EXPERIMENTAL PARAMETERS OF IGNITED CONGESTION EXPERIMENTS OF LIQUID HYDROGEN IN THE PRESLHY PROJECT

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ABSTRACT
Liquid hydrogen (LH2) has the potential to form part of the UK energy strategy in the future and therefore could see widespread use due to the relatively high energy density when compared to other renewable energy sources. To study the feasibility of this, the European Fuel Cells and Hydrogen Joint Undertaking (FCH JU) funded project PRESLHY undertook pre-normative research for the safe use of cryogenic LH2 in non-industrial settings. Several key scenarios were identified as knowledge gaps, and both theoretical and experimental studies were conducted to provide insight into these scenarios. This included experiments studying the effect of congestion on an ignited hydrogen plume that develops from a release of LH2; this paper describes the objectives, experimental setup, and a summary of the results from these activities. Characterisation of the LH2 release, hydrogen concentration and temperatures measurements within the resulting gas cloud was undertaken along with pressure measurements both within the cloud and further afield. Various release conditions and congestion levels were studied. Results showed that at high levels of congestion, increased overpressures occurred with the higher flow rates studied, including one high order event. Data generated from these experiments is being taken forward to generate and validate theoretical models, ultimately to contribute to the development of regulations, codes, and standards (RCS) for LH2.

1.0 INTRODUCTION

1.1 Background

The Pre-Normative Research into the Safe Use of Liquid Hydrogen (PRESLHY) [1] project was formed from a consortium of partners to address knowledge gaps identified with high-risk liquid hydrogen (LH_2) accident scenarios so as to enable the safe implementation of the widespread use of LH_2 in a non-industrial setting. This report outlines a series of flow congestion and ignition experiments of cryogenic hydrogen releases undertaken at the HSE Science and Research Centre, Buxton, UK, which form part of Work Package 5 of the PRESLHY project.

The objective of this experimental campaign was to determine the effect of differing levels of congestion upon the ignition behaviour of a cryogenic hydrogen plume. To this end, 23 ignited trials were carried out where cryogenic hydrogen was released into a steel congestion frame. Two levels of congestion were studied and in addition the initial conditions of the release were altered (including the release pressure and orifice diameter) in order to investigate various hydrogen scenarios.

2.0 METHOD

2.1 Facility

The experiments were conducted using a bespoke LH2 release facility located on a 32 m diameter concrete pad at the HSE Science and Research Centre, Buxton, UK. LH2 was supplied by Air Liquide. The release system consisted of insulated steel pipework, remotely operated valves and instrumentation with measurement of pipework temperature and pressure at various points, and measurement of the mass flow rate. The release height was approximately 0.8 m above the ground for these experiments and 100 mm away from the surface of the congestion rig.

The congestion rig was formed as a steel frame consisting of 18, 1 m^3 sections configured as a 3 m square base with a height of 2 m; this is shown in Figure 1. Congestion was achieved by the addition of removable sections in the form of ladder-like structures, hereafter referred to as congestion frames. Each of these congestion frames was made up of 26 +/- 1 mm (nominal 1") diameter cylindrical bars spaced 125 mm apart between two 5 mm x 50 mm bars. The frames had varying lengths dependent on the position in the rig. Scaffold poles (o.d. 48 mm) were also inserted vertically to achieve a higher level of congestion where required. The poles were placed in a pattern with 11 in each 1 m^2 area of the grid and protruded from the congestion frame. Two test conditions (low and high congestion) were studied as detailed in Table 1.

Table 1. Congestion blockage levels by area and volume.

	Bottom half area blockage ratio (m^2/m^3)	Top half area blockage ratio (m^2/m^3)	Bottom half volume blockage ratio (%)	Top half volume blockage ratio (%)
Low congestion	0.80	1.00	1.54	1.93
High congestion	1.53	1.33	4.20	4.60

In order to avoid misfires, stage gerbs, which are pyrotechnic igniters that create a fountain of sparks, were used as an ignition source. The ignition system was separate from the other systems and could be configured for either front or rear ignition points, moving the centre of the explosions accordingly. This is displayed in Figure 1.

