Large-scale hydrogen deflagrations and detonations

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Abstract

Large-scale deflagration and detonation experiments of hydrogen and air mixtures provide fundamental data needed to address accident scenarios and to help in the evaluation and validation of numerical models such as the AutoReaGas code (used by Mitsubishi Heavy Industries, Ltd). Several different experiments of this type were performed. Measurements included flame-front time of arrival (TOA) using ionization probes, blast pressure, heat flux, high-speed video, standard video, and infrared video. The large-scale open-space tests used a hemispherical 300-m^3 facility that confined the mixture within a thin plastic tent that was cut prior to initiation of a deflagration. Initial homogeneous hydrogen concentrations varied from 15% (~ 3.7 kg) to 30% (~ 7.3 kg). An array of large cylindrical obstacles was placed within the mixture for some experiments to explore turbulent enhancement of the combustion using objects similar in scale to what might be found at a refuelling station. All tests were ignited at the bottom center of the facility using either a spark or, in one case, a small quantity of high explosive to generate a detonation. Spark-initiated deflagration tests were performed in a 1/5-scale tunnel using homogeneous hydrogen mixtures to compare against similar tests performed in the open space. Several experiments performed in the 1/5-scale tunnel released 0.1 and 2.2 kg of hydrogen into the tunnel with and without ventilation to represent, respectively, a release from a fuel cell vehicle or the storage cylinder on a hydrogen transport. For some tunnel tests, obstacles representing vehicles were used to investigate turbulent enhancement. A test was performed to investigate any enhancement of the deflagration due to partial confinement produced by a narrow gap between aluminum plates, similar to gaps that might be found between equipment in a hydrogen processing facility or refuelling station. The attenuation of a blast wave was investigated using a 4-m-tall protective blast wall, such as that which might be placed around a hydrogen production facility, storage yard, or refuelling station to protect surrounding structures. Finally, a large-scale hydrogen jet experiment was performed in which 27 kg of hydrogen was released vertically into the open atmosphere in a period of about 30 s to simulate the bursting of interconnecting piping between large high-pressure storage tanks. The hydrogen plume spontaneously ignited early in the release.
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1. 300-m^3 Experiments

SRI International constructed a 300-m^3 facility from an aluminum geodesic dome frame covered with a thin tent to retain the hydrogen and air mixture up to the point of initiation. PCB model 113A36 quartz blast pressure sensors were placed in steel plates along the ground surface together with ion probes, built by Professor Sato of Toho University in Japan, and/or Nanmac E-12-1-C-U fast-responding thermocouples, which were used to monitor the flame-front propagation. Additional flame-front detectors were placed vertically over the ignition source and attached to a pole. Initiation was at the bottom center of the facility using the spark from a 40-J capacitive discharge unit for deflagrations or a 10-g high-explosive booster charge (5.2×10^4 J) for detonations. PCB model 113A36, 112M343, and 137A23 quartz blast pressure sensors and Vatell HFM-8E/H heat flux sensors were placed along the ground surface in the free field.

The tent was constructed from high-density polyethylene (HDPE) film having a thickness of 0.0254 mm. The tent material needed to be cut quickly to prevent confinement of the mass flow during a deflagration (not required for detonations). Fine wires were attached to aluminum projectiles that were
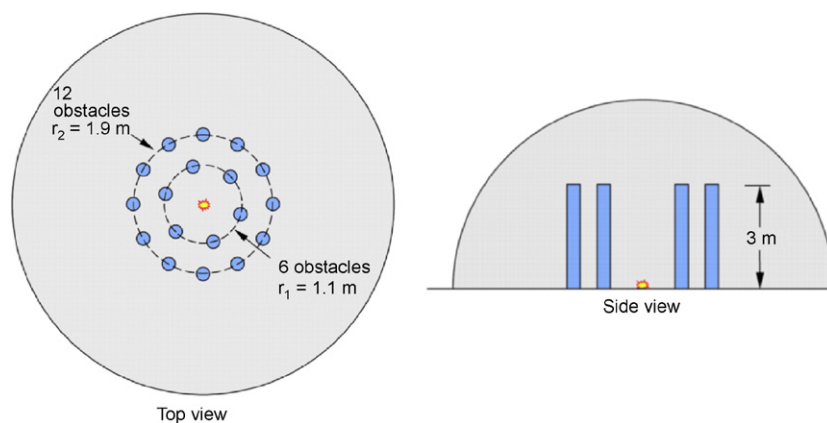
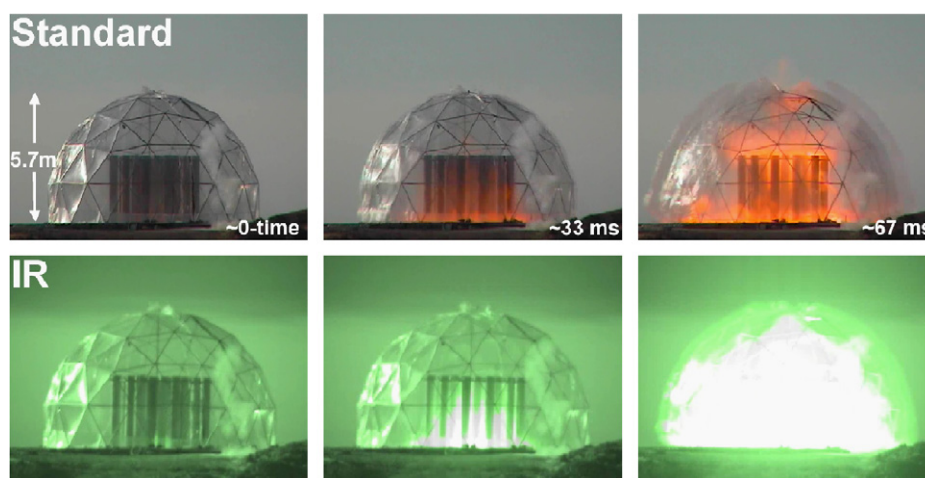Fig. 1. Obstacle array to study turbulent enhancement.

