FLAMMABILITY PROFILES ASSOCIATED WITH HIGH-PRESSURE HYDROGEN JETS RELEASED IN CLOSE PROXIMITY TO SURFACES

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ABSTRACT

This paper describes experimental and numerical modelling results from an investigation into the flammability profiles associated with high pressure hydrogen jets released in close proximity to surfaces. This work was performed under a Transnational Access Agreement activity funded by the European Research Infrastructure project, H2FC.

The experimental programme involved ignited and unignited releases of hydrogen at pressures of 150 and 425 barg through nozzles of 1.06 and 0.64 mm respectively. The proximity of the release to a ceiling or the ground was varied and the results compared with an equivalent free-jet test. During the unignited experiments concentration profiles were measured using hydrogen sensors. During the ignited releases thermal radiation was measured using radiometers and an infra-red camera. The results show that the flammable volume and flame length increase when the release is in close proximity to a surface. The increases are quantified and the safety implications discussed.

Selected experiments were modelled using the CFD model FLACS for validation purposes and a comparison of the results is also included in this paper. Similarly to experiments, the CFD results show an increase in flammable volume when the release is close to a surface. The unstable atmospheric conditions during the experiments are shown to have a significant impact on the results.

1.0 INTRODUCTION

The presence of surfaces affects the dispersion behaviour of jets, impacting the flammable extent of combustible gases. The importance of the effect will depend on the distance between the jet and the surface, on the momentum of the jet and the buoyancy forces. In addition, the presence of the surface affects turbulence, inducing recirculation zones and may result in a Coanda effect. Through these combined effects on the flammable extent, surfaces can directly impact risk analysis and thus require a thorough understanding.

The dispersion behaviour of high-pressure hydrogen jets released in close proximity to a surface is not fully understood. There are indications that the extent of the flammable region is significantly increased (1) (2) and so a better understanding of this phenomenon is required to enable safety distances to be specified with greater certainty.

1.1 Objectives

- To gain a better understanding of the dispersion behaviour of an unignited high-pressure hydrogen jet released close to a surface

- To gain a better understanding of the influence of surface proximity on ignited high-pressure hydrogen releases
- To generate experimental data to validate computational fluid dynamics (CFD) modelling

1.2 Programme of Work

Four separate test series were performed:

- Unignited experiments of high-pressure hydrogen jet releases close to the ground (SERIES 1)
- Ignited experiments of high-pressure hydrogen jet releases close to the ground (SERIES 2)
- Unignited experiments of high-pressure hydrogen jet releases close to a ceiling (SERIES 3)
- Ignited experiments of high-pressure hydrogen jet releases close to a ceiling (SERIES 4)

For each series performed, six configurations were investigated with two repeats of each configuration. Two different flow conditions were chosen to give similar free jet distances to the lower flammability limit (LFL) but using differing nozzle sizes and pressures. A flow rate of 6-8gs^{-1} was anticipated (3) to give an estimated distance to the (LFL) of 4-5m for a free jet (4). The hydrogen reservoirs were known to decrease in pressure during each test, which was between 20-40s long, the final pressure being approximately 90% of the initial pressure. Table 1 describes the tests:

Table 1: Test matrix for unignited and ignited releases of high-pressure hydrogen close to the ground and close to the ceiling

Test Storage Pressure (barg)	Orifice Size (mm)	Series 1-2									Series 3-4					
		Distance from Ground (m)									Distance from Ceiling (m)					
		0.05			0.48			1.22			0.08			0.49		
150	1.06	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6
425	0.64	10	11	12	13	14	15	16	17	18	10	11	12	13	14	15

2.0 EXPERIMENTAL SET UP

2.1 Test Facility

The HiPress test facility is situated at the Dale Head site at HSL, Buxton (Figure 1). It comprises:

- Two 50l storage vessels with 1000barg working pressure which are suitable for hydrogen service and ½” bore pipework
- A gas booster compressor to charge the vessels from a hydrogen delivery pack pressure of <175barg up to 1000barg
- A remote operation, release timing and firing control system to perform and monitor and record test sequence data including temperatures and pressures within the pipework

A simplified process and information diagram (P&ID) of the release system is shown in Figure 2. The only alterations required were the inclusion of a nozzle at the pipe exit and some pipe extension to alter the release height.

Figure 1: HiPress Facility at HSL

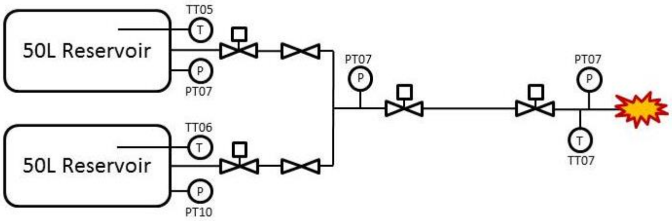


Figure 2: Simplified P&ID of Release System

2.2 Release Conditions

Two flow conditions were identified; 425barg through a 0.64mm nozzle and 150barg through a 1.06mm nozzle. The orifice sizes quoted were measured independently using a microscope and micrometre and the pressures were determined to maintain a common free jet distance to LFL (calculated at 4.6m (4)). These orifices and pressures were calculated to produce flow rates of 6.7gs^{-1} and 7.3gs^{-1} hydrogen for flow conditions/nozzle sizes of 425barg/0.64mm and 150barg/1.06mm respectively (3).

