DESIGNING AN INHERENTLY SAFE H_2 INFRASTRUCTURE: COMBINING ANALYTICAL, EXPERIMENTAL, AND NUMERICAL INVESTIGATIONS TO OPTIMIZE H_2 REFUELING STATIONS SAFETY BY PASSIVE MITIGATION

Houssin-Agbomson, D.[1], Herzig, A.[2], Autuore, A.[2], Molesworth, M.[2], Riso, V.[2], Soubeyran, A.[1], Lu, B.[3], Wei, Z.[3] and Prasad, A.[2]

[1] Air Liquide Research and Development, Innovation Campus Paris, 1 chemin de la Porte des Loges, 78354 Les Loges-en-Josas, France, deborah.houssin@airliquide.com

[2] Department of Mechanical Engineering, University of Delaware, Newark, DE 19716-3140, US

[3] Air Liquide Research and Development, Innovation Campus Delaware, Newark, DE 19702, US

ABSTRACT

Natural ventilation is a well-known passive mitigation method to limit hydrogen build-up in confined spaces in case of accidental release [1-3]. In most cases, a basic design of H_2 infrastructure is adopted and vents installed for natural ventilation are adjusted according to safety targets and constraints of the considered structure. With the growing H_2 mobility market, the demand for H_2 refueling infrastructure in our urban environment is on the rise. In order to meet both safety requirements and societal acceptance, the design of such infrastructure is becoming more important. In this study, a novel design concept is proposed for the hydrogen refueling station (HRS) by modifying physical structure while keeping safety consideration as the top priority of the concept. In this collaborative project between Air Liquide and the University of Delaware, an extensive evaluation was performed on new structures of the processing container and dispenser of HRS by integrating safety protocols via passive means. Through a SWOT analysis combined with the most relevant approaches including analytical engineering models, numerical simulations [4], and dedicated experimental trials an optimized design was obtained and its safety enhancement was fully evaluated. A small-scale processing container and an almost full-scale dispenser were built and tested to validate the design concepts by simulating accidental H_2 release scenarios, and assessing the associated consequences in terms of accumulation and potential flammable volumes formation. A conical dispenser and a V-shaped roof-top processing container, which were easy to build and implement, were designed and tested for this proof-of-concept study. This unique methodology, from conception, fundamental analysis, investigation and validation through experimental design, execution, and evaluation, is fully described in this study.

1.0 CONTEXT AND MOTIVATION

Clean Hydrogen and Fuel Cell Electric Vehicles (FCEV) have developed significantly in the past years in order to respond appropriately to the challenges associated with the transition to a Net-Zero Carbon Economy.

Associated infrastructure, in particular, Hydrogen Refueling Stations (HRS) have also developed to respond to the increasing needs for Hydrogen in the mobility sector. The need to mainstream Hydrogen in the mobility sector requires higher levels of accessibility of HRS in the public environment. Thus, it is necessary to deploy inherently safe hydrogen refueling stations without increasing footprint of such infrastructure because of excessively drastic safety distances and barriers. That is the reason why this study was led in order to integrate the safety by modifying physical structure of the HRS while keeping safety consideration as the top priority of the concept without neglecting the aesthetic aspects for a good integration in urban environment.

In order to propose a response to these challenges, students from the University of Delaware were called upon to put their knowledge in design and conception at the service of safety, supported by a team of experts in risk management from the US and French Research Centers of Air Liquide.

2.0 INVESTIGATED APPLICATIONS

2.1 The refueling station

The refueling station (Fig. 1) is composed of two main parts:

- The processing part which is a private area hosting the hydrogen storage, the compression units, the cooling system and all the additional equipment required to distribute hydrogen in the requested conditions at 350 or 700 bar for buses, cars or trucks respecting the established filling protocols,
- The forecourt which is a public area hosting the dispenser connected to one or several nozzles for the fueling of the fuel cell vehicles.

Figure 1. Hydrogen refueling station.
Forecourt with dispenser under canopy and processing part behind the wall.

In the processing part, some equipment is in free field, others are in confined spaces, packed in containers. In the forecourt, the dispenser is a kind of cabinet protecting some equipment (e.g. valves, pressure transducer, flowmeter…) and piping connected together by fittings.

Thus, both in the processing part and for the dispenser, the environment is confined and in case of accidental release, hydrogen can accumulate until reaching flammable limits. However, it is well-known that thanks to natural ventilation - through dedicated openings - it is possible to limit hydrogen build-up in these confined spaces. And, in most cases, engineers of the design office play mainly with the size of the ventilation apertures to respect defined safety targets.

In this original study, the idea is to take the opportunity of the creativity of students in design, in order to investigate other ways to mitigate hydrogen build-up. It has been decided to make a focus on two parts of the refueling station: one is a “generic” container for the processing part - named processing containers in this study - and the other is the dispenser in the forecourt part. Then, the first step has been to imagine new shapes for these two essential bricks of the refueling station, before assessing the concepts efficiency and benefit.

2.2 Design concepts and choice

Several concepts were proposed for both processing container and dispenser. A medley of concepts is presented in Fig. 2 for the processing container and the dispenser.