Fig. 2. Obstacle experiment with 30% hydrogen mixture.

launched from four small guns. The fine wires were placed between the 300-m^3 support frame and the plastic tent. The projectile quickly pulled the wire through the tent material, cutting it into four sections in about 120 ms, at which time the mixture was ignited.

Hydrogen was introduced into the facility, and mixing fans circulated the mixture. The concentration was monitored using an H2scan model 11320021 sensor. The mixture was drawn from near the top as well as near the bottom of the facility to check for stratification, which typically varied by less than 2% hydrogen by volume. The mixing continued for approximately 15 min to ensure a homogeneous mixture before testing. Each experiment was recorded using digital video camcorders (standard and infrared). In addition, for some tests, a high-speed video was taken using a Phantom v7.1 camera. Weather conditions at the test facility were monitored using a Davis Vantage Pro weather station.

We performed several experiments in which the hydrogen concentration was varied between 15% ($\sim$ 3.7 kg) and 30% ($\sim$ 7.3 kg) by volume. Deflagrations were initiated along with one detonation. Some deflagration tests included cylindrical obstacles to investigate the possibility of turbulent enhancement of the deflagration. The obstacles are representative of what

might be found at a hydrogen production facility or refuelling station. Eighteen cylinders measuring 0.46 m in diameter by about 3 m tall were placed symmetrically around the ignition point in two rings as shown in Fig. 1.

The volume blockage ratio was about 11%. Fig. 2 shows standard and infrared video frames from a 30% hydrogen experiment with obstacles. Fig. 3 shows blast and heat flux data measured at a range of 15.61 m from the ignition point for tests without obstacles (4-03 and 7-03) and a test with obstacles (4-04). Fig. 4 plots the Sachs-scaled surface burst overpressure and impulse, where

$$R_0 = (E/P_0)^{1/3} \tag{1}$$

where E is the energy release, J, P_0 the ambient air pressure, Pa.

It is clear that for these obstacles no enhancement of the deflagration occurs, which is in sharp contrast to the results from smaller scale experiments having the same volume blockage [1]. In the smaller scale tests the obstacle was a rectangular symmetric array of pipes with a nominal diameter of 21 mm, duplicating one of the obstacles used for the EMERGE experiments [2]. It may be that in this case the size of the obstacles is large enough so that the level of turbulence in the mass flow
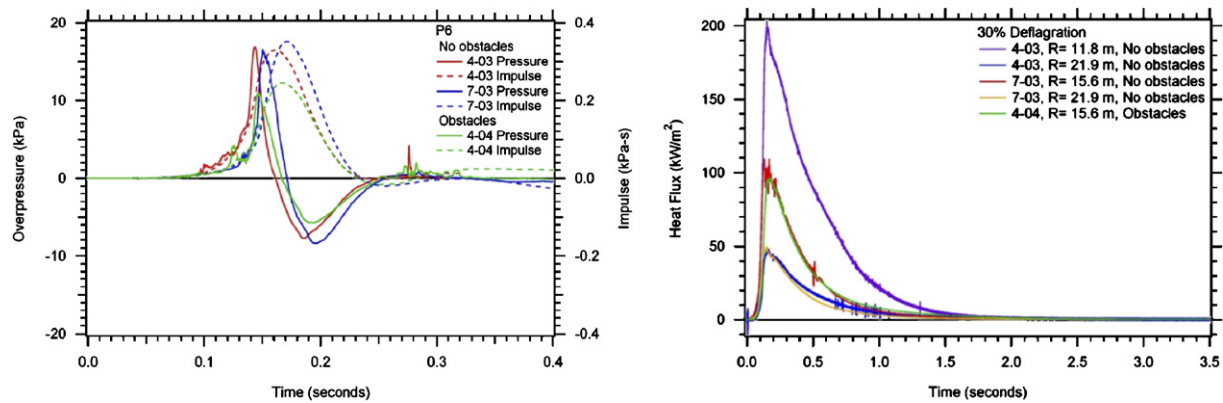
Fig. 3. Blast data from deflagration tests with and without obstacles at a range of 15.61 m.
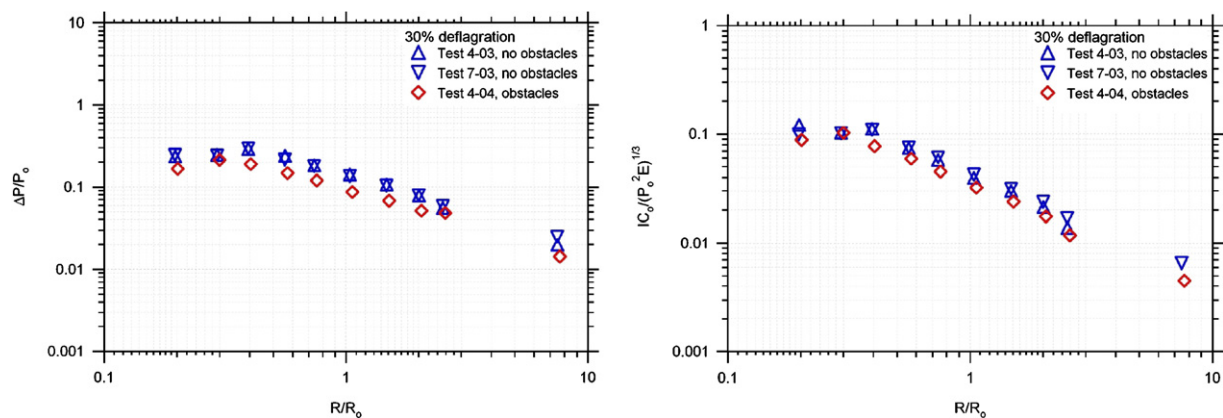