The distances from the ground surface (Series 1 and 2) and ceiling surface (Series 3 and 4) were varied by adapting the pipework with two 90º bends (Figure 3). Five separate release heights were used with only one configuration active at a time: 0.05m, 0.48m, 1.22m, 2.51m and 2.92m. The 1.22m represents a free jet height at which the ground and ceiling surfaces play no role in the evolution of the hydrogen jet plume.

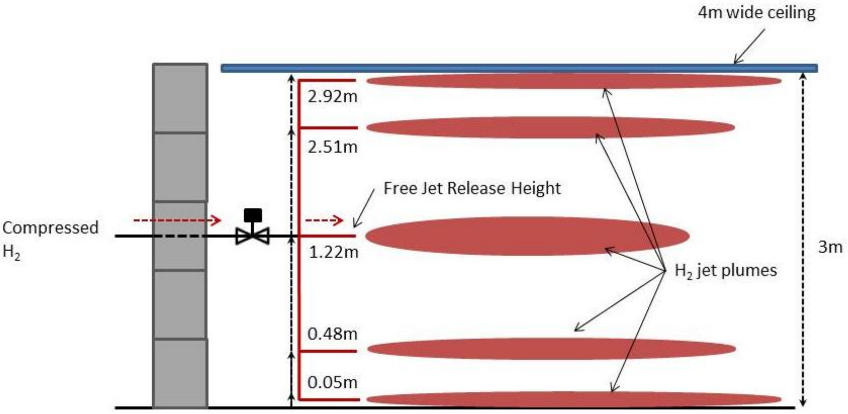


Figure 3: Five Possible Jet Release Height Configurations

The 0.05m and 0.48m jet heights were chosen as it was thought that the 0.05m would be heavily affected by its proximity to the ground surface and the 0.48m less so, but still affected. By varying the jet height close to the ground, the effects of jet plume extension could be examined with hydrogen's natural buoyancy lifting the jet away from the ground surface.

In order to examine the effects of jet plume height with buoyancy negated, a ceiling was constructed. This ceiling was constructed from mild steel and stretched 12m along the line of the release point and 2m either side of it at a height of 3m (Figure 4). It was supported at the sides of the ceiling, but there were no central supports to interfere with plume formation. The two heights of 2.51m and 2.92m represent the closest comparisons physically possible to the ground release heights (0.05m and 0.48m).

Figure 4: Ceiling Construction Over Release Point

2.3 Ignition Mechanism

For Series 2 and 4, ignition of the hydrogen plume was required. In order to ensure ignition was achieved without the build-up of a flammable cloud, a propane pilot light was used. This was positioned close to the release nozzle and lit prior to the start of the test, remaining lit for the duration of the test.

2.4 Instrumentation

Different instrumentation was used for the unignited and ignited test series, as detailed below.

2.4.1 Concentration Measurement

Five GDS Technologies F1 Gas Sensor katharometer type hydrogen sensors were used for Test Series 1 and 3. These sensors detect changes in thermal conductivity of the sample gas and a signal is produced. They provide an output from 0-100% v/v of hydrogen and are temperature compensated to account for ambient air temperature changes. The quoted accuracy of the sensors is +/- 1% FS. In order to sample the hydrogen from the releases, each sensor was coupled with its own individual pump sampling at a flow rate of approximately 10l/min. These sensors were arranged in a sampling array using 6mm nylon tubing to minimise disturbance to the hydrogen jet plume.

The positioning of the sampling array was altered axially from the release nozzle from test to test to try to optimise the distance to the LFL (4% v/v in air for hydrogen). Sensor locations quoted in this report are axial distances from the release nozzle for each given release height and do not alter in any other plane. The datum for the release distances is the nozzle outlet.

2.4.2 Heat Flux Measurement

During the ignited tests, Series 2 and 4, heat flux measurements were made using fast response (50ms) ellipsoidal radiometers, which measure only radiative heat and have a range of 110kW/m^2 with a 160° field of view. Three heat flux sensors were used and were located at a 2m offset to each release in the axial plane. Sensor locations quoted in this report are axial distances from the release nozzle for each given release height and do not alter in any other plane. The datum for the release distances is the nozzle outlet.

2.4.3 Thermal Imaging

For the ignited test series a FLIR thermal imaging camera was used, which measures in the 7.5-13µm spectral range and was set to a temperature range of 0-500ºC. It has a sensitivity of <0.08ºC and an accuracy of ±2% of black body temperature.

2.4.4 Meteorological Measurement

The wind speed and direction were measured for each test at close proximity (approx. 4m away) and at the same height as the free jet release (1.22m) using a GILL Instruments ultrasonic anemometer. Temperature and humidity were also measured on the test site.

3.0 SIMULATION PERFORMED

The simulations were performed using the software FLACS-Hydrogen from GexCon (5). FLACS uses a rectilinear grid. In the case of jet simulations, a zone made of cubic cells is defined next to the leak origin. From that initial zone, the grid is stretched to a coarser rectangular grid away from the leak orifice. The cell size of the initial cubic zone is determined by the leak area. Thus the computational domain was set to be 60m long 60m wide and 20m high. A typical domain was discretized in 339,815 cells with a minimum cell size of 12.5mm and 10.7mm for the 150barg and 425barg release respectively. The maximum cell size was 1.5m at the domain boundary. For each test, depending on the direction of the wind, the domain boundaries were defined as either wind or nozzle. Grid sensitivity studies were performed and showed that the results varied by less than 5%.

