AN ANALYSIS OF THE EXPERIMENTS CARRIED OUT BY HSL IN THE HYINDOOR EUROPEAN PROJECT STUDYING ACCUMULATION OF HYDROGEN RELEASED INTO A SEMI-CONFINED ENCLOSURE IN REAL WIND CONDITIONS, AND COMPARISON WITH EXISTING ANALYTICAL MODELS.

Deborah Houssin-Agbomson, Simon Jallais

Air Liquide – Paris-Saclay Research Center,
1 chemin de la Porte des Loges – 78354 Les Loges-en-Josas, France,
deborah.houssin@airliquide.com

ABSTRACT

Experimental work on hydrogen releases consequences in a 31-m^3 semi-confined enclosure was performed in the framework of the collaborative European Hyindoor project. Natural ventilation effectiveness on hydrogen build-up limitation in a confined area was studied for several configurations of ventilation openings and of release conditions, in real environmental conditions [1]; influence of wind on gas build-up was observed as well. This paper proposes a critical analysis of these experiments carried out by HSL and compares results with analytical approaches available in open scientific literature. The validity of these models in presence of wind was broached.

1.0 CONTEXT

The understanding of the influence of real weather conditions (reinforcing or opposing wind) on hydrogen accumulation in a semi-confined space is an important knowledge gap. The ALDEA modelling tools (Air Liquide Dispersion and Explosion Assessment tools) developed by Air Liquide R&D have been validated but not really in real weather conditions, particularly when wind is significant. In the framework of the Hyindoor European project, HSL (Health and Safety Laboratory - UK) performed new experiments on hydrogen build-up in a naturally ventilated enclosure outdoor-located and thus exposed to real wind conditions. The objective of this report is to describe Hyindoor experimental results, compare experimental results with the ALDEA tools, and understand wind impact on hydrogen build-up and dispersion regime.

2.0 HSL EXPERIEMENTAL SETUP

2.1 Description of the enclosure

The HSL experimental set-up (Fig. 1) consists in a 31-m^3 enclosure with a cross sectional area of 2.5 m by 2.5 m and a length of 5 m [1].

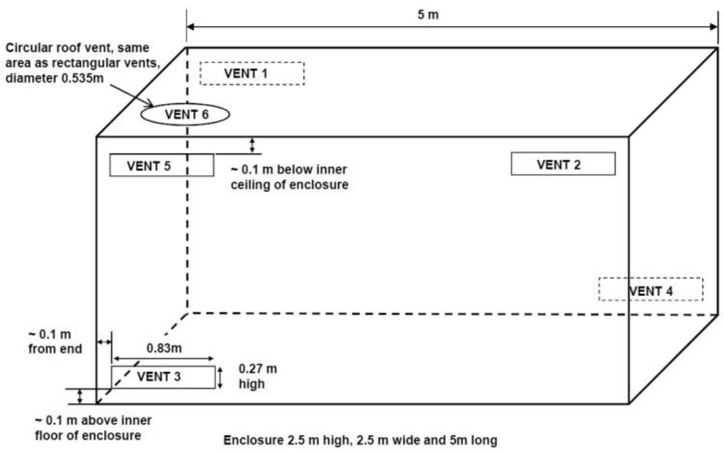


Figure 1. Scheme of the HSL 31-m^3 test facility [1].

Five similar vents (0.83 m width and 0.27 m in height) are located on the sides of the enclosure and one circular vent of same area is located on the roof (Fig. 2). Depending on the studied configuration, these openings dedicated to enclosure ventilation can be open or closed.

(A) (B)

Figure 2. Picture a vertical ventilation opening (A) and of the roof chimney (B) [1].

From this experimental set-up, two ventilation modes can be studied:

- “one-opening” ventilation mode,
- and “two-openings” ventilation mode.

