A COMPARISON STUDY INTO LOW LEAK RATE BUOYANT GAS DISPERSION IN A SMALL FUEL CELL ENCLOSURE USING PLAIN AND LOUVRE VENT PASSIVE VENTILATION SCHEMES

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Abstract

The development of a 'Hydrogen Economy' will see hydrogen fuel cells used in transportation and the generation of power for buildings as part of a decentralised grid, with low power units used in domestic and commercial environmental, situations. Low power fuel cells will be housed in small protective enclosures, which must be ventilated to prevent a build-up of hydrogen gas, produced during normal fuel cell operation or a supply pipework leak. Hydrogen's flammable range (4-75%) is a significant safety concern. With poor enclosure ventilation, a low-level leak (below 10 lpm) could quickly create a flammable mixture with potential for an explosion. Mechanical ventilation is effective at managing enclosure hydrogen concentrations, but drains fuel cell power and is vulnerable to failure. In many applications (e.g. low power and remote installation) this is undesirable and reliable passive ventilation systems are preferred. Passive ventilation depends upon buoyancy driven flow, with the size and shape of ventilation openings critical for producing predictable flows and maintaining low buoyant gas concentrations. Environmentally installed units use louvre vents to protect the fuel cell, but the performance of these vents compared to plain vertical vents is not clear. Comparison small enclosure tests of 'same opening area' louvre and plain vents, with leak rates from 1 to 10 lpm, were conducted. A displacement ventilation arrangement was installed on the test enclosure with upper and lower opposing openings. Helium gas was released from a 4mm nozzle at the base of the enclosure to simulate a hydrogen leak. The tests determined that louvre vents increased average enclosure hydrogen concentrations by approximately 10% across the leak range tested, but regulated the flow. The test data was used in a SolidWorks CFD simulation model validation exercise. The model provided a good qualitative representation of the flow behaviour but under predicted average concentrations.

Keywords: hydrogen safety, helium, passive venting, louvre vent, fuel cell enclosure

Nomenclature

nlpm	Normal litre per minute
lpm	Litre per minute
stp	Standard temperature and pressure
LFL	Lower flammable limit (4%)
C_d	Discharge coefficient

1.0 INTRODUCTION

1.1 Background to the investigation

The impact of climate change, the depletion of fossil fuels and the global policy drive towards carbon reduction has led to a technology push for renewable forms of energy, improved energy efficiency and decentralised generation which aims to achieve social, economic and environmental sustainability. The concept of a Hydrogen Economy is gathering momentum to achieve these objectives. Hydrogen, the most abundant element in the universe, can be used as an energy carrier, able to release its energy usefully in many ways. It can be combined with other gaseous fuels to improve combustion and reduce carbon emissions in boilers and engines. It can also be burnt in isolation as a clean fuel producing only water as a by-product. A popular choice is its use in Hydrogen fuel cells to generate electricity, again producing water (and heat) as a by-product.

Fuel cells are versatile machines, which are easily scaled up to produce greater amounts of electricity. They are already used to power vehicles and produce heat and power in homes. Small low power hydrogen fuel cells are becoming popular to replace diesel generators in remote locations and for lighting and telephone towers. They can quietly and cleanly produce consistent levels of energy for extended periods without maintenance. Small fuel cells are housed in enclosures for protection. However, because fuel cells emit small amounts of hydrogen and there is the possibility of a leak from supply pipes, it is necessary to ventilate the enclosure to remove it. Hydrogens wide flammable range (4-75%) means that explosive mixtures can quickly develop, even at low hydrogen leak rates. Effective and reliable ventilation is therefore essential.

Mechanical ventilation systems are effective, but add costs, drain power from the fuel cell and are vulnerable to failure. Passive ventilation systems which can remove hydrogen and manage concentrations below the lower flammable limit (LFL) are therefore preferred. Passive ventilation depends upon buoyancy driven flow and small natural driving forces to move air and hydrogen through the enclosure. The performance of a passive ventilation system is very much dependent upon the size, shape and position of the ventilation openings and on local environmental conditions. Many small fuel cell deployments will be out in the environment and exposed to nature. Vent design now becomes important as water must not enter the enclosure. Passive flow in the enclosure can be affected by wind forces and vents are also liable to being blocked by foliage. It may even be necessary to install grills to prevent rodents and insects from gaining access and damaging pipes and circuitry. What appears to be a simple ventilation solution requires complex safety considerations.

1.2 Passive ventilation

Passive hydrogen management is viable due to inherent reliability and hydrogen's suitability as a buoyant gas [1]. Passive ventilation schemes for the removal of pollutants from buildings, air-flow management and thermal control are well established [2], so there is confidence in the application of these concepts to small fuel cell enclosures to manage concentrations below the LFL [3]. An extensive review of the conditions responsible for producing natural ventilation found that density differences and buoyancy are the driving forces in scenarios where wind forces are absent [2]. Two distinct regimes of ventilation were identified: (i) mixing ventilation (e.g. via a single upper vent, which allows an exchange of gas through a two-way flow) which produces an (approximately) uniform concentration throughout the interior of an enclosure and (ii) displacement ventilation (e.g. via two vents one located near the top and one near the bottom, with gas flow in one direction) where the gas is stratified into distinct layers [2].

The effect of vent geometry on natural ventilation in a small enclosure was investigated using the GAMELAN one cubic metre facility, with a single high-level vent and helium as the buoyant gas [4]. It was found that the vertically tallest vent quickly achieved a homogenous upper layer, producing a high density gradient. The terms 'passive ventilation' and 'natural ventilation' have been introduced and are often used interchangeably to denote a naturally driven ventilation system (i.e. one which is passive in nature and is not driven by a mechanically forced system). However, in small enclosure ventilation schemes, where a buoyant gas flow is introduced an important distinction has been identified [5], with a more precise usage of the terms being defined.

For natural ventilation (applicable to the flow of air) the 'neutral plane' (where internal pressure is equal to external air pressure) is assumed to be positioned approximately half-way up the opening. However, under passive ventilation conditions, which can occur for lighter than air gases, particularly those capable of filling the entire enclosure, such as hydrogen (for a single vent scenario), the neutral plane can be positioned anywhere between the half-way point and the bottom of the ventilation opening. This distinction allowed the derivation a generalised expression for the gas concentration for a well-mixed, single upper vent passive ventilation scenario. Real life enclosures though will have multiple upper and lower ventilation opening. The passive ventilation distinction still applies, but the neutral plane will be located at a point in the enclosure between the upper and lower openings for the leak rates under consideration here.