For each scenario, the flow is choked at the jet exit. The jet outlet conditions, i.e. the leak rate, temperature, effective leak area, velocity and the turbulence parameters (turbulence intensity and turbulent length scale) for the flow, were calculated using an imbedded jet program in FLACS. FLACS also calculated the time dependent leak and turbulence parameter data for continuous jet releases during high-pressure vessel depressurisation. The estimation assumes isentropic flow conditions through the nozzle, followed by a single normal shock (whose properties are calculated using the Rankine-Hugoniot relations), which is subsequently followed by expansion into ambient air. FLACS uses the k-ε turbulent model and the ideal gas equation of state. FLACS was extensively validated against experimental data and reasonable agreement was seen for hydrogen dispersion simulations for various release conditions (6).

Fifteen unignited jets close to the ground and one jet close to the ceiling were modelled with FLACS using the flow and ambient conditions prevailing at the moment of each corresponding experiment. This resulted in a mass flow rate average of 7.62g/sec and 6.04g/s for the 150barg and 425barg releases respectively. These mass flow rates varied slightly based on the corresponding experiment starting pressure. The releases lasted for 20s for the 150barg storage pressure and 40s for the 425barg storage pressure.

Average wind velocity and average wind direction were used based on the conditions prevailing during each experiment. For test 7 and 8 an averaged wind direction of 120° and 205° with a wind speed of 1.6m/s and 2m/s were used respectively, as shown in Figure 5. A Pasquill class D (neutral) was used. The ground roughness was set at 5mm and a reference height of 1.22m was used. To quantify the effect of the wind on the results, free jet releases at 150barg and 425barg, as well as an attached jet release close to a ceiling at 425barg were modelled without wind.

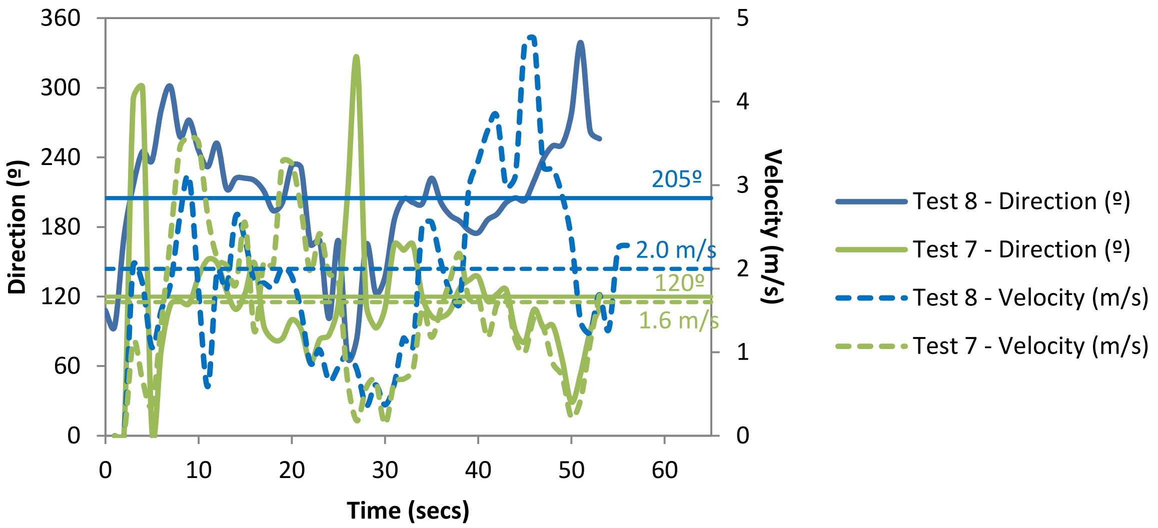


Figure 5: Wind direction and velocity prevailing during the experiments and their average for Test 7 and 8

4.0 RESULTS

4.1 Flow Rates and Pressure

The pressure decay curve for Test 1, Series 1 is shown below in Figure 6.

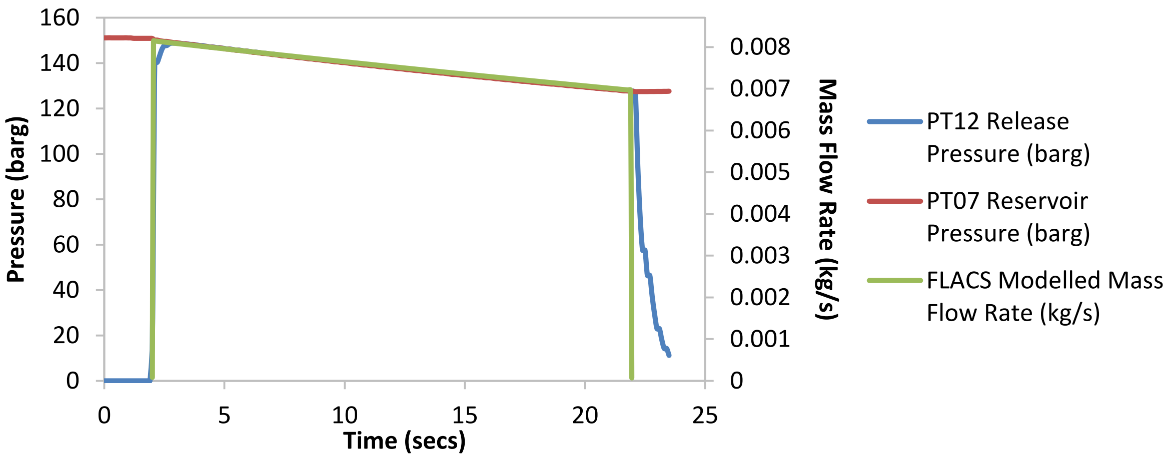


Figure 6: Rig Pressures Test 1, Series 1

Figure 6 shows that the reservoir pressure decreased from 151.2barg to 127.4barg during the 20s release through a 1.06mm nozzle. It includes the mass flow rate modelled with FLACS jet program for Test 1 of Series 1 with an average mass flow rate of 7.46g/sec. This equates to a pressure drop to 84% of the starting pressure. From this pressure data and knowing the reservoir temperatures, the average actual flow rate during the test can be calculated (7), equation 1:

$$Z(p,T) = \frac{p}{\rho RT} = 1 + \sum_{i=1}^{9} a_i \left(\frac{100K}{T}\right)^{b_i} \left(\frac{p}{1\,MPa}\right)^{c_i} \qquad [1]$$

where: Z – compressibility factor; p - pressure, kPa; ρ - density, mol/l; R - gas constant, J/mol.K; T - temperature, K;