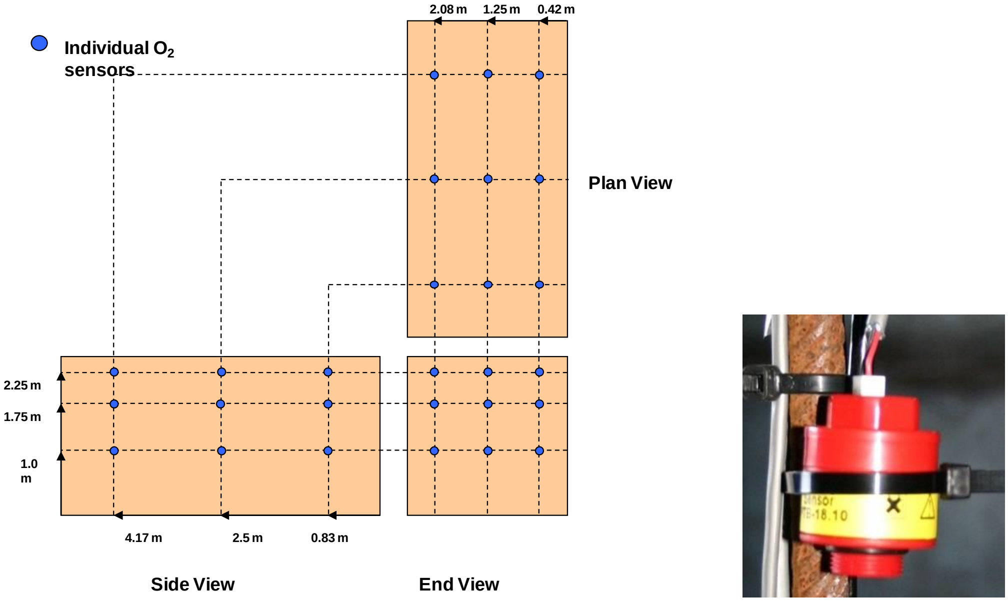
Hydrogen was released through a pipe that was located in the centre of the enclosure and directed vertically upwards. The release point was 0.5 m above the floor. Sub-sonic releases were performed at a low pressure through mass flow controllers and a 10 mm internal diameter outlet pipe. Sonic flow releases were made at higher pressures (> 10 barg) through smaller nozzles (< 1 mm diameter).

2.2 Metrological device

The hydrogen concentration was measured using twenty seven electrochemical cell oxygen sensors (Fig. 3(B)) mounted in “layers” at heights of 1 m, 1.75 m and 2.25 m (see Fig. 3(A)).

Hydrogen concentrations are then calculated from the oxygen depletion measurements when steady state is reached (i.e. no significant deviation of O_2 measurements as time function).

Based on the initial uncertainty of the oxygen sensors, the deducted hydrogen concentration has to be higher than 1% to be considered with a satisfying confidence.



(A) (B)

Figure 3. Position of oxygen sensors (A), and picture of used oxygen sensor (B) [1].

NB: Unfortunately, due to a non appropriate placement of the sensors, the distribution of the hydrogen concentration according to the altitude inside the enclosure was not studied through HSL experiments.

2.3 Wind speed measurement, correction and wording

Weather conditions close to the enclosure were monitored: i.e. wind speed and angle, ambient temperature and humidity.

Wind speed and direction were measured at a height of 4.2 m above the ground (3.4 m above the floor of the enclosure, which in turn was 0.8 m above the ground). The wind direction (i.e. the direction from where it blew) was measured relative to North.

The retained wind angle corresponds to the angle between the mean wind direction and the normal direction to the vent as presented in the Fig. 4.

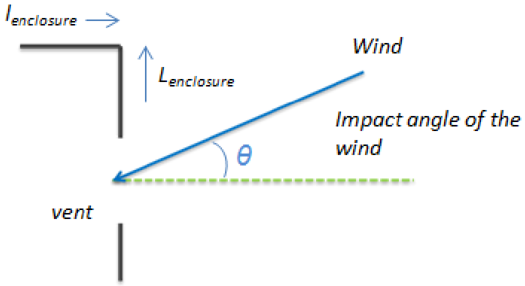


Figure 4. Scheme of wind angle.

The wind speed given in this report has been corrected from the height of measurement and from the wind direction according to the following equation from BS 5925 (1991) [2]:

$$U_w = U_{wm} \cdot \cos(\theta) \cdot \left(\frac{H_{vent}}{H_w}\right)^{0.14}, \qquad (1)$$

where U_w – corrected wind speed (i.e. height and angle), m.s^{-1}; U_{wm} – wind speed measurement, m.s^{-1}; θ – impact angle of the wind, °; H_{vent}, – location of the vent (i.e. altitude), m; H_w – height of wind speed measurement, m.