Fig. 4. Scaled overpressure and impulse for deflagrations with and without obstacles.

is low. Future tests might use hot-wire anemometry to quantify the level of turbulence. Similar results were obtained for experiments where the hydrogen concentration was 15% by volume. Repeat tests with 30% hydrogen tests show very good repeatability, as shown in Fig. 4; however, additional repeat tests need to be done for the 15% hydrogen tests to quantify scatter. These tests plus previous work [3] indicate that the flame front is constantly accelerating, thus making it difficult to use small-scale experiments to assess the safety hazards of large-scale accidents. Models such as the Baker–Tang–Strehlow depend on a constant flame speed. The data collected may be useful in refining such a model to account for the flame speed acceleration.

In one experiment (7-04), we used 10 g of C-4 high explosive to initiate a detonation in a 30% hydrogen mixture. Fig. 5 shows high-speed video frames from the experiment. The video, together with ionization probe data, was used to determine a detonation velocity of 1980 m/s, which is in good agreement with the C–J detonation velocity for a stoichiometric mixture of hydrogen and air [4]. Blast and heat flux waveforms are shown in Fig. 6 for the 15.61-m range. The detonation data scales are shown in Fig. 7 and are in good agreement with the Dorofeev [5] and Baker–Strehlow–Tang (B–S–T) [6] analytic curves for hydrocarbon vapor cloud detonations. The curve for a hemispherical TNT surface burst is also shown [7].

2. Tunnel experiments

We conducted a series of experiments in a 78.5-m-long tunnel that had a cross-sectional area of 3.74 m^2 as shown in Fig. 8. This tunnel represents a specific vehicle tunnel at about 1/5 scale with a large cross-section compared to typical vehicle aspect ratios. Homogeneous mixtures ranging from 9.5% to 30% hydrogen were contained within a 37-m^3 volume at the center of the tunnel by HDPE plastic film barriers, which were cut prior to spark ignition (bottom center of the mixture volume). Additional experiments explored the release of hydrogen (0.1 kg in 20 s and 2.2 kg in 420 s) into the tunnel both without and with forced ventilation. These experiments modelled the scaled release through a safety valve on a vehicle fuel tank or from one cylinder of a fuel tank truck and at a typical scaled tunnel ventilation rate (1.6 m^3/s). The mixture within the tunnel was captured using sample bottles at various positions for later analysis of hydrogen concentration. For some tests, model vehicles measuring 940 mm (L) × 362 mm (W) × 343 mm (H) were placed down the center of the tunnel on the concrete floor. Each vehicle was separated from the next by about one vehicle length as shown in Fig. 9. The vehicles represented an areal blockage ratio of 0.03. Standard and IR video were taken of the deflagration, and blast pressure was measured both inside and
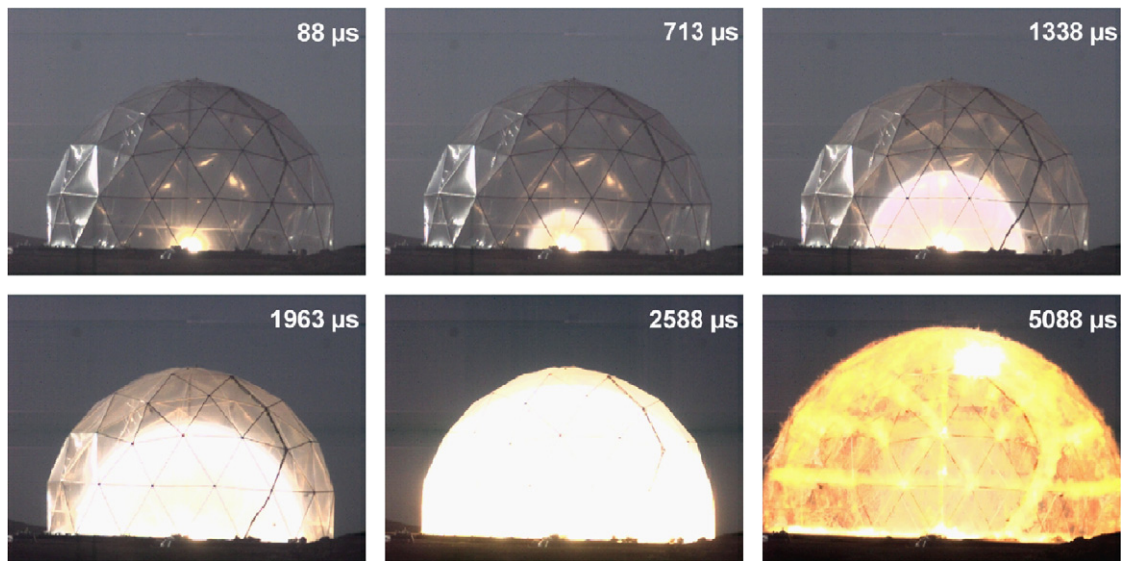
Fig. 5. High-speed video frames from the detonation test.
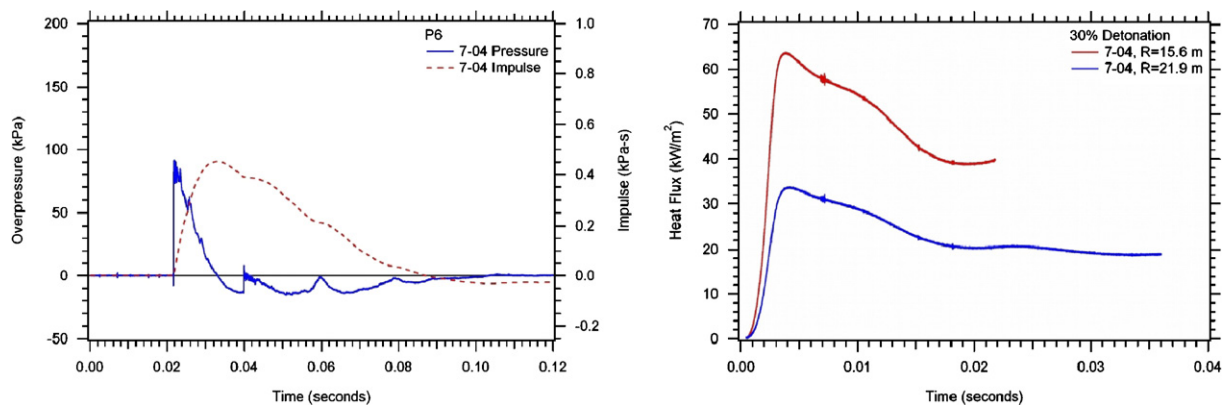