The flow rate was, on average, 7.74gs^{-1}, which compares well to the predicted 7.3gs^{-1}. A high-pressure example is Test 10, Series 1, in which the pressure decreased from 425.4barg to 376.0barg during a 40s release through a 0.64mm orifice. This equates to a pressure drop to 88% of the starting pressure and calculates as an average flow rate of 6.05gs^{-1}, which compares well to the predicted 6.7gs^{-1}.

During the test programme the measured flow rates appeared to vary by ±10%. This may be due to slight blockages within the nozzle or expansion and contraction of the nozzle caused by the varying ambient temperatures, especially during the ignited releases.

Figure 7 shows releases with different reservoir pressures at the same release height of 0.48m from the ground with approximately the same overall flow rate. It is evident from the graph that both pressures follow the same trend, which is expected given the similar flow rates.

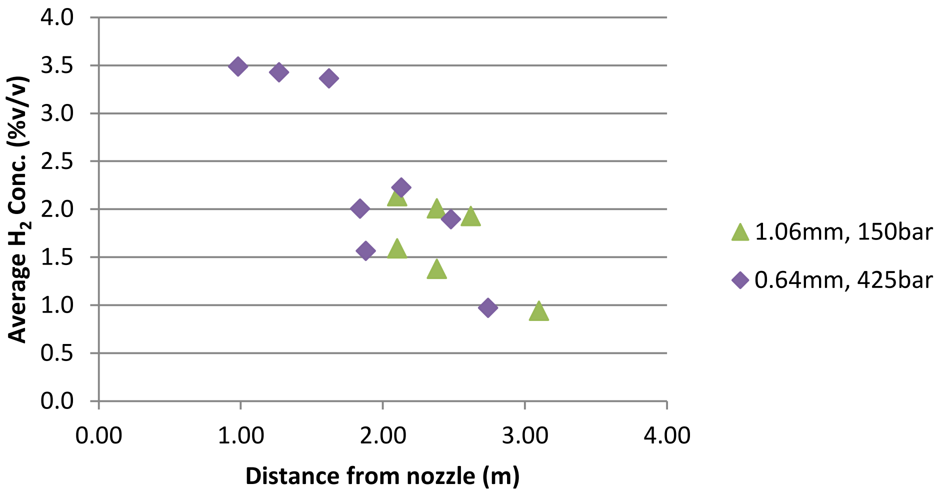


Figure 7: Average hydrogen conc. for 150barg (Tests 4-6) and 425barg (Tests 13-15) from Series 1

4.2 Hydrogen Concentration

Figure 8 shows the hydrogen concentration evolution during a typical release from Series 1. A 'steady-state' period is difficult to determine (especially in this case) so an average concentration is calculated based on the total release time for each test at a given sampling point. As expected, the trend is that the further from the release nozzle, the lower the hydrogen concentration as the sensors are at the same height. The variation in hydrogen concentration seen in Figure 8 is due to instability in the wind conditions during the test. Without wind instability the concentrations should plateau during the release, albeit, with a slight drop off due to source pressure decay.

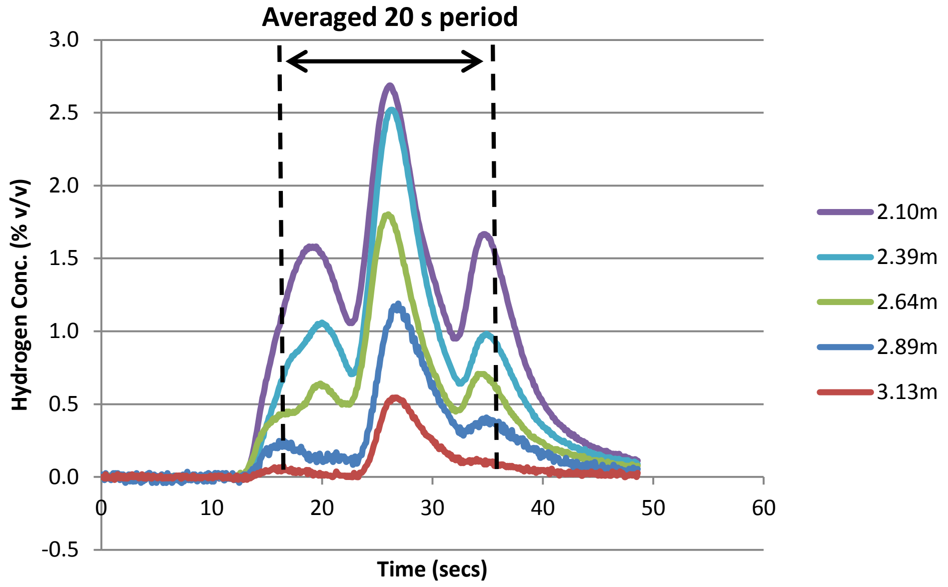


Figure 8: Hydrogen concentration Test 8, Series 1

Figure 9 shows a comparison between the effects of nominally identical releases close to the ground (0.05m) and at a free-jet height (1.22m). Some data has been omitted from this chart as it was performed with a different sampling orientation. The hydrogen concentrations shown in Figure 9 are an average taken during the release. Figure 9 shows there is a noticeable increase in hydrogen concentration at the same given distance from the nozzle between the ground releases and the free-jet releases.

