EXPERIMENTAL STUDY ON HYDROGEN EXPLOSIONS IN A FULL-SCALE HYDROGEN FILLING STATION MODEL

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ABSTRACT

In order for fuel cell vehicles to develop a widespread role in society, it is essential that hydrogen refueling stations become established. For this to happen, there is a need to demonstrate the safety of the refueling stations. The work described in this paper was carried out to provide experimental information on hydrogen outflow, dispersion and explosion behaviour. In the first phase, homogeneous hydrogen-air-mixtures of a known concentration were introduced into an explosion chamber and the resulting flame speed and overpressures were measured. Hydrogen concentration was the dominant factor influencing the flame speed and overpressure. Secondly, high-pressure hydrogen releases were initiated in a storage room to study the accumulation of hydrogen. For a steady release with a constant driving pressure, the hydrogen concentration varied as the inlet airflow changed, depending on the ventilation area of the room, the external wind conditions and also the buoyancy induced flows generated by the accumulating hydrogen. Having obtained this basic data, the realistic dispersion and explosion experiments were executed at full-scale in the hydrogen station model. High-pressure hydrogen was released from 0.8-8.0mm nozzle at the dispenser position and inside the storage room in the full-scale model of the refueling station. Also the hydrogen releases were ignited to study the overpressures that can be generated by such releases. The results showed that overpressures that were generated following releases at the dispenser location had a clear correlation with the time of ignition, distance from ignition point.

INTRODUCTION

In order for the 'hydrogen economy' to become a reality, not only is their a requirement to develop the fuel cell technology and associated equipment and infrastructure in an economic manner, but also it is necessary to demonstrate that all aspects of the supply and use of hydrogen can be performed safely. Osaka Gas Co., Ltd. has been operating a hydrogen refuelling station [1] safely as a demonstration plant, in parallel with developing a compact hydrogen reformer [2], (see Figure 1). However, in 2003, Osaka Gas joined the Japanese National Project on Hydrogen, with the aim of carrying out further work to investigate the safety aspects of hydrogen refuelling stations. One of the particular aims of this work was to help establish a suitable 'safety zone' around such a station.

Figure 1: Osaka Gas's hydrogen station (left) and hydrogen production unit, HYSERVE (right)

The way in which an accidental release of hydrogen would behave will be strongly affected by the layout and size of any hydrogen refuelling station. As a result, a realistic scale model of a refuelling station was built for the purposes of these studies. In this way, the dispersion tests and explosion tests that were carried out reproduced realistic conditions should such accident possibly happen. All of the experiments were planned by Osaka Gas working together with Advantica Ltd. and were conducted by Advantica at their Spadeadam test site.

As experimental data were already available demonstrating the behaviour of hydrogen dispersion and explosion in an unobstructed environment, the main thrust of this work was to obtain a range of data to illustrate hydrogen behaviour in confined and/or congested regions. The factors studied and the outcome from the experiments are summarised in diagrammatic form in Figure 2.

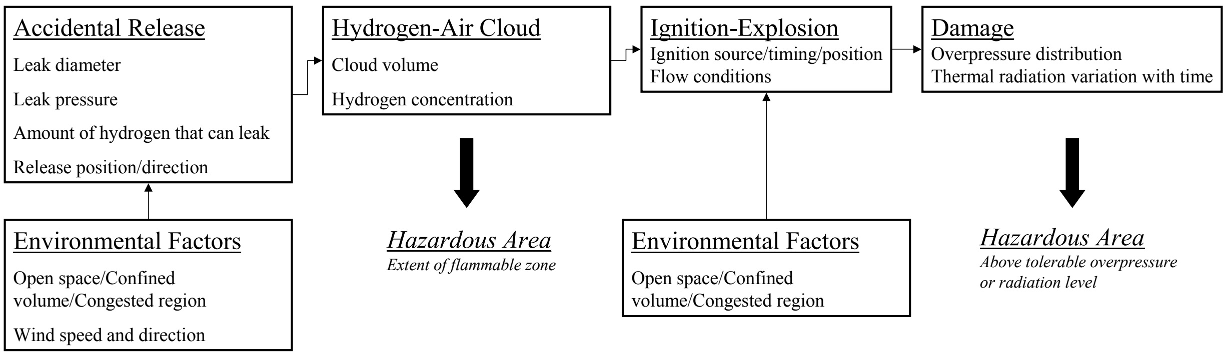


Figure 2: Aspects studied in the experiments

EXPERIMENTAL PROGRAMME

The experimental programme that was followed is shown in Figure 3.