1.3 Ventilation openings

Fuel cell enclosures use louvre vents. Louvre vents have horizontal slats in the opening (Figure 1), which provide more protection against environmental influence. However, their performance against a standard plain vent is not clear. Studies on passive ventilation performance are frequently based on plain rectangular open vents, which facilitate mixing and displacement ventilation. The discharge coefficient (C_d), a measure of vent flow resistance, can be determined for plain vent openings, however, for standard louvre vents (Figure 1 (a)) there is more to consider. The openings are at an angle, offset from the vertical and their shape is not always rectangular. These characteristics of louvre vents will increase flow resistance and the flow regime through the enclosure. As such data obtained for plain vents cannot be simply applied to louvre vents with the same opening area. It is therefore necessary to undertake comparison tests to determine the degree of flow impairment. Wind pressure and direction also impact upon the discharge coefficient. The vent design applied to a small enclosure requires a sound safety case. Information about the relationship between gas leak rate, enclosure gas concentration, stratification and vent flow resistance will inform and optimise enclosure safety design. A SolidWorks Flow Simulation study was conducted using the test data to validate a CFD model.

(a) (b)

Figure 1 (a) Standard louvre vent (b) Fuel cell enclosure rig, louvre ventilation opening design

1.4 Experimental setup

A test rig was constructed consisting of a Perspex (shatter-resistant transparent thermoplastic) outer chamber (1m x 1m x 2m long), which provided a containment for a 0.144m^3 enclosure (0.6m x 0.6m x 0.4m) (Figure 2) and prevented drafts affecting enclosure ventilation flow. The small enclosure (Figure 3) represented a passively ventilated small fuel cell enclosure, which facilitated the investigation of vent design on passive buoyant gas ventilation behaviour. A cross flow displacement ventilation arrangement was incorporated, with opposing upper and lower openings (20mm high x 360mm wide), which were adapted with horizontal louvre slats to investigate their effect (Figure 1(b)).

The louvre and plain vents were fabricated with the same vertical opening area. The louvre vents were fitted with two 10mm horizontal louvre extensions across the full vent width (Figure 1(b)). Any difference in passive ventilation flow between the two arrangements could therefore be attributed to a change in flow resistance or discharge coefficient, due to the presence of the horizontal louvre extensions. A mass flow controller was connected to a helium (A grade) 9 m^3 (STP) cylinder adjacent to the rig and was used to introduce Helium (used as a safe analogue for Hydrogen) into the enclosure via a vertical 4mm diameter nozzle, centrally positioned 100mm from the base of the enclosure, to simulate a leak from a fuel cell. A series of tests with plain vents and simplified louvre vents was undertaken using helium leak rates from 1 to 10 normal litres per minute. Observations of dispersal behaviour and gas concentration achieved were made.