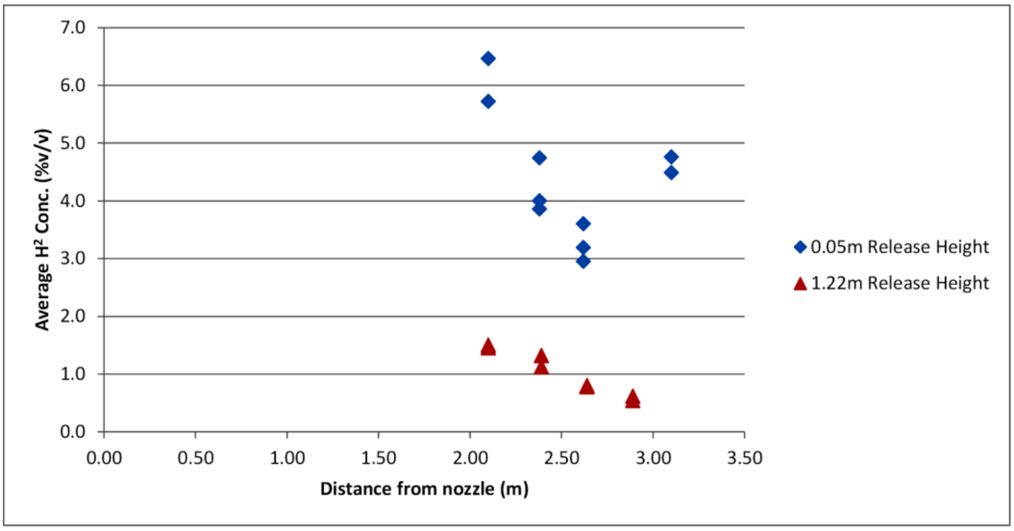


Figure 9: Average hydrogen conc. for free-jet (Tests 7-9) and ground release (Tests 1-3), Series 1

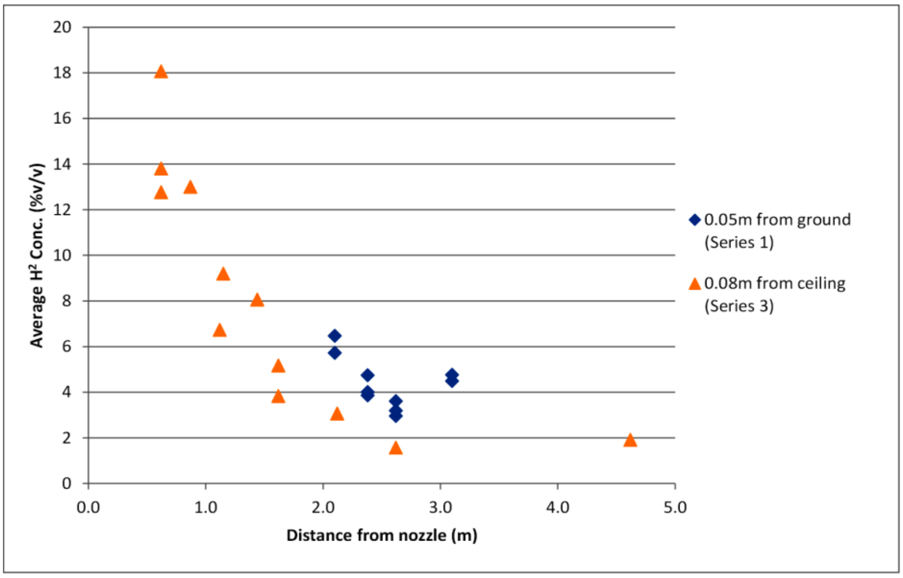


Figure 10: Average hydrogen conc. for 0.05m from ground (Tests 1-3) and 0.08m from ceiling (Tests 1-3), Series 1 and 3 respectively

Figure 10 displays the results from Tests 1-3 for both Test Series 1 and 3 at 150barg. The only significant difference is the proximity to the ground (0.05m for Series 1) and the proximity to the ceiling (0.08m for Series 3) and hence the effect buoyancy has on hydrogen concentration. It appears that proximity to the ground slightly increases the distance to LFL: 2.5m at the ground and 2m at the ceiling. This difference is minor and the plume seemed to behave similarly in its evolution and dispersion.

4.3 Simulation Comparison

The experiments were carried out in highly unstable windy conditions with time dependent directions and velocities, which cannot be set accurately in the CFD tool. The wind greatly affects the concentration profile of the jets (Figure 11). Compared to the experiments, the CFD simulations over-predict the extent of jets in most cases (Figure 12). This has implications for the use of CFD tools to predict the behavior of hydrogen releases close to surfaces in the presence of highly unstable wind conditions.