In this document opposing and reinforcing winds are employed to describe the orientation of the wind compared to the location and the function of the ventilation openings.

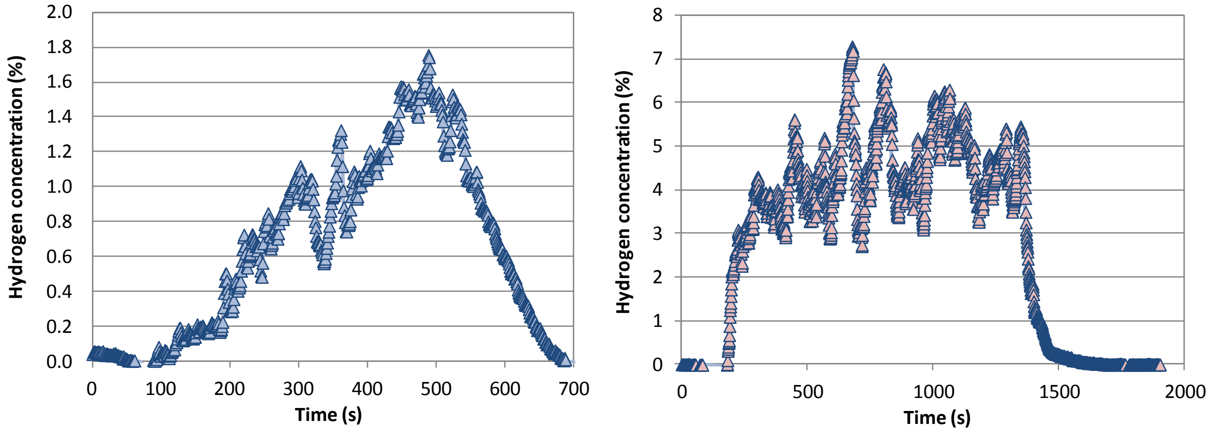
The opposing wind is a wind blowing on top vent(s) for “one-” and “two-openings” ventilation configurations (i.e. hydrogen-air outlet), and reinforcing wind is a wind blowing on bottom vent(s) for “two-openings” ventilation configurations (i.e. fresh air inlet).

3.0 EXPERIMENTAL RESULTS

3.1 Data selection

The experiments and measurements carried out by HSL were published by Hooker et al. (2014) [3], and are summarised in Table 1, where the hydrogen release rate is given in [NL.min^{-1}] – i.e. normalised flow rate at 1 atmosphere and 0°C. Average wind speed and wind direction were calculated from measurements recorded during the full duration of each test. Final hydrogen concentration measurements are used to determine average steady-state concentration values.

Regarding the whole of the results obtained by HSL, several critical points appeared on the steady state establishment, and on the accuracy and/or the stability of the measurements (see Fig. 5).



(A) (B)

Figure 5. Examples of results obtained by HSL on hydrogen concentration at 2.25 m.
(A) Steady state not reached, (B) instability of the hydrogen concentration measurements.

For this reason, Air Liquide R&D decided to perform its own data treatment and defined two criteria to assure that the steady-state of the experiments was reached during the tests sequences:

- $T_{ss} > 0.3 \cdot T_{exp}$ (with T_{ss}, the duration of the steady state and T_{exp}, the total duration of the experiment),
- Relative Mean Square Deviation (RMSD) of the nine sensors at 2.25 m must be less 35%.

Based on these criteria, many experiments were rejected of this study (see Table 1).

Table 1. Assessment of the validity of the experiments and the associated results.