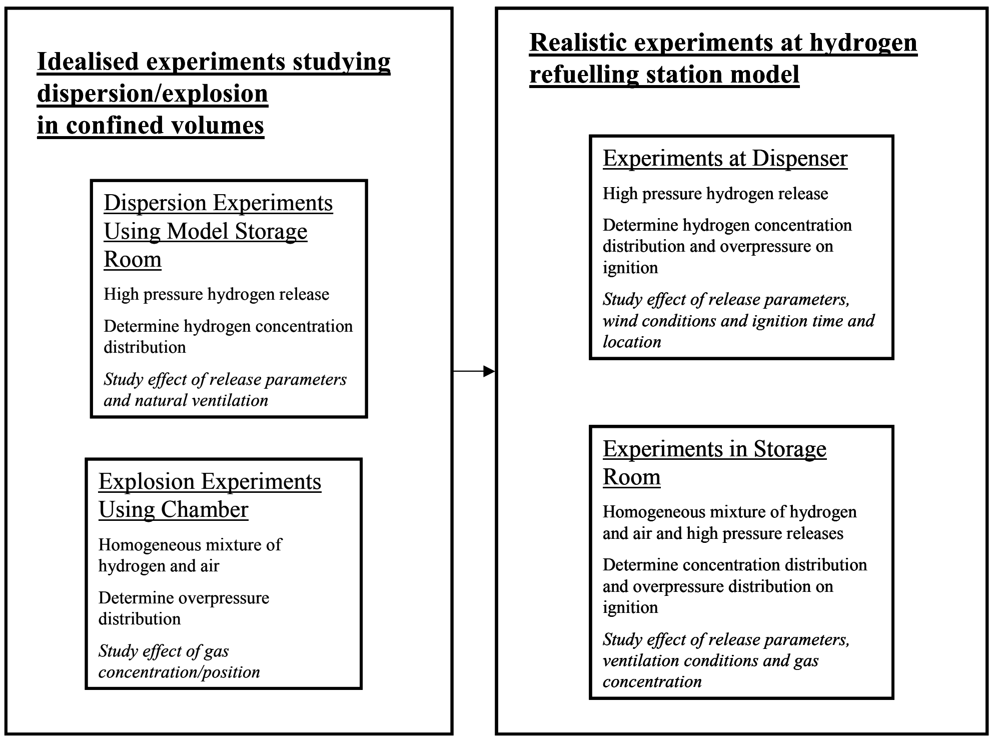


Figure 3: Outline of experimental progamme

First of all, dispersion and explosions experiments were carried out to acquire the basic data for hydrogen behaviour in confined region. Then, a realistic scale model of a hydrogen refuelling station was constructed and experiments using high-pressure hydrogen were executed in the dispenser area and in the storage room. The results that were obtained are outlined in the sections below.

DISPERSION AND EXPLOSION EXPERIMENTS IN A MODEL STORAGE ROOM

Dispersion experiments

A realistic scale model of a storage room was fabricated to study the distribution of hydrogen concentration produced within the room by a hydrogen leak. The hydrogen was released at high pressure through one of two different size of nozzle. The hydrogen volume concentration distribution was monitored using 30 oxygen sensors, located inside the room. In reality, a storage room would be equipped with either mechanical ventilation or natural ventilation. Natural ventilation was used in this experimental programme. A picture of the room is shown in Figure 4, along with a schematic demonstrating the different ventilation conditions that were studied. The roof was always fully closed, but natural ventilation openings were located along the top 1m of either two or all four of the sidewalls. These ventilation openings had an effective open area of 50%.

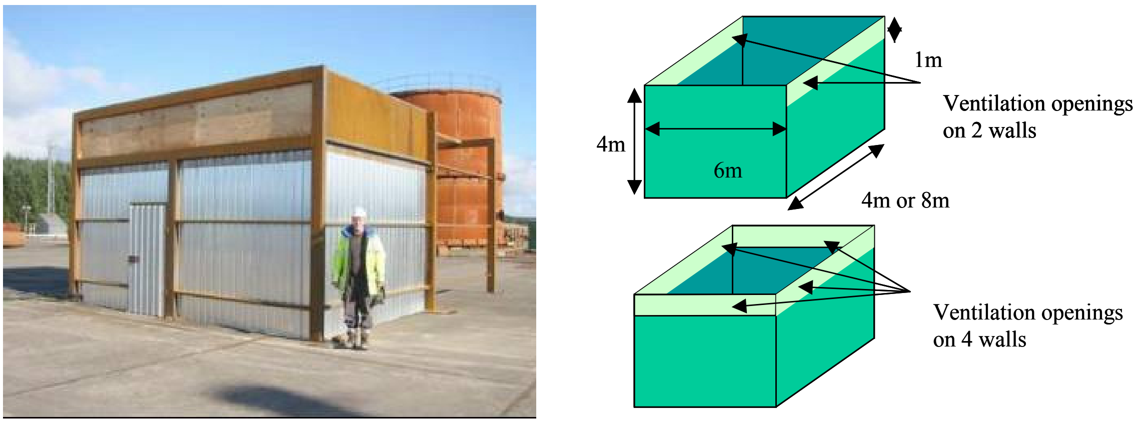


Figure 4: Structure of storage room

Table 1 lists the conditions studied in the experiments. In this series, the release pressure was maintained at a constant value of 10Mpa, with nozzle diameters of 0.8mm or 1.6mm being used to study hydrogen gas build-up from representative 'pinhole' leakages.

