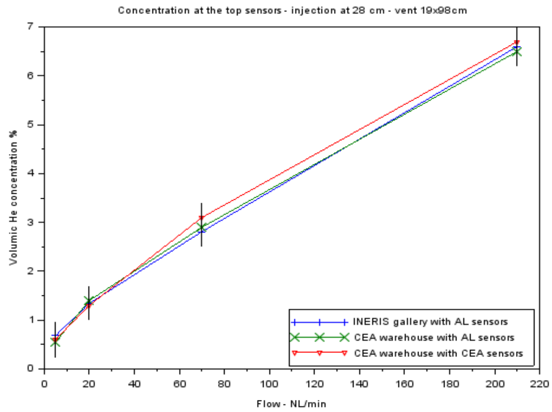



**Figure 5** – Maximum concentration of helium at the top of the enclosure for different flow rates and for 3 tests campaigns: table and corresponding curves. Exp. I is located at INERIS, Exp. II at CEA and Exp. III at CEA but with CEA's own sensors.

It is possible to note that the deviation from the mean measurement is lower than an absolute 0.2%. We also point out that the vertical mast's location is different in the former CEA experiments (performed with CEA sensors). The mast is located on the side wall at the right of the vent. Therefore the error of reproducibility takes into account various flow meters, various geographical locations (CEA indoor and INERIS gallery) as well as various sensors (CEA and Air Liquide) and sensors location in the box. The observed accuracy is nevertheless within the expected range of calibration error of the sensors combined with the expected error of the flow meters. The standard deviation for the relative error of reproducibility is less than 5%.

#### 4.1.b Comparisons for 1 m$^3$ enclosure at Air Liquide and INERIS

Those comparisons have been made on a closed box. Therefore they won't be mentioned here in this article but they will be presented in a further article. We only indicate that they are in line with the observations made with the 2-m$^3$ box and two vents.

#### 4.1c General reproducibility tests at INERIS

We also perform reproducibility tests for a large number of the experiments carried out at INERIS. The initial reproducibility tests were done on the closed 1-m$^3$ enclosure. For different flow rates, 5 series of experiments are carried out and their results compared. The average reproducibility is better higher than 0.1% for the concentration measurements.

Consequently, for the two vents configurations, the reproducibility tests were done in an extensive way only for each major change of configuration: change of enclosure, change of gas, change of injection diameter. As for the flow rates changes, only one reproducibility test is done per flow rate. The standard deviation for those tests was lower than 0.05% which is the sensitivity limit of the sensors. The maximum discrepancy observed was of 0.15%.

### 4.2 Hydrogen versus helium comparisons on 2-m$^3$ enclosure

As in Figure 6, the maximum measured concentration at the top of the enclosure, for each injection diameter and each gas are given. The flow rate is varied from 5 NL.min$^{-1}$ up to 210 NL.min$^{-1}$ for the experiment conducted with helium.

It can be noted that the flow rates are indicated in the table only for helium. The corrections according to similitude law (5) are applied for hydrogen, the corresponding flow being 5.2, 20.8, 73 and 218.1 NL.min$^{-1}$.

| **Diam** mm | **flow rate $h_e$** NL/min | **$C_{max}$ $h_e$** %vol | **$C_{max}$ $h_2$** %vol |
|---|---|---|---|
| **27** | 5 | 0.68 | 1.06 |
| **4** | 5 | 0.88 | 1.09 |
| **27** | 20 | 1.34 | 1.83 |
| **4** | 20 | 1.41 | 1.73 |
| **27** | 70 | 2.81 | 3.35 |
| **4** | 70 | 2.74 | 3.3 |
| **27** | 210 | 6.6 | 6.17 |
| **4** | 210 | 4.69 | 5.44 |

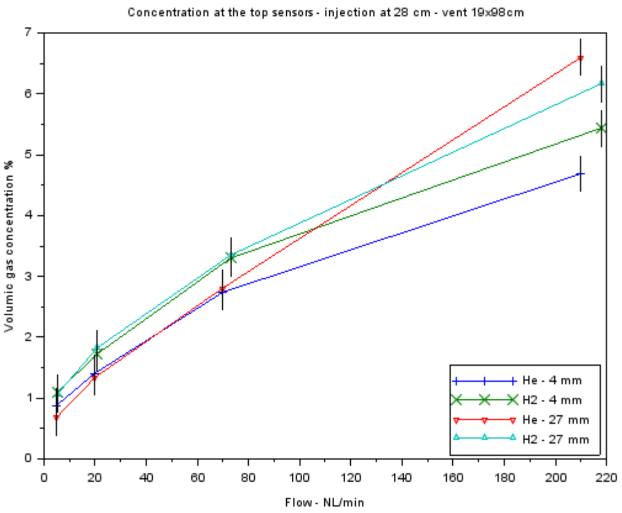



**Figure 6** – Helium and hydrogen release – Maximum volume concentrations at different flow rates and for 4 mm and 27 mm injection diameters: table and corresponding curves.

