EXPERIMENTAL STUDIES ON VENTED DEFLAGRATIONS IN A LOW STRENGTH ENCLOSURE

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ABSTRACT

This paper describes an experimental programme on vented hydrogen deflagrations, which formed part of the Hyindoor project, carried out for the EU Fuel Cells and Hydrogen Joint Undertaking. The purpose of this study was to investigate the validity of analytical models used to calculate overpressures following a low concentration hydrogen deflagration. Other aspects of safety were also investigated, such as lateral flame length resulting from explosion venting. The experimental programme included the investigation of vented hydrogen deflagrations from a 31 m^3 enclosure with a maximum internal overpressure target of 10 kPa (100 mbar). The explosion relief was provided by lightly covered openings in the roof or sidewalls. Uniform and stratified initial hydrogen distributions were included in the test matrix and the location of the ignition source was also varied. The maximum hydrogen concentration used within the enclosure was 14% v/v. The hydrogen concentration profile within the enclosure was measured, as were the internal and external pressures. Infrared video images were obtained of the gases vented during the deflagrations. Findings show that the analytical models were generally conservative for overpressure predictions. Flame lengths were found to be far less than suggested by some guidance. Along with the findings, the methodology, test conditions and corresponding results are presented.

1.0 NOMENCLATURE

K_G	gas explosion constant (bar m s^{-1})
S_u	laminar burning velocity of the flammable mixture (m s^{-1})
L_F	lateral flame length from the explosion vent (m)
V	volume of the enclosure (m^3)

2.0 INTRODUCTION

Hydrogen energy applications may require that systems be used inside rooms or enclosures (e.g. for security reasons). The accidental release of hydrogen within a room or enclosure can potentially lead to the formation of a flammable mixture and an explosion. In this context it is necessary to understand the explosion relief required to limit the overpressures arising from deflagrations of hydrogen accumulations to an acceptable level, typically of the order of 10 kPa (100 mbar) for iso-container type structures. This paper describes a series of experiments that have been carried out by the United Kingdom's Health and Safety Laboratory (HSL) for the European Union (EU) Fuel Cells and Hydrogen Joint Undertaking (FCH JU) project "HyIndoor" (http://www.hyindoor.eu) and comparison of the results with analytical models.

3.0 PRE-TEST MODELLING

One issue of practical concern to those involved in specifying explosion relief for industrial structures has been the limited availability of reliable predictive methods for hydrogen. To illustrate this, pre-test calculations were carried out by HSL using a number of methods available in the literature at the start of the Hyindoor project, using the design pressure of the HSL enclosure, 20 kPa, as a maximum. The vent opening pressure, P_{stat}, was set to zero as the actual vent opening pressure was not determined at this time.

HSL carried out calculations using BS EN 14994:2007 "Gas explosion venting protective systems" [1] and the models described by Molkov and co-workers [2, 3].

3.1 BS EN 14994:2007

BS EN 14994:2007 can be used to calculate the minimum explosion venting area, but can also be used to estimate gas explosion pressures within a vented enclosure. The approach uses a gas explosion constant, K_G, which has units of bar m s^{-1}. Although BS EN 14994:2007 has a limit of 500 bar m s^{-1} which would invalidate its use for hydrogen mixtures approaching stoichiometric, its use for lean hydrogen mixtures may appear to be reasonable, since the K_G value for lean mixtures will be less than 500 bar m s^{-1}. K_G can be estimated using the approach described in NFPA 68 [4],

$$K_G = K_{G,ref} \times S_u / S_{u,ref} \ , \tag{1}$$

where S_u is the laminar burning velocity of the flammable mixture. The calculations were based on reference values of $K_{G,ref}$ = 550 bar m/s and $S_{u,ref}$ = 3 m/s. The laminar burning velocity, S_u, for each mixture was taken from Koroll et al. [5] and Bragin [6]. The values from Bragin (2012) are much slower and therefore less conservative than the values from Koroll et al. (1993). Note that the method given in BS EN 14994:2007 is applicable to cases where P_{stat} is at least 100 mbar (10 kPa) and so its use in this situation is outside the normal range.

3.2 Molkov Models (pre-2011)

HSL used the Molkov models described by Molkov [2, 3]. In the model described by Molkov et al. (1999), the explosion pressure is calculated from the turbulent Bradley number; the model described by Molkov (2001) is essentially a conservative version of the model described by Molkov et al. (1999). The laminar burning velocities used were as described in section 3.1.

3.3 Results of Pre-test Calculations

The engineering models described in the previous sections were used to estimate explosion pressures in the HSL test facility for a range of initial hydrogen concentrations (up to 15% v/v) and vent areas (up to 6.4 m^2). The hydrogen concentration refers to the molar fraction and was assumed to be uniform throughout the enclosure. The HSL enclosure has vents in the roof and sidewalls. The roof vents are relatively large (0.8 m^2) and their sole purpose is to provide explosion relief (i.e. under normal operation they are covered by a suitable explosion relief panel). Conversely, the sidewall vents (hereafter referred to as passive vents) are relatively small (0.23 m^2) and their primary function is to provide passive ventilation of unignited releases.

Results are presented in Table 1 (note that calculations were not always carried out for cases where the estimated pressure rise was clearly going to exceed 20 kPa, marked as "ND" in the table). As shown in Table 1, there was considerable variation in the results. For example, the overpressure for a hydrogen concentration of 15% v/v and vent area of 6.4 m^2 varied between 3 kPa (calculated using Molkov et al., 1999 with laminar burning velocity from Bragin, 2012) and 7.3 kPa (calculated using Molkov, 2001 with laminar burning velocity from Koroll et al., 1993). Overall, the model described by Molkov (2001) was more conservative than the BS EN 14994:2007 calculations, which were more conservative than the model described by Molkov et al. (1999).