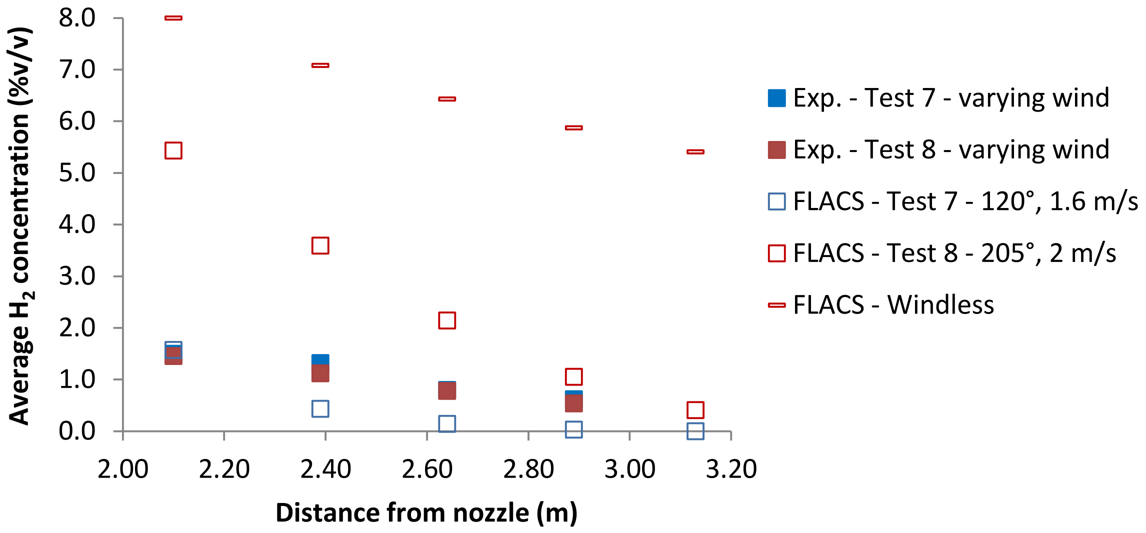


Figure 11: Average hydrogen concentration for Tests 7 and 8 and for corresponding free jet simulations without wind

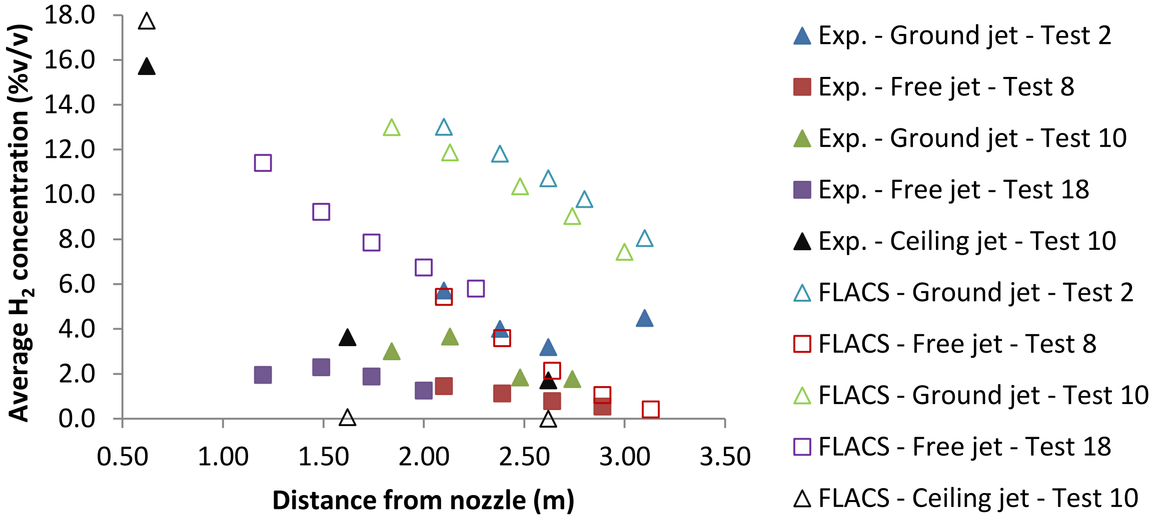


Figure 12: Average hydrogen concentration for free jets, ground releases and ceiling releases from Series 1 and 3

4.4 Radiative Heat Flux

The radiative heat flux for Test 1, Series 2 is shown in Figure 13. At 0m downstream of the nozzle and 2m from the jet, the radiative heat reaches ≈ 1.7kWm^{-2} and appears to reach a steady state immediately and remain at that level for the duration of the release (20s). The increased variation in the base level can be attributed to the propane pilot light. This reduces with increased distance downstream from the nozzle.

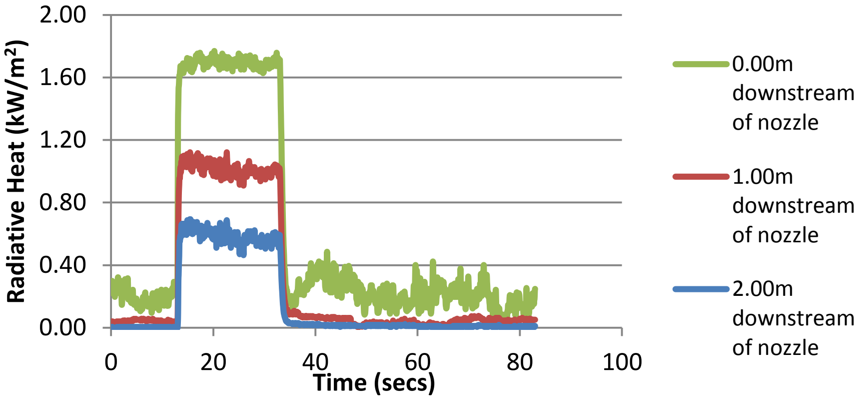


Figure 13: Radiative heat flux from Test 1, Series 2 at 2m from release

A 'no harm' criterion for jet-fires has been established at 1.6kWm^{-2} (8). This is the heat flux level at which no discomfort will be felt regardless of exposure time. Of the tests performed during Series 2 and 4, only Tests 1-3 recorded a maximum radiative heat flux greater than the 'no harm' level. The majority of test results fall below the criterion.