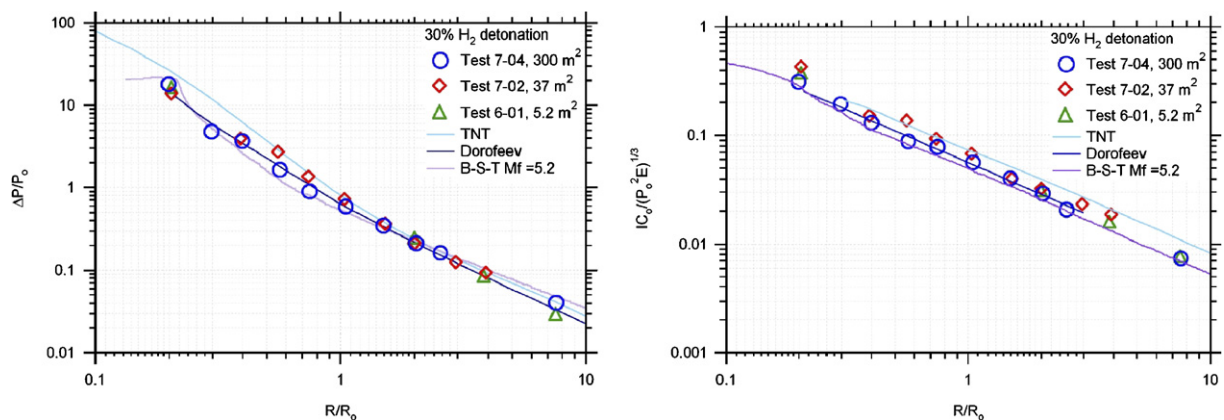Fig. 6. Blast data from the detonation at 15.61 m.

Fig. 7. Scaled overpressure and impulse for a detonation.

outside the tunnel. Flame position versus time was measured for some of the homogeneous tests using ion probes.

The homogeneous tests showed that the 9.5% (0.32 kg) hydrogen mixture produced pressure pulses too low for the sensors to detect. The 20% (0.67 kg) mixture produced pressure pulses that measured about 35 kPa throughout the length of the tunnel. The 30% (1 kg) experiment produced a significant pressure pulse of about 150 kPa (much greater than an equivalent unconfined experiment, where a maximum pressure of 10 kPa was recorded). The presence of the vehicle models had no

Fig. 8. Tunnel facility.
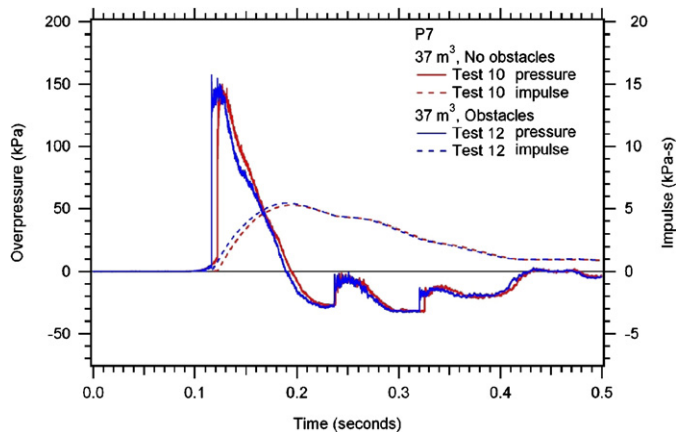

Fig. 9. Model vehicles in the tunnel.

