CHARACTERISATION OF THE HAZARDS FROM JET RELEASES OF HYDROGEN

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ABSTRACT

Hydrogen is a convenient energy storage medium; it can be produced from fossil fuels and biomass via chemical conversion processes, or from intermittent renewable sources, like wind and solar, via electrolysis. It is the fuel of choice for the clean fuel-cell vehicles of the future. If the general public are to use hydrogen as a vehicle fuel, customers must be able to handle hydrogen with the same degree of confidence, and with comparable risk, as conventional liquid and gaseous fuels. For the safe design of retail facilities, through the development of appropriate codes and standards, it is essential to understand all the hazards that could arise following an accidental release of hydrogen. If it is to be stored and used as a high-pressure gas, the hazards associated with jet releases from accidental leaks must be considered. This paper describes work by Shell and the Health and Safety Laboratory to characterise the hazards from jet releases of hydrogen. Jet release experiments have been carried out using small leaks (circular holes ranging from 1 mm to 12 mm diameter) at system pressures up to 150 barg. Concentration measurements were made in the unignited free jets to determine the extent of the flammable cloud generated. Ignited jets were observed both in the visible and infrared to determine the flame size and shape. The experimental results for the extent of the flammable cloud and jet flame length were found to be in good agreement with model predictions.

1.0 INTRODUCTION

There is currently widespread interest in hydrogen and the role it may play in the future. Hydrogen is a convenient energy storage medium; it can be produced from fossil fuels and biomass via chemical conversion processes, or from intermittent renewable sources, like wind and solar, via electrolysis. It is the fuel of choice for the clean fuel-cell vehicles of the future.

If the general public are to use hydrogen as a vehicle fuel, customers must be able to handle hydrogen with the same degree of confidence, and with comparable risk, as conventional liquid and gaseous fuels. For the safe design of retail facilities, through the development of appropriate codes and standards, it is essential to understand all the hazards that could arise following an accidental release of hydrogen. It has been argued that hydrogen's wide limits of flammability, low ignition energy, very high burning velocity, and susceptibility to detonate present more of a safety challenge than conventional fuels [1]; it certainly behaves differently from conventional hydrocarbon fuels in several respects and a good quantitative understanding is required to ensure that it is handled safely [2].

If hydrogen is to be stored and used as a high-pressure gas to refuel vehicles, the hazards associated with jet releases from accidental leaks must be considered. A jet release in the open will result in a flammable cloud, and if this finds a source of ignition the result will be a cloud fire that burns back leaving a jet fire burning from the leak until the supply is controlled or exhausted. Knowledge of the extent of the flammable cloud, and that of the jet fire if it becomes ignited, is an essential part of managing the potential hazard and quantifying the risk posed. In this paper we concentrate on the consequences of a leak and do not consider the likelihood of it occurring, beyond noting that accidental leak frequencies will be very low in a well-engineered system.

This paper describes work by Shell and the Health & Safety Laboratory (HSL) to characterise the hazards from jet releases of hydrogen. Concentration measurements were made in the unignited free jets to determine the extent of the flammable cloud generated. Ignited jets were observed both in the visible and infrared to determine the flame size and shape. The results were compared with predictions from models developed and validated for jet releases of hydrocarbons.

Section 2 describes the test facilities set up at HSL to characterise jet releases at system pressures up to 150 barg. Section 3 describes the release modes used, and Section 4 the measurements made. In Sections 5 and 6 we present a selection of results from the unignited releases, and the ignited releases, respectively. In Section 7 we compare the results with model predictions. Section 8 gives our conclusions and describes further work.

2.0 TEST FACILITIES

Two discharge systems were used: one designed for low-pressure releases and the other for high-pressure releases. The low-pressure system was designed to provide a flow of up to 9 kg/min of hydrogen at 25 barg and to have a maximum working pressure of 50 barg. Two discharge orifice diameters (6 mm and 12 mm) and three nominal discharge pressures (5 barg, 15 barg and 25 barg) were chosen to study a range of jet momentum. This system could maintain an exit pressure of 25 barg for approximately two minutes with the 172 barg supply system used (four multi-cylinder packs of 17 cylinders). The high-pressure system was designed to have a maximum working pressure of 150 barg. Discharge orifices of varying diameters (1, 3, 4, 6, and 12 mm) and various nominal, discharge pressures (between 10 and 150 barg) were chosen to study a range of momentum jet releases. With the supply system used (eight multi-cylinder packs), the maximum discharge pressure could only be maintained for a few seconds with the largest orifice before the pressure began to drop. All the releases were aimed horizontally, 1.5 m above the test pad.