Test #	**Release rate ($NL.min^{-1}$)**	**Duration of the stationary state relative at the release duration**	**Average RMS for sensor at 2.25 m**	**Validation of tests or raison to reject it**	**Final status**
1	**150**	**48%**	**14%**	**OK**	**Studied**
2	150	6%	22%	Max not reached	Rejected
3	**300**	**49%**	**21%**	**OK**	**Studied**
4	**150**	**68%**	**33%**	**OK**	**Studied**
5	300	74%	49%	Too noisy	Rejected
6	**600**	**59%**	**33%**	**OK**	**Studied**
7	**150**	**63%**	**32%**	**OK**	**Studied**
8	150	8%	14%	Max not reached	Rejected
9	**250**	**28%**	**4%**	**OK**	**Studied**
10	**800**	**36%**	**20%**	**OK**	**Studied**
11	1200	0%	0%	Max not reached	Rejected
12	1200	84%	40%	Too noisy	Rejected
13	800	44%	42%	Too noisy	Rejected
14	**1000**	**63%**	**25%**	**OK**	**Studied**
15	1200	27%	21%	Max not reached	Rejected
16	150	14%	5%	Max not reached	Rejected
17	**800**	**30%**	**3%**	**OK**	**Studied**
18	**800**	**67%**	**18%**	**OK**	**Studied**
19	150	11%	3%	Max not reached	Rejected
20	**130**	**30%**	**5%**	**OK**	**Studied**
21	**917 - 928**	**44%**	**7%**	**OK**	**Studied**
22	**887**	**71%**	**15%**	**OK**	**Studied**

Test #	Release rate ($NL.min^{-1}$)	Duration of the stationary state relative at the release duration	Average RMS for sensor at 2.25 m	Validation of tests or raison to reject it	Final status
23	325 - 335	13%	2%	Max not reached	Rejected
24	172	19%	7%	Max not reached	Rejected
25	169	14%	4%	Max not reached	Rejected
26	169	14%	7%	Max not reached	Rejected
27	792 - 837	13%	4%	Max not reached	Rejected
28	815	8%	4%	Max not reached	Rejected

Thus, on the twenty eight experiments carried out by HSL, only thirteen have been considered as successful by Air Liquide R&D, regarding to the two defined criteria described beyond.

The validated experiments could be separated in two categories and will be separately studied:

- "One-opening" ventilation configurations: experiments with open vent(s) only on the upper part of the enclosure (side wall or roof),
- "Two-openings" ventilation configurations: experiments with two open vents localized on the side walls at heights significantly different.

3.2 Retained results and exploitation

Regarding the selection of the Table 1, retained results are presented and exploited in this section.

3.2.1 One opening configurations

Table 2 summarizes the experimental results retained for one opening configurations study. All the openings are located at the top of the enclosure, close to the roof or on the roof for the chimney case.

Table 2. Steady state hydrogen concentration in the enclosure for experimental configurations with "one-opening" ventilation mode and concentration distribution.

Exp	Open top vents	Flow rate ($NL.min^{-1}$)	Corrected wind velocity Eq.(1) ($m.s^{-1}$)	Vent exposed	Steady state H_2 (%)
1	Two top vents on opposite side	150	1.52	Top vent	0.7
3	Two top vents on opposite sides	300	0.00	Top vent	2.9
4	Two top vents on opposite sides	150	2.18	Top vent	0.6
6	Two top vents on opposite sides	600	2.26	Top vent	3.0
7	One top vent	150	2.60	Top vent	2.8
9	One top vent	250	0.00	None	11.6
20	Chimney	130	1.94	Chimney	8.1

Available data enable to build conclusions on effects of the following main parameters:

- release flow rate,
- ventilation area,
- openings location,
- and wind.

Despite the non appropriate location of the sensors, it seems to be no strong hydrogen stratification (i.e. no increase of hydrogen concentration all along the height of the enclosure), and the hydrogen concentration is almost homogeneous in all the enclosure. This regime is classified as mixing regime by Linden (1999) [4].

According to the results presented in Table 2, the following conclusions are highlighted:

- The increase of the release flow rate increases the hydrogen build-up inside the enclosure for a same ventilation area (see experiments 1-3-6 and 7-9),
- The increase of the vent area decreases the hydrogen build-up (see experiments 1-7: one top vent compared to two top vents),
- Compared to a side vent configuration, the hydrogen build-up is increased by using a roof chimney (see experiments 7-20).

Concerning wind effects, experiments 3 (300 $NL.min^{-1}$) and 6 (600 $NL.min^{-1}$) in Table 2 show that for a same ventilation area, the wind has a positive effect on hydrogen mitigation. Actually the hydrogen concentration is decreased despite a higher release flow rate due to a stronger blowing wind.

3.2.2 Two Openings configurations

Experiments and associated results studied for the "two openings" ventilation mode are presented in Table 3.