Fig. 10. Pressure waveforms near the tunnel end for experiments without and with vehicle models.

effect on the deflagration, perhaps since the blockage ratio was so small. Future tests will incorporate larger vehicles such as models of buses. It is also possible that the turbulent enhancement may be small for this scale of obstacle. The pulse for the 30% hydrogen deflagration formed a shock as it propagated down the length of the tunnel, as shown in Fig. 10, for tests without and with vehicle models as obstacles.

Fig. 11 shows the peak overpressure and impulse as a function of range from the ignition point. The data indicate that the 30% hydrogen test without vehicle model obstacles (Test 10) is the same as a test with vehicle models (Test 12). The 20%

hydrogen test without vehicle models (Test 11) has much lower values.

We released 0.1 kg of hydrogen in 20 s at the center of the tunnel for Tests 14 and 15. Before igniting the mixture at the top of the tunnel over the release point, we captured mixture samples at various ranges from the nozzle. Table 1 shows the measured concentrations, which were lean. The mixtures were ignited in both cases, but the pressure pulse was below the measurement capability of the sensors.

We released 0.1 kg of hydrogen in 20 s for Test 16 at the inlet end of the tunnel with the ignition point at the top of the tunnel over the nozzle. The tunnel had a forced ventilation rate of $1.6 \, \text{m}^3/\text{s}$. Test 17 released 2.2 kg in 420 s at the inlet end of the tunnel with the same ventilation rate. Table 2 lists the hydrogen concentration as a function of the range from the release point (positive ranges are toward the downstream end of the tunnel). No ignition took place in either test, even though for Test 16 the maximum concentration was above the 4% lower flammability limit for hydrogen (noncoherent upward flame propagation).

3. Partial confinement experiment

Two aluminum plates were placed within the 37-m³ facility to study the effect of partial confinement on the deflagration of a stoichiometric mixture of hydrogen and air. The plates were mounted as shown in Fig. 12, forming a gap of 10 mm. The mixture was ignited at the bottom center between the plates. The partial confinement might cause the flame speed to increase, enhancing the deflagration and possibly causing a transition to a detonation. Similar partial confinement might be found within production facilities or at refuelling stations. Dynasen CA-1040 ionization pins were used to monitor the flame-front position, and pressure sensors were used to measure the resulting blast. Standard and IR video were also taken of the experiment.

The experiment showed no increase in the flame speed. The measured pressures and impulse are shown in Fig. 13. The test with the plates had pressure or impulse values that were the same as or a little lower than an identical experiment that had no plates. There was no enhancement of the deflagration for the selected gap or plate dimensions used in this experiment.
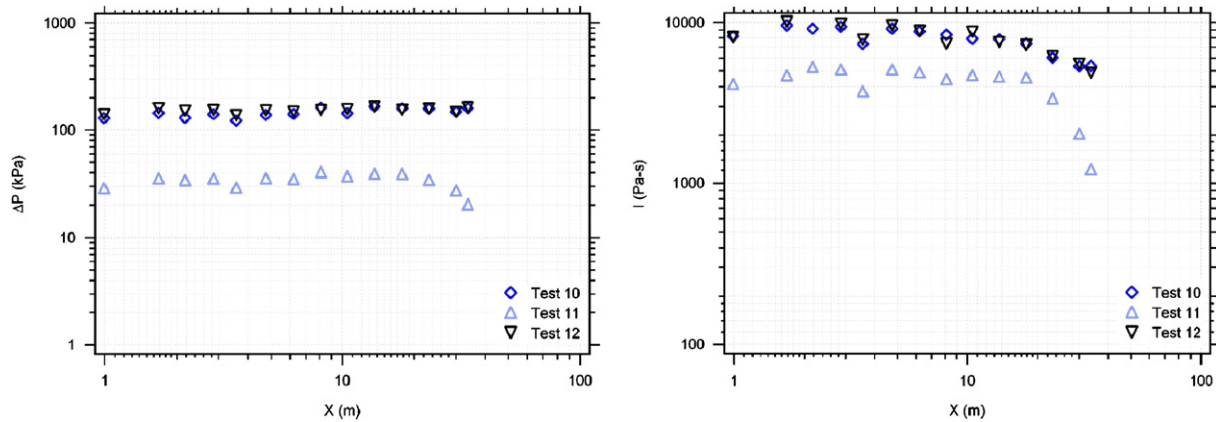
Fig. 11. Blast data for Test 10 (30%), Test 11 (20%) without obstacles, and Test 12 (30%) with obstacles.

Table 1
Tests 14 and 15 hydrogen concentration

Range[a] (m)	Test 14 H$_2$ (%)	Test 15 H$_2$ (%)
−9.16	0	0
−6.10	4.7	3.3
−3.05	—	4.9
0.00	15.0	12.0
3.04	—	4.9
6.09	4.5	3.3
9.14	2.9	0
12.19	0	0

[a]Horizontal range from the release point.