3.0 RELEASE MODES

There were two modes in which the hydrogen could be released and the experiments performed:

(1) Hydrogen was released and ignited from an ignition source located close to the release nozzle. These releases resulted in hydrogen jet flames.

(2) Removing the ignition source at the release point produced unignited releases. These releases produced hydrogen gas clouds.

A PC-controlled induction coil spark unit, located at a pre-determined ignition location, provided ignition for the jet flames.

4.0 EXPERIMENTAL MEASUREMENTS

4.1 Release conditions

The pressure and temperature of hydrogen in the release pipe, close to the release nozzle, were recorded during each trial. The pressure was measured either side of the release valve, whereas the gas temperature was only recorded downstream of the release valve, close to the release orifice. The air temperature, relative humidity, wind speed and direction were measured at the release point using a hand held weather station, and compass. The weather measuring equipment used was a Wessels, Type DA 40 H, Digital Hygro/Thermo Anemometer (TE031). The weather conditions were recorded just prior to each trial. Wind direction and wind speed measurements were recorded for tests in which gas concentration measurements were made. For the medium-pressure releases, the wind speed and direction were measured at 1.5 m above the ground using a Vector Instruments weather station fixed to the release pipe, 12.5 m from the release orifice.

4.2 Concentration measurements

The concentration of hydrogen in the unignited plume was derived from measurements of the oxygen concentration within the cloud. It was assumed that any decrease in the concentration of oxygen was caused by displacement of oxygen by hydrogen gas. The concentration of oxygen in the vapour cloud was measured using "AO2 Oxygen CiTicel" sensors. These are self-powered, electrochemical oxygen sensors capable of measuring oxygen concentrations in the range 0-100 volume percentage (vol. %). The sensors are of a self-powered, metal-air battery type, comprising an anode, electrolyte and an air cathode. The CiTicel oxygen depletion sensors were calibrated against a calibrated oxygen gas analyser (Servomex Oxygen analyser 570A). The results showed that the following relationship holds:

$$\text{Concentration of oxygen} = (V_m / V_0) \times 20.9\ \% \qquad (1)$$

where V_0 is the sensor output in air, V_m is the sensor voltage in a reduced-oxygen atmosphere. If oxygen is displaced by hydrogen, the concentration is given by:

$$\text{Concentration of hydrogen} = 100\% \times (V_0 - V_m) / V_0 \qquad (2)$$

The CiTicel AO2 sensors produce an output voltage of 0 – 62 mV (9-13 mV in air) depending on the concentration of oxygen. This is relatively small, so amplifiers were used to increase the signal before it was logged.

Twenty CiTicel AO2 Oxygen sensors were used in each of unignited release trials. The sensors were located at heights of 1.0, 1.5 or 2.0 m above the ground, depending on their position downstream, relative to the release nozzle. The sensors were orientated so that the opening on the sensors was perpendicular to the direction of gas flow, i.e. across the flow of gas. The sensors were not exposed to a hydrogen jet fire, so no precautions to protect against heat were adopted.

Figs. 1(a) and 1(b) show one of the arrays of CiTicel sensors used to measure the concentration of hydrogen from low-pressure releases at different positions in the gas cloud and Figs. 2(a) and 2(b) show one of the arrays for the high-pressure releases.

Figure 1(a). Oxygen depletion sensors for low pressure releases (behind release nozzle)

Figure 1(b). Oxygen depletion sensors for low pressure releases (towards the release nozzle)

Figure 2(a). Oxygen depletion sensors for high pressure releases (behind release nozzle)

Figure 2(b). Oxygen depletion sensors for high pressure releases (towards release nozzle)

4.3 Visual and thermal imaging

Video cameras were used to monitor and record the trials. An FLR Systems SC2000 thermal imaging system, operating in the range of wavelength 7–13 μm, was used to produce a thermal image of each of the ignited releases. This camera was positioned to view the resulting jet fire from one side. The camera measured the thermal emissions and the blackbody temperatures using the Stefan-Boltzman law.