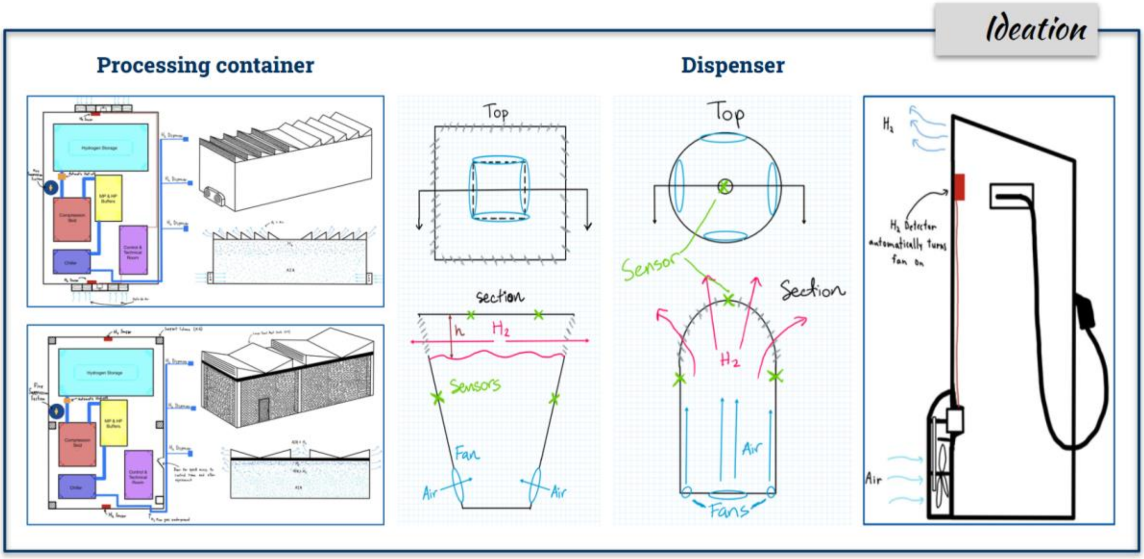
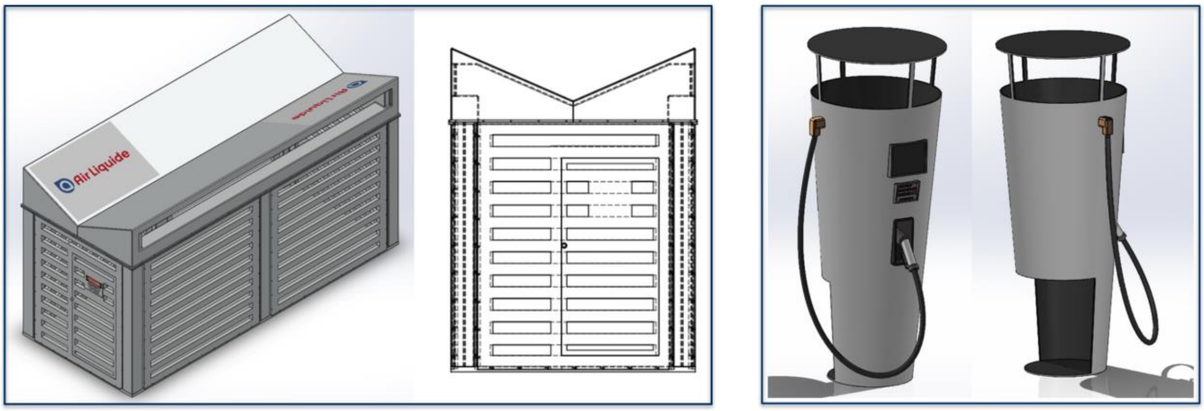


Figure 2. Concepts for the processing container and the dispenser.

Criteria were established in order to orientate the choice of the concepts to be tested:

- significantly different from existing,
- assessable concept,
- not too much costly,
- easy-to-deploy,
- time-to-market considerations.

Finally, for the study, one concept was retained for each process brick: i.e. one for the processing container, and one for the dispenser (see Fig. 3).



(A) (B)

Figure 3. Retained concepts for the processing container (A) and the dispenser (B).

3.0 METHODOLOGY AND MEANS

As previously mentioned, the first step of this study consisted in creating design ideas for the processing container and the dispenser, and define the concepts to be investigated based on the specific criteria presented in the previous section.

For the evaluation of the benefits of the concepts, the main parameter, which has been taken into account, is the accumulation of hydrogen inside the processing container and the dispenser - in case of realistic accidental releases - considering natural ventilation as the passive mitigation barrier limiting the concentration.

There are several ways to assess the efficiency of the proposed concept:

- analytical approaches based on well-known and published “engineering” models,
- numerical simulations,
- and experimental simulations.

According to the concept to be evaluated - its complexity and its size - a combination of these approaches was used. Methodology, means and associated objectives are detailed in the next sections for each technical brick.

3.1 Safety objectives and sizing hazardous scenarios

Containers in the processing part of the refueling station and dispenser in the forecourt were analysed in order to identify the potential accidental events to be considered to define the key safety requirements.

One of the foreseeable hazardous event is the hydrogen accidental release. In confined spaces, if a release is not detected and stopped, hydrogen can accumulate until reaching and exceeding the lower flammable limit (e.g. 4% of hydrogen). In this case, the ignition of the flammable volume can lead to an explosion, more or less important, depending on multiple parameters (e.g. H_2 amount and concentration, internal congestion, turbulences...).

But these critical conditions can be avoided thanks to natural ventilation which is a passive mitigation solution to limit build-up in case of unexpected leak. Thus, in this study, a maximum of 4% of hydrogen was fixed as the safety target and is therefore the parameter for assessing the efficiency of the concepts.