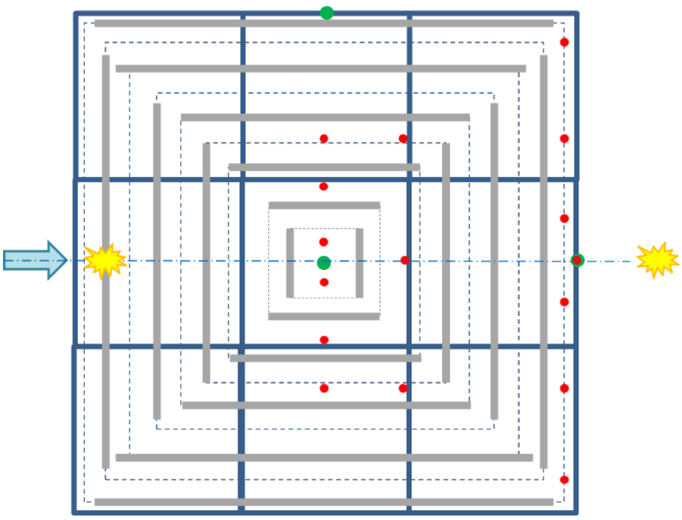

Figure 1. Schematic of the congestion frame including grid pattern, ignition points (yellow), concentration/temperature measurements (red) and pressure transducers (green).

To characterise the overpressure, 8 Kulite HKL-375 (M) series pressure transducers were arranged in and around the congestion rig, centred on the midpoint. Figure 2 shows a diagram of the concrete pad with the pressure transducer locations marked. Each stood approximately 0.5 m off the ground and was oriented 90° from the expected blast wave to register an incident blast pressure. K1 to K4 were held horizontally and K5 to K8 were held vertically. The distance from the centre of the congestion frame is shown, however the distance from the centre of the explosion is dependent on the ignition location – for example, K1 and K2 are 8 m and 13 m from the front ignition point but 5 m and 10 m from the rear.

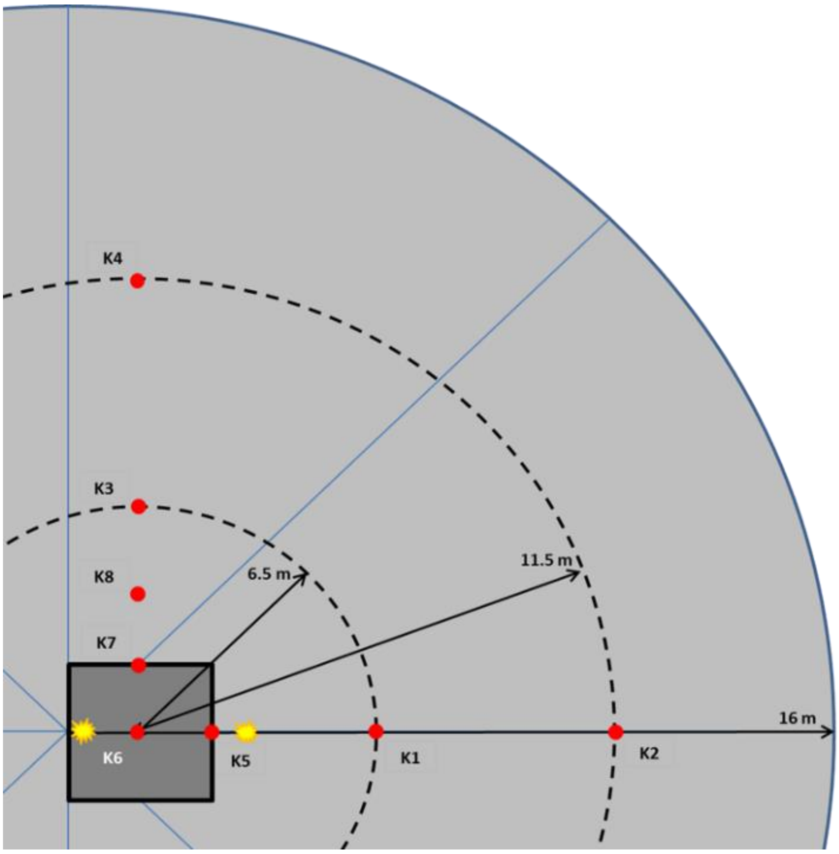

Figure 2. Diagram of pressure transducer locations.

For the majority of trials the peak noise levels were recorded with noise measurements being taken at two locations approximately 215 m from the centre of the concrete pad using Bruel and Kjaer 2238 Mediators.

The temperature and hydrogen concentration was measured inside the congestion frame at 16 points, arrayed as displayed in Figure 1. Each point held a type T sheathed thermocouple collocated with a stainless steel gas sampling line. These sampling lines ran approximately 30 m and each connected to a Xensor thermal conductivity XEN-5320 sensor. The HyWAM system to determine hydrogen concentration was supplied by NREL with a logging rate of 4 Hz.

Ambient conditions prior to trials using two systems: a Skye SKH-2053 temperature and humidity probe mounted alongside a WindSonic ultrasonic anemometer on a 3 m high stand on the downwind edge of the concrete pad approximately 20 m from the release point; and a PCE-FWS-20 weather station positioned locally to the release station at 1.5 m height.