4.4 Data logging

The data recorded were logged on a Dell Pentium, OptiPlex GX1P PC. The computer was fitted with three Data Translation, DT3000 series, data logging cards, each capable of recording 32 channels of data. During the trials, the computer was programmed to record data at a frequency of 10 Hz.

5.0 RESULTS FROM UNIGNITED RELEASES

More than 60 unignited release experiments were performed with orifice sizes ranging from 1 to 12 mm and release pressures from 5 to 150 barg. Typical data for a 25 barg release with a 12 mm orifice, and a 135 barg release with a 3 mm orifice, are illustrated in Figs. 3 and 4 respectively.

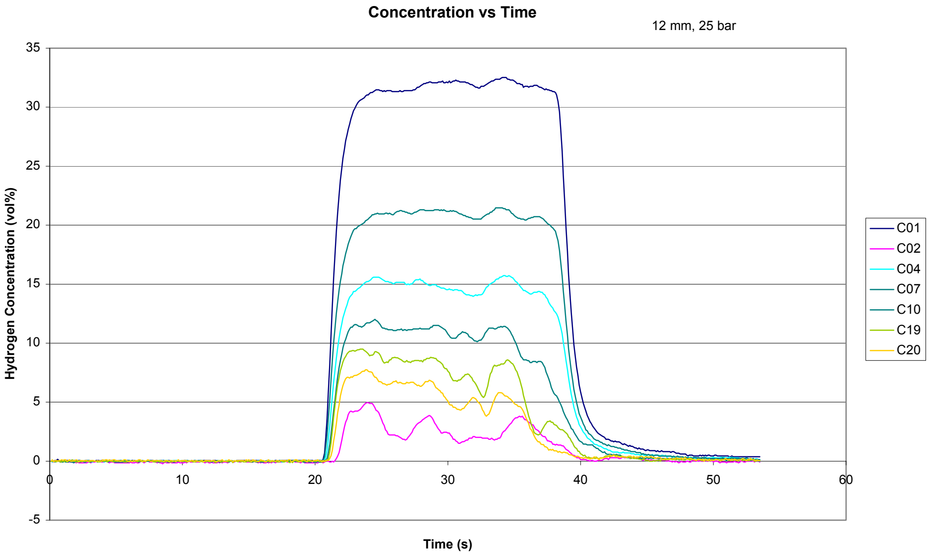

Figure 3. 25 barg release from a 12 mm orifice. Hydrogen concentrations measured at positions: 1.8, 2.7, 3.8, 4.8, 5.9, 6.8 and 9.0 m downstream from the release point.

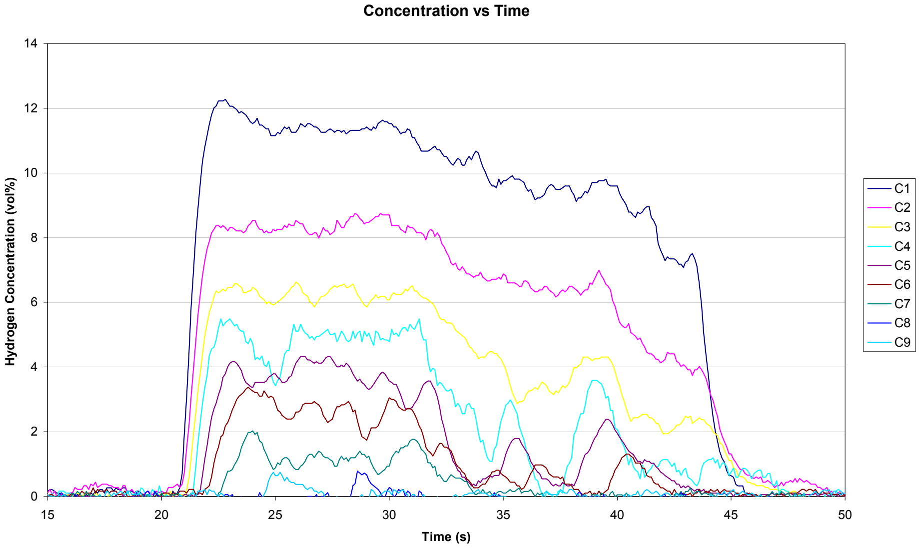

Figure 4. 135 barg release from a 3 mm orifice. Hydrogen concentrations measured at positions: 3, 4, 5, 6, 7, 8, 9, 10 and 11 m downstream from the release point.