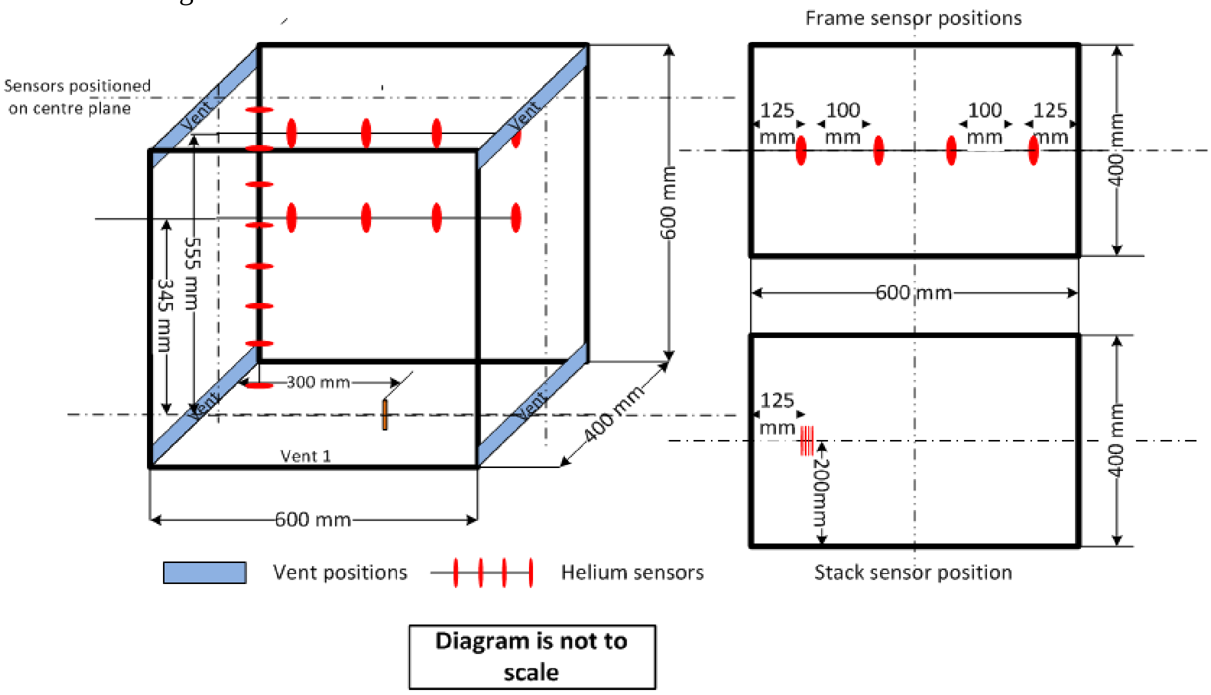


Figure 2- Experimental scheme, showing the position of helium sensors and vents

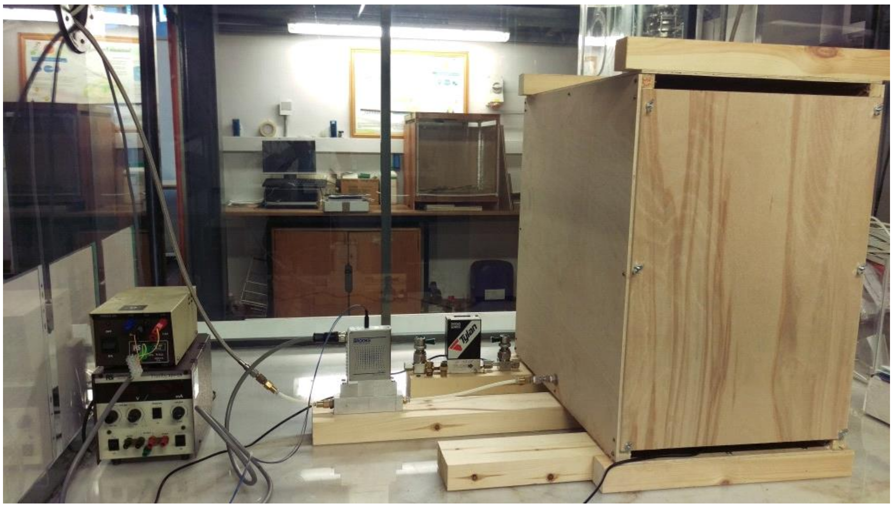
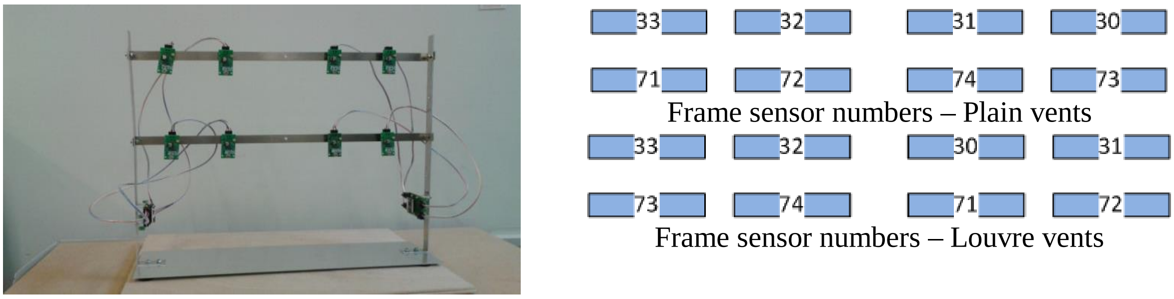


Figure 3 Fuel cell enclosure rig showing standard plain ventilation openings

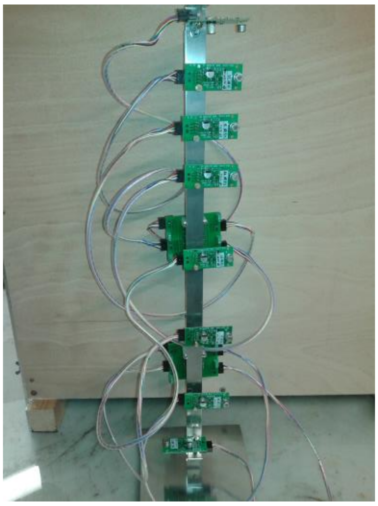
Eight 'MEMS' (Micro electro mechanical system) helium sensors (XEN-TCG3880) were incorporated into the small enclosure. Two sensor arrangements were used in the experiments. The first arrangement comprised of two horizontal lines of four sensors (Figure 4 (a)) in the upper part of the enclosure (Figure 4 (c)) at heights of 345mm and 555mm above the enclosure floor. This arrangement was used to establish an average helium concentration in the upper part of the enclosure.

The second arrangement comprised a single vertical column of eight sensors (Figure 4 (b)) placed centrally near to one of the vented walls. This arrangement was used to provide data on the helium concentration gradient within the enclosure and information about buoyant gas stratification that may be present. Data from the sensors was collected via a USB link to LabVIEW software.

A series of experiments was carried out to investigate and compare the performance of plain and louvre ventilation openings with the same opening area, with regards to the effect on helium gas concentrations in the enclosure.



(a) Frame mounted sensors and sensor numbers



(b) Sensor stack

(c) Frame sensors in enclosure

Figure 4 Helium sensor arrangements

1.5 CFD modelling

Computational Fluid Dynamics (CFD) codes solve the partial differential equations for the conservation of mass, momentum (Navier–Stokes), energy, chemical concentrations, and turbulence quantities. Solutions provide the field distributions of pressure, velocity, temperature, the concentrations of water vapour (relative humidity), gas and contaminants, and turbulence parameters.

CFD codes hold many modelling uncertainties, requiring modelling assumptions and user interpretation, but are widely used for engineering predictions [6]. Advantages of CFD are the potential to provide detailed flow patterns and temperature distributions throughout the space and can deal with complex geometry. Multi-zone computational fluid dynamics modelling is the main tool for predicting ventilation performance [7].

The SolidWorks Flow Simulation CFD software has been used to create computer models of the experimental test setup and the plain and louvre vent arrangements. SolidWorks Flow Simulation solves the Navier-Stokes equations to predict laminar and turbulent flows. Turbulent flows are solved using the Favre-averaged Navier Stokes equations, where time averaged effects of the flow turbulence on flow parameters are considered [8]. The k-ε transport equations for turbulent kinetic energy and its dissipation rate are applied in this study. SolidWorks Flow Simulation code has not been validated for the scenarios under investigation, and so this study provides valuable information on the codes suitability. CFD simulations at the ten helium leak rates were run for the plain and louvre vent models.

Each simulation was run to a steady state position and helium concentrations determined at the sensor points. The CFD model scenarios were as per those for the experimental study.

2.0 Results – experimental

For each experiment, the helium gas build up was allowed to pass through the transient phase and reach a steady state position for each leak rate. Helium concentration data from the eight sensors was retrieved via the USB link to an adjacent PC. A time averaged section of steady state data has been used to provide average helium concentration results, following the approach in Cariteau [4].

2.1 Plain vents

The plain vent tests were conducted to provide a standard against which to measure the performance of the subsequent louvre tests. Two sets of tests were undertaken using the two sensor arrangements.

Frame sensors - The frame sensor results (Figure 5) show a distinct difference in concentrations achieved by the sensors on the upper and lower bars of the frame. The lower bar at 345mm does not exceed 0.41% at the highest leak rate. The top bar at 555mm achieves a maximum of 6.87% at 10 lpm, with the LFL achieved between 4 and 5 lpm. The maximum average concentration of all the sensors is 3.45% at 10lpm. This sensor arrangement clearly shows the buoyant nature of the gas and a build-up in the upper part of the enclosure.