Table 3. Steady state hydrogen concentration in the enclosure for experimental configurations with "two-openings" ventilation mode and concentration distribution.

Exp	**Open vents**	**Flow rate ($NL.min^{-1}$)**	**Corrected wind speed ($m.s^{-1}$)**	**Exposed vent**	**Steady State H_2 concentration**
10	Two top vents on opposite sides and one at the bottom	800	0.78	Top	4.4%
14	One top vent and one bottom on the opposite side	1000	1.41	Top	5.9%
17	Chimney and near bottom vent (vent 3)	800	1.27	Chimney	8.9%
18	Chimney and opposite bottom vent (vent 4)	800	2.25	Chimney	5.5%
21	Chimney and opposite bottom vent (vent 4)	923 (sonic)	2.22	Chimney	5.4%
22	Chimney and opposite bottom vent (vent 4)	887	2.37	Chimney	6.7%

From Table 3, some conclusions can be drawn:

- The increase of ventilation area induces a decrease of hydrogen build-up as already observed,
- The increase of the release flow rate increases the hydrogen build-up inside the enclosure for a same ventilation area (see experiments 10-14),
- With a wind blowing on the top vent, compared to a top side vent configuration, the hydrogen build-up is increased by using a roof chimney (see experiments 22-14). With a chimney, the wind cannot enter in the enclosure and thus positive mixing effect on hydrogen mitigation is minimized,
- The sonic release seems to decrease hydrogen concentration compared to a buoyant release (see experiments 21-18). This is certainly due to an intense mixing in the enclosure by the high momentum of the jet which induces a decrease of hydrogen concentration,
- The aspect ratio has effects on ventilation according to the location of the apertures (see experiments 17-18). Actually, if the lower vent is near the upper one, the ventilation is only local and there is hydrogen enrichment due to the under-ventilation of a part of the enclosure. At the opposite, if the lower vent is far to the upper one, the sweeping of the enclosure is more efficient and hydrogen build-up is reduced.

4.0 COMPARISON OF THE HSL EXPERIMENTS WITH ENGINEERING MODELS

4.1 Description of available modelling approaches

The ALDEA-CL3 and ALDEA-CL2 tools, developed by Air Liquide R&D on the basis of published engineering models, have been used for comparison with the HSL experimental data.

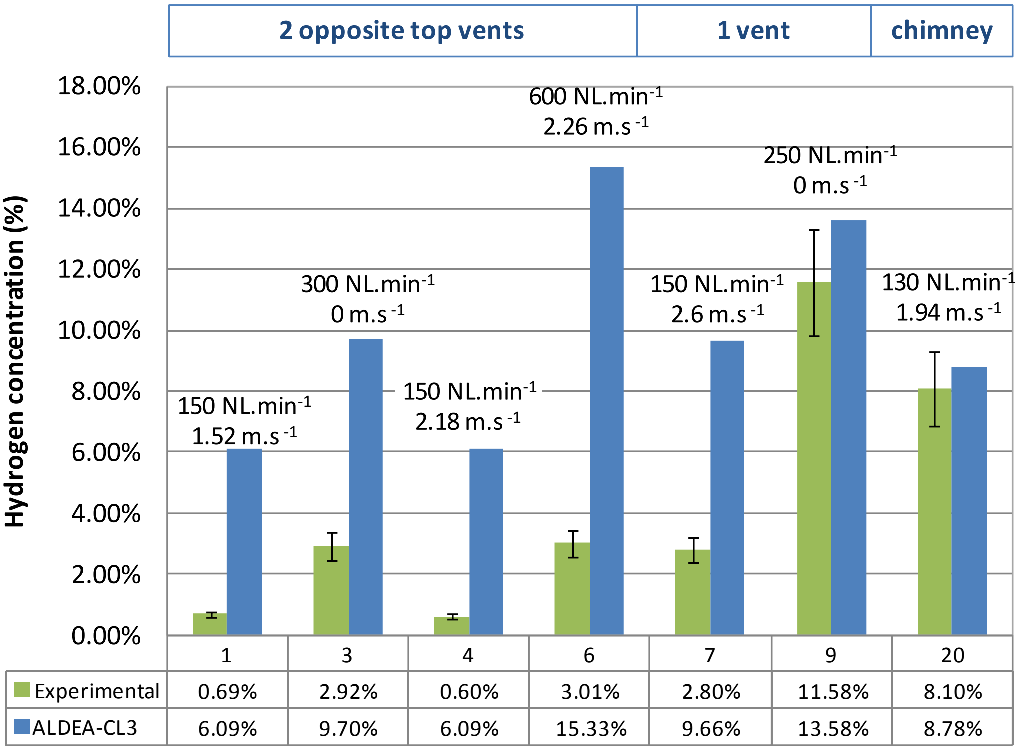
ALDEA-CL3 is based on Linden approach [4] considering only the buoyancy of H_2-air mixture inside the enclosure. It could be used for calculations in one- or two-openings of natural ventilation configurations. This approach was validated by comparing experimental results (without wind) published in open scientific literature [5].