Table 2
Tests 16 and 17 hydrogen concentration

Range[a] (m)	Test 16 H$_2$ (%)	Range[a] (m)	Test 17 H$_2$ (%)
−0.73	5.0	−0.73	3.2
2.24	4.9	5.29	3.1
5.29	3.7	11.49	3.1
8.34	3.6	17.58	3.2
11.49	2.8	23.33	3.3
14.43	1.0	29.68	3.3
17.58	0	35.78	3.3
20.54	0	38.82	3.3
23.33	0	44.92	3.5
26.62	0	50.69	3.8
29.68	0	57.37	3.8
32.73	0	63.42	3.9

[a]Horizontal range from the release point.

4. Protective blast wall experiment

One possible way to protect structures surrounding a refuelling station in an urban environment is to erect a protective blast wall. Previous experiments [3] with a 2-m-tall by 10-m-wide wall demonstrated a significant reduction ($\sim$ 20%) in overpressure and impulse behind the wall along the ground surface. Calculations indicate that the protection might extend to two to three times the height of the wall, and that the blast attenuation diminishes with range behind the wall. We performed
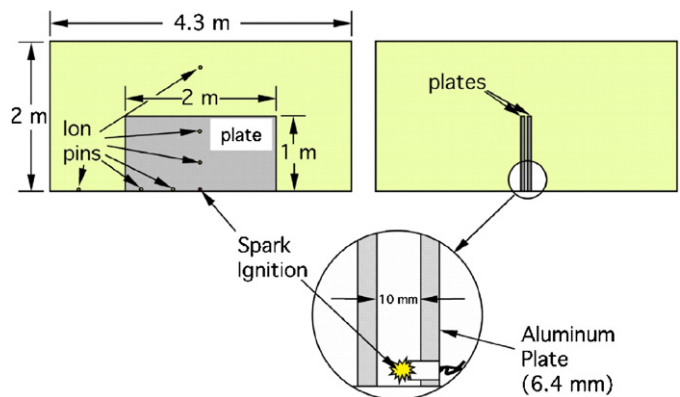

Fig. 12. Experiment design to study deflagration within a narrow gap.

an experiment using a 4-m-tall by 10-m-wide wall subjected to the deflagration of a stoichiometric source with a volume of 5.26 m^3. The edge of the source was placed 4 m from the front surface of the wall. Fig. 14 shows the experiment. Numerical modelling showed that the proximity of the hillside had little effect on the pressures measured on the wall and behind the wall. Pressure sensors were used to monitor the blast along the ground surface, on the front of the wall, and at two elevations (4 and 8 m) behind the wall. The scaled blast data and wall location are shown in Fig. 15.

This data, previous experiments [3], and numerical calculations suggest that the reduction of blast extends to at least twice the height of the wall; however, this explosive source produced a lower blast than tests without a wall, so a direct comparison cannot be made.

5. Large-release experiment

We designed and built a facility to study the release and ignition of large quantities of hydrogen (27 and 54 kg released in 30 s) that might result from the catastrophic failure of a storage container. Hydrogen for these experiments was stored in two vessels that had a total water volume of about 16.2 m^3. Hydrogen is expected to be stored at pressures from 30 to
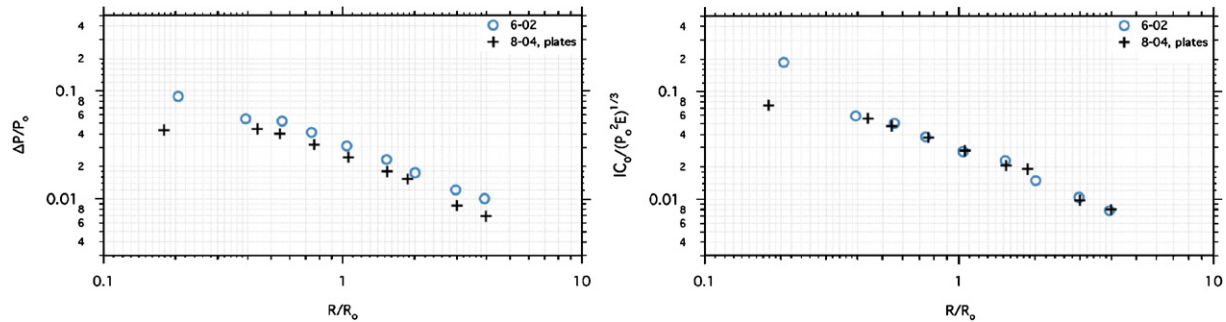
Fig. 13. Scaled blast data from a test without the plates (6-02) and a test with the plates (8-04).

Fig. 14. Protective blast wall experiment.

70 MPa; however, the existing tanks could be safely pressurized to 2.4 MPa. The experiment was designed to match a calculated release rate profile from a high-pressure storage tank where the gas was released through a toroidal-throat critical nozzle with a diameter of 42 mm, which was oriented vertically. Three 18-m-tall towers surrounded the release point and supported a mixture capture system designed to obtain hydrogen concentration at discrete locations and times before ignition for later analysis. An array of 110-mJ continuous-spark igniters was placed axially around the plume 5 m above the nozzle. Pressure transducers were installed in the free field along with a heat flux sensor. Standard, IR, and high-speed video were used to document the flame jet. A weather station was used to record wind speed, wind direction, temperature, humidity, and barometric pressure.