We observe that hydrogen concentrations are slightly higher than the helium ones for the lower flow rates (below 100 NL.min$^{-1}$). The difference never exceeds 0.5% in absolute which is just slightly above the expected reproducibility error. In this flow range, it is also possible to notice that the results depend on the nature of the injected gas whereas they are more or less not impacted by the injection's diameter. In fact, the differences of concentrations represent, at the most, less than 0.1% when changing the diameter for a fixed flow rate.

For the highest flow rate, 210 NL.min$^{-1}$ helium-equivalent, there are stronger differences. Hydrogen and helium concentrations are dropping when the diameter decreases from 27 mm to 4 mm. The spread between the concentrations for each gas and each diameter is twice as large for helium than for hydrogen, leading to a more important concentration of helium than hydrogen for the 27 mm injection diameter.

In **Figure 7**, we plot on the graph the vertical profiles of the concentration for a 27mm injection, at 70 NL.min$^{-1}$ (the threshold where spread in the behavior is starting) and at 210 NL.min$^{-1}$. Vertical profiles are also given at 210NL.min$^{-1}$ for a 4 mm diameter injection. We can observe the 2 layers structure described by Linden (3,4). For the 27 mm injection, the position of the interface is almost the same for hydrogen and helium at any flow rate. On the other end, the interface position is moving along with a change of injection's diameter from 27 down to 4 mm. In the case of the injection of gas through the 4 mm diameter,the upper zone is almost twice thicker than with the 27 mm injection. It appears that inertial effects play an important role for small diameters (injection velocity is approximately 50 times higher for the 4 mm diameter injection).

The differences of density between helium and hydrogen lead to different forations of the top layer at high injection velocities (around 300 $m.s^{-1}$ at 210 $NL.min^{-1}$) while the buoyancy effects stay more or less the same.

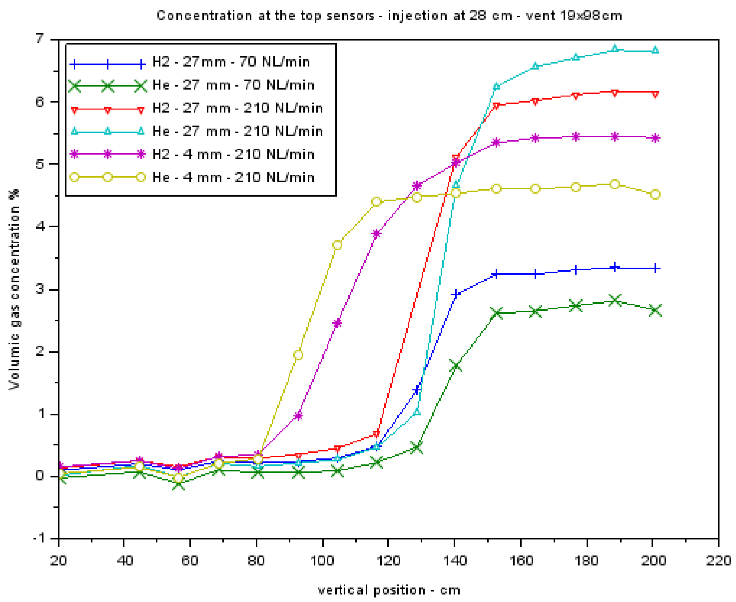



**Figure 7-** Vertical concentration profiles at different flow rates and injection diameter for helium and hydrogen

When inertial effects are important, it would be useful to develop an improved similitude law when using helium as a direct substitute for hydrogen. Indeed, the similitude law equation (5) based on equation (1) is not directly applicable since the interface's height is different for helium and hydrogen when inertial effects are important. It should be kept in mind that that equation 5 was deduced from this hypothesis among others.

Let us suppose the equation (5) is satisfied and express equation (1) for hydrogen and for helium. Dividing the concentrations of hydrogen and helium $X_f(H_2)$ and $X_f(H_e)$ and eliminating equation (5) in this expression leads to:

$$X_f(H_2)h(H_2)^{5/3} = X_f(H_e)h(H_e)^{5/3}$$

Therefore, when we use the similitude equation (5), we observe that the quantity $X_f h^{5/3}$ should be conserved. To sum up this result, whenever Linden model - ie equation (1) - is valid, if we chose flow rates satisfying the similitude law given by equation (5), we can only be sure to conserve the quantity $X_f h^{5/3}$. One of the major consequences is that if the structure of the top layer – i.e. the interface's height – is different for the two gases, the concentration will then also be different for the two gases. It also proves that any similitude law based on the sole flow rates cannot succeed whenever the layer structure will be different for the two gases.

As an illustration we are doing the simple following calculation: for a helium flow rate of 210 $NL.min^{-1}$ a hydrogen flow rate of 218 $NL.min^{-1}$ and the 4 mm injection diameter, the ratio of measured helium and hydrogen concentrations should induce a ratio of interface height of 1.09. This ratio seems to be in good agreement with the curves on **Figure 7**.