Through the analysis of the system, regarding pressure conditions, equipment, diameter of pipes and feedback from operations, a maximum flow rate of 100 $NL.min^{-1}$ was chosen to evaluate the resilience in terms of safety of the proposed concepts for processing containers and dispensers.

3.2 Evaluation of the dispenser concept

For the dispenser concept, analytical, experimental and numerical approaches were used. Their specificities are described in the following sections.

3.2.1 Analytical approach

Pre-calculations were performed for a preliminary calibration of the studied parameters, the finalization of the sizing of the mock-ups and the adjustment of the test matrix before launching the construction of the dispensers and performing experimental trials.

Thus, the well-known buoyancy-driven dispersion analytical approach proposed by Linden (1999) [1] for the assessment of the maximum concentration in a naturally ventilated enclosure was used:

- in mixing ventilation regime: ventilation apertures located only in the upper part of the enclosure, leading to the mixing of the released light gas in the whole volume of the enclosure,
- and in displacement ventilation regime: ventilation apertures located in the upper and lower parts of the enclosure, giving a stratification with an upper layer enriched and homogeneous in released gas compared to the lower layer free of it.

3.2.2 Experimental simulations

Among the ideas proposed by the students of the University of Delaware, the conical dispenser, as presented in Fig. 3(B), was retained and constructed at near real-scale (see Fig. 4).

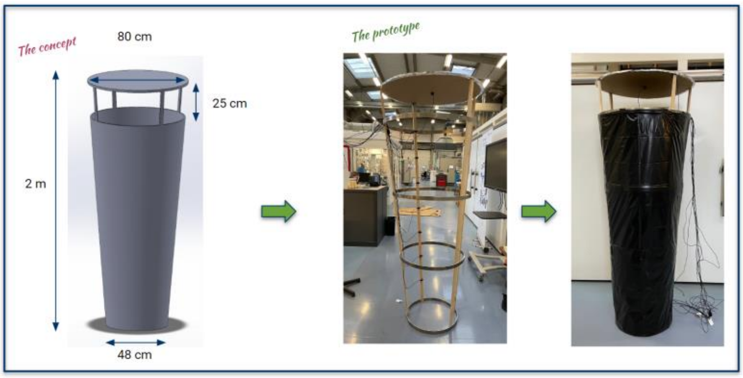


Figure 4. Conception of the near real-scale conical dispenser prototype for experimentations.

To enrich the investigations and compare the efficiency of this design, several options and configurations (see Fig. 5) were tested at near real-scale as well:

- the conical dispenser with only upper ventilation openings (D1),
- the conical dispenser with upper and lower ventilation openings (D2),
- the conical dispenser with only lower ventilation openings (D3),
- a cylindrical dispenser with only upper ventilation openings (D4).

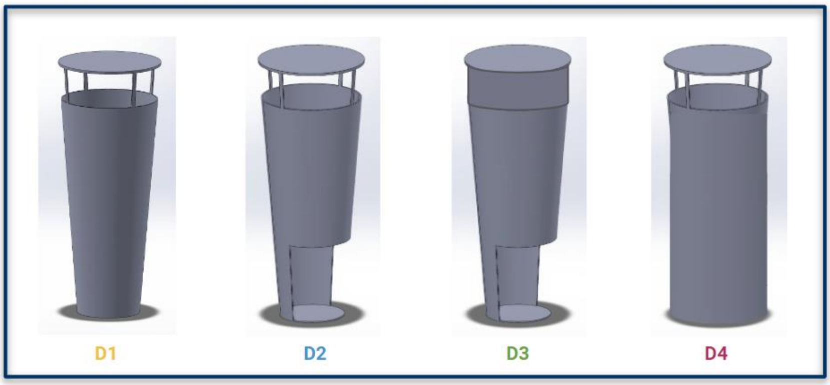


Figure 5. Dispenser tested configurations.

The objective of this exploratory work is to characterize the dispersion of hydrogen leaks inside the dispenser for different chosen accidental scenarios and understand the influence of real geometries and natural ventilation configurations. To achieve this safely through experiments, helium is used instead of hydrogen, which has been proven to be a relevant substitute [5].

Releases are generated at the targeted flow rate with two different Brooks flow controllers - 0-100 (SLA5851) and 0-600 NL.min^{-1} (SLA5853) - calibrated each year. The injection point is vertical upward, through a 4-mm diameter circular nozzle, located at 90 cm from the lower base of the dispenser. Based on commonly used accidental flow rates and taking into account feedback from operations, experiments were carried out with release flow rates from 5 to 100 NL.min^{-1}.

The sensors used are Xensor Xen-TCG 3880 catharometers (also known as thermal conductivity detectors). In presence of helium, a conductivity difference is measured and the concentration is directly deduced from this measurement, with reactivity (around 1 s) and accuracy (0.02% in absolute). Minicatharometers were specifically calibrated using helium-air mixtures from 0.5 to 60%-He.

Helium concentrations measured by the minicatharometers - as a function of time and height - are recorded each 1 s. Distribution of helium concentration is considered to be only in one dimension according to previous results, that is why, sensors are placed aligned on a vertical rod, each 25 cm from the bottom to the top of the dispenser.

The injection is stopped after reaching the steady state; i.e. when helium concentrations are stable in the time.

Maximum concentration and concentration distribution, from the bottom to the top of the dispenser, characterize the dispersion and the efficiency of the natural ventilation for the studied configuration.