Note that a further model applicable to weak enclosures was published by Molkov and Bragin [7] during the Hyindoor project and the fit of the HSL experimental data to that model is discussed in section 5.

Table 1. Over pressures (in kPa) calculated using BS EN 14994:2007, Molkov et al (1999) and Molkov (2001) and laminar burning velocities from [a]Bragin (2012) and [b]Koroll et al. (1993)

Method	Hydrogen molar fraction (% v/v)	Laminar burning velocity (m/s)	Overpressure for various vent areas and hydrogen/air mixtures (kPa)							
			2 passive vents	4 passive vents	2 passive vents and 1 roof vent	4 passive vents and 1 roof vent	1 roof vent	2 roof vents	4 roof vents	8 roof vents
			$0.46m^2$	$0.92m^2$	$1.26m^2$	$1.72m^2$	$0.8m^2$	$1.6m^2$	$3.2m^2$	$6.4m^2$
BS EN 14994: 2007	8	0.08[a]	220	67	39	23	85	26	8	2
	10	0.14[a]	ND	ND	ND	ND	ND	ND	19	6
	10	0.18[b]	ND	ND	ND	ND	ND	ND	23	7
	12	0.22[a]	ND	ND	ND	ND	ND	ND	ND	8
	12	0.48[b]	ND	ND	ND	ND	ND	ND	ND	12
	14	0.36[a]	ND	ND	ND	ND	ND	ND	ND	11
	14	0.77[b]	ND	ND	ND	ND	ND	ND	ND	15
	15	0.44[a]	ND	ND	ND	ND	ND	ND	ND	12
	15	0.91[b]	ND	ND	ND	ND	ND	ND	ND	17
Molkov et al. (1999)	8	0.08[a]	8	3	2	1	3	1	0	0
	10	0.14[a]	22	7	5	3	9	3	1	0
	10	0.18[b]	32	11	7	4	14	5	2	1
	12	0.22[a]	ND	ND	10	6	20	7	2	1
	12	0.48[b]	ND	ND	34	21	69	23	8	3
	14	0.36[a]	ND	ND	ND	ND	ND	ND	5	2
	14	0.77[b]	ND	ND	ND	ND	ND	ND	18	6
	15	0.44[a]	ND	ND	ND	ND	ND	ND	8	3
	15	0.91[b]	ND	ND	ND	ND	ND	ND	24	8
Molkov (2001)	8	0.08[a]	57	17	10	6	22	7	2	1
	10	0.14[a]	139	53	31	18	68	20	7	2
	10	0.18[b]	168	83	48	28	104	32	12	4
	12	0.22[a]	ND	ND	ND	ND	ND	ND	18	6
	12	0.48[b]	ND	ND	ND	ND	ND	ND	71	21
	14	0.36[a]	ND	ND	ND	ND	ND	ND	ND	14
	14	0.77[b]	ND	ND	ND	ND	ND	ND	ND	53
	15	0.44[a]	ND	ND	ND	ND	ND	ND	ND	21
	15	0.91[b]	ND	ND	ND	ND	ND	ND	ND	73

3.0 EXPERIMENTAL DETAILS

3.1 Test Matrix

The experimental work at HSL involved three distinct test series.

Test Series 1: The relationship between the hydrogen concentration (well-mixed/quiescent), ignition position, explosion relief area and explosion pressure, with the explosion relief provided by explosion relief vents in the enclosure roof.

Test Series 2: The relationship between the hydrogen concentration (well-mixed/quiescent), ignition position, explosion relief area and explosion pressure, with explosion relief provided by passive vents in the enclosure walls.

Test Series 3: The explosion relief of inhomogeneous/turbulent hydrogen-air mixtures arising from realistic hydrogen release scenarios (stratified hydrogen-air mixtures and jet releases), with explosion relief provided by passive vents in the enclosure walls.

The use of passive vents in test series 2 and 3 was motivated by earlier work on dispersion and accumulation [8, 9], which sought to investigate the ability of the same passive vents to prevent the formation of a flammable atmosphere. Specifically, test series 2 and 3 sought to investigate the explosion venting capability of passive vents if they should fail to perform their primary function (to prevent the formation of a flammable atmosphere).

Test series 3 sought to extend the investigation to more realistic scenarios. Two types of test were carried out in test series 3; those in which there was a stratified hydrogen distribution with low concentrations in the bottom half of the enclosure and high concentrations (up to 10% v/v) in the upper half of the enclosure before ignition (tests WP3/21, WP3/22 and WP3/26) and those in which the average concentration in the enclosure was low (about 1% v/v) but close to the ignition point there were high concentrations coupled with relatively turbulent conditions associated with the jet source (tests WP3/24, WP3/25, WP3/27 and WP3/28).

3.2 Experimental Arrangement

A carbon steel enclosure with an internal volume of approximately 31 m^3 (2.5 m by 2.5 m by 5 m) was used. The interior walls of the enclosure are predominately flat, while the exterior walls feature a number of more substantial horizontal and vertical structural beams. The enclosure sits on top of six large concrete blocks that raise it off the ground by 0.8 m and has a 2.5 m long porch attached to the vent 2 / vent 4 end. A photograph of the enclosure is shown in Figure 1. The enclosure was situated in the open air and so exposed to the weather during the experiments.