Nevertheless, if we could design a model connecting the height of the top layer to the diameter of injection, we could then build a similitude law based both on the flow rates (equation 5) and the diameters of injection. This supposition requires further investigations.

At last, in the absence of such an improved similitude law, helium still remains a good substitute to hydrogen for conservative prediction of hydrogen concentrations. Indeed, we showed that is the case for plumes injections. Concerning the inertial jet injections, we observe that concentrations of helium rapidly rise at higher levels than for hydrogen, with increasing flow rates. In the worst case, helium and hydrogen concentrations show the same evolution with the increasing flow rates, at 4 mm. Helium can then prefectly be used as a conservative substitute.

### 4.3 Hydrogen versus helium comparisons on 1 m$^3$ enclosure

We proceed with the same comparisons summarized in Figure 8.

| Injection (mm) | flow rate NL/min | $C_{max}\ h_e$ $\%_{vol}$ | $C_{max}\ h_2$ $\%_{vol}$ |
|---|---|---|---|
| **27** | 10 | 1.79 | 1.80 |
| **4** | 10 | 1.97 | 2.04 |
| **27** | 20 | - | 2.52 |
| **4** | 20 | 2.76 | 3.0 |
| **27** | 60 | - | 5.03 |
| **4** | 60 | 4.35 | 4.99 |
| **27** | 100 | 8.23 | 6.69 |
| **4** | 100 | 4.84 | 6.15 |
| **27** | 210 | - | 11.12 |
| **4** | 210 | - | 7.38 |

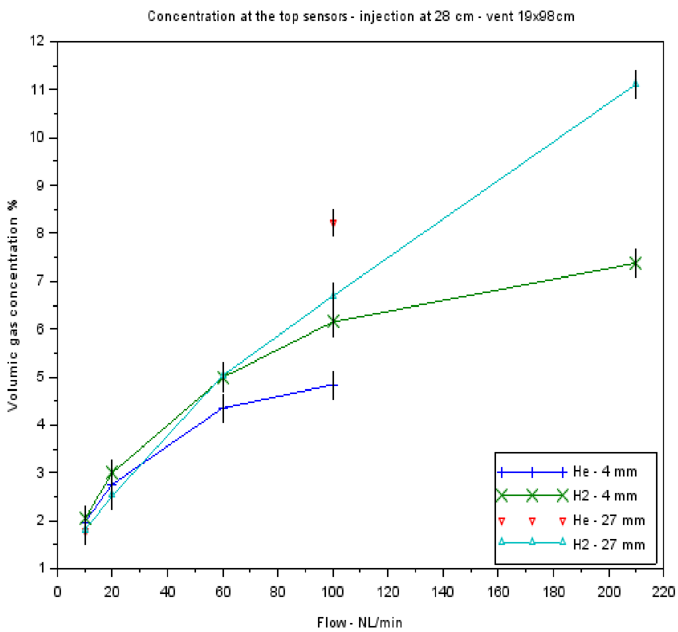



**Figure 8** - Maximum concentrations for helium and hydrogen injection in the 1-m$^3$ enclosure.

Below 60 NL.min$^{-1}$, we observe that the differences between hydrogen and helium - for each flow rate – are standing within the range of sensor's calibration accuracy. Starting from 60 NL.min$^{-1}$ up to 210 NL.min$^{-1}$, it is possible to observe the same phenomenon than with the 2-m$^3$ enclosure: a strong spread of the results depending on the injection's diameter. The spread is twice stronger for helium than for hydrogen. The missing data – left side table on figure 8 - for helium in the case of the 27mm injection will be completed in a further article.

### 5.0 CONCLUSIONS

With existing similitude law applied to injection's flow rates based on Linden model, it appears that helium cannot be directly used as a substitute for hydrogen to predict the distribution of the gas concentration. They would not be representative of what we could have obtained with hydrogen at the same flow rates. So helium as a replacement for hydrogen has mainly an interest to validate models.

Nevertheless, for a plume release, helium gives a good prediction which only worsens when the flow turns into a jet at the nozzle's exit. A first explanation of the relative inadequacy of the similitude law relative failure in this case lies in the change of structure of the layers - such as the thickness of the interface - with inertial flows. Therefore further analysis needs to be done. At the moment, we can only say that quantity $X_f h^{5/3}$ should be conserved applying the similitude law.

We may hope to find a direct similitude between hydrogen and helium based on both flow rates (Eq. (5)) and injection diameters. In that case, a modification of both flow rate and injection diameter could lead to the same concentration read-outs for hydrogen. Such a similitude would be more likely to be accurate since the injection's diameter and the flow rate allow to control both the Reynold's and the Richardson's numbers, which we expect to determine the concentration distribution.

At last, helium can be used as a good substitute for hydrogen to build up models and determine physical constants of those models. Linden (3,4) and Carazzo (7) have indeed successfully built models with other components than hydrogen (salted water, volcano's burst), models that proved to be predictive for helium, and also for hydrogen (for example for plume release). Using various gas or liquids to validate those models helps to find out what are the effective non dimensional parameters driving the dispersion process.

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