2.2 Procedure

For consistency, prior to each day of testing, the temperature of the bulk LH2 was reduced to close to the normal boiling point by venting some ullage gas and lowering the pressure so cooling the liquid. The pressure in the ullage could be raised above the vapour pressure of the liquid by allowing LH2 from the bottom of the tank into a heat exchanger and feeding the gas back into the top of the tank. Immediately before each set of releases the pipework was purged; firstly with nitrogen, then with ambient hydrogen gas. Once the purge was complete, LH2 could be introduced to the pipework. The release before ignition was not a set time, but a steady state in the output was required so the congestion rig was saturated by the time of ignition. This steady state was defined as a stable measured temperature at the release nozzle, which would reduce from ambient to a flat value. This process ensured that the phase of the hydrogen in each initial condition was similar and typically two-phase flow. The period to reach steady state also ensured that the congestion frame was saturated from the initial conditions, meaning that ignition occurred during well-established releases with the maximum hydrogen possible present in the frame from the initial conditions. Care was taken to avoid ignitions if the hydrogen cloud, indicated by the mist, had moved to an undesirable location.

3.0 RESULTS AND DISCUSSION

3.1 Result Overview

A series of 23 ignited congestion trials were conducted. Table 2 shows the initial conditions of each trial, the peak measured overpressure (and the location of that pressure transducer), the noise measured, and approximate maximum pressures recorded at a range of 6.5 and 11.5 m from the centre of the congestion rig. Unless otherwise stated, the local 5 minute average wind speed was less than 2.7 m/s.

Table 2. Summary of results.

Test No.	Orifice size (mm)	Tanker P (kPa Gauge)	Ignition point	Congestion level	P max (kPa)	P max location	Noise (dB)	P max 6.5m (kPa)	P max 11.5m (kPa)
1	6	100	Front	Low	1	K6	*NM	0.2	0.1
2	12	100	Front	Low	52	K7	*NM	4.0	2.3
3	25.4	100	Front	Low	16	K5	*NM	0.5	0.4
4	12	100	Front	Low	3	K5	123	1.2	0.7
5	25.4	100	Front	Low	2	K5	117	1.1	0.5
6	12	100	Front	Low	4	K5	125	1.2	0.7
7	25.4	100	Front	Low	38	K5	114	0.7	0.4
8	12	100	Rear	Low	7	K6	*NM	1.4	0.8
9*	12	100	Rear	Low	4	K6	123	1.0	0.5
10	25.4	100	Rear	Low	1	K6	108	4.0	0.2
11	6	500	Front	Low	14	K5	122	1.3	0.7
12	12	500	Rear	Low	39	K5	132	4.0	2.5
13	12	500	Front	Low	13	K5	131	5.0	3.0
14	12	500	Rear	Low	53	K5	127	2.0	1.2
15	12	500	Front	Low	10	K5	132	4.0	2.0

Test No.	Orifice size (mm)	Tanker P (kPa Gauge)	Ignition point	Congestion level	P max (kPa)	P max location	Noise (dB)	P max 6.5m (kPa)	P max 11.5m (kPa)
16	12	500	Rear	Low	55	K6	134	4.0	2.0
17	12	500	Front	Low	67	K5	129	3.0	1.5
18	25.4	500	Front	Low	4	K5	120	1.5	0.7
19	25.4	500	Rear	Low	15	K5	137	7.0	4.0
20	6	100	Front	High	1	K6	*LA	0.3	0.2
21	12	100	Front	High	15	K5	134	4.0	2.5
22	12	100	Front	High	13	K5	132	6.5	4.0
23*	12	100	Front	High	128	K5	145	47.0	20.5

*NM Noise measurements not made, *LA Noise too low to discern from local ambient noise.

3.2 Results and discussion: Low congestion tests

Trials 1 and 11 were carried out through a 6 mm nozzle and on ignition showed consistently low overpressures and noise. For these trials, a qualitative review of video footage showed a much smaller visible mist was present when compared to other nozzle sizes, indicating that, at steady state, a much lower hydrogen inventory was present within the rig in these trials. Trial 2 was unique as it is the only trial in which the peak overpressure was measured at position K7, which was off the centreline of the release. This suggests that for that ignition, the cloud was off centre, and this was observed qualitatively and is corroborated by the higher local 5 minute average wind speed of 3.4 m/s.

Trials 3 to 7 were conducted at 100 kPa (gauge) tanker pressure and a front ignition location with trial nozzles either a 12 mm or 25.4 mm orifice. Peak overpressures were consistently measured at K5 and those from the larger nozzle were typically higher, due to the larger hydrogen inventory at steady state. However, trial 5 showed particularly low measured overpressures and a qualitative review of post-trial video footage shows a swirling wind on the pad, suggesting that dilution of the cloud may have contributed the lower than predicted result. Although not categorized specifically during these trials, this highlights the potential impact of weather effects on experimental output.