Figure 1. Exterior of the HSL enclosure with a passive vent (vent 1) open.

Eight explosion relief vents, each 0.8 m^2, could be fitted into the roof of the enclosure. Five passive vents (each 0.83 m wide and 0.27 m high) were located on the side walls. The vents in the walls and roof could be closed off using steel plates when not being used. In all but one of the experiments the selected explosion relief area was initially covered with 20 micron polypropylene sheeting, pre-perforated around its perimeter to facilitate a "clean" opening of the cover during a deflagration (Figure 2). This method has been used previously by Bauwens et al [10]. Whilst passive vents would normally be open to the atmosphere, in these experiments they were covered with weak plastic film to avoid wind effects within the enclosure. This arrangement typically gave an opening overpressure of approximately 1 – 2 kPa for the relief panels used at HSL. One experiment was carried out using loosely held foil as the explosion relief cover but this method was problematic; although it resulted in a low opening overpressure of fractions of kPa, the foil was easily dislodged and damaged by the wind.

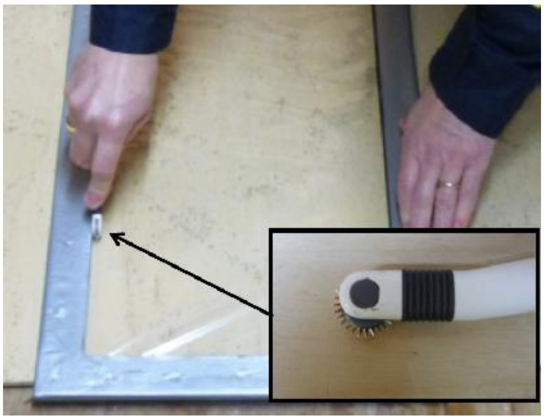

Figure 2. Perforating the polypropylene film for the explosion relief

Test series 1 and 2 involved well-mixed, quiescent hydrogen / air mixtures. In these tests the hydrogen was introduced to the enclosure through venturi mixers (air amplifiers) as shown in Figure 3. Test series 3 involved non-homogeneous hydrogen distributions. In these tests the hydrogen was introduced using the vertical release arrangement, also shown in Figure 3, as used in the Hyindoor project for the work on dispersion and accumulation [8, 9]. Two small holes in the floor of the enclosure were used in all of the tests to prevent a build-up of pressure inside the enclosure during hydrogen addition.

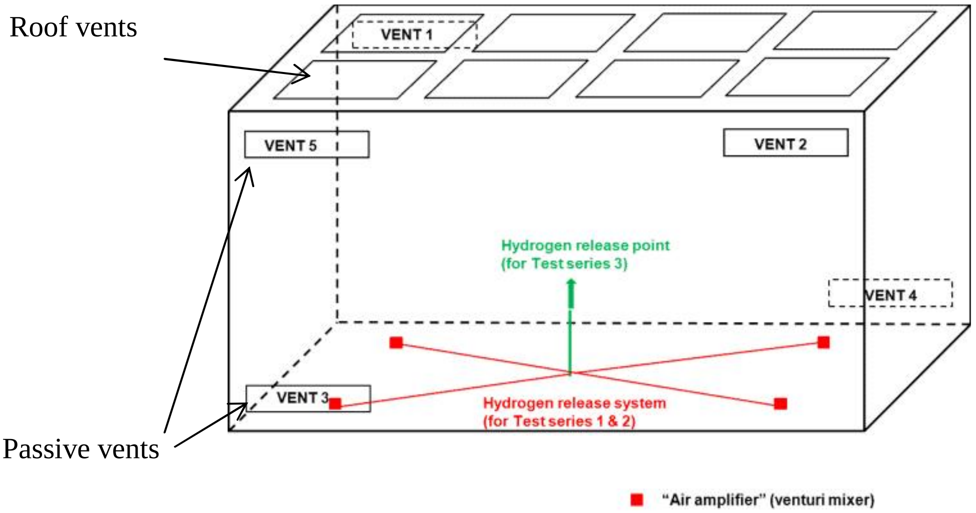

Figure 3. Hydrogen release systems used for the three test series

For all of the quiescent tests (test series 1, 2 and 3), sufficient time (at least 30 seconds) was allowed for the turbulence to subside to a background level before the mixture was ignited. Figure 4 shows velocity fluctuation measurements before and after a hydrogen release. The velocities were measured using bidirectional probes orientated in three dimensions mounted at a height of 0.5 m close to the hydrogen release point. After approximately 10 seconds the turbulence had decayed to the background level (the background turbulence measurements are believed to be higher than the actual levels present due to the anemometer instruments operating close to their minimum resolution).

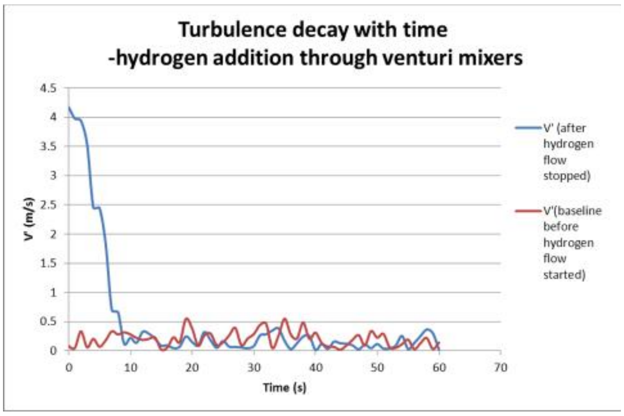

Figure 4. Decay of turbulence after hydrogen flow stopped

In test WP3/26, ignition occurred at the same time as the hydrogen valve closure was started so as to initiate the deflagration with a higher level of turbulence. In tests WP3/24, WP3/25, WP3/27 and WP3/28 the hydrogen was ignited approximately 1 minute after the hydrogen flow was started. The spark was initiated at the same time that the hydrogen supply valve started to close (the valve takes about 3 seconds to close fully).