Table 1: Conditions used for the first series of dispersion experiments

Release Parameters	Gas	Hydrogen
	Pressure	10 MPa
	Diameter	0.8mm or 1.6mm
	Direction	Horizontal Vertically upwards or downwards
	Location	Corner, Adjacent to sidewall Centre of enclosure
Enclosure	Dimensions	Height 4m Depth 4m Width 8m or 4m
	Size of Ventilation Opening (50% open)	Height 1m Present on 2 sidewalls or all 4 sidewalls

It was found that an approximate steady-state was recorded at each sensor within about 3 minutes of the start of the release. The average hydrogen concentration in the room was determined in this steady-state from the individual sensor readings and the resulting values are shown in Table 2. The hydrogen mass flow rate changed linearly with the nozzle area, because the flow speed is choked for both size of nozzle diameters. It was found that the combination of the buoyancy-induced and wind-driven ventilation was sufficient to keep the average concentration of hydrogen in the room to below 17%, even in the cases when the ventilation was present only on tow walls, as in Experiment 1.

Table 2: Results of the first series of dispersion experiments

Experiment number	Nozzle diameter, mm	Hydrogen flow rate, m^3/h	Room width, m	Effective open area for ventilation, m^2	Wind speed, m/s	Average hydrogen concentration in enclosure, %
1	1.6	600	4	4	1.5	16.8
2	1.6	600	4	10	5.0	5.0
3	0.8	150	4	4	4.9	5.1
4	1.6	600	8	8	3.7	3.7
5	1.6	600	8	14	4.2	3.3
6	0.8	150	8	8	4.3	4.3

Explosion experiments

A test chamber was used to study the overpressure distribution produced by hydrogen explosions, such as might occur under unfavourable circumstances following the ignition of a hydrogen-air mixture that had accumulated in a storage room following a leak. A picture of the chamber and a schematic showing the layout is given in Figure 5.

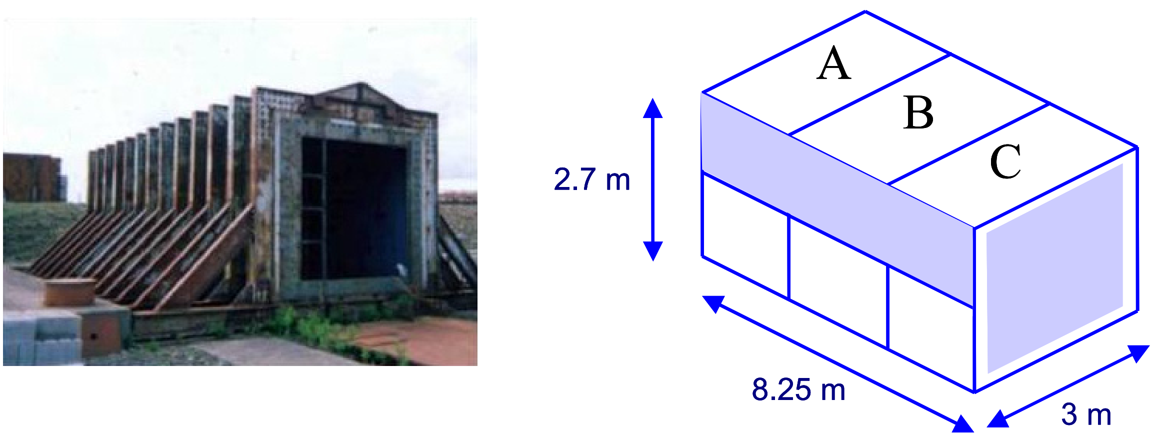


Figure 5: Chamber structure

The front face of the chamber was open in all of the experiments and, in some cases, the upper half of the two long sidewalls were also open. One third of the chamber inside was filled with a gas mixture and was ignited by a single electric spark at the center of the gas cloud. Overpressure measurements were made inside and outside the chamber. The flame arrival time at various locations within the chamber was also measured. The conditions are summarized in Table 3. Other than for the equipment used to make the measurements, the chamber was empty.

Table 3: Conditions used in the explosion experiments in the chamber

Gas Cloud Parameters	Volume	22 m^3
	Hydrogen concentration	15%, 30%, 40% or 50%
	Cloud position (see Figure 5)	A, B or C
Enclosure Parameters	Dimensions	2.7m high, 3m wide, 8.25m long
	Vent openings	Front face (all tests) Upper half of two long sidewalls (some tests)
Ignition Parameters	Method	Single electric spark
	Position	Centre of gas cloud

The relationship between the peak overpressure measured outside the chamber and the distance from its open, front end is shown in Figure 6. The measurements shown in this figure are for experiments that had an opening on the front face only (i.e. the vents in the sidewall were not present).