Trials 8 to 10 were analogous to Trials 3 to 7 but with rear ignition; again, both 12 mm and 25.4 mm orifices were studied. Peak overpressures were consistently measured at K6 however those measured during the release through the 25.4 mm nozzle was lower than those through the 12 mm nozzle for these tests.

Trials 12 to 17 were tests involving the same initial conditions of 500 kPa (gauge) tanker pressure releases through the 12 mm nozzle and the low level of congestion, but with alternating ignition locations. These repeats were completed to establish an indication of the variation of trial outcome during replication. When grouped by ignition location, the average measured peak overpressure is 30 kPa for front ignitions and 0.49 for rear ignitions, although there is much higher variation in the front ignitions.

Trials 18 and 19 (conducted with similar initial conditions to trials 12 to 17, but with the 25.4 mm nozzle), the peak overpressure was higher for the rear ignition, although the average was lower than the measured overpressures for the similar 12 mm nozzle releases. For trial 19, however, this shows a significant discrepancy between the noise at 215 m and the measured overpressure.

Overall, a general data pattern that was observed was that the increased tanker pressure reliably increases the noise and overpressure levels on ignition. This is due to higher mass flow rates and flow speeds resulting in a greater mass of hydrogen being combusted and higher initial turbulence levels. However, the nozzle size shows different behaviour, with the 6 mm and 24.5 mm nozzle typically showing lower noise levels than the 12 mm nozzle. While it is likely that the low mass flow rates of the 6 mm nozzle result in a much lower hydrogen inventory inside the congestion rig, it is postulated that the low than predicted results from the 25.4 mm nozzle are primarily an effect of mixing and cloud stoichiometry at the point of ignition , with the releases through the 25.4 mm nozzle being too rich within the congested array to efficiently combust the hydrogen.

3.3 Results and discussion: High congestion tests

Trial 20 was conducted with a 100 kPa (gauge) tanker pressure and a high level of congestion. It can be seen from Table 2 that the level of congestion present did not appear to have a significant impact on the measured overpressures as both trial 1 (low congestion) and 20 (high congestion) show similar behaviour. Trials 21 to 23 were repeat tests with initial conditions of 100 kPa (gauge) tanker pressure, 12 mm nozzle and front ignitions using the high level of congestion. All three tests were carried out in sequence within a period of about 40 minutes in very similar average weather conditions. Trials 21 and 22 showed consistent behaviour, but 23 showed almost a tenfold increase in overpressure. This is shown in Figure 3, which has the overpressure output from K1 and K2 for each of the three trials. Pressure transducers K1 and K2 were approximately 8 m and 13 m from the front ignition point respectively, along the centre line of the release on the far side of the congestion. The maximum pressure for trial 23 measured within the congestion frame was approximately 128 kPa measured at K5.