3.2.3 Numerical simulations

In order to enlarge the investigations and complete experiments, numerical simulations were performed with the commercial code ANSYS FLUENT 2022 R2 [6] with a significantly higher flow rate for the conical dispenser configuration open top and bottom (i.e. D2-dispenser). In fact, has been numerically studied a flow rate of 0.12 $kg.s^{-1}$ corresponding to $8 \cdot 10^4$ $NL.min^{-1}$ of H_2 which is the maximum accidental flow rate - considering the dispenser - thanks to flow restrictors and excess flow valves commonly installed in the current refueling stations.

Fluent is a commercial Fluid Mechanics software, which solves Navier-Stokes equations using a finite volume method. In the current investigation, a 3-D Cartesian grid is used. Concerning the viscosity model, the RANS (Reynolds-averaged Navier-Stokes) approach using k-epsilon realizable for turbulence modeling is applied.

In previous studies, RANS simulations were compared with experimental data for the dispersion of helium inside closed and semi-confined cubic enclosures [7]. Good agreement was found in these configurations of release and ventilation. Additionally, in most industrial cases, it is a common choice as the calculation cost and grid precision dependency is much lower.

3.3 Evaluation of the processing container concept

As for the dispenser, analytical, experimental and numerical approaches were used to investigate efficiency in terms of H_2 build-up mitigation of the proposed design for the processing container.

3.3.1 Analytical approach

For the processing container, as shown in Fig. 3(A), an original design was proposed: a V-shaped roof-top container with longitudinal louvers distributed regularly over the entire height of the four vertical walls in order to foster natural ventilation and mitigate passively - but even more efficiently - H_2 build-up in case of accidental release.

The Linden approach (1999) [1] was used in order to perform pre-calculations. Due to the distribution of the openings (i.e. from the bottom to the top), it is assumed that the dispersion will follow the displacement ventilation regime described by Linden.

To assess the maximum concentration inside the container and validate the use of the Linden approach, calculations were performed for the real size of the proposed container and for a reduced scale of this container (1 m^3) which corresponds to the available enclosure of the test facility.

3.3.2 Experimental approach

Experiments were carried out to learn more about the efficiency in terms of H_2 build-up mitigation according to the specific design and ventilation arrangement proposed for the processing container, as illustrated by the Fig. 3(A).

The studied parameters were the following:

- impact of the inclination of the roof with plain vertical walls (i.e. V-shaped roof-top),
- impact of the louvers on the vertical walls with a non-inclined roof,
- efficiency of the combination of inclined roof and louvers.

The corresponding configurations are concretely shown in the Fig. 6.

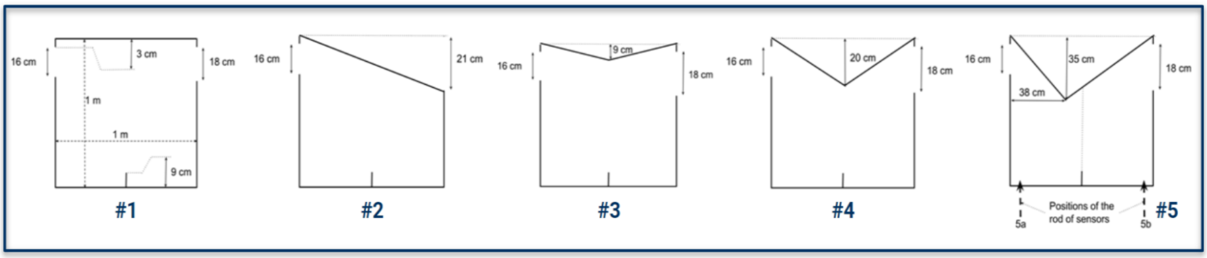


Figure 6. Inclined roof tested configurations.

Unlike the dispenser, it is not possible to carry out full-scale experimental tests for the processing container.

Thus, two types of installations were set-up to better understand the ventilation efficiency according to the type and the distribution of the ventilation openings:

- an enclosure of 1 m^3 in which helium releases were carried out and helium concentrations were measured on the entire height of the enclosure (see Fig. 7(A)),
- a more reduced scale mock-up immersed in water with air injection to simulate the hydrogen release, in order to observe the paths used by inlet and outlet flows (see Fig. 7(B)).

(A) (B)

Figure 7. Experimental set-ups for the processing container.

- ***Helium releases in a 1-m^3 enclosure***

For the 1-m^3 enclosure, same equipment as for the experimental study of the dispenser has been used: Brooks flow controllers for helium injections and Xensor Xen-TCG 3880 catharometers for helium concentration measurements.

Several configurations of natural ventilation (e.g. roof inclination, distribution and location of the ventilation apertures…) were simulated to assess the impact on the hydrogen build-up and compare the experimental measurements with the maximum concentration calculated by the Linden approach.

As presented in Fig. 3(A), the proposed design for the ventilation of the processing container presents a specific distribution of the ventilation openings located just below the roof and on the vertical walls. In order to understand the role of the openings and their benefits, the experimental work was sequenced and configurations were studied step-by-step: i.e. roof inclination first, then distribution on the walls, and to finish combination of both configurations.