ALDEA-CL2 is based on Lowesmith works (2007) and takes into account the buoyancy and also the effect of the wind [6]. It has been validated in real conditions for H_2-CH_4 mixtures and real atmospheric conditions of reinforcing wind (NaturalHy project), and also validated for H_2 against lots of experiments. Lowesmith approach has to be used for “two-openings” ventilation mode [5].

4.2 Comparison of HSL experimental results with ALDEA tools

4.2.1 “One-Opening” configurations

Fig. 6 presents the comparison of experiments and modelling with ALDEA-CL3 in “one-opening” configurations.



	1	3	4	6	7	9	20
🟩 Experimental	0.69%	2.92%	0.60%	3.01%	2.80%	11.58%	8.10%
🟦 ALDEA-CL3	6.09%	9.70%	6.09%	15.33%	9.66%	13.58%	8.78%

Figure 6. Comparison between model and experimental results for “one-opening” configurations.

NB: When two vents are located on opposite sides of the enclosure, the configuration is simply modelled as one vent on a side with a higher length.

Fig. 6 clearly shows that, in all of the studied cases, ALDEA-CL3 overestimates hydrogen concentration compared to experiments.

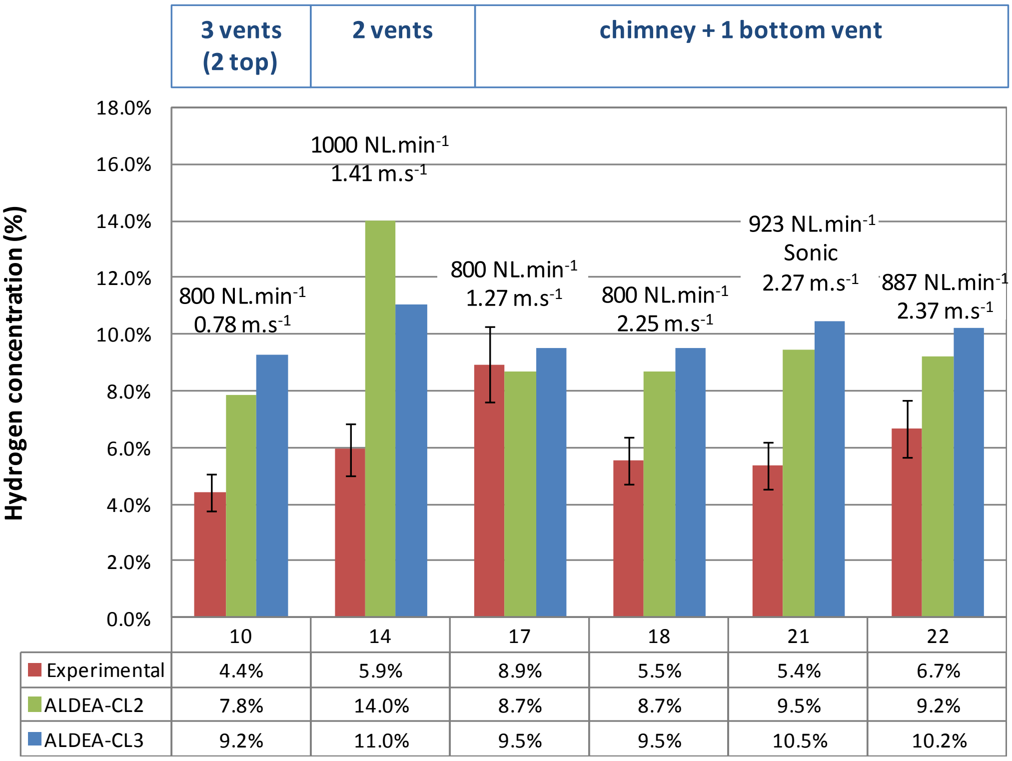
The deviations observed between calculated values and experiments are mainly due to the positive effects of wind on mitigation of hydrogen build-up which are not translated in the Linden approach. Thus calculated values of hydrogen concentrations are higher than real values when wind is significant.