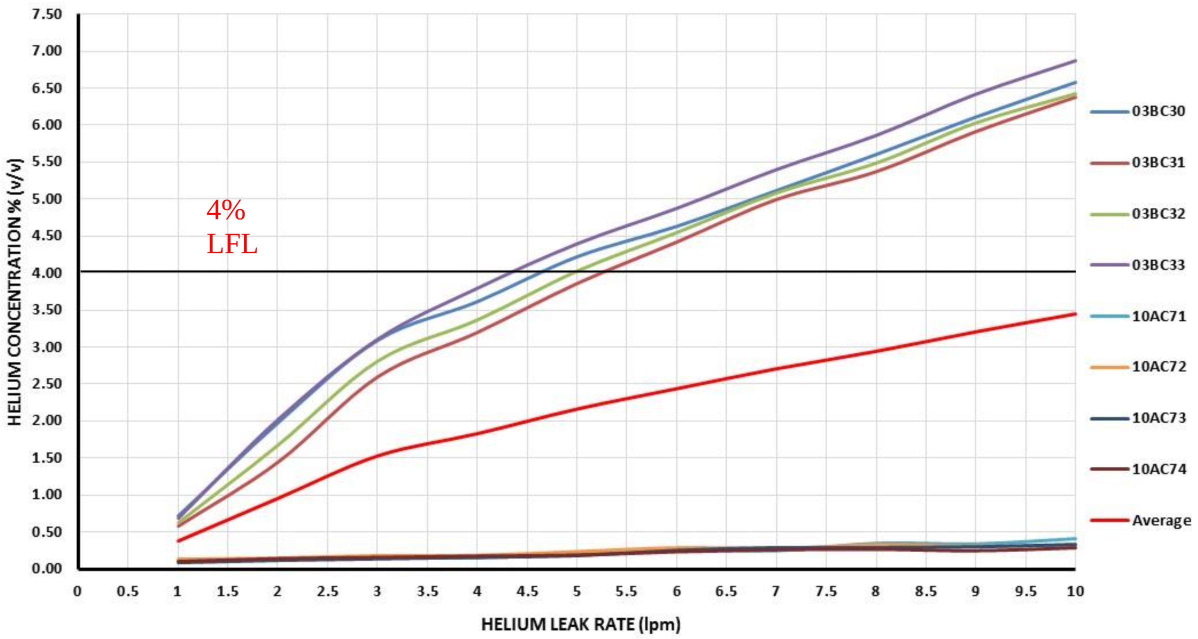


Figure 5 Graph for plain vent enclosure showing helium concentration against leak rate

Stack sensors - The stacked sensor arrangement provides more information about how the concentration changes with height in the enclosure, as the leak rate increases (Figure 6). At the 3lpm stage there is a clear development in the regime inside the enclosure with an increase in gas concentration higher up and the formation of a more distinct stratified layer is evident. Concentrations above 4% are present above about 460mm and from 4 lpm onwards. The displacement ventilation regime has created the expected stratified layer. This layer thickens and concentrations increase as the flow rate increases.

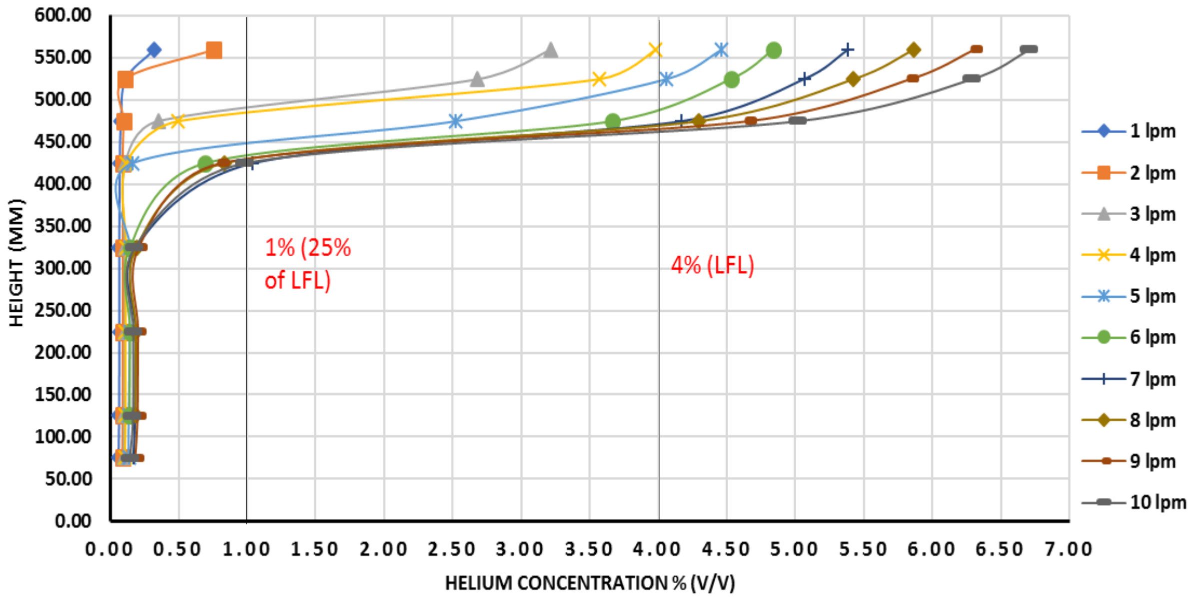


Figure 6 Graph for plain vent enclosure showing height against helium concentration

2.2 Louvre vents

Frame sensors – The graph of helium concentration against leak rate for the louvre vent enclosure (Figure 7) is similar to the plain vent graph in shape, but the concentrations at the upper row of sensors are higher, peaking at 7.23% at 10lpm. Two of the lower sensors have higher concentrations also.