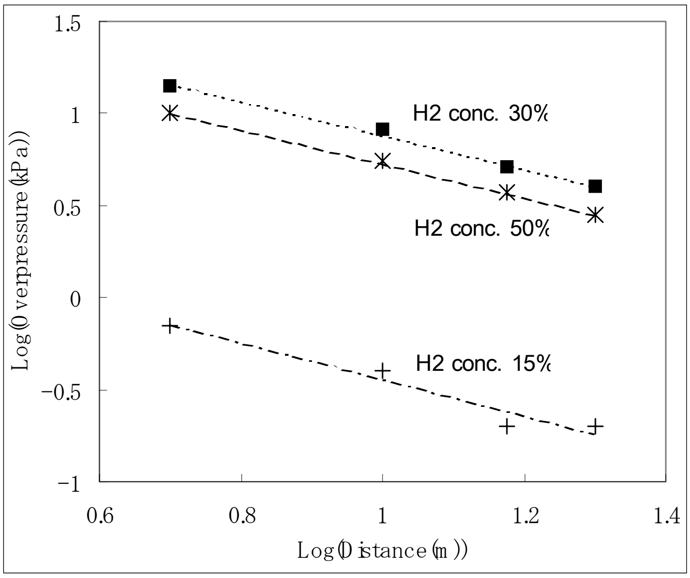


Figure 6: Correlation between overpressure and distance (results for experiments without side vents)

The peak overpressure is seen to decrease almost inversely with distance from the front face. The overpressure itself is bigger than has been reported for explosions of a comparably sized, unconfined hydrogen cloud [3]. The effect of hydrogen concentration on the overpressure is illustrated in Figure 7. The overpressure that is generated is related to the flame speed and, as shown, the largest flame speeds were measured for hydrogen concentrations of 30-40%. (The average values as the flame progressed within the enclosure are shown in this figure). For such concentrations, pressures in excess of 9.8 kPa were measured outside of the enclosure. On the other hand, a hydrogen concentration of 15% generated only a small overpressure, being below 1 kPa for the whole of the external area. An overpressure of up to about 9.8 kPa is generally recognised as being tolerable for human beings. It can be see therefore that any safety zone around such an enclosure depends strongly on the hydrogen concentration and, as shown in the dispersion experiments, this in turn depends on the release and ventilation conditions.

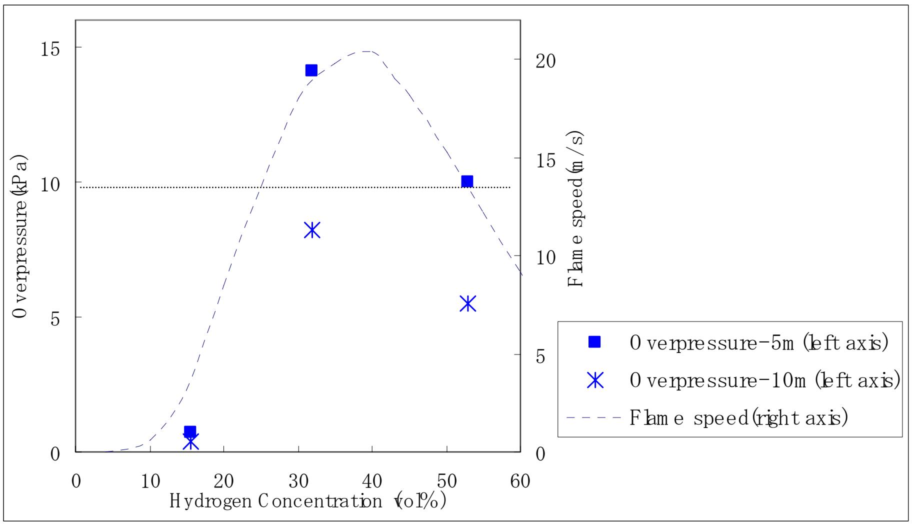


Figure 7: Effect of hydrogen concentration (experiments without side ventilation, overpressure results shown for external locations 5m/10m from front end)

DISPERSION AND EXPLOSION EXPERIMENTS USING A MODEL OF A HYDROGEN STATION

Although the previous experiments have provided basic data on dispersion and explosion in enclosures, such as a storage room, the situation at a filling station would be somewhat different. The hydrogen could be stored at a higher pressure and the high-pressure storage cylinders in the storage room would act as obstacles that could promote flame acceleration in the event of an explosion. Also, because of the finite inventory of hydrogen that is available, any release that occurs would be transient in nature. This could be particularly important for a larger leak, as the driving pressure will decrease rapidly. In order to investigate such factors, a realistic scale model of a filling station was constructed and a further series of dispersion and explosion experiments was performed. First of all, a layout for a hydrogen refuelling station was designed with help from Shimizu Corporation, as shown in Figure 8. The design was selected to achieve the capacities noted in Table 4. Two of the sides of the station had a 2m high perimeter wall and the other two sides were left open to represent a filling station located near to a road junction. A part of these boundary walls was constructed from concrete with a thickness of 150 mm and this was instrumented to measure its displacement and strain.