The experiments 9 and 20 are acceptably predicted by ALDEA-CL3. In the first case experiments was carried out a day without wind, and in the second case the top vent is a chimney for which the wind has no influence due to its orientation (horizontal, thus wind cannot enter inside the enclosure).

To conclude, Linden approach implemented in ALDEA-CL3 gives hydrogen concentrations higher than those measured in non-negligible wind conditions. This conclusion is a positive point for the actual method employed for risk assessment or design support, since it is here demonstrated that the recommended approach is conservative.

4.2.2 *“Two-Openings” configurations*

Fig. 7 presents the comparison between HSL experimental data and calculated values from ALDEA tools.



	10	14	17	18	21	22
🟥 Experimental	4.4%	5.9%	8.9%	5.5%	5.4%	6.7%
🟩 ALDEA-CL2	7.8%	14.0%	8.7%	8.7%	9.5%	9.2%
🟦 ALDEA-CL3	9.2%	11.0%	9.5%	9.5%	10.5%	10.2%

Figure 7. Comparison between models and experimental results for “two-openings” configurations.

As for “one-opening” experiments, ALDEA-CL3 and ALDEA-CL2 overestimate experimental measurements of hydrogen concentration. These overestimations confirm the positive influence of the wind on hydrogen mitigation.

Experiment 14 in Fig. 7 shows the difficulty to model the influence of wind in an opposing configuration. In these conditions, the Lowesmith approach (ALDEA-CL2), taking into account wind conditions, is more conservative than the Linden approach (ALDEA-CL3).

In fact, in real conditions, opposing wind creates mixing and then hydrogen dilution in the enclosure whilst the Lowesmith model considers only a negative effect of the wind avoiding the exit of the hydrogen-air mixture from the enclosure.

For the chimney cases, the main conclusions are the following:

- At low wind velocity, a good agreement is obtained between ALDEA-CL2 and ALDEA-CL3 modelling (simulated without considering wind due to the chimney presence) and measurements (see experiment 17). It shows that low wind velocity on a chimney has no influence on hydrogen build-up,
- For higher wind velocity, the calculated values are higher than experiments (see experiments 18-21-22). This could be due to the sweeping effect of the wind above the chimney which contributes in evacuating outlet hydrogen-air mixture.

5.0 CONCLUSIONS

From the experimental works carried out by HSL and post-treated by Air Liquide R&D, conclusions and recommendations can be written.

The main conclusions are the followings:

- In the conditions investigated, wind has always a positive impact leading to a decrease of hydrogen build-up compared to no-wind conditions, whatever the configurations of the openings for the natural ventilation; wind participates to the hydrogen build-up mitigation,
- ALDEA-CL3 (Linden approach, without wind consideration) overestimates hydrogen build-up for “one-” and “two-openings” ventilation mode compared to experiments in real weather conditions,
- ALDEA-CL2 (Lowesmith approach, enabling wind consideration) overestimates hydrogen build-up for “two-openings” ventilation mode compared to experiments in real weather conditions,
- Wind effects are minimized for the configurations using a chimney as top vent; effects of wind are very limited due to the orientation of this ventilation aperture. Thus the ALDEA tools are in good agreement with these experimental cases.

Recommendations regarding the analysis presented in this publication are:

- It seems to be not necessary, even unproductive, to protect from wind hydrogen energy applications since wind has shown a positive effect on hydrogen mitigation in conditions addressed by the HSL-Hyindoor experiments,
- Actual analytical tools and methods, employed for risk assessment or design support – i.e. ALDEA-CL3 and ALDEA-CL2 – can be used since it is here demonstrated that these approaches are conservative.

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