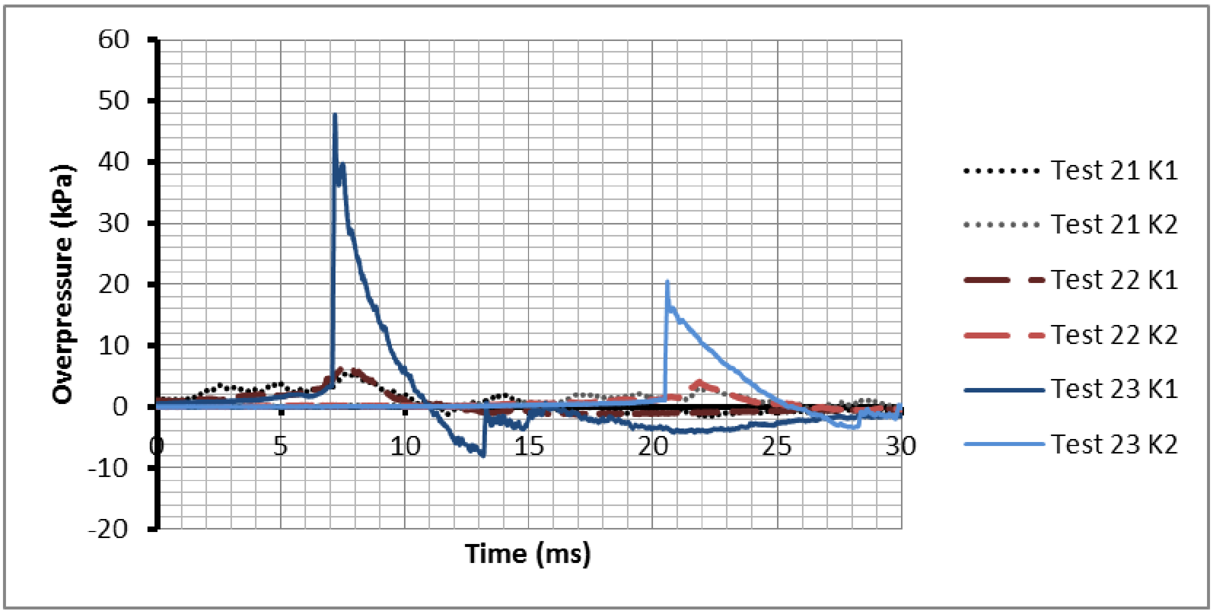

Figure 3. Overpressure results comparison for the repeated trials 21 to 23.

Test 23 produced a severe explosion that caused damage to the building housing the cameras and showed a qualitatively different behaviour to other the two preceding tests. High overpressures and the shape of the pressure peaks showing a large discontinuous increase in pressure following the passage of a shock, suggest a high order deflagration or detonation (Level 8-10 in the TNO Multi Energy

Method [2]). However, due to the similar shock transition speeds across the series of three tests, it is unclear if Test 23 was a DDT or a more highly developed deflagration event. This is discussed in more detail in Section 3.3.1.

3.3.1 Discussion of Test 23: High Order Response

As detailed above, Test 23 showed a significantly stronger response to ignition than other analogous initiation trials. Mathematical treatment of the data (Figure 4) shows that Friedlander curves [3] fit well to the positive pressure pulse measured. Equation 1 shows the Friedlander curve, where t* is the duration of the positive pulse. Fitting the curves to the data is shown in Figure 4.

$$P = P_{max} e^{-\frac{t}{t^*}} \left(1 - \frac{t}{t^*}\right), \quad (1)$$

Where *P* – pressure, Pa; *t* – time, s.

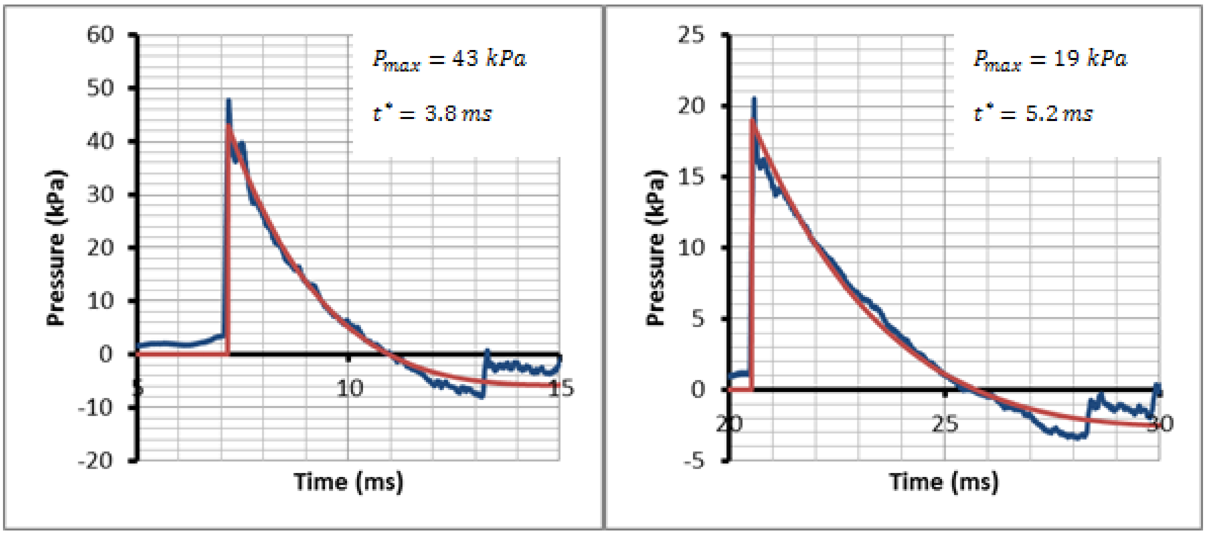

Figure 4. Test 23 – Friedlander curve fitting of pressure gauges response K1: 6.5 m (left figure) and K2: 11.5 m (right figure) distance from centre along jet axis.

Friedlander curve fitting allows the maximum pressure to be estimated more reliably than simply reading the maximum measured peak pressure values (as these can be affected by noise and very high frequency structural responses to shock in the sensors).