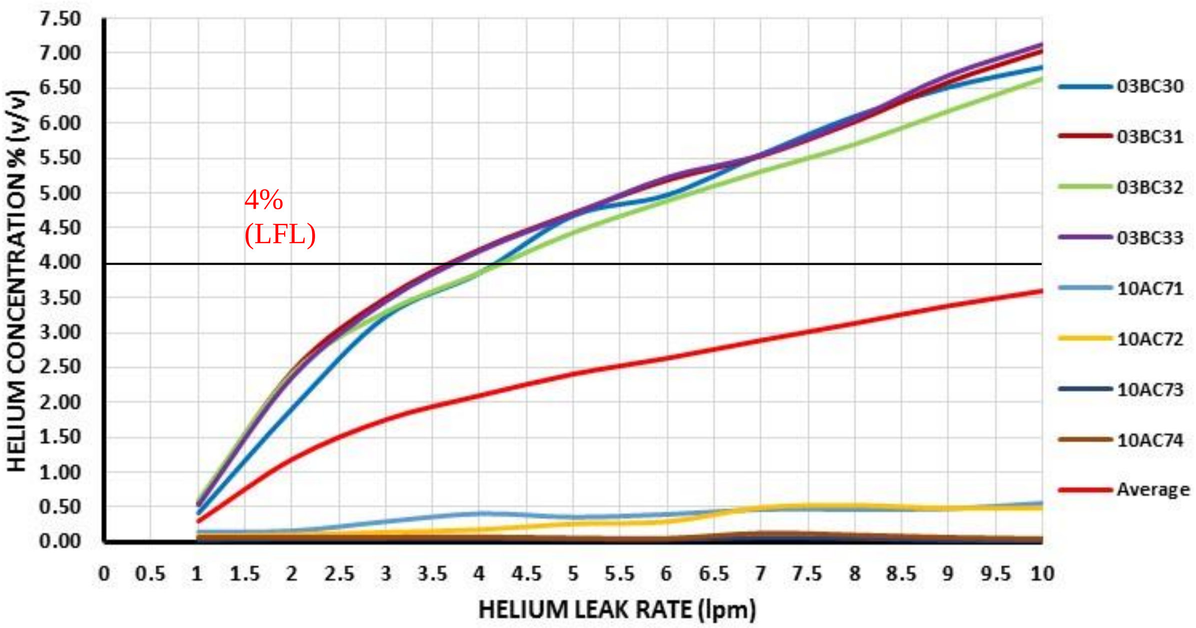


Figure 7 Graph for louvre vent enclosure showing helium concentration % (v/v) against leak rate

Stack sensors – The graph of height against helium concentration (Figure 8) shows that the ventilation regime within the enclosure has changed with the addition of horizontal louvres. The stratified layer that was above 450mm with out louvre vents is now deeper and touches 350mm with a concentration of 1% for the 10lpm leak rate. Concentrations become more consistent at the top three sensors as leak rate increases. Stratification is evident, with the reduced passive ventilation flow leading to a build up of buoyant gas at the top of the enclosure. The LFL is now exceeded at 3lpm and all flow rates exceed 25% of the LFL in the uppermost part of the enclosure.

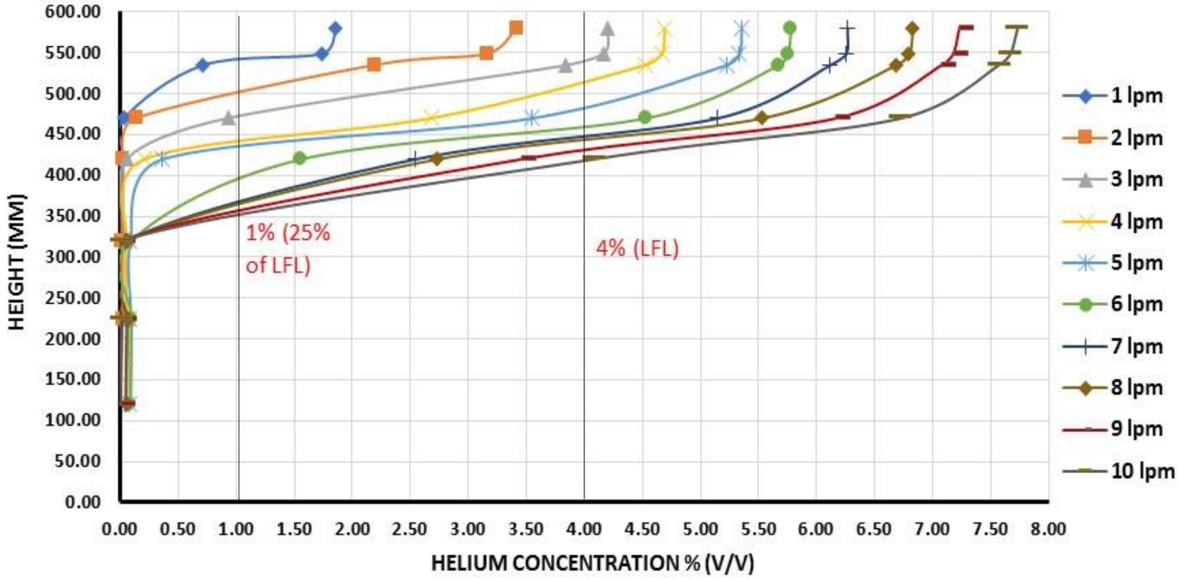
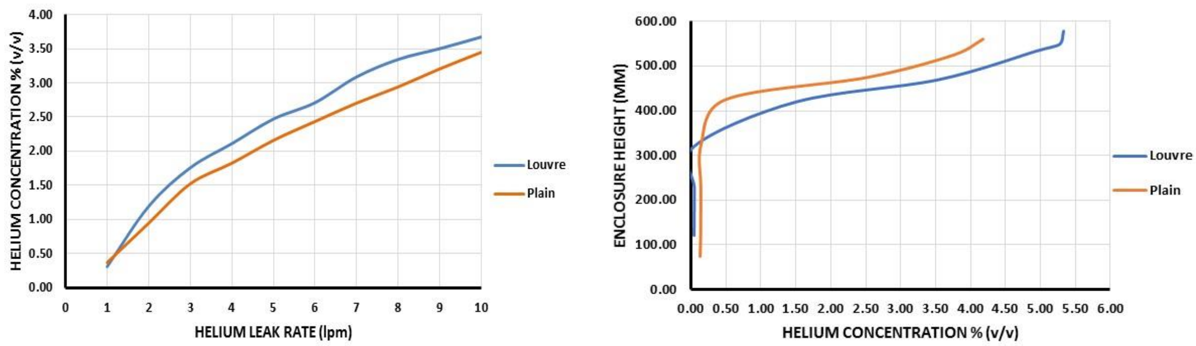


Figure 8 Graph for louvre vent enclosure showing height against helium concentration