- ***Air releases in a down-scaled mock-up immersed in water***

For the immersed reduced mock-up, the Archimedes Number approach (see Formula (1)) has been used to compare the motion of the fluids due to density differences, as presented below:

$$Ar = \frac{g \cdot L^3 (\rho_1 - \rho_2)}{\rho_1 \cdot \nu^2}, \quad (1)$$

where Ar – dimensionless Archimedes number; g – gravitational acceleration, $m.s^{-2}$; L – characteristic length, m; ρ_1 – density of the "ambient" fluid, $kg.m^{-3}$; ρ_2 – density of the "releasing" fluid, $kg.m^{-3}$; ν – kinematic viscosity of the "ambient" fluid, $m^2.s^{-1}$.

Nevertheless, the design of the mock-up has to be accurately scaled down to match the flow of a full-scale model. In fact, for the full-scale scenario with hydrogen, the releasing gas is 14 times lighter than air, meaning two fluids with a similar density ratio would have to be chosen for the flow within the reduced scale "air in water" experiments to be helpful in any way. Knowing that air is approximately 800 times lighter than water, the ratio sizing the reduced mock-up has been defined thanks to comparison of H_2-air and Air-water specific gravities (i.e. $\Delta\rho/\rho$).

Specific gravities for the both systems being very close - 0.93 for H_2-air versus 0.99 for Air-water - and round approximately to 1, make the Archimedes number approach valuable.

Assuming for this study, that the length involved in the Archimedes number formula is the height of the processing container, which is 3 m, the Archimedes number reaches a value of $9.6 \cdot 10^{11}$ considering a release of H_2 in air.
For the reduced scale mock-up, iterations were performed changing mock-up height in order to obtain an Archimedes number of the same magnitude order considering a release of air in water. Thus the retained value has been a height of 15 cm (20 times smaller than the full-scale length), giving an Archimedes number of $3.3 \cdot 10^{10}$, which is acceptable for the investigated phenomenon.

This ratio of 20 has been applied to the rest of the dimensions for a fully modeled, scaled down hydrogen processing container.

3.3.3 Numerical approach

Numerical simulations were slightly investigated for the processing container by the students from the University of Delaware with SimScale. SimScale is a computational fluid dynamics (CFD) cloud-based engineering platform allowing simulating laminar and turbulent flows for incompressible and compressible fluids.

The main objective with these non-expert simulations was to complete the observations made thanks to the immersed mock-up and confirm the distribution of the entering and exiting flows in the mock-up through roof and wall openings.

Work performed with SimScale is a very preliminary numerical work, allowing quick answers, but deeper investigations will have to be done for more rigorous conclusions.

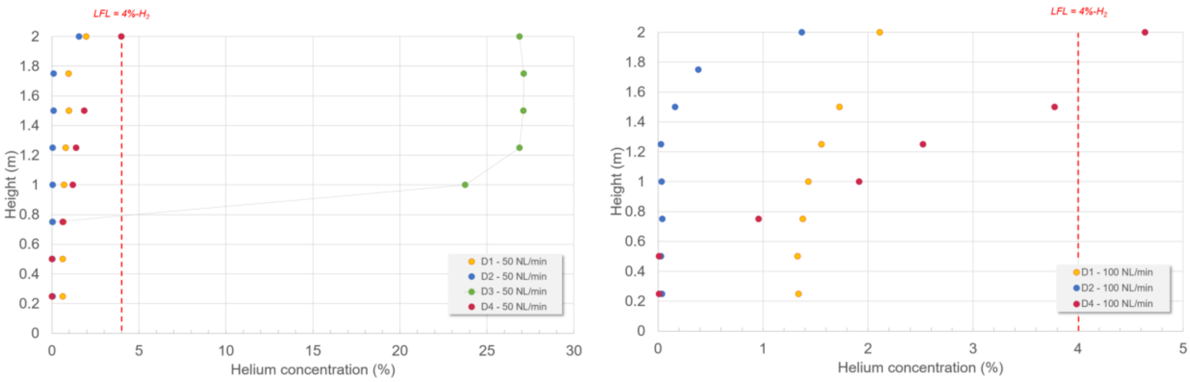
4.0 RESULTS AND DISCUSSION

4.1 The dispenser concept

Experimental measurements of the helium concentration on the entire height of the dispenser for the different studied configurations are presented in Fig. 8 for 50 and 100 $NL.min^{-1}$ release rates.

Unsurprisingly, the D2-dispenser - with the largest and distributed ventilation area at the top and at the bottom - provides the best ventilation efficiency with the lowest helium concentrations and amount. In fact, it can be noted that for this concept the concentration is zero in a large volume of the lower part of the dispenser, while for the other configurations concentration levels are higher than zero in this part.

The worst case in terms of build-up mitigation is obviously obtained for the dispenser only ventilated by bottom apertures (D3). For this configuration with a release of only 50 NL.min^{-1}, the stoichiometry (i.e. 30%-H_2) is almost reached while for the other configurations 4% of hydrogen is the very maximum.



(A) (B)

Figure 8. Helium distribution on the height of the dispensers at steady state for 50 NL.min^{-1} (A) and 100 NL.min^{-1} (B) helium releasing flow rate.

Regarding the impact of the shape of the dispenser, for the same ventilation opening location (i.e. at the top) and for the same ventilation area, the conical dispenser (D1) is more efficient compared to the cylindrical dispenser (D4) (see Fig. 8 and Table 1).

When possible, comparisons between concentration measurements and calculated values with the Linden approach were carried out. The results are presented in Table 1. Note that calculations for enclosures ventilated only by bottom vents, as is the D3-configuration, are not possible with the Linden approach. Additionally, experiments were not performed at 50 NL.min^{-1} for D4-dispenser.

Table 1. Experimental and calculated maximum helium concentrations for several release flow rates.