The time of passage between K1-K2 and K3-K4 was in the range 13.35 -13.41 ms which gives an average shock velocity of 372 - 374 m/s. Relating this shock speed to Kingery-Bulmash blast calculation [4] by variation of TNT equivalence to achieve the desired shock velocity leads to an overpressure prediction of around 24 kPa which is reasonably consistent with the measurements taken during the trials. This implies that detonation of at least part of the hydrogen cloud may have occurred in test 23.

On review of the primary data from the trials 21 to 23, it was noted that the measured overpressures were higher at K1 and K2 than K3 and K4 (which were at 90 degrees to the LH2 jet centre line). There are a number of potential explanations for this:

1. **Residual asymmetry in the pressure field with higher overpressures in the direction of propagation of the (high order) explosion**. This is difficult to discount completely but it was not observed in the Buncefield detonation trials [5] and detonation asymmetry typically decays

rapidly with distance from the shock centre: as a consequence this is not thought to be the source of K1 to K4 variation.

2. **Variation in the location of the exploding gas cloud.** Review of the high speed video record for Trial 23 showed rapid combustion of the parts of the cloud along the line to K1/K2 both in and just outside the congestion rig. In contrast there was residual slower combustion of parts of the cloud observed outside of the congestion rig on the line towards K3/K4. An unequal concentration hydrogen/air distribution caused by local weather conditions could have contributed to this and would explain K1 to K4 variation.

However, Figure 5 compares the concentration profiles close to the downstream edge of the congestion array in Tests 21 and 23, immediately prior to ignition indicating very similar hydrogen / air concentrations were present.

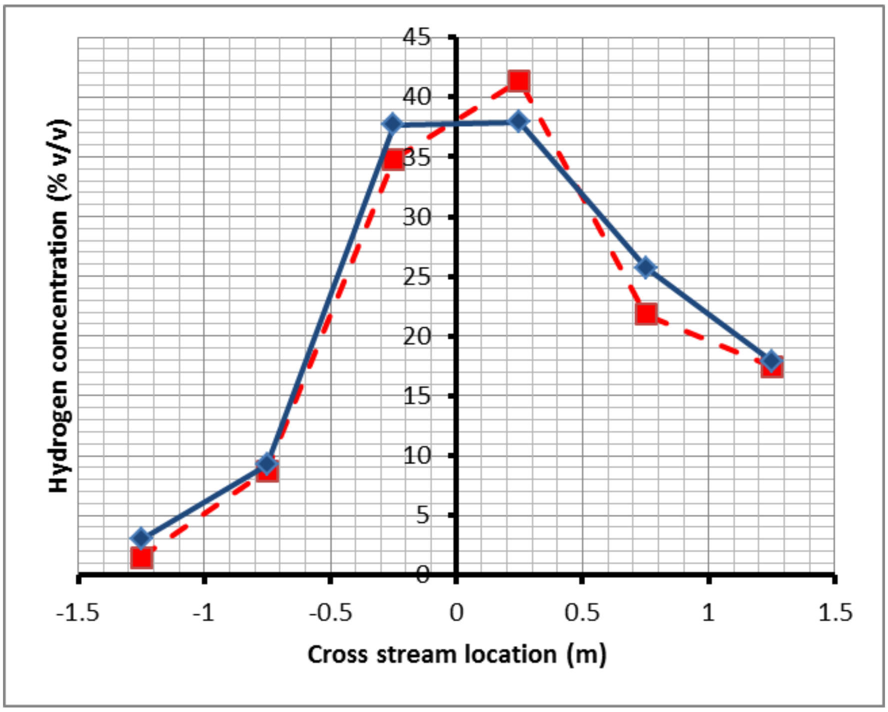

Figure 5. Comparison of the concentration profiles 2.9 m downstream in Tests 21 and 23.

Although not detailed here, data from the average hydrogen concentration over all of the measurements points for both trials was around 2% v/v higher for Test 23 immediately prior to ignition. This low level of concentration variation would be predicted to make only a marginal difference to the observed flame speed and associated overpressure. Further testing is required to assess the significance of the Test 23 trial results but it may suggest that small changes in congestion or cloud structure in this flammable range (eg due to transient wind effects or localised eddy effects) may push the combustion over the boundary between a relatively stable explosion and one that self-accelerates to very high speed or DDT. By way of example, Figure 6 shows that immediately prior to ignition in Test 23 the cloud shape was affected by a sudden strengthening of the opposing wind suggesting that the high order event may have been impacted by the transient, localised wind condition.

Figure 6. Series of stills showing sudden gust immediately prior to ignition for Test 23.