It is significant that none of the more than 60 jet releases spontaneously ignited. Hydrogen has a reputation for igniting for no apparent reason but clearly not all high-pressure hydrogen releases ignite. Mechanisms for the spontaneous ignition of hydrogen leaks have been postulated and these have recently been reviewed [3].

6.0 RESULTS FROM IGNITED RELEASES

Figs. 5(a) to 5(d) show images of flames produced for releases through orifices of 6 mm and 3 mm diameter, as viewed with a thermal imaging camera and a digital video camera. The left-hand column shows images produced on the thermal imaging camera and the right-hand column shows the same image as seen on the digital optical camera. In the case of the thermal images, temperature scales are produced assuming an emissivity of 1.0 for the flame. Fig. 6 shows distances, measured from the release point, along the centre-line of the jet release. These scales are the same as those in Figs. 5(a) to 5(d). The FLR Systems SC2000 thermal imaging camera provided a good view of the hydrogen flames, showing the flame structure in some detail.

Image from thermal camera **Image from optical camera**

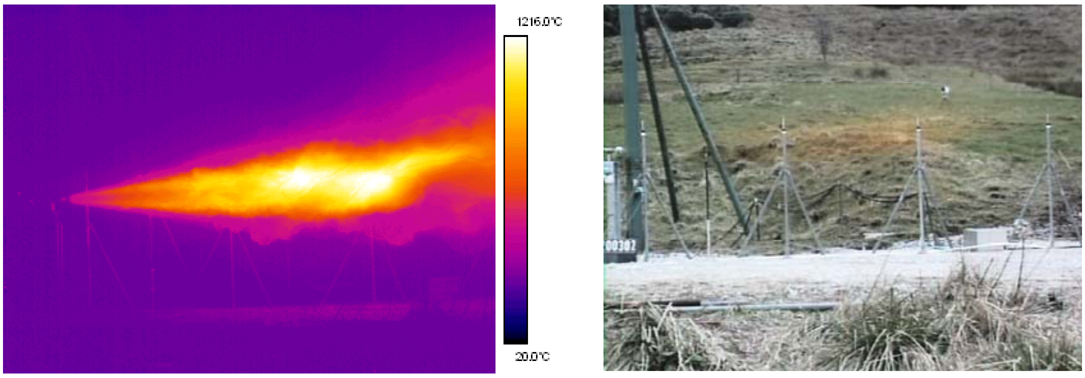

Figure 5(a). Diameter 6 mm; Pressure 70 barg

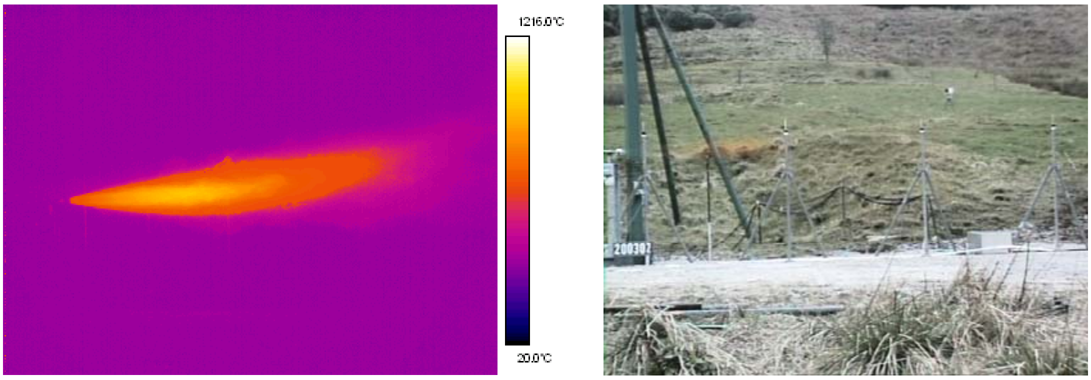

Figure 5(b). Diameter 3 mm; Pressure 50 barg

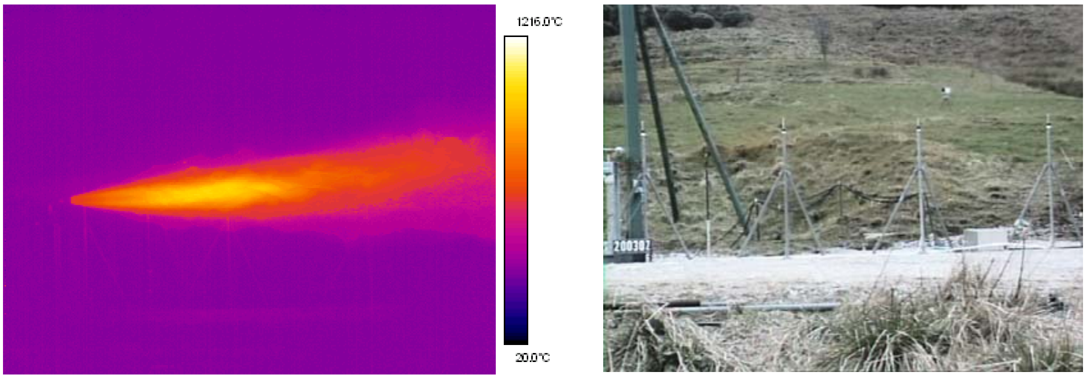

Figure 5(c). Diameter 3 mm; Pressure 100 barg

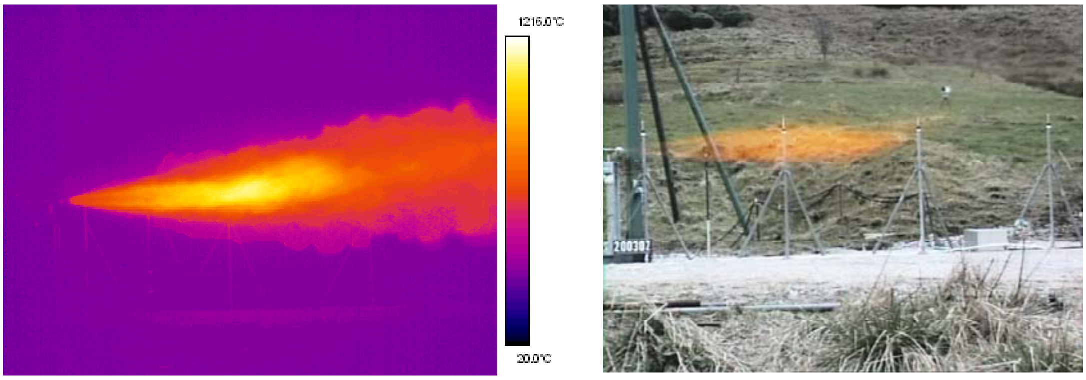

Figure 5(d). Diameter 3 mm; Pressure 130 barg

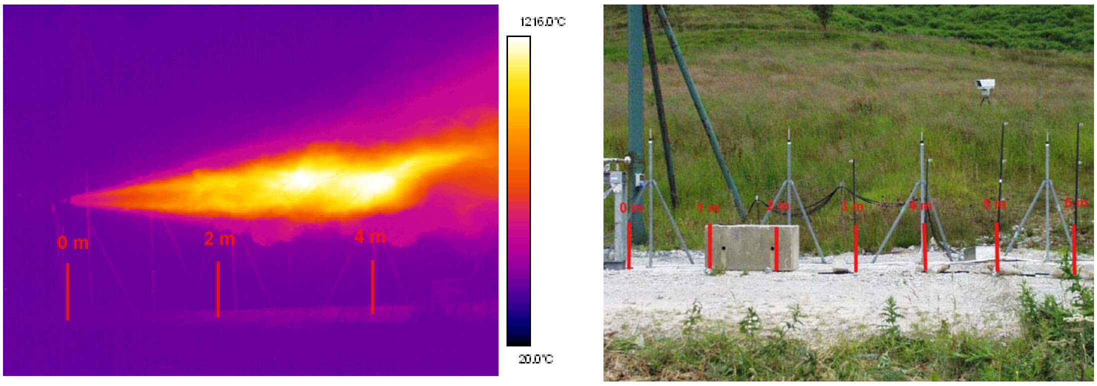

Figure 6. Images showing distance along centre-line of jet

Figs. 7(a) and 7(b) illustrate the difference in visibility of a hydrogen jet flame in daylight and at dusk, respectively. Both figures show an ignited jet release from an orifice of 12 mm and at a pressure of 25 barg.