Table 4: Specification of the hydrogen filling station

Hydrogen production capacity	300 Nm^3/h
Hydrogen compressor flow	500 Nm^3/h
Hydrogen storage	3500Nm^3
Number of hydrogen dispensers	2

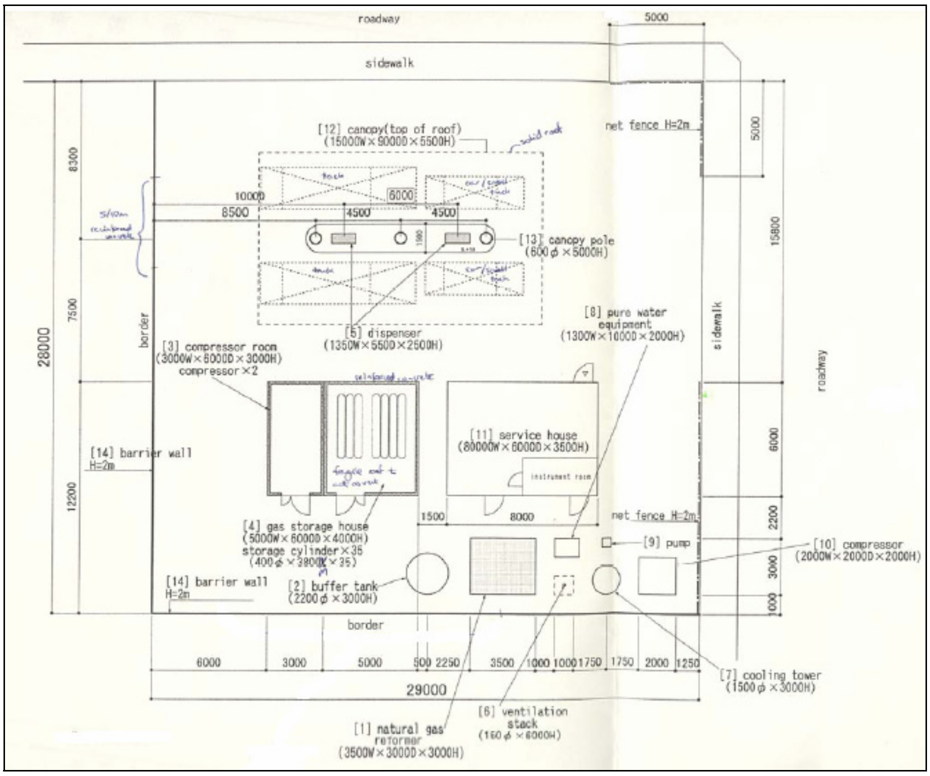


Figure 8: Layout of hydrogen refueling station model (designed by cooperation with Shimizu Corporation)

Figure 9 shows the structure of storage room for the high pressure hydrogen. The room was 5m wide by 6m long with a height of 4m. The walls of the room were constructed from reinforced concrete to a height of 3m, with the top 1m of the gap between the roof and the walls was either open on all sides of had a mesh screen with 50% open area to provide ventilation. The roof was made from lightweight cladding.

Figure 9: Storage room for high pressure hydrogen (left) and cylinder models (right)

High pressure storage cylinders with a capacity of 250L are typical of those that would be used at a hydrogen station in Japan and, as is also shown in Figure 9, an array of such ‘model’ cylinders was positioned inside the storage room. In practice, the amount of hydrogen that would be released in the event of a leak will depend on the location and size of the release and also whether the release is detected and action is taken to isolate the leaking sections of pipe work or vessels. The release of gas from one storage cylinder was taken to be a representative ‘worst-case’ to be studied in this programme. The initial pressure of the cylinders for the majority of the experiments was set at 40MPa. In addition, releases from a smaller inventory of 125L were also considered.

Dispersion experiments in the storage room

The dispersion experiments were carried out inside the storage room, whilst the array of 35 cylinders was present. The experimental conditions that were studied are shown in Table 5. Three sizes of nozzle were employed and the ventilation openings at the top of the sidewalls were either 100% or 50% open.

Table 5: Conditions for the dispersion experiments inside the storage room

Release Parameters	Gas	Hydrogen
	Pressure	40 MPa
	Diameter	0.8mm ,1.6mm or 8mm
	Direction	Horizontal
	Location	Centre of enclosure
Enclosure	Dimensions	Height 4m Depth 6m Width 5m
	Size of Ventilation Opening	Height 1m Present on all 4 sidewalls 50% open or 100% open

Once the release was initiated the pressure in the cylinder containing the hydrogen fell, as shown in Figure 10. In the case of the release through a nozzle of 8mm diameter, ca. 65Nm^3 of hydrogen was released during the first 10 seconds. Such a rapid decay would make it very difficult to detect the leakage and shut any valves to isolate the supply before most of hydrogen is released. Also shown in Figure 10, are some predictions obtained using an outflow model to predict the transient decay of pressure in the vessel. This shows that a simple model, based in this case on perfect gas behaviour, is adequate to predict the observed trends.