We were concerned about spontaneous ignition, which had been observed on previous large-scale releases. We took precautions to eliminate debris from the hydrogen distribution system. We also prevented static buildup by wetting the ground surface before the test and eliminated catalytic reactions by checking the hardware for platinum metals. The release occurred with a light wind (5.4 m/s) and very high relative humidity conditions (91%). Spontaneous ignition occurred about 360 ms after the start of the release as shown by the high-speed video frames in

Fig. 16. The ignition occurred near the location of one of the sampling stations. Fig. 17 shows an example of blast pressure and heat flux from the experiment. The premature ignition precluded a capture of the hydrogen concentration in the plume. The high-speed video was analyzed to obtain flame speed. Fig. 18 shows that the initial upward burning flame propagated at a speed of about 110 m/s. The initial flame consumed the available hydrogen until additional hydrogen was added by the flow, and then the upward burning flame speed was about 38 m/s. The downward burning flame speed was about 105 m/s.

6. Summary

We performed deflagration and detonation tests in a 300-m^3 hemispherical volume, a deflagration in a narrow gap between plates, deflagration tests in a sub-scale vehicle tunnel, a deflagration test using a 4-m-tall protective blast wall, and a test of a large-scale release of hydrogen.

Test results show that obstacles representative of those found at production facilities or refuelling stations did not enhance the combustion. Earlier tests [1] documented a transition to detonation for a rectangular obstacle array lattice using 21.3-mm-diameter tubing with a volume-blocking ratio of 11%. The lack of enhancement may be due to relatively low levels of turbulence caused by obstacles at this large scale. Additional measurements, perhaps with hot-wire anemometers, might be used to quantify the turbulence levels. The 300-m^3 30% detonation test data show good agreement with small-scale experiments and analytic curves for hydrocarbon vapor cloud detonations.

In a partial confinement experiment, a homogeneous 30% hydrogen mixture was ignited within a narrow gap between metal plates. The data indicate that no enhancement of the deflagration took place.

We performed experiments to examine the effects of homogeneous gas mixture deflagrations and hydrogen release deflagrations in a sub-scale vehicle tunnel (approximately 1/5 of full scale). For the homogeneous experiments the pressure and impulse were nearly constant over the tunnel length. The 30% hydrogen test showed a significant enhancement of the deflagration when compared with free-field events. These tests show that the confinement of the hydrogen by the tunnel significantly raises the hazard. Ventilation during a release reduces the hazard dramatically. Releases of small quantities of hydrogen (i.e.,
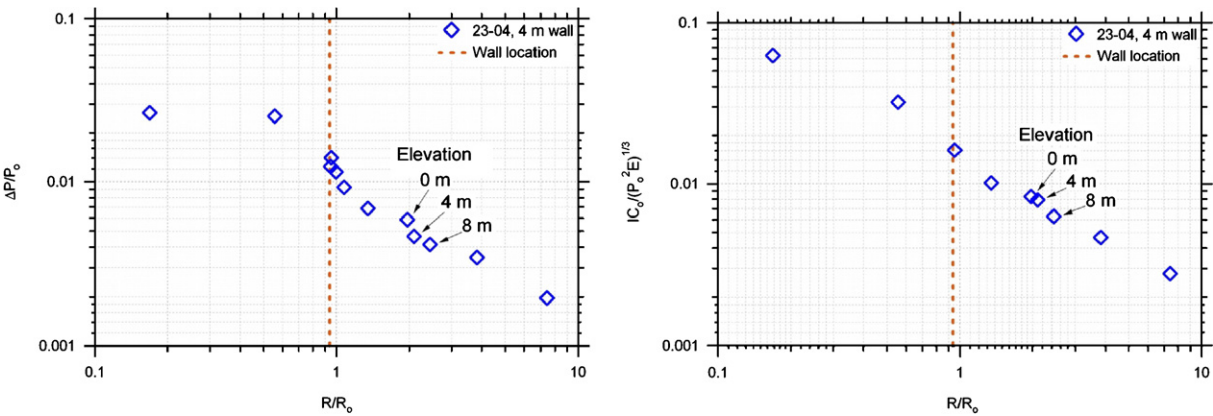
Fig. 15. Scaled pressure and impulse from the protective blast wall experiment.
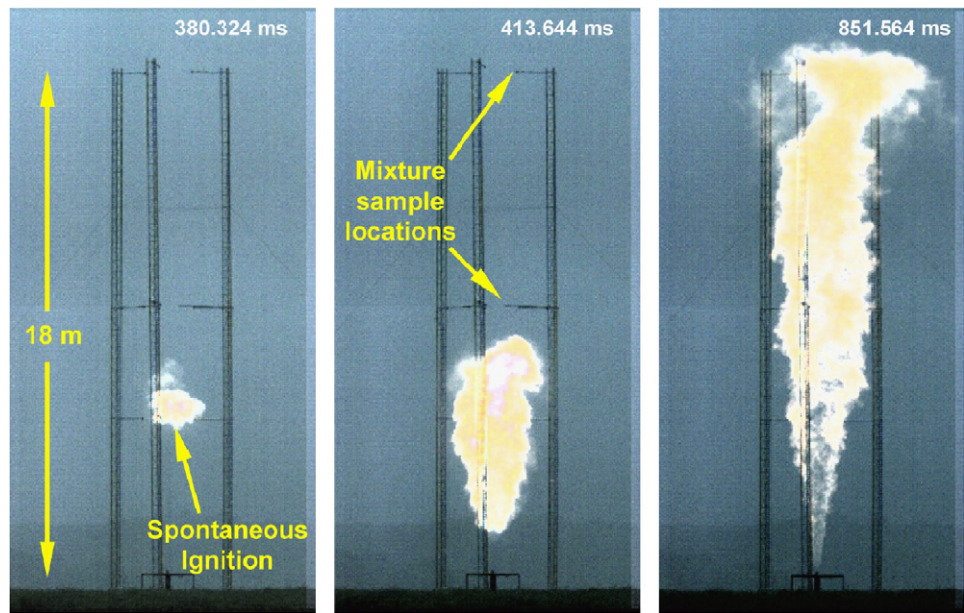