Release flow rates		**5 NL.min^{-1}**		**50 NL.min^{-1}**		**100 NL.min^{-1}**	
Approach		*Exp.*	*Linden*	*Exp.*	*Linden*	*Exp.*	*Linden*
D1-dispenser		0.8%	0.5%	2%	2.4%	2.3%	3.8%
D2-dispenser		0.7%	0.3%	1.3%	1.4%	1.4%	2.3%
D3-dispenser		6.3%	-	26%	-	36%	-
D4-dispenser		0.8%	0.8%	N/A	2.4%	4.5%	5.6%

Even if, in most cases Linden approach seems to overestimate helium concentrations, Table 1 shows a satisfying agreement between experiments and the analytical approach. The overprediction of the Linden approach is conservative and goes in a safe way.

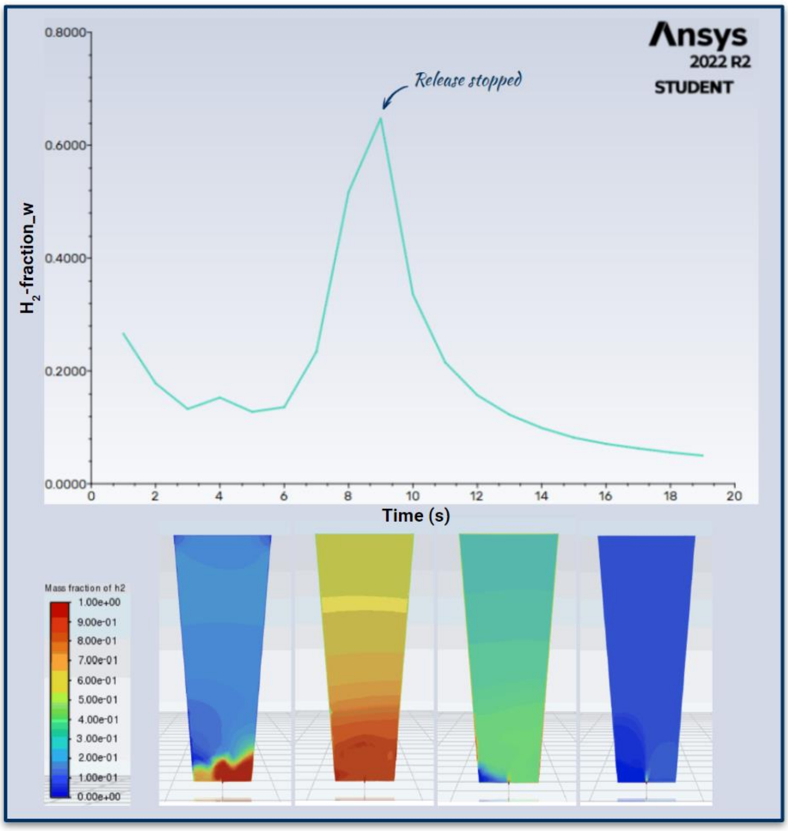


Figure 9. Numerical simulation of spatial and temporal H_2 concentration distribution for a 0.12 kg.s^{-1} release in the D2-dispenser.

To enlarge investigations, the D2-dispenser - providing the highest ventilation - was numerically modeled. A catastrophic release of 0.12 kg.s^{-1}, which is the maximum flow rate possible for the current refueling stations, was considered. Fig. 9 presents the results: it can be seen that 60%-H_2 in weight (corresponding to more than 80% in volume) can be reached with this level of flow rate for the considered ventilation system. However, if the release is stopped, acceptable concentration levels are found in 10 s. These results are very preliminary and will be refined for the next steps of this collaborative research work.

4.2 The processing container concept

The proposed design for the processing container is a bit complex in terms of ventilation openings distribution, as shown in Fig. 3(A). In order to study the efficiency of the concept and evaluate the ventilation possibilities, several configurations were experimentally tested on the 1-m^3 enclosure.

To correctly assess the impact of roof inclination and vertical distribution of the ventilation openings, tests were sequenced. Thus, first, the inclination of the roof has been evaluated, and then for the most interesting roof configuration, openings on the vertical walls were added.

Table 2 gives the results in terms of maximum helium concentration measured in the 1-m^3 enclosure, at steady state and for helium releases from 5 to 100 NL.min^{-1}, without distributed openings on the vertical walls.

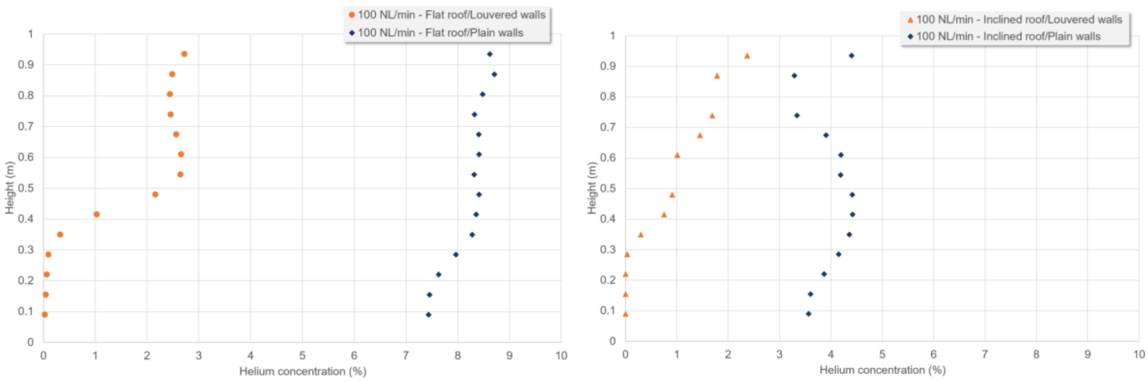
Table 2. Impact of the roof inclination on maximum helium concentrations experimentally measured for several release flow rates.