The hydrogen concentration was analysed by measuring the change in oxygen concentration using seven oxygen sensors positioned in a vertical line as shown in *Figure 5*. The oxygen sensors were electrochemical type with an accuracy of +/- 0.1% v/v, corresponding to an uncertainty of about +/- 0.5% v/v in the hydrogen concentration.

In all experiments, the hydrogen was ignited by an AC spark. The spark was moved to various locations depending on the test series; however, it was always moved along the centreline of the long axis of the enclosure (i.e. always at 1.25 m from the side walls with passive vents in them).

In most of the experiments in Series 1, the gas mixture was ignited low down at the far end of the enclosure from the explosion relief area to maximise the potential for an external explosion and so maximise the internal over-pressure (position FL shown in Figure 6).

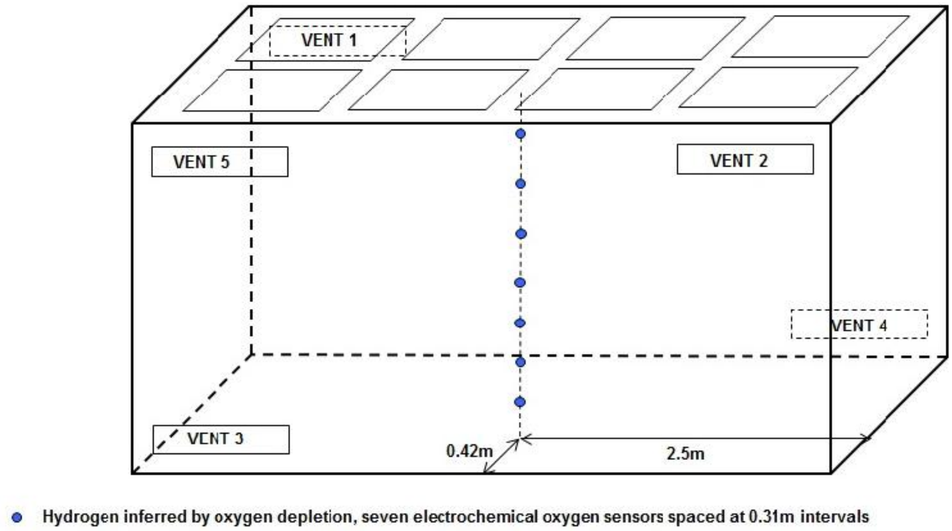

Figure 5. Position of gas composition sensors

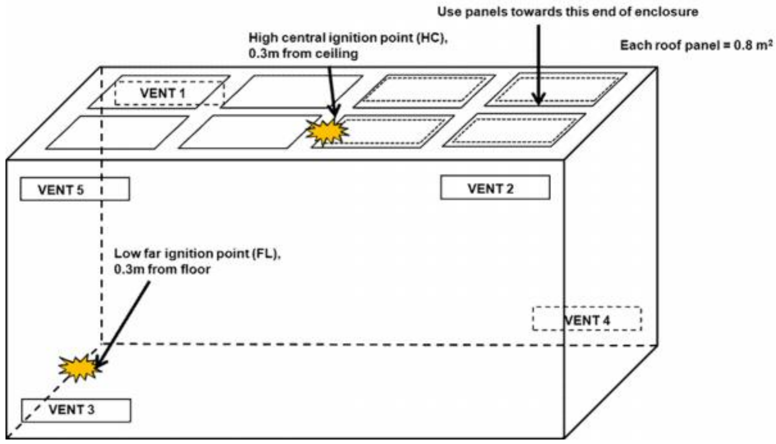

Figure 6. Positions of explosion relief panels and ignition sources for test series 1

For most of the test series 2 experiments, the ignition source was positioned at low level, at the far end from the open upper passive vents, equidistant from the side walls, as shown in Figure 7. This was again to maximise the internal explosion pressure.

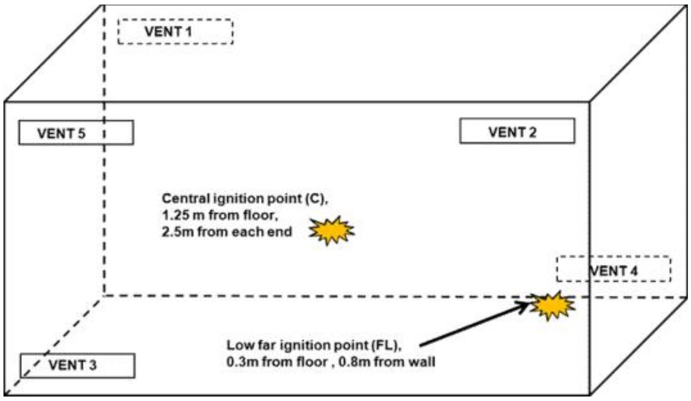

Figure 7. Ignition position for test series 2

For test series 3, the ignition source was positioned at a high level at the far end from the open upper passive vents for the tests with stratified / gradient mixtures that had reached high average concentrations. This was necessary as the mixture was too lean to ignite towards the floor of the enclosure. For the low average concentration, ignited jet experiments the ignition source was placed within the jet of hydrogen itself. The positions of the ignition sources for test series 3 are shown in Figure 8.