3.4 TNO Multi-Energy Method (MEM)

A well-established method of estimating energy release from gas explosions is to use the blast curves from the TNO Multi-Energy Method (MEM) [6]. For a high order explosion in the relevant range of scaled distances R' the scale overpressure is as shown in equations 2 and 3.

$$\frac{P}{P_0} = 0.467R'^{-1.58}, \quad (2)$$

Where *P* – pressure, Pa; *R'* is the scaled distance in equation 3.

$$R' = \frac{R}{(E/P_0)^{1/3}}, \quad (3)$$

Where *P* – pressure, Pa; *R* – distance, m; *E* – energy, J.

The measured values of pressure ratio P/P_0 at a range of 11.5 m from the rig centre range for Trials 23 were 0.14 (location K4) and 0.19 (location K2). According to the MEM fit given above this corresponds to a range of reduced distances of R'= 1.76 to 2.1.Due to the experimental arrangement and the uncontrolled method of gas cloud formation, there is some expected variation in the accuracy of the determination of R (ie the actual distance to the explosion centre) and so the calculations have a degree of uncertainty. However, to allow discussion, the value of R has been assumed to be 11.5 m at positions K2 and K4. With this assumption, the data indicates a range of energies for the explosion observed in Trial 23 of between 16 and 27 MJ. In order to provide a data envelope, if the K2 gauge were estimated to be at 10.5 m (ie closer to the edge of the congestion frame), the upper limit on the energy estimate would reduce to 21 MJ.

Within Figure 3, smaller overpressure peaks can be observed for Tests 21 and 22. This suggests that the difference in overpressures between, for example, Test 21, and 23 was caused by a difference in the extent to which ignition occurred at the flame front and the consequent efficiency of conversion of energy into blast. This is illustrated in Figure 7 which shows the change in blast overpressure as the speed of explosion and TNO explosion category changes. The observed changes in overpressure roughly correspond to the difference between a high order explosion TNO level 8-10 in Test 23 and a TNO Level 4 explosion in Test 21.

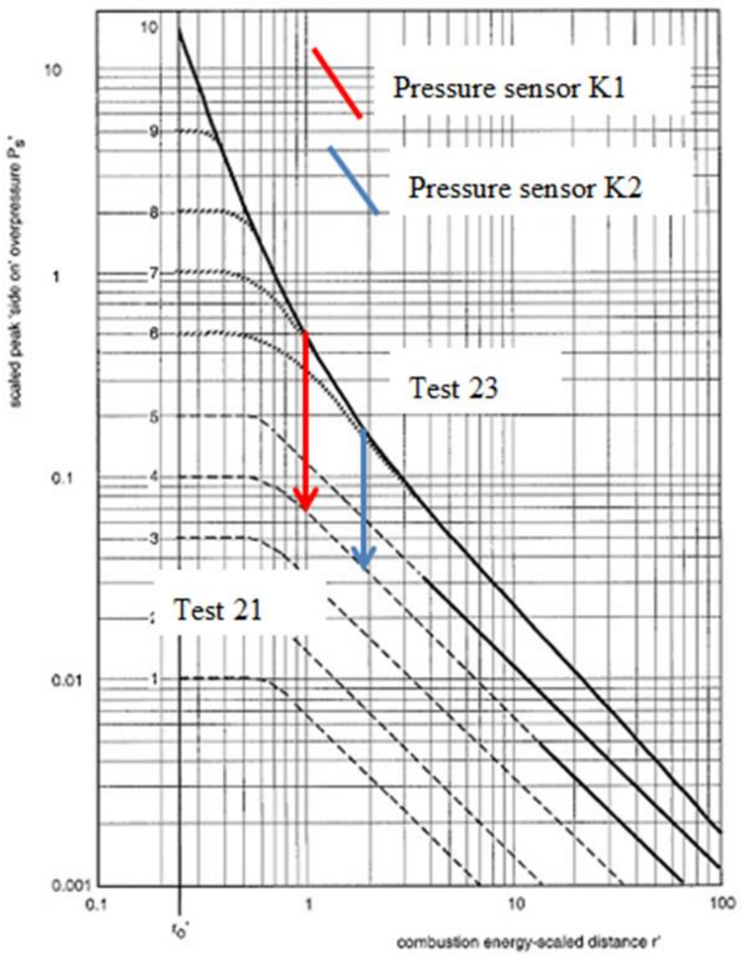

Figure 7. Change in flame speed (TNO Explosion Level) between Test 23 and 21.

This implies that Test 23 was a true high order event and different in character to that of Test 21 when assessed using the MEM method. However, further consideration of the assessment method is given in Section 3.5.