Figure 14 shows a comparison between the radiative heat flux taken from two tests with nominally the same release conditions varying only in distance from the ground. There is a clear distinction between the heat flux output with the ground release outputting ≈ 40% more radiative heat than the free-jet release. This increase may be attributed to an increase in particulate due to the jet proximity to a concrete surface, however, similar levels of heat flux gain were found during the equivalent ceiling surface release which is made from steel with no loose particulate.

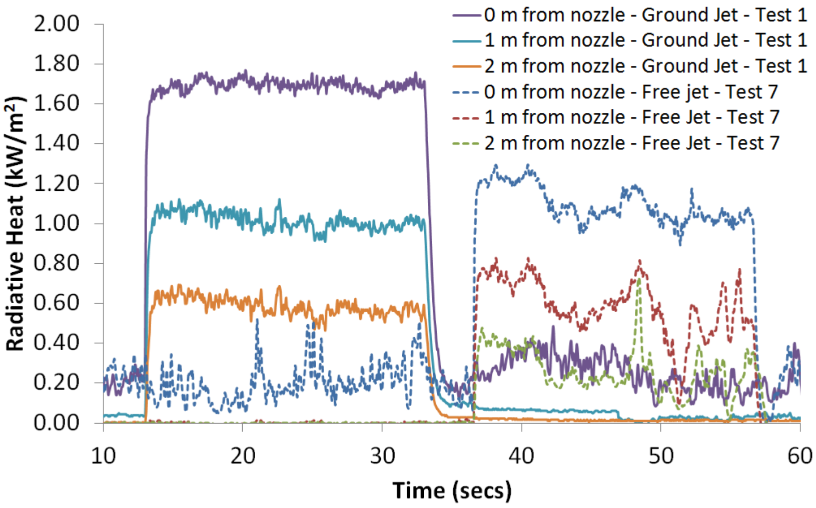
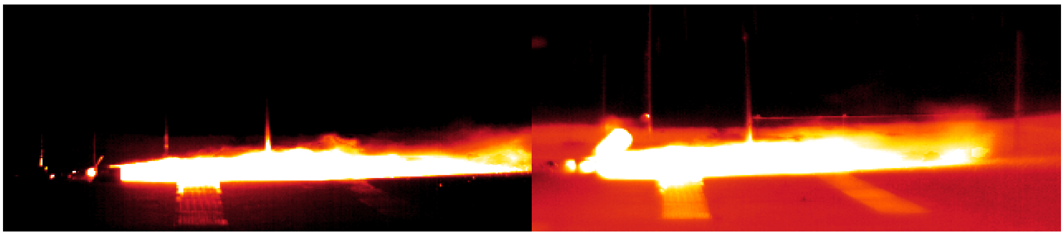


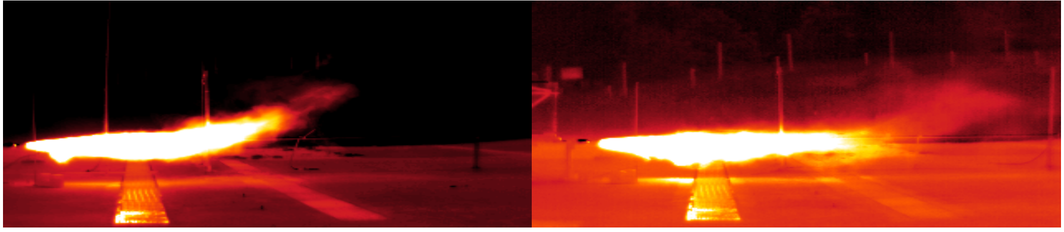
Figure 14: Experimental radiative heat flux downstream from nozzle for Test 1 and 7, Series 2, 2m from release

4.5 Thermal Imaging

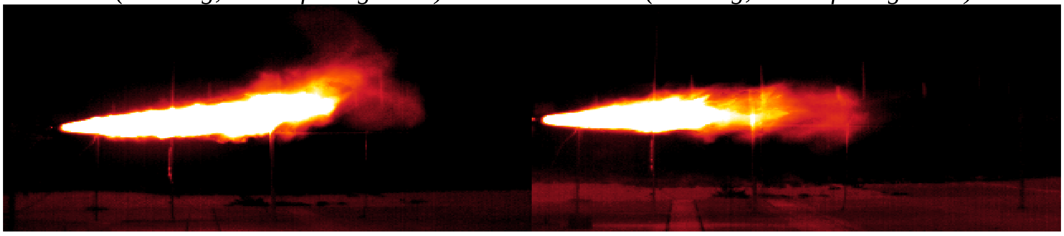
Thermal imaging was used for all of the ignited tests in Series 2 and 4. Still images of each test regime scaled to a maximum of 70ºC (shown as white hot in Figure 15: A-J). In each still, the temperature scale is maintained for comparative purposes and the camera's position is nominally the same.