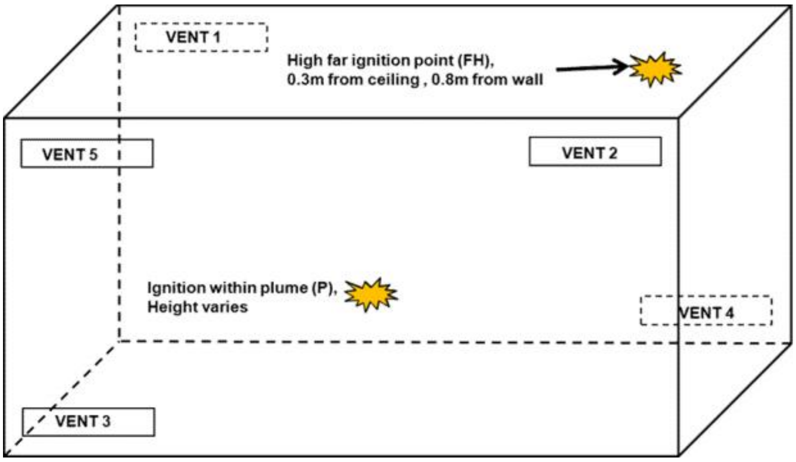

Figure 8. Ignition position for test series 3

The internal pressure in the enclosure was measured using two Kistler pressure transducers with a measurement range of up to 250 kPa. These were mounted flush with the wall of the enclosure in the same plane as vents 2, 3, and 5, as shown in Figure 9.

For test series 1, external pressures were measured vertically above the explosion relief, using two further Kistler pressure transducers (0-250 kPa), positioned at 2.5 m and 5 m above the roof of the enclosure. The positions of the external pressure measurements are shown in Figure 9. For test series 2 and 3, the external pressure sensors were placed at 1 m and 3.5 m from the open upper passive vent, vent 1, as shown in Figure 10, with the pressure sensors in line with the centre of the open vent.

The pressures were logged at 200 kHz, time-averaged over 100 samples. A 25 Hz low-pass Bessel filter could be applied to the data to remove acoustic effects.

Additional instrumentation used included internal temperature measurements using Type K thermocouples, meteorological monitoring using a weather station local to the test pad and further ultrasonic wind speed monitors in close proximity to the enclosure, and video/IR footage of vented explosions (external to the enclosure).

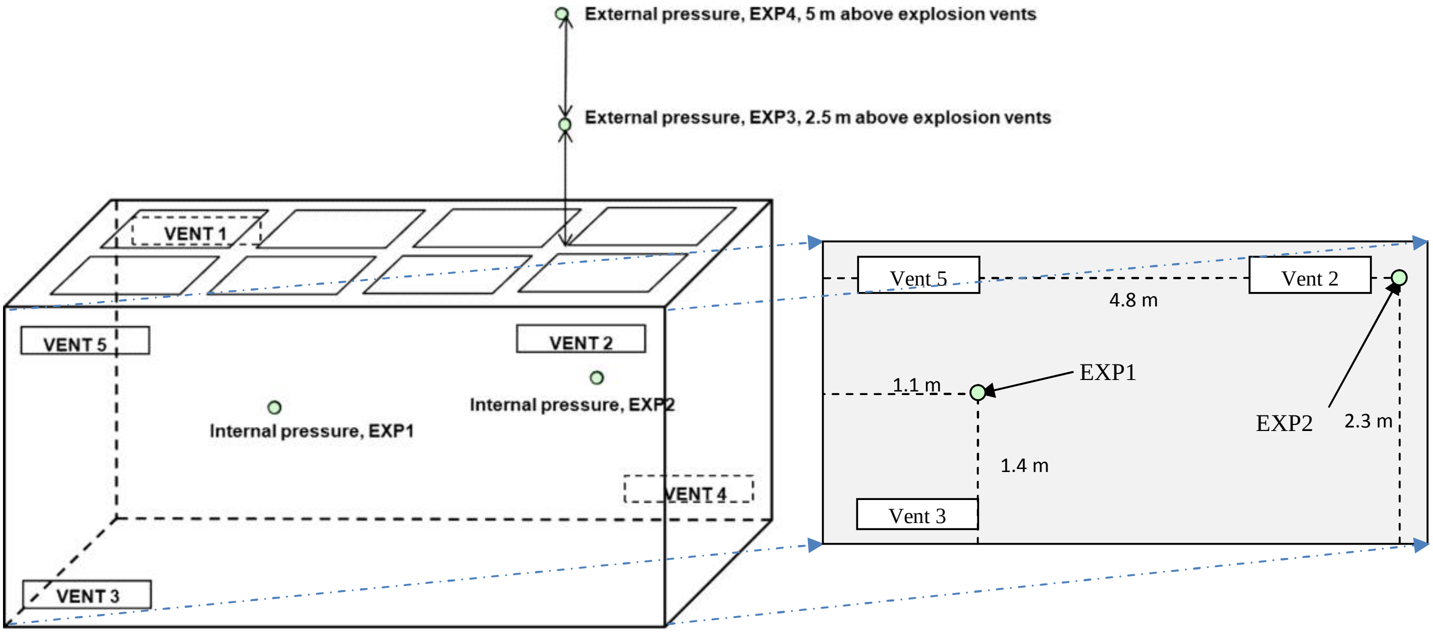

Figure 9. Positions of internal and external pressure measurement sensors for test series 1