Figure 7(a).

Figure 7(b).

The energy radiated by hydrogen flames is predominantly from hot water vapour emission in the infrared, and hence invisible to the eye. In sunlight, the flames from burning hydrogen are only visible by the heat haze formed. The energy radiated is much less than from luminous hydrocarbon flames and thus people or objects are less likely to get burned unless they are actually hit by a hydrogen jet flame.

The optical camera images in Figs. 5(a) to (d), and 7(a), show that in daylight the hydrogen jet flames are barely visible, with only a slight orange glow sometimes discernable. In the dark an orange coloured flame is clearly visible, Fig. 7(b). This colour is due to naturally occurring particulate matter in the air being entrained into the flame. The particulate matter contains sodium and results in spectral line emission at 589.59 nm and 588.99 nm in the orange part of the spectrum. This has been unequivocally demonstrated by spectral analysis of hydrogen jet flames [4].

7.0 MODEL PREDICTIONS

Concentration predictions were made using the HGSYSTEM [5] jet dispersion model AEROPLUME with a postprocessor developed for the Shell FRED models. For comparison with the experimental data the post-processor function needed to predict concentrations along a line at constant height from the ground. As this is not accessible directly from FRED the data processing was performed using standalone models, however, the models are otherwise the same as those in Shell's hazard consequence modelling package Shell FRED 4.0 [6]. The jet flame model in Shell FRED 4.0 was used to predict the jet flame lengths for the ignited releases. All of the models used were developed specifically for hydrocarbon fuels and have been validated for a wide range of hydrocarbons but not hydrogen.

7.1 Dispersion of unignited releases

The unignited release time-series data were averaged to provide values for model comparison. As can be seen from Figs. 3 and 4, the sensed concentration can vary during the release and the variability increases with distance from the source. Clearly an average over the whole time-series is inappropriate as it is biased to lower values. We decided to construct a 5 s moving average through the data and to chose the window having the largest average concentration as indicative of the "instantaneous" concentration relevant to flammability assessment.

Individual runs give few data points and so we have chosen to group similar releases together to assess the overall consistency with model predictions. There is variability between runs at otherwise similar release conditions and it is important to recognise this. A barrier to more precise comparisons is that the jets did not always follow the line of the sensors. Fig. 8 shows four nominally similar tests that deviate by up to 0.5 m in their centreline position at 3.8 m downwind from the source.

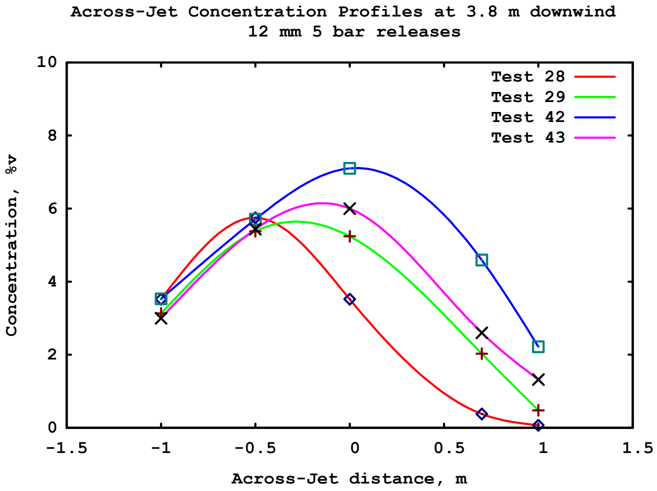

Figure 8. Across-jet profiles of concentration showing that the jets were not always aligned with the sensor axis.

This across-jet information was obtained at most for one downwind location and in some tests lateral measurements were made at only one side of the array so it is not possible to "correct" for centreline position with any certainty. We therefore accept that there are confounding processes and restrict the comparison to a generic on-axis prediction. All releases were carried out at low wind speed and a value of 2 m/s was used for the model. Fig. 9 shows results for runs (including those in Fig. 3) that were nominally 25 barg releases against a prediction for 25 barg. The nozzle size was 12 mm.