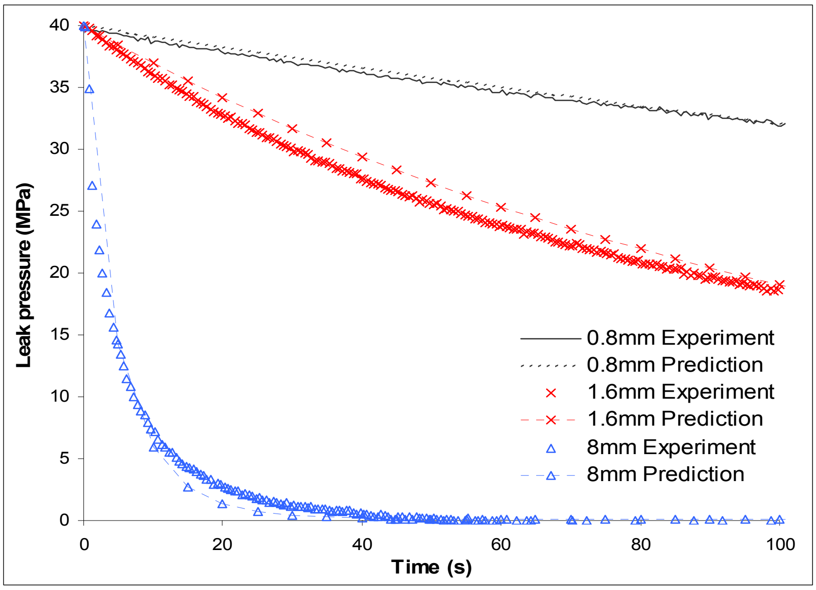


Figure 10: Decay of pressure in the cylinder for the different size of nozzles

The average hydrogen concentration measured in the room for these three experiments is shown in Figure 11. Figure 11a) shows that a concentration of around 4% was measured for the release through a nozzle with a diameter of 1.6 mm. This result suggests that even though the initial storage pressure is 40MPa, a flammable gas mixture is unlikely to be produced throughout the room for leaks with a diameter of below

1.6mm. However, as Figure 11b) shows, the release through the 8mm diameter nozzle reached an average concentration of 27%, presenting a potential explosion hazard, albeit for a short period of time (less than a minute). The predictions of a simple gas accumulation model, [4], are also shown in these figures. The model is able to predict the concentration observed in the experiments involving more slowly varying pressures very well, but tends to over-predict the concentration that was observed in the experiment carried out with a nozzle with a diameter of 8mm. This may reflect a weakness in the model, which ignores the time taken for the gas to mix within the room (and so would overestimate a growing concentration field, but underestimate a decaying one), or may point to the finite response time of the measuring instrumentation.

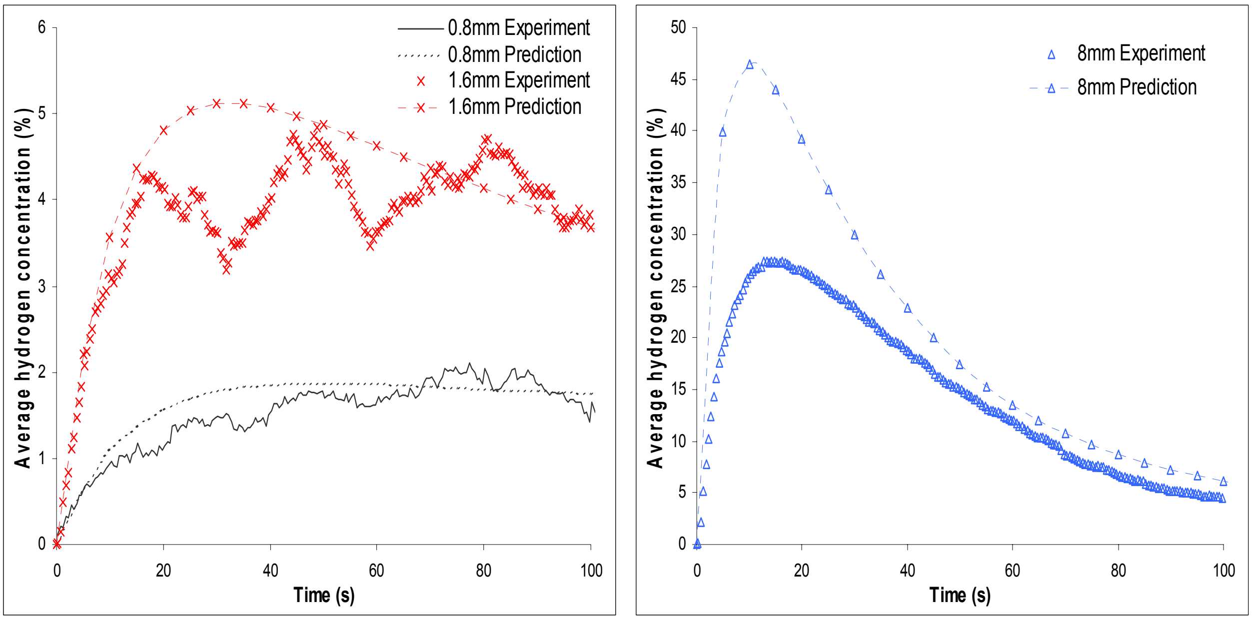


Figure 11: Average hydrogen concentration observed for different nozzle diameters