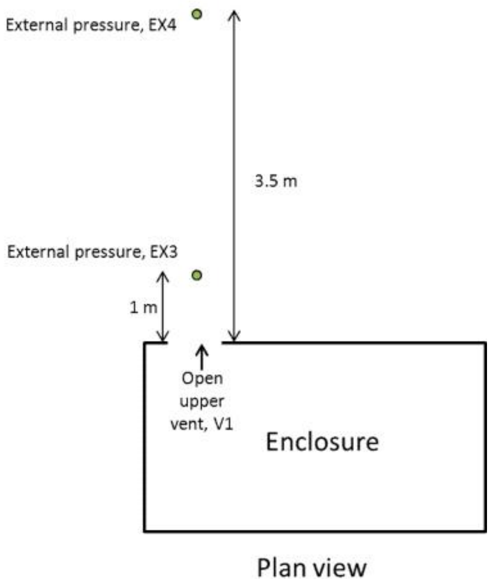

Figure 10. Positions of external pressure measurement sensors for test series 2 and 3

4.0 EXPERIMENTAL RESULTS

The initial test conditions and experimental pressure measurements are summarised in Table 2. A number of trends are evident from the experimental data.

i. Ignition far away from the vent(s) leads to a higher over-pressure than ignition close to the vent(s).

ii. The deflagration overpressure decreases when the vent area is increased.

iii. Explosion relief via passive vents on the side walls appears to be as effective as explosion relief vents of equal area on the roof (for mixtures of up to 10% v/v).

iv. Vented deflagration of a stratified hydrogen-air mixture leads to higher maximum overpressure compared to uniform hydrogen-air composition with the same hydrogen inventory.

The effects of hydrogen distribution on the overpressure are illustrated by the results from tests WP3/16 and WP3/22. Both tests had a measured mean concentration of about 8% v/v and a vent area of about 0.45 m^2. Test WP3/16 had a fairly homogeneous hydrogen distribution with a maximum measured hydrogen concentration of 8.3% v/v and led to an overpressure of 1.1 kPa, whilst test WP3/22 had a stratified hydrogen distribution with a maximum measured concentration of 12.1% v/v and led to an overpressure of 5 kPa to 6 kPa.

It is thought that the higher overpressures observed for stratified distributions were caused by faster flame propagation and higher expansion coefficient associated with locally higher hydrogen concentrations (closer to the stoichiometric concentration) and possibly higher levels of turbulence generated as the flames propagated along the enclosure ceiling [11].

Table 2. Test matrix and main results of HSL experimental campaign.