Release flow rates		**5 NL.min^{-1}**	**20 NL.min^{-1}**	**50 NL.min^{-1}**	**100 NL.min^{-1}**
Configuration 1		1.4%	2.5%	4%	8.5%
Configuration 2		1.6%	3.8%	7%	14%
Configuration 3		0.8%	2.1%	3.9%	7.5%
Configuration 4		0.8%	2%	3.5%	4.5%
Configuration 5a	*a*	0.3%	1.4%	3%	1.5%
Configuration 5b	*b*	1%	2.3%	5%	6%

By considering that the configuration with the flat roof is the reference case, the experiments highlighted that the double inclination of the roof fosters helium build-up mitigation: lower concentrations are obtained in configuration 4 (40%-slope roof) compared to the reference (i.e. configuration 1, zero slope) and to the configuration 3 with a weaker slope (18%-slope roof).

The more inclined the roof is, the lower the maximum concentration in the enclosure is. Nevertheless, in case of asymmetric roof inclination, depending on the release location, it can be observed that in one part of the enclosure the helium concentration is very low (configuration 5a) and in the other part the concentration is significantly higher (configuration 5b). Thus, not systematically knowing where the release can occur, it seems prudent to recommend a symmetrical inclination of the roof.

To complete the evaluation of the proposed concept for the processing container, louvers were added on the four vertical walls, and this ventilation configuration was tested with the flat roof (configuration 1) and with the inclined roof (configuration 4: 40%-slope roof).



(A) (B)

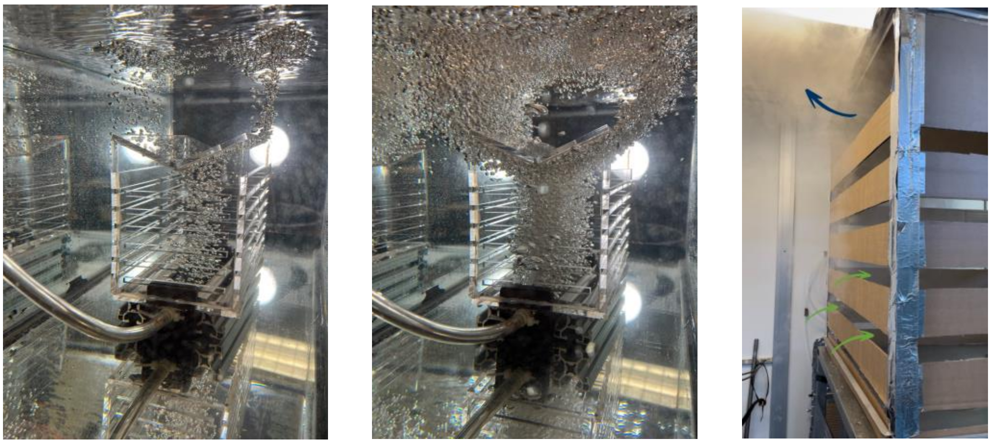
Figure 10. Helium distribution on the height of the 1-m^3 enclosure at steady state with and without louvered walls for flat roof (A) and inclined roof (B) configurations for a 100 NL.min^{-1} helium release.

For flat and inclined roof, ventilation area being higher with louvered walls, the measured concentrations are lower. The decrease is significantly higher for the flat roof with a reduction of the maximum concentration around 68% against 48% for the inclined roof with a 100 NL.min^{-1} helium release.

Concerning the concentration distribution, with the louvered walls, it can be observed a transition from a mixing to a displacement ventilation regime, which is characterized by a concentrated homogeneous upper layer, and a concentration close to zero in the lower part of the enclosure. This observation is completely clear for the flat roof and a little bit more nuanced for the inclined roof configuration.

Nevertheless, in the inclined roof configuration, even if the reduction of the maximum concentration due to the louvered walls is less important, it can be noticed that the impact on the global amount of helium is significant and diminished with the addition of louvers, since the concentration in the downer part of the enclosure is zero; unlike the plain walls configuration where the lower part concentration is very close to one of the upper part (i.e. maximum).

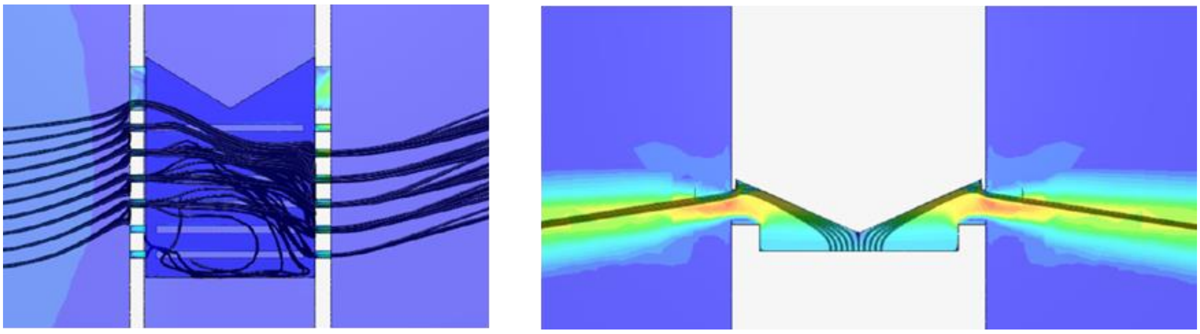
The immersed down scaled mock-up brings additional understanding on the role of the openings in the gas build-up mitigation, highlighting the preferential paths (see Fig. 11(A) and 11(B)). It has been confirmed by additional tests performed at upper scale in the 1-m^3 enclosure by generating puffs of smoke outside the enclosure close to apertures while helium was injected inside (see Fig. 11(C)). Thus the pictures of the Fig. 11, obtained for low and high release flows, show the releasing gas exit from the enclosure through the openings close to the inclined roof; the louvers on the walls only serving for the inlet fluxes from outside.