The later experiments in the programme provided evidence that the average hydrogen concentration in the room could be decreased significantly by increasing the effective area in the ventilation openings to 100% from 50% or by reducing the maximum gas inventory that could be released. Figure 12 gives examples of this, including data from an experiment in which the inventory of the cylinders was reduced to 125L. The predictions of the simple model are in similar agreement to that shown in Figure 11b) and so overestimate the observed peak concentration, although to a slightly lesser extent.

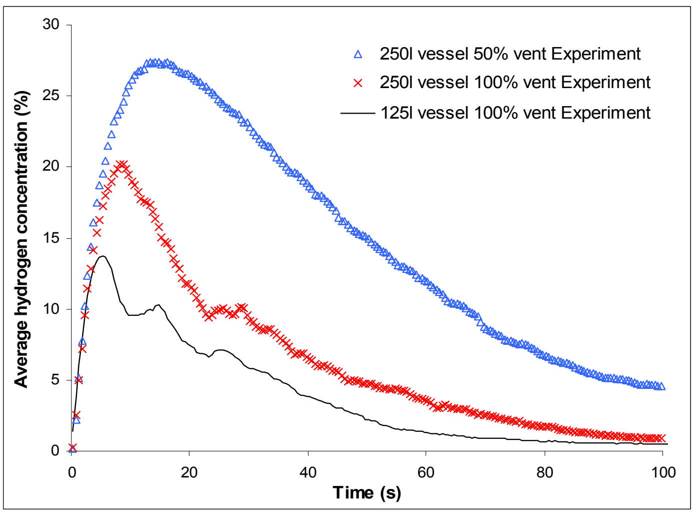


Figure 12: Average hydrogen concentration with smaller vessel and increased ventilation area

Explosion experiments in the storage room

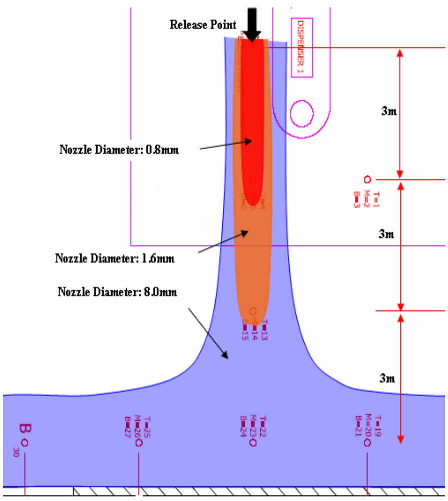
Experiments were performed to investigate the explosions produced by the ignition of a homogeneous hydrogen air mixture in the storage room. The hydrogen concentration was varied from 8% to 26%. As with the explosion experiments carried out in the empty chamber, the hydrogen concentration was shown to have a significant affect on the overpressure. Below a concentration of 15% hydrogen, there were no places that experienced overpressures that were above the tolerable limit. However, the explosion with a hydrogen concentration of 26% generated high overpressures and the whole area of the station experienced values in excess of the tolerable limit. Indeed, the pressures were sufficiently large to cause a number of cracks on the concrete wall of the storage room.

Table 6: Results from explosion experiments using homogeneous mixtures in the model storage room

Experiment Description	Hydrogen Concentration in Room, %	Maximum Measured Overpressure, kPa	
		Inside Room	At station boundary
Homgeneous explosion $120m^3$ volume Central ignition with spark	8	Minimal	Not detected
	15	0.4 –1.3	3.1 – 3.4
	26	>100	28 – 111

Dispersion Experiment at the dispenser

A number of gas dispersion experiments were carried out in the station model to study the concentration distribution produced by a number of different releases of high pressure hydrogen from a dispenser. Again, three different size of nozzle was employed and the hydrogen was released from a storage vessel containing 250L at 40MPa initially. The maximum extent of the resulting flammable gas region produced for each test is shown in Figure 13a). The hydrogen was directed horizontally and an approximately cylindrical flammable gas cloud was formed downstream of the release by the jet. In the case of the nozzles with diameters less than or equal to 1.6mm, the maximum extent of the flammable gas was 6m from nozzle. On the other hand, the jet from the 8mm diameter nozzle formed a relatively large flammable cloud, extending along the boundary wall. A simple jet transient dispersion model, [5], was used to predict the concentration on the centerline of the flow and this is compared with the observations for the three experiments in Figure 13b). Again the model predicts the more slowly varying experiments with the 0.8mm and 1.6mm nozzle reasonably well, but overpredicts the observed concentration in the near field for the 8mm nozzle.