Test Series	Test No.	Hydrogen condition	Explosion relief	Nominal Conc'n (% v/v)	Actual Measured Mean Conc'n (% v/v)	Actual Range of Conc'n (% v/v)	Ignition point	Explosion relief available	Relief panel area (m2)	Panel burst overpressure (kPa)	Overpressure, filtered (kPa)		Overpressure, unfiltered (kPa)		Comments
											Internal	External	Internal	External	
	WP3/6	Well-mixed	Foil very loosely fixed in place	10	9.69	9.1 - 10.2	Low, far end (FL)	2	1.6	0.1	0.1	0.1	1.6	0.1	Relief vents opened slight delay between them, pressure log triggered manually
	WP3/8	Well-mixed	Perforated 20micron sheet	10	9.57	8.7-10.0	Low, far end (FL)	2	1.6	0.5	0.5	0.1	1.3	0.1	Relief opened well, tearing along perforations and flying away
	WP3/9	Well-mixed	Perforated 20micron sheet	12	12.08	11.1-12.8	Low, far end (FL)	4	3.2	0.6	0.7	0.4	4.4	0.6	Relief opened well, tearing along perforations and flying away
	WP3/10	Well-mixed	Perforated 20micron sheet	14	14.18	13.9-14.5	Low, far end (FL)	4	3.2	0.8	2.8	2.3	4.5	3.7	Relief opened well, tearing along perforations and flying away
1	WP3/11	Well-mixed	Perforated 20micron sheet	10	10.39	10.2 - 10.5	Low, far end (FL)	1	0.8	0.7	4.2	1.5	9.3	2.9	Relief opened well, tearing along perforations and flying away
	WP3/12	Well-mixed	Perforated 20micron sheet	10	10.30	10.1 - 10.4	High, centre (HC)	1	0.8	0.7	0.7	0.2	2	0.6	Relief opened well, tearing along perforations and flying away
	WP3/13	Well-mixed	Perforated 20micron sheet	8	8.08	7.4 - 8.7	Low, far end (FL)	1	0.8	0.6	0.6	0	0.6	0	Relief opened well, tearing along perforations and flying away
	WP3/14	Well-mixed	Perforated 20micron sheet	12	12.16	11.7 - 12.4	Low, far end (FL)	2	1.6	0.6	1.6	1	6.2	1.4	Relief opened well, tearing along perforations and flying away
	WP3/15	Well-mixed	Perforated 20micron sheet	14	13.78	13.1 - 14.2	Low, far end (FL)	2	1.6	1.1	3.4	3.1	6.4	4.1	Relief opened well, tearing along perforations and flying away
	WP3/16	Well-mixed	Perforated 20micron sheet	8	8.01	7.4 - 8.3	Centre	4 passive vents available (1,2,3 & 4)	0.448m2 effective	1.1	1.1	ND	1.1	ND	Only upper relief panels opened - bottom panels remained intact (effective vent area = 0.448m2)
	WP3/17	Well-mixed	Perforated 20micron sheet	10	9.42	8.2 - 10.3	Centre	4 passive vents available (1,2,3 & 4)	~0.62m2 effective	1.3	1.3	ND	1.4	ND	Only upper relief panels fully opened - bottom panels remained ca. 25 - 50% closed (effective vent area ~ 0.62m2)
2	WP3/18	Well-mixed	Perforated 20micron sheet	10	9.86	9.3 - 10.4	Low, far end (FL)	4 passive vents available (1,5,4 & 3)	0.896	1.6	1.8	0.1	3.2	0.3	
	WP3/19	Well-mixed	Perforated 20micron sheet	10	9.71	8.7 - 10.4	Low, far end (FL)	2 passive vents available (1 & 5)	0.448	1.6	8.1	0.1	11.8	0.6	
	WP3/20	Well-mixed	Perforated 20micron sheet	10	9.87	9.0 - 10.5	Low, far end (FL)	2 passive vents available (1 & 3)	0.448	1	4.4	0	7.5	0	
	WP3/21	Stratified	Perforated 20micron sheet	10 max.	6.49	0.1 - 10.5	High, far end (FH)	2 passive vents available (1 & 5)	0.448	2	2	0	2	0	150 Nl/min release rate, sub-sonic, 10 mm diameter
	WP3/22	Stratified	Perforated 20micron sheet	10 max.	8.05	0.1-12.3	High, far end (FH)	2 passive vents available (1 & 5)	0.448	1	5	0	6	0	150 Nl/min release rate, sub-sonic, 10 mm diameter
	WP3/24	Sub-sonic jet, 10 mm diameter	Perforated 20micron sheet	N/A	1.09	0 - 100	1.5m above release	2 passive vents available (1 & 5)	0.224m2 effective	1	1	0.1	1	0.1	300 Nl/min for 62 seconds: Only one panel opened
3	WP3/25	Sub-sonic jet, 10 mm diameter	Perforated 20micron sheet	N/A	1.96	0 - 100	1.5m above release	2 passive vents available (1 & 5)	0.224m2 effective	2.8	2.8	0.2	2.8	0.2	600 Nl/min for 55 seconds, only one panel opened
	WP3/26	Stratified	Perforated 20micron sheet	10 max.	6.34	0.1 - 10.1	High, far end (FH)	2 passive vents available (1 & 5)	0.448	2.5	2.5	0	2.5	0	150 Nl/min release rate; igntion before hydrogen flow stopped to investigate turbulence (compare with WP3/21)
	WP3/27	Sonic jet; 0.9mm diameter, 16.5 bar a	Perforated 20micron sheet	N/A	0.95	0 - 100	0.1m above release point	1 passive vent (1)	0.224	2	2	0	2	0	440 Nl/min for 62 seconds
	WP3/28	Sub-sonic jet, 10 mm diameter	Perforated 20micron sheet	N/A	1.30	0 - 100	1m above release point	1 passive vent (1)	0.224	2	2	0	2	0	412 Nl/min for 68 seconds; compare with WP3/27

Examples of the traces obtained from the internal and external pressure measurements are shown in Figure 11. The traces show internal and external pressures before and after filtering.

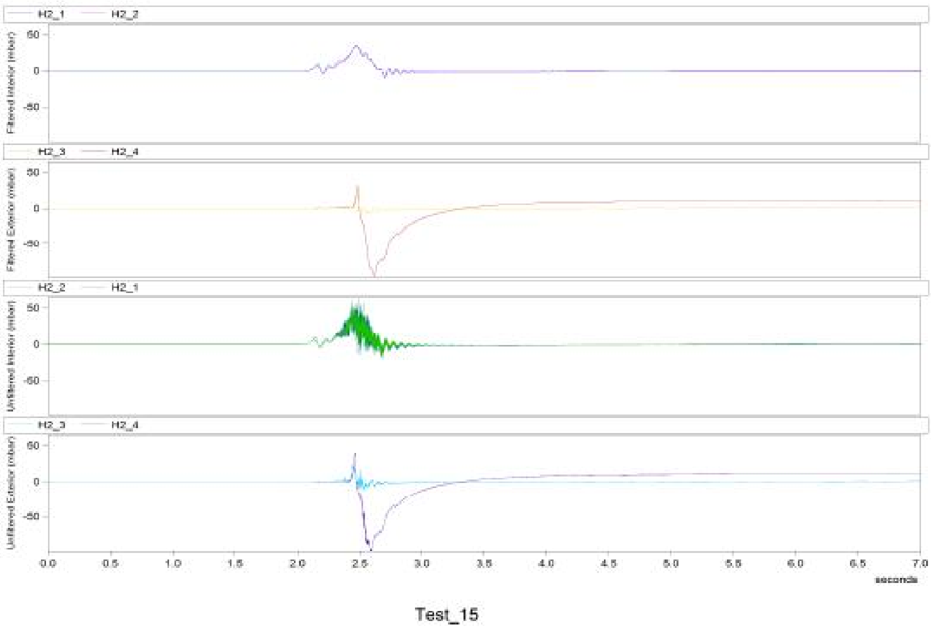

Figure 11. Pressure traces for Test WP3/15 - 14% v/v well-mixed, 1.6 m^2 relief in roof, far - low ignition. Traces from top to bottom are: internal pressures (filtered); external pressures (filtered); internal pressures (unfiltered); external pressures (unfiltered)

5.0 POST-TEST COMPARISON WITH IMPROVED CORRELATION FOR OVERPRESSURE CALCULATION

An improved correlation was published by Molkov and Bragin [7] during the Hyindoor project. A post-test comparison has been made between the measured over-pressures within the enclosure, for all of the reported HSL experiments with quiescent mixtures. This comparison, shown in Figure 12, shows that the Molkov and Bragin (2013) method provides reasonable, slightly conservative predictions.