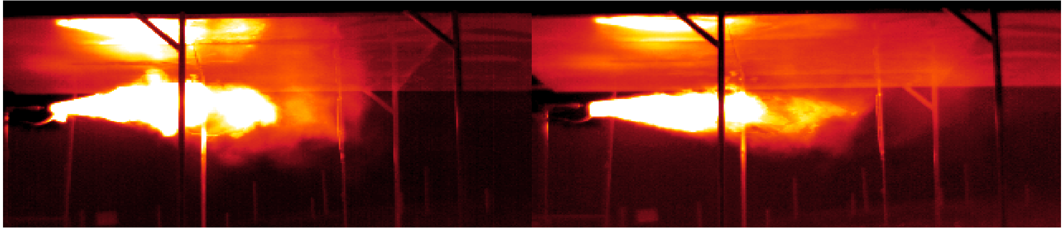
A (150barg, 0.05m from ground) *B (425barg, 0.05m from ground)*



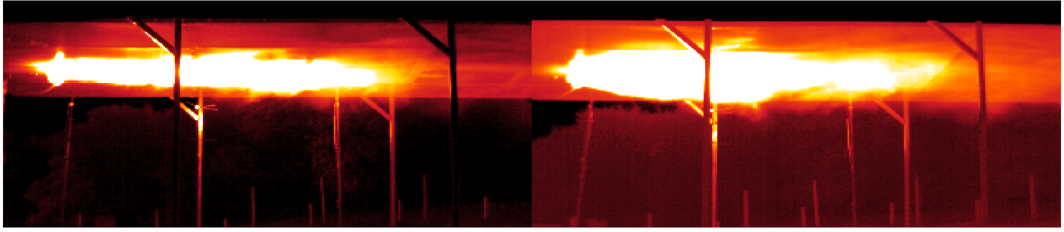
C (150barg, 0.48m from ground) *D (425barg, 0.48m from ground)*



E (150barg, 1.22m from ground) *F (425barg, 1.22m from ground)*



G (150barg, 0.49m from ceiling) *H (425barg, 0.49m from ceiling)*



I (150barg, 0.08m from ceiling) *J (425barg, 0.08m from ceiling)*

Figure 15: A-J: Infra-red (IR) images of the different test regimes

In order to investigate flame lengths a number of physical markers can be used. For the ground and free jet release images (Figure 15: A-F) the steel cable tray covers on the ground can be used. These are at distances of 1.65m and 2.85m downstream from the nozzle. For the ceiling release images (Figure 15: G-J) the ceiling stanchions can be used. These are at distances of 1.4m and 3.4m downstream from the nozzle. With this information, approximate flame distances (>70ºC) can be estimated (Table 2).

Table 2: Test regime estimated flame lengths

	Estimated flame length for >70ºC (m)	
Distance from surface (m)	**150barg release**	**425barg release**
0.05 (ground)	4.4	4.8
0.48 (ground)	2.8	2.9
1.22 (free-jet)	2.7	2.6
0.49 (ceiling)	2.2	2.4
0.08 (ceiling)	3.2	3.2

From Table 2 and Figure 15 it is clear there is little difference in the flame length to 70ºC for low pressure (150barg) and high-pressure (425barg) releases. However, it is evident in images of Figure 15: C-F that the lower pressure releases were more buoyant as the flame tip lifts compared with the momentum dominated high pressure releases.

Table 2 and Figure 15 also show that there was a slight reduction in flame length for the equivalent ceiling releases, compared with those close to the ground. This correlates well with the unignited data and Figure 10, which suggested that the distance to LFL and hence flame length was slightly reduced for ceiling releases compared with the equivalent ground releases. Further to this, the IR data reveals that the flammable distance to 70ºC was considerably further than the distance to LFL as measured in the unignited tests, e.g. Test 1-3, Series 1 = 2.5m compared to Test 1-3, Series 2 = 4.4m.

CONCLUSIONS

In total, 66 jet releases of high-pressure hydrogen were performed. Half of the tests were unignited releases and the other half ignited. The main outcomes are listed below:

- The expected mass flow rates from both flow conditions (150barg, 1.06mm nozzle & 425barg, 0.64mm nozzle) during testing were within 10% of calculated values
- The pressure drop during each test was on average 11% of the starting reservoir pressure
- As distance downstream from the nozzle increases, the hydrogen concentration decreases
- Distance to LFL increases the closer to a surface (0.05m – 0.5m) hydrogen is released, in comparison with a free jet release (1.22m). This is confirmed by CFD simulation and experimentation
- The distance to LFL appears to be the same for flow conditions (150barg, 1.06mm nozzle & 425barg, 0.64mm nozzle) with mass flow rates of 7.5 and 6.0g/s respectively. Therefore the distance to LFL for a higher pressure release (425barg) would be increased compared with the equivalent lower pressure release (150barg)
- The distance to LFL is slightly increased for an equivalent release close to the ground compared with close to a ceiling. This means buoyancy is reducing the distance to LFL and decreasing the overall flame length
- A maximum radiative heat flux was measured as 1.8kWm^{-2} at a distance of 2m; this is barely enough to cause any pain as the threshold for “no-harm” is 1.6kWm^{-2}. Therefore a sonic release of hydrogen at ≤7.7g/s between 150 and 425barg is unlikely to cause harm from heat effects outside of the jet itself regardless of exposure time

- The longest flame length seen was from a release 0.05m from the ground at 425barg at a distance of 4.8m, which is twice the length of the equivalent free jet release
- The CFD simulations over-predict the extent of jets in most cases. This is likely to be due, in part, to the highly unstable ambient conditions encountered during the experiments, which could not be reproduced in the CFD tool. This has implications for the use of CFD tools to predict the behavior of hydrogen releases close to surfaces in the presence of unstable wind conditions

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