2.3 Comparison of plain and louvre vent results



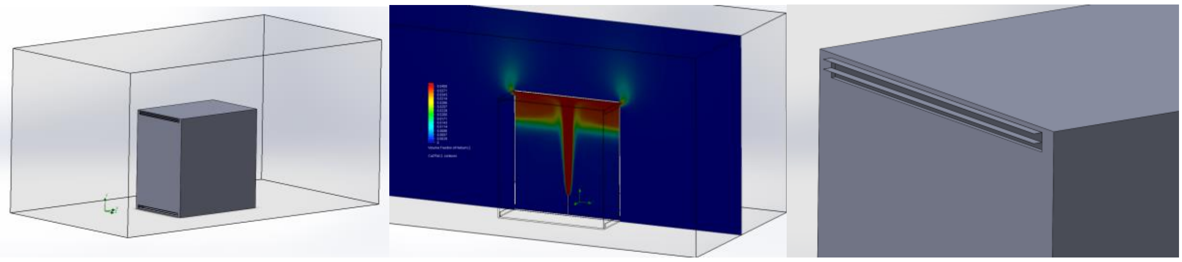
(a) (b)

Figure 9 Graph showing (a) Average helium concentration against leak rate for plain and louvre vents (b) Height against average helium concentration for plain and louvre vents

Figure 9(a) shows the average helium concentration in the fuel cell enclosure, taken from all sensor positions on the frame sensor configuration, at all leak rates, for plain and louvre vents. The concentration achieved using louvre vents is consistently higher than with plain vents, apart from at 1lpm, where it dips below slightly. With louvre vents, the enclosure concentration is on average, across the range of leak rates, 10.35% higher than for plain vents. Figure 9(b) shows the average helium concentration at each sensor position across all leak rates for louvre and plain vents. Louvre vents achieve higher concentrations and a deeper stratified layer. The maximum helium concentration achieved for plain vents, is over one percentage point less than that achieved with louvre vents. However, concentrations are higher for plain vents lower down in the enclosure, but this is only at about 0.1%. This correlates with figure 9(a) at 1lpm where plain vent concentrations are higher.

2.4 Results – CFD

A simplified CAD model was created in SolidWorks (Figure 10(a)), one with plain vents and one with louvre vents (Figure 10(c)). A computational domain equivalent to the outer enclosure was created and a series of simulations were run at flow rates from 1 to 10 lpm. Point source data was then extracted for helium concentration at the equivalent experimental sensor positions.



(a) (b) (c)

Figure 10 SolidWorks Flow Simulation CFD images (a) Enclosure (b) Cut plane at 5lpm (c) Louvres

2.5 Plain vents – CFD data

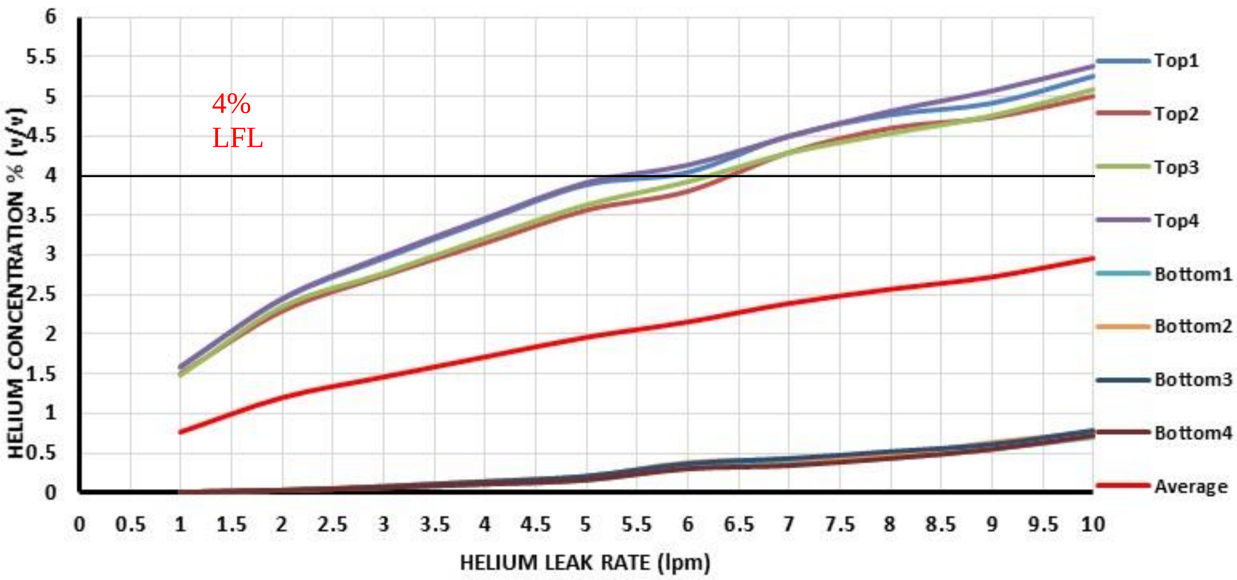


Figure 11 Graph for plain vent enclosure showing helium concentration against leak rate

Frame sensor positions –Figure 11 presents the frame sensor position CFD concentration data. The overall trends in terms of increasing concentration with increased leak rate are similar to those for the experimental data in figure 5. The simulations have reproduced the flow behaviour, but have not replicated the helium concentrations. Notable differences are that CFD helium concentrations are higher for the top sensor positions at low leak rates, and the CFD top sensor concentrations at higher leak rates are lower than with the empirical data.

Stack sensor positions- Figure 12 presents CFD data for enclosure height against helium concentration. The trends produced by the experimental data of increasing concentration with height are reflected in the CFD data. However, the LFL is not exceeded until 6lpm (4lpm for empirical data), the maximum achieved is 5.29% at 10lpm (6.7% for empirical data), and the depth of the buoyant gas layer is deeper across the leak rate range. The 1 and 2lpm data series also both exceed the 1% (25% of LFL) mark, whereas the empirical data did not.