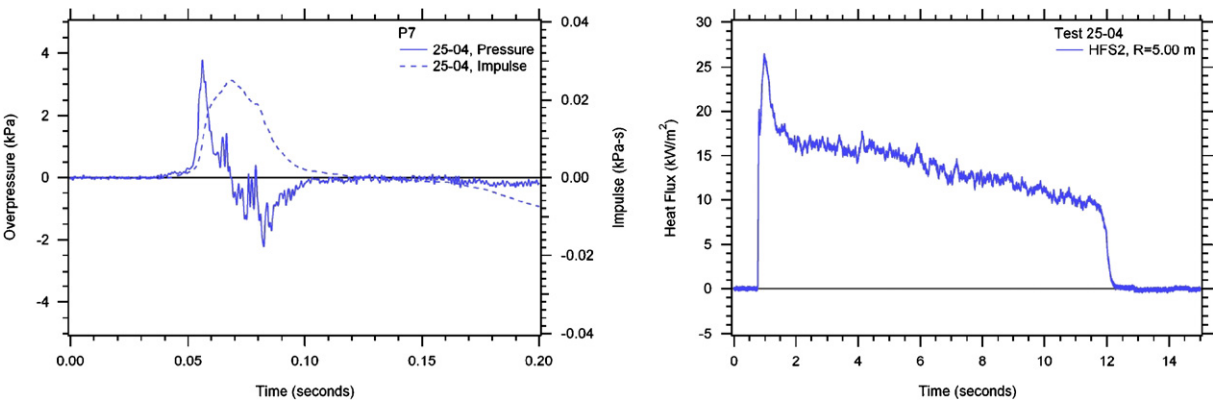Fig. 16. High-speed video frames from large-release experiment (25-04).

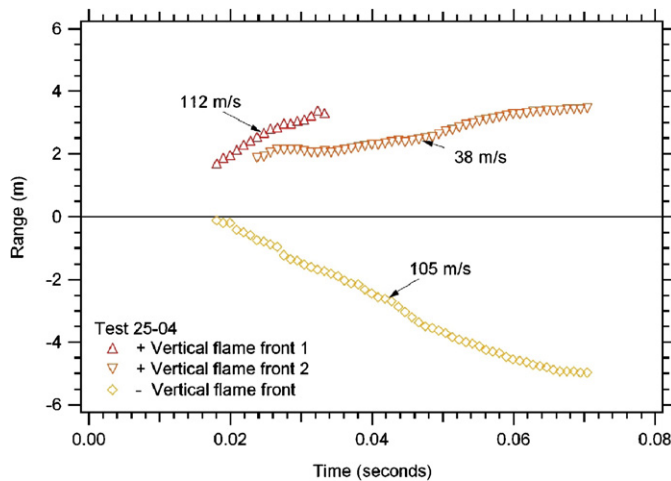Fig. 17. Blast pressure and heat flux measurements from the large-release experiment (25-04).

Fig. 18. Flame speed measured from the high-speed video on the large-release test (25-04).

through a vehicle fuel tank safety release valve) into the tunnel produced very lean concentrations. The experiments show that proper ventilation of a tunnel can significantly reduce the chance of an explosion in the case of a leak. Further study is required to examine the effect of higher release rates. It is possible that a high release rate in a ventilated tunnel could still produce a near homogeneous mixture at close to stoichiometric conditions.

A deflagration test was performed to evaluate the effect of a 4-m-tall protective blast wall. These results, together with previous work [3] and calculations, suggest a drop in peak overpressure and impulse at close range behind the wall to at least twice the height of the wall. This means that a blast wall may protect structures to perhaps twice the height of the wall or higher. The reduction in blast diminishes with increasing distance behind the wall. Additional tests using a hydrogen detonation would be useful to examine the effect of the wall on higher-pressure shocks.

Finally, we performed a large-scale release of hydrogen (~ 27 kg released in 30 s) to study the catastrophic failure of the interconnecting pipes between non-vehicular storage tanks. Steps were taken to minimize static charge buildup and to eliminate scale and debris in the hydrogen distribution system in an effort to prevent spontaneous ignition. However, the experiment spontaneously ignited shortly after the start of the release. High-speed video shows that the ignition occurred on or near one of the sampling station rods. Spontaneous ignition has been observed before with large-scale hydrogen releases, but not small scale. The mechanism leading to spontaneous ignition is not understood, but possible causes include static charge buildup, friction heating of particulates within the flow, catalytic reactions with certain metals (i.e., platinum group), or shock dissociation of molecular hydrogen at the nozzle that might cause an ignition on recombination. Further study is required to understand this phenomenon.

Acknowledgment

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