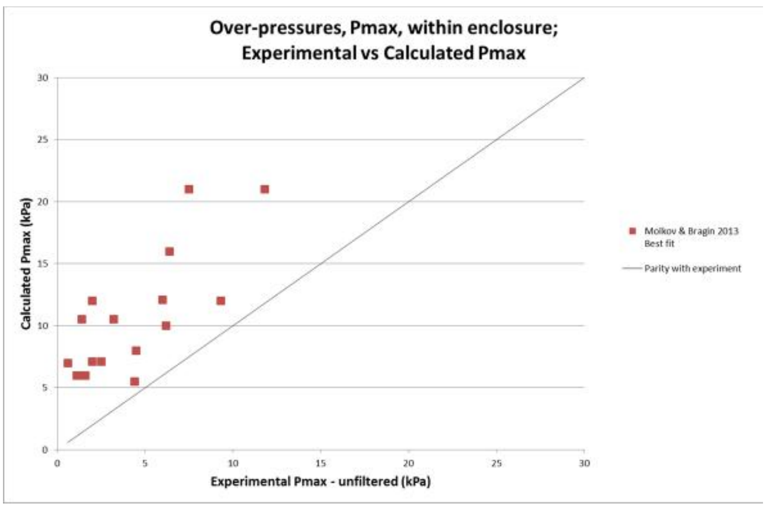

Figure 12. Comparison of measured over-pressures within the enclosure over-pressures calculated using Molkov and Bragin (2013)

6.0 EXTERNAL FLAME LENGTH

One aspect of practical interest in relation to separation distances is the extent to which a flame extends laterally from a vent in the side of a vessel. A predictive method is given in BS EN 14994:2007 [1]:

$$L_F = 5V^{\frac{1}{3}}$$

where L_F is the flame length (in metres) and V is the enclosure volume (in cubic metres).

The prediction from this method was compared with measured flame lengths from the HSL experiments (i.e. until the flame is less than 70°C). Whereas the BS EN 14994 method would have predicted a flame length in excess of 15 m the experimentally observed lengths were less than 2.5 m as seen in Figure 13. The method given in EN 14994:2007 applies to a single vent in a compact enclosure subject to internal over-pressures up to 1 bar (100 kPa) and so the predicted flame lengths could be expected to be larger than those determined in these experiments. However, it would appear that the method may be used conservatively for lower internal over-pressures typically required for industrial enclosures (up to, say, 10 kPa).

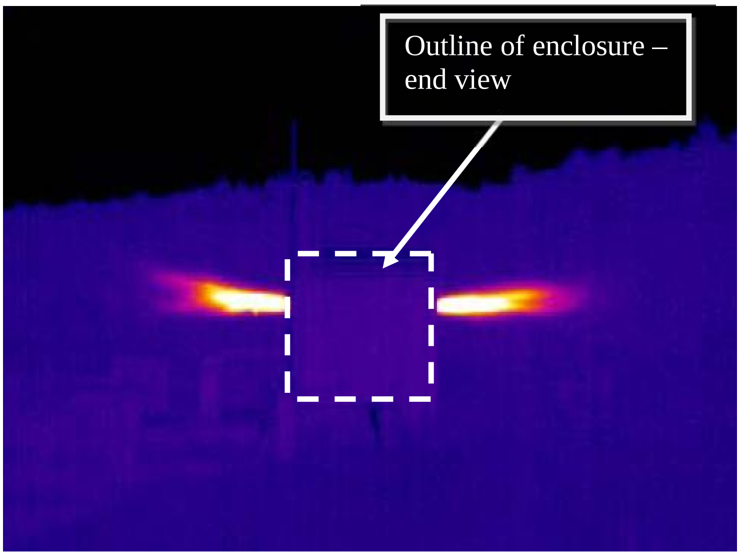

Figure 13. Infra-red image of Test WP3/19 - 10% v/v well-mixed, 2 passive vents (0.45m^2), far - low ignition.

7.0 CONCLUSIONS

Experiments have been carried out at a scale of 31 m^3 to investigate the overpressures resulting from deflagrations of lean hydrogen-air mixtures. Hydrogen concentration and distribution (homogeneous and inhomogeneous), vent area and position, and ignition position were investigated.

Experimental overpressure data from quiescent tests have been compared to those calculated using a model developed by Molkov and Bragin [7] which gives reasonable, slightly conservative values.

A number of general trends were observed:

i. Ignition far away from the vent(s) leads to a higher over-pressure than ignition close to the vent(s).

ii. The deflagration overpressure decreases when the vent area is increased.

iii. Explosion relief via vents in side walls appears to be as effective as via vents of equal area in the roof (for mixtures containing up to 10% v/v hydrogen).

iv. Vented deflagration of a stratified hydrogen-air mixture leads to higher maximum overpressure compared to uniform hydrogen-air composition with the same hydrogen inventory.

v. The lateral flame lengths from the passive vents were considerably less than predicted using the method of BS EN 14994:2007.

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