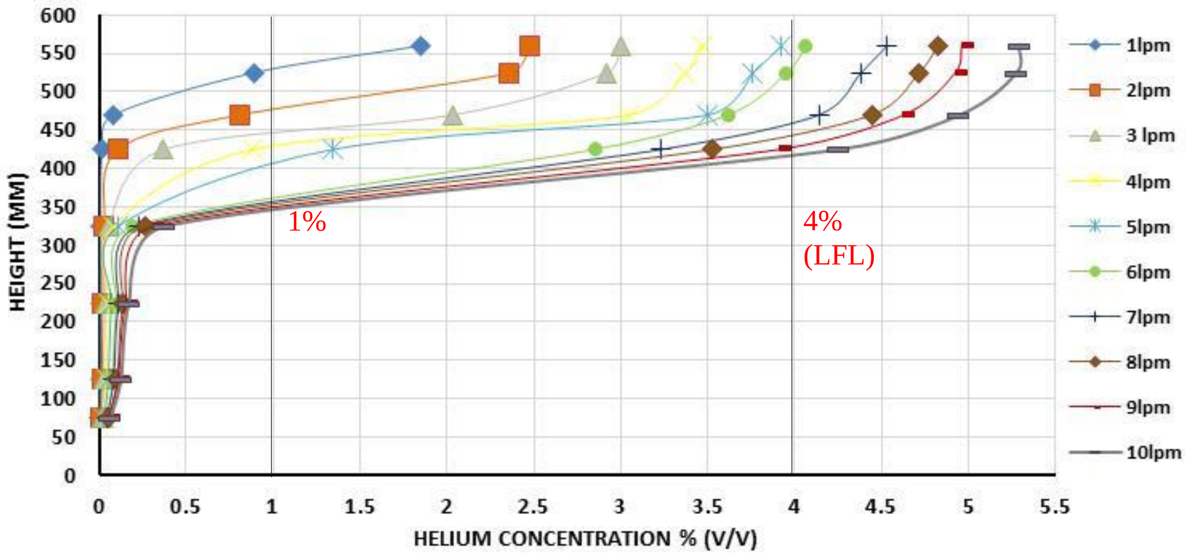


Figure 12 Graph for plain vent enclosure showing height against enclosure helium concentration

2.6 Louvre vents – CFD data

Frame sensor positions – Figure 13 presents frame sensor CFD data for concentration against leak rate. The trends presented are similar to those found with the experimental data in figure 7, with flow behaviour replicated, but broadly lower concentrations. The LFL is not exceeded by the top sensor positions until the 4.75lpm point (3.75lpm with empirical data). Concentrations are marginally higher than the CFD data for plain vents, but are much lower than the empirical data. Bottom sensor point data is also lower than for CFD plain vents, notably so at the higher leak rates.

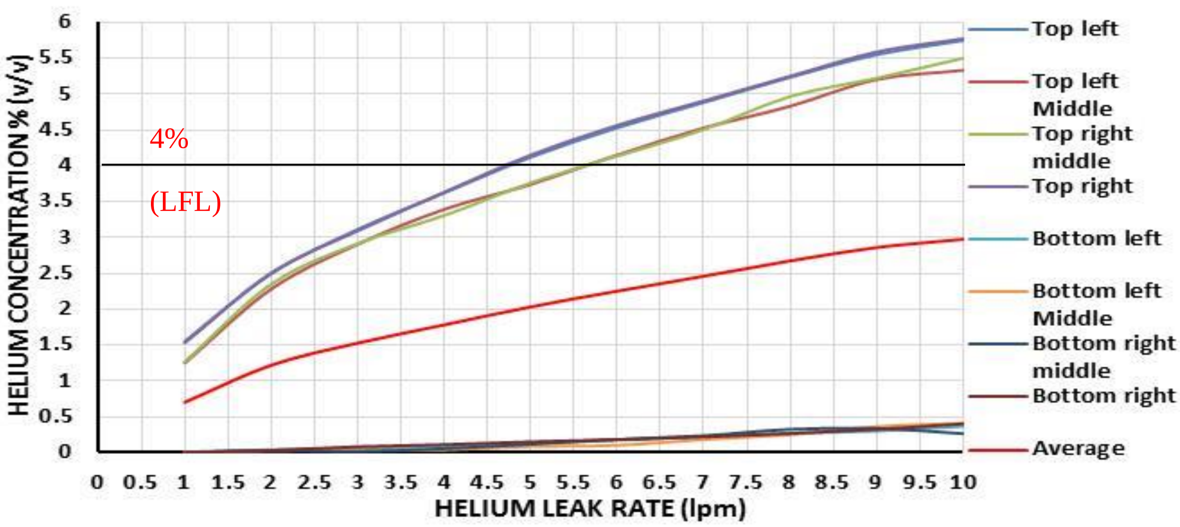


Figure 13 Graph - louvre vent enclosure showing helium concentration against leak rate

Stack sensor – Figure 14 presents louvre vent CFD data for enclosure height against helium concentration. The experimental trends of increasing concentration with height are present, but with broadly lower concentrations. The LFL is now exceeded at 5lpm (6lpm for CFD plain vent tests and 3 for experimental louvre vents tests). The depth of the stratified layer appears shallower than for the CFD plain vent data in figure 11, which is the opposite to what was found with the experimental tests.

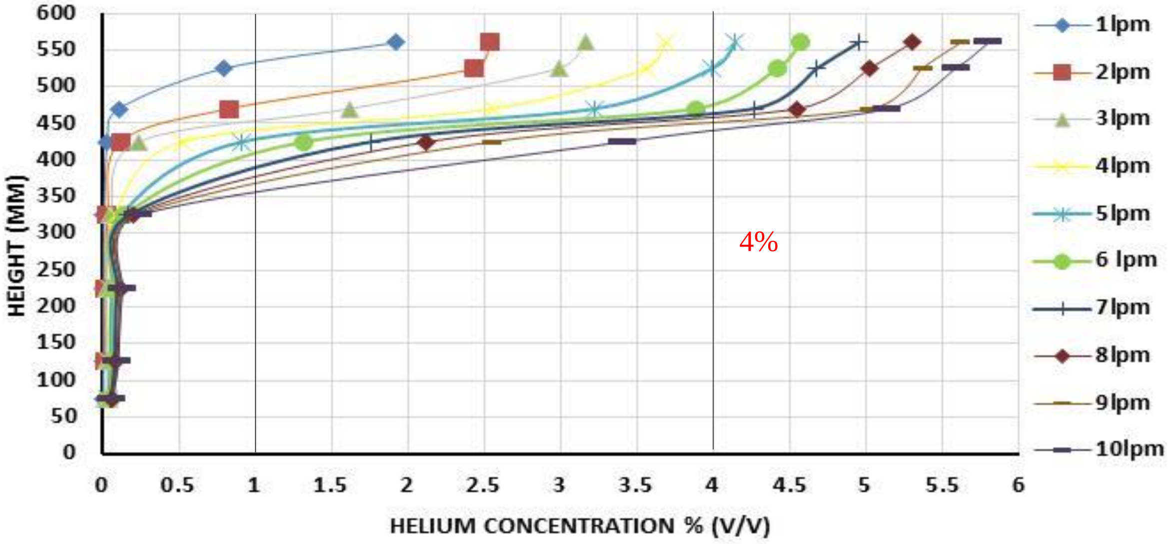


Figure 14 Graph for louvre vent enclosure showing height against enclosure helium concentration