(A) (B) (C)

Figure 11. Observation of the outlet fluxes and preferential paths with immersed down scaled mock-up of the processing container for low (A) and high release flow (B), and with smokes in the 1-m^3 enclosure (C).

This flow distribution has been confirmed by the numerical simulations performed with SimScale software presented in Fig. 12(A) for inlet fluxes and Fig. 12(B) for outlet fluxes near the roof.



(A) (C)

Figure 12. (A) Air entering in the processing container through wall louvers, (B) hydrogen exiting by roof vents.

5.0 CONCLUSIONS

A novel design concept was proposed by students from the University of Delaware for the hydrogen refueling stations by modifying physical structure. The objective of this research work was to demonstrate the benefit in terms of safety of such designs for dispenser and processing containers. Natural ventilation - as a passive mitigation way to limit the hydrogen build-up in case of accidental release in confined spaces - was investigated thanks to smart configurations.

Analytical, experimental and numerical approaches were combined in order to evaluate hydrogen concentration and distribution.

For the experimental part, helium was used as a surrogate of hydrogen in order to work safely. Near real-scale mock-ups were constructed for the dispenser study, and down scaled mock-ups for the processing container.

This work highlighted that analytical calculations using Linden approach - in most cases - overpredict the helium concentration compared to the results obtained experimentally.

For the dispenser, it has been shown that a conical shape fosters the helium mitigation compared to the cylindrical shape for a same ventilation area. The size of the ventilation apertures, which was pre-defined thanks to Linden approach, was oversized regarding a safety target aiming at not reaching 4% of hydrogen. Thus, the dimensions of these apertures could be reduced and/or grids could be added in order to avoid unwanted materials/objects inside the dispenser cabinet.

For the processing container, it has been highlighted - at reduced scale - that an inclined roof with a sufficient slope can foster the hydrogen build-up mitigation and decrease the maximum concentration. Additionally, by adding louvers on vertical walls, build-up mitigation is improved as well because increasing surfaces dedicated to ventilation, but not only. In fact, it has been observed that in combination with roof openings, the louvers serve only to inlet fluxes; they do not participate in exiting released gas. But, by allowing roof openings to be used only for gas exit, discharges on the ventilation openings are lower and loss in ventilation efficiency are limited. Moreover, concentration distribution is also positively impacted by the louvers, by a transition from a homogeneous concentration in the whole enclosure to a layered concentration distribution where the released gas is only concentrated in the upper part of the enclosure. Therefore, the global amount of released gas is significantly reduced.

Numerical simulation was investigated for dispenser and container topics. Numerical simulations seem to match with experimental observations. However, at this stage, the preliminary results obtained are more qualitative than quantitative, and it is sure that further work is required in order to be able to extrapolate the experimental results for other sizes and other designs.

To conclude - with concrete, qualitative and quantified results - this study provides reflexion avenues for smartly changing the design of hydrogen refueling stations, fostering the safety and improving their aesthetic for a better integration in urban environment.

ACKNOWLEDGMENTS

The authors acknowledge the University of Delaware, and the Air Liquide Group for the financial support of this research.

REFERENCES

1. Linden, P., The Fluid Mechanics of Natural Ventilation, Annual Review of Fluid Mechanics, 1999, 31, pp. 201-238.
2. Molkov, V., Shentsov, V. and Quintere, J., Passive Ventilation of a Sustained Gaseous Release in an Enclosure with One Vent, International Journal of Hydrogen Energy, 2014, 39(15), pp. 8158-8168.
3. Cariteau, B. and Tkatschenko, I., Experimental Study of the Effects of Vent Geometry on the Dispersion of a Buoyant Gas in a Small Enclosure, International Journal of Hydrogen Energy, 2013, 38(19), pp. 8030-8038.
4. Prasad, K., Pitts, W.M. and Yang, J.C., A Numerical Study of the Release and Dispersion of a Buoyant Gas in Partially Confined Spaces, International Journal of Hydrogen Energy, 2011, 36(8), pp. 5200-5210.
5. Bernard-Michel, G. and Houssin-Agbomson, D., 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, International Journal of Hydrogen Energy, 2017, 42(11), pp.7542-7550.
6. Ansys Inc., editor. ANSYS FLUENT theory guide, 23-01-2009.
7. Bernard-Michel, G., Cariteau, B., Ni, J., Jallais, S., Vyazmina, E., Melideo, D., Baraldi, D. and Venetsanos, A., CFD benchmark based on experiments of helium dispersion in a 1 m^3 enclosure for plums and buoyant jets, ICHS 5th, 9-10 September 2013, Brussels.