3.5 Comparison between MEM and TNT equivalence methods

It should be noted that the use of a single equivalent quantity of TNT (eg via the use of the Kingery-Bulmash blast calculation [4]) is inconsistent with the TNO MEM blast curves. At close range (pressures over 10 kPa) the energy in a gas explosion would have to be twice the explosive energy of a TNT charge to generate the equivalent overpressures. For example, the energy of the gas explosion required in Test 23 has been calculated to be in the order of 20 MJ, whereas the mass of the TNT charge that would produce the same effect at this range is only around 2 kg – which would have an explosive energy release of about 9 MJ.

To study this effect, Groethe et al [7] carried out a 300 m^3 hemispherical stoichiometric hydrogen (approximately 29.5 vol % in air) detonation (E= 864 MJ) which was analysed by Mélani et al. [8] and shown to fit the TNO blast prediction for a high level explosion.

In a similar study, Wakabayashi et al [9] carried out hydrogen detonations in a cylindrical tent with height and diameter of 3.4 m with test concentrations (v/v) of 21%, 28.7% and 52%. At 21% the measured overpressures (in the 10-50 kPa range) were substantially less than those for a TNT explosion with a similar explosive energy release calculated on the basis of 4.533 MJ/kg. However, at 28.7% the pressures measured by Wakabayashi were close to the level expected for a TNT charge with a similar explosive energy. The gas cloud was significantly different in shape to that used by Groethe and assumed in the MEM, but the discrepancy remains to be explained.

Wakabayashi et al also found that the very fuel rich clouds (52% v/v) caused pressures equal to those for the stoichiometric case (in the range of pressures <100 kPa). The impulse from these fuel rich ignitions was also much larger than that of stoichiometric mixtures. The conclusion was that rapid entrainment and combustion of additional oxygen can occur so quickly and efficiently that it contributes directly to the combustion and subsequent energy release. This aligns closely with the hypothesis suggested for Test 23.

Due to the difficulties identified by the various studies, correlation of gas explosions to TNT equivalent cannot be used to unequivocally link data from Test 23 to severity of response. From the above, it is unclear whether Test 23 progressed via DDT or not. It was however noted that none of the transducers adjacent to or within the congestion array recorded close to the C-J pressure even though the pressure trace did show a "classical" detonation curve of positive and negative phases. Pressures were also in excess of 120 kPa which does suggest that the explosion was at TNO MEM Level 8-10 but again, some further investigation is required to confirm the presence or absence of post-ignition DDT. The results do however suggest that minor changes to congestion level or concentration / stoichiometry in the cloud structure are important contributors to the consequences of ignition. .

4.0 CONCLUSION

The objective of this experimental campaign was to determine the effect of different levels of congestion upon the ignition behaviour of a cryogenic hydrogen plume. To this end, 23 ignited trials were carried out whereby cryogenic hydrogen was released into a steel congestion frame. As well as two levels of congestion, the initial conditions of the release were aligned with similar conditions to the other experiments carried out as part of the wider PRESLHY project.

The results show that an increasing hydrogen inventory, either through an increased release pressure or larger nozzle, can result in a larger event upon ignition. The mixing of the plume with the surrounding air also plays a part in the post-ignition response; for example, some releases through the largest release orifice diameter showed lower overpressures compared to smaller diameter orifices potentially due to the hydrogen cloud being too rich.

A severe deflagration or detonation was observed in one trial, although trials with similar initial conditions did not show the same behaviour. This has been attributed to wind conditions causing recirculation of the hydrogen / air cloud encouraging a slightly higher hydrogen volume concentration within the congestion frame at ignition.

Notwithstanding the possible variability introduced by atmospheric wind conditions, results suggest the following for LH2 releases during tanker operations under the conditions studied:

i) For a low level of congestion (Volume blockage ratio <1.5%, Area blockage <1 m2/m3, Congestion length scale 25-50 mm) there is little risk of uncontrolled flame acceleration. An assumption of TNO Level 5 would be appropriately conservative when applied to the portion of the cloud within the congested area.

ii) For densely congested areas (Volume blockage ratio >4 %, Congestion length scale 25-50 mm) with a volume of more than approximately 15 m^3 then it would be appropriate to assume that a high level explosion or DDT could occur. A contribution from mixing efficiency (e.g.

via increased congestion or impingement of wind) and cloud stoichiometry is thought to be contributing factors to the severity of the response.

The definitive boundary of congestion level beyond which severe explosion has a higher propensity to occur was not been determined. However, it is proposed that it would be appropriate to assume that a severe explosion could occur for congested volumes of limited size or of intermediate levels of congestion.

5.0 ACKNOWLEDGEMENTS & DISCLAIMER

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 779613. The HSE work programme acknowledges funding from its sponsors Shell, Lloyd's Register Foundation and Equinor and instrumentation provided by NREL and Dräger. The contents of this paper, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

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