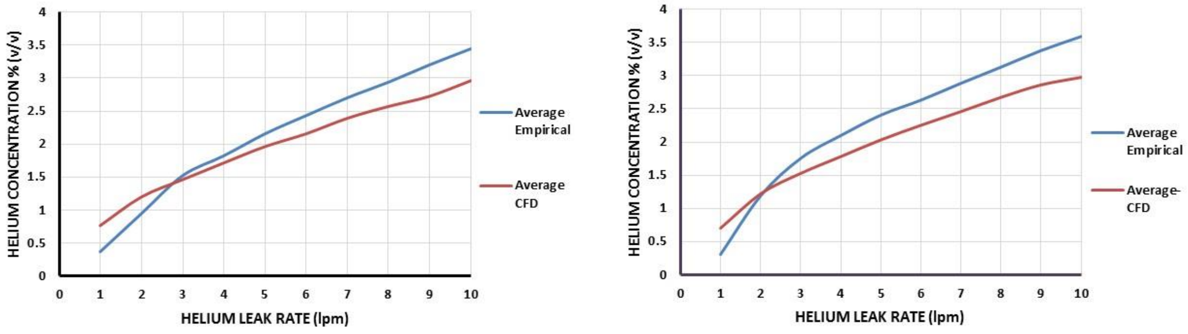
3.0 Conclusion

Passive hydrogen removal research is motivated by accident prevention and the need to understand hydrogen's behaviour in hazardous scenarios [9]. A hydrogen leak can be followed by the evolution of a hydrogen-air cloud which, if within the flammable mixture range, has the potential for ignition, fire or deflagration with thermal/pressure effects which can threaten life and property. Confinement scenarios have more serious outcomes since significant explosion overpressures can be developed [10]. The two scenarios tested in this investigation are therefore significant as the effect of louvre vents fitted to small enclosures can potentially increase hydrogen concentrations to flammable levels.

The louvre vents tested were of the simplest design and only comprised a horizontal extension, leaving the vertical vent area unchanged. Proprietary louvre vents more usually feature an angled downward facing opening with curved ends, providing some wind protection, but which are likely to further impede flow. The empirical data shows that the addition of louvre slats to the vent opening has in fact led to an increase in buoyant gas concentrations in the enclosure. The higher concentrations are found, as expected with a buoyant gas, in the upper part of the enclosure. Of importance, though is the fact that the stratified layer, formed by a displacement passive ventilation system, is deeper with louvre vents, increasing the volume in which a flammable mixture may be present.

As the only change is the addition of louvres, the increase in concentration and flammable volume can be attributed to them. The louvres are increasing the flow resistance of the vents. This will include the flow of fresh air into the enclosure from the lower vents and the expulsion of the buoyant gas/air mixture from the upper vents. The presence of louvre vents appears to have affected the discharge coefficient, leading to reduced flow and a build-up of buoyant gas, providing a measure of regulation. A further effect is the movement of the neutral pressure level further down the enclosure. At the low leak levels tested this is not a huge concern, but at greater leak rates flow reversal and failure of the passive ventilation regime is likely as the enclosure fills with buoyant gas.

The CFD simulations run as a validation exercise produced qualitative results that suggested the model was behaving in the way expected. However, quantitative data provided helium concentrations that were at variance with the empirical tests, mostly under predicting. Comparisons of average enclosure concentration (figure 15 (a) plain vents and (b) louvre vents) showed the results to be close, over predicting low leak rates and underpredicting high leak rates, above 2.7lpm for plain vents and 2lpm for louvre vents. Model refinement is required to bring the predictions closer to reality.



(a) (b)

Figure 15 Comparison of average frame sensor concentrations for (a) plain vents (b) louvre vents

This investigation has attempted to replicate low level hydrogen leaks into a small fuel cell enclosure with multiple plain or louvred ventilation openings. The data has provided insight into the point at which flammable concentrations are reached and the effect of louvres on ventilation flow. Louvres impede passive ventilation flow of a buoyant gas, increasing internal concentrations. Alternative ventilation schemes such as the use of chimneys may be more appropriate in some applications, allowing the buoyant gas a vertical path out of the enclosure, although weather protection on top of the chimney may impede flow. Flues that take gas horizontally, some distance away, from the enclosure may also be viable.

4.0 Acknowledgements

Acknowledgements are made to Dr James Ingram and Dr Paul Holborn at London South Bank University (LSBU) for their support in this work. Also to Sellafield Ltd for co-sponsorship and funding of the project and to BOC Ltd for providing access to SolidWorks Flow Simulation CFD.

5.0 References

1. Hübert, T 2011). Hübert, T.; Boon-Brett, L.; Black, G.; Banacha, U. (2011); Hydrogen sensors – A Review; Journal of Sensors and Actuators B: Chemical; 157, pp. 329–352
2. Liddament, M.W. (1996); A Guide to Energy Efficient Ventilation; Air Infiltration and Ventilation Centre, IEA Energy Conservation in Buildings and Community Systems Programmed; Coventry
3. Bachellerie, E.; Arnould, F.; Auglaire, M.; de Boeck, B.; Braillard, O.; Eckardt, B.; Ferroni, F.; Moffett R. (2003); Generic approach for designing and implementing a passive autocatalytic recombiners PAR-system in nuclear power plant containments; Journal of Nuclear Engineering and Design; 221, pp. 151–165.
4. Cariteau, B., Tkatschenko, I. (2013); Experimental study of the effects of vent geometry on the dispersion of a buoyant gas in a small enclosure; International Journal of Hydrogen Energy; 38, 8030-8038
5. Molkov, V., Shentov, V, Quintiere (2014): Passive ventilation of a sustained gaseous release in an enclosure with one vent; International Journal of Hydrogen Energy; 39 (2014) 8158-8168
6. Chen Qingyan (2007); Design of natural ventilation with CFD; Sustainable urban housing in China, principle ventilations and case studies for low energy design; Springer
7. Chen, Qingyan (2009); Ventilation performance prediction for buildings: A method overview and recent applications; Building and Environment (2009), 44, 4, 848-858
8. Dassault Systems (2015); Technical Reference; SolidWorks Flow Simulation 2015
9. Weiner S.C. (2014); Advancing the hydrogen safety knowledge base; International Journal of Hydrogen Energy; 39 (2014) 20357-20361
10. Molkov V. Fundamentals of hydrogen safety engineering. eBook (search hydrogen), www.bookboon. com; October 2012.