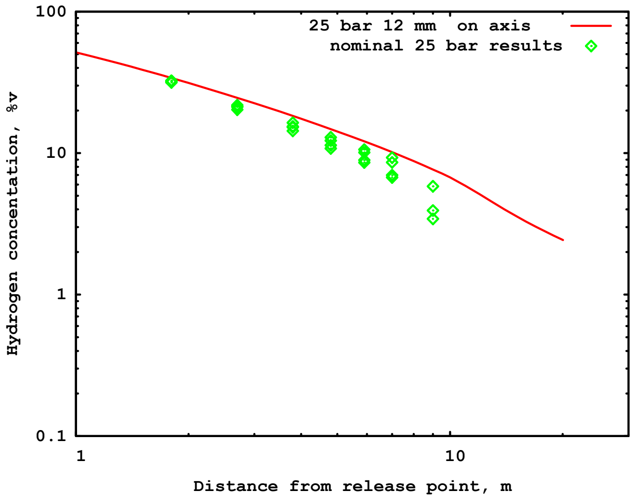

Figure 9. Comparison between predicted on-axis hydrogen concentration and measurements for nominally 25 barg releases.

The model provides a very good upper bound to the data. Buoyancy effects begin to affect the jet beyond 10 m and the slight inflection in slope is where the trajectory begins to curve upward. Model calculations to assess the effect of an offset of 0.5 m for the jet axis show that the effect is very significant at distances less than 8 m. The measurements at the furthermost location (9 m) appear to be falling off faster than the predictions. It is not clear if this is a real effect or an artefact of the averaging procedure or measurement technique given the increasing variation in the time-series at that distance. Using the overall highest measured concentration reduces the effect.

7.2 Jet flame lengths

The predicted jet flame lengths for the tests shown in Figs. 5(a) to 5(d) are given in Table 1.

Table 1. Model predictions.

Orifice diameter (mm)	Release pressure (barg)	Mass flow rate (kg/s)	Length of visible flame (m)	Flame lift-off (m)	Total flame length (m)
6	70	0.1	5.9	1.2	7.1
3	50	0.018	3.0	0.6	3.6
3	100	0.035	3.9	0.8	4.7
3	130	0.045	4.3	0.9	5.2

The predictions of total flame length can be compared with the images shown in Figs. 5(a) to 5(d) and using the distance markers shown in Fig. 6. It can be seen that the predicted total flame lengths are greater than the horizontal extent of the hottest part of the flame from the thermal images. The FRED jet flame model predicts the length of the visible (luminous) part, characteristic of hydrocarbon flames, and the lift-off distance between the release orifice and start of the visible flame. The total flame length predicted by FRED provides a conservative estimate of the extent of a hydrogen jet flame from a high-pressure leak.

8.0 CONCLUSIONS AND FURTHER WORK

The work described has resulted in a better understanding of the hazards posed by accidental releases of hydrogen from pressurised systems. The results can be used to validate hazard consequence models that are an essential part of hazard and risk assessments.

Prediction of dispersion using models developed for hydrocarbons showed good agreement with data. Similarly, the predicted total flame length provides a conservative estimate of the extent of a hydrogen jet flame from a high-pressure leak. This increases confidence that existing tools can be used for hydrogen assessments without modification.

Hydrogen jet fires are distinctly different from those produced by hydrocarbon fuels. Without soot formation that produces the luminosity in hydrocarbon flames, the energy radiated is much less, and is predominantly from hot water vapour emission in the infrared, and hence invisible to the eye.

Hydrogen flames can therefore be difficult to see in daylight, but people or objects are also less likely to get burned unless they are actually hit by the jet flame.

It is recognised that in practice much higher pressures may be used: 700 barg for passenger cars, to store sufficient hydrogen for an acceptable range. However, we have no reason to believe that soundly based models, validated for lower pressures, cannot be used to predict the extent of the flammable cloud, or jet flame length, at much higher pressures. Such predictions are an important element in developing soundly based set-back distances for hydrogen facilities.

In this paper we have considered the safe dispersion of hydrogen from a pressurised leak in an open environment, and the resultant jet fire if the leak is ignited. Delayed ignition of a jet release into a confined or congested environment can create an explosion hazard, this scenario is being studied in ongoing work, sponsored by a consortium lead by Shell Hydrogen.

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