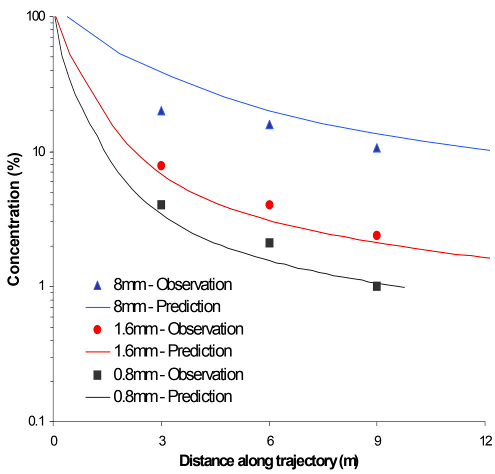


Figure 13: Hydrogen concentration

Explosion experiments at the dispenser

Under the same condition as the dispersion experiments described above, the gas cloud that was formed by an 8mm diameter nozzle was ignited by electric spark at a location 4m point from nozzle. As can be seen from Figure 14, the ignition time from the start of the release had a significant effect on the overpressure that was produced. The peak overpressure was increased as the time to ignition was reduced. It appears that the log of overpressure decreased linearly with the log of ignition time.

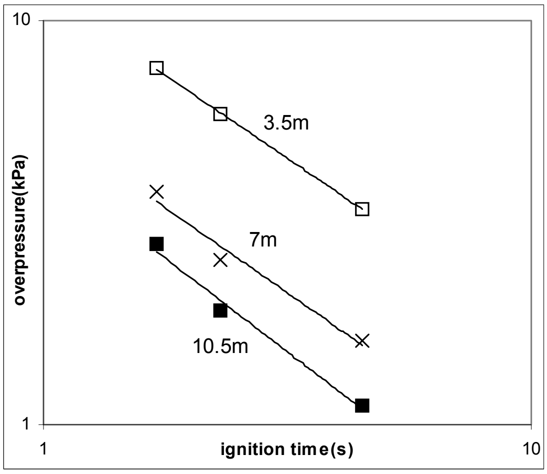


Figure 14: Correlation between ignition time and Overpressure

The biggest overpressure was observed for an ignition delay of 1.2 seconds and the overpressure distribution that was obtained there is illustrated in Figure 15. Overpressures exceeding the tolerable level were only measured in the immediate vicinity of the release location. Compared to the confined explosions, the hazards of explosion at dispenser are greatly reduced.

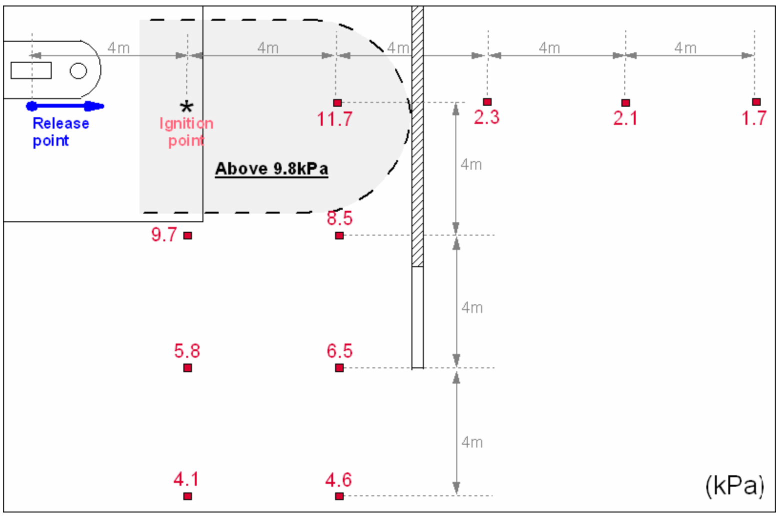


Figure 15: Overpressure distribution for explosion at dispenser

CONCLUSIONS

In order to help investigate the risks at hydrogen refueling station, dispersion and explosion experiments were carried out in a full scale model. The dispersion experiments in the storage room revealed that leak diameter, the volume of hydrogen released and the ventilation characteristics of the room significantly affected the hydrogen concentration produced. Explosion experiments in confined enclosure also revealed that the resulting overpressure varied significantly with hydrogen concentration. The size of the resulting hazardous area was negligible for the explosions in the storage room for hydrogen concentrations of up to 15%, but the whole of the filling station experiences overpressures exceeding the tolerable limit for an explosion with a hydrogen concentration of 30%. In contrast, explosions produced following releases from the dispenser showed that there was only a small hazardous area around release nozzle. From a practical viewpoint, the work demonstrates that the great benefit to be obtained from being able to detect hydrogen leakage and isolate the supply before the hydrogen concentration in an enclosed space reaches 15%. Reducing the inventory in any one line (e.g. to below 125L) or designing a room to have sufficient ventilation will also be effective in reducing the concentration or extent of any hydrogen accumulation. Finally, these experimental results are also of use in their own right in that they can be utilized for modeling study to broaden the application of current assessment models.

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