Available online at www.sciencedirect.com
ScienceDirect
Journal of Power Sources 159 (2006) 144–148
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

Short communication

# Experiments on hydrogen deflagration

Y. Sato [a], H. Iwabuchi [a,*], M. Groethe [b], E. Merilo [b], S. Chiba [c]

[a] Research and Development Department, The Institute of Applied Energy 14-2, Nishishinbashi 1-Chome, Minato-ku, Tokyo 105-0003, Japan
[b] SRI International, Poulter Laboratory, 333 Ravenswood Avenue, Menlo Park, CA 94025, USA
[c] SRI International, Park Side House 8F, 2 Ichibancho, Chiyoda-ku, Tokyo 102-0082, Japan

Available online 24 July 2006

**Abstract**

Deflagrations of hydrogen mixed with air have been studied in an open space and inside a shock tube to provide fundamental data needed for safety evaluations and validation of computer models. The open space tests were performed in 5.2- and 37-$m^3$ rectangular tents and in a 300-$m^3$ hemispherical tent that were filled with quiescent, homogenous mixtures ranging from 15 to 57% hydrogen by volume. The mixture was contained by a very thin plastic membrane that was cut just prior to igniting the mixture with a spark at the bottom center to prevent confinement of the mass flow. The information collected included flame front propagation monitored with ionization probes, the pressure–time histories of the resulting blast, and radiated heat obtained from thermal flux sensors. In these experiments the following results were obtained. (i) Deflagration of 30% hydrogen generated a much higher overpressure than deflagration of 9.5% natural gas. (ii) The flame propagation velocity and generated pressure were remarkably influenced by the hydrogen concentration. (iii) Turbulence caused by obstacles within the gas mixture and increasing the gas mixture volume increased the speed of the flame propagation and the overpressure. (iv) The combustion inside a tube also showed a high-speed deflagration. These results are useful to re-examine the existing codes and standards.


*Keywords:* Hydrogen; Explosion; Deflagration; Detonation; Pressure

## 1. Introduction

SRI International has developed a suite of testing facilities for the Institute of Applied Energy (IAE) to acquire data on the deflagration and detonation of hydrogen and air mixtures. The program is administered through the New Energy and Industrial Technology Development Organization (NEDO) as part of the Development for Safe Utilization and Infrastructure of Hydrogen program. Initial tests were performed at small-scale within a prismatic tent having a volume of about 5.2 $m^3$ [1]. A rectangular lattice obstacle array duplicating that used on the EMERGE [2] experiments (volume blockage ratio = 10.9%) was used on some small-scale tests to study turbulent deflagrations. The flame front position as a function of time was monitored with ionization pins and the resulting blast was measured with pressure transducers. The dimensions of the small-scale facility were scaled up by a factor of 1.92 to create a medium-scale facility with a volume of 37 $m^3$ [3]. Tests included lean mixtures of 20% $H_2$, stoichiometric mixtures of 30% $H_2$, and rich mixtures of 57% $H_2$. Deflagrations and detonations were studied.

A large-scale facility was constructed to enclose a volume of 300 $m^3$. A geodesic dome frame supports a thin plastic membrane to form a tent to contain the hydrogen/air mixture. Two tests have been performed in which a stoichiometric hydrogen and air mixture were ignited by a spark. Additional tests include a lean mixture test with 15% $H_2$ and a detonation test with a stoichiometric mixture ignited by an explosive.

A rapid release of large quantity of hydrogen and the consequent deflagration have been investigated. Deflagration of hydrogen in a large tube as a model of a tunnel has been studied.

## 2. Experimental

Tests have been or are being performed that explore the interaction of the blast wave with a protective wall, scaling of blast parameters from small, medium, and large-scale deflagrations and detonations, turbulent enhancement from obstacles, the effects from a rapid large-scale release of hydrogen that is ignited to form a flame jet, and the confinement effect of tubes.

The mixture for the small, medium, and large-scale tests is contained within a thin (0.008–0.025 mm) polyethylene film

* Corresponding author. Tel.: +81 3 3508 8894; fax: +81 3 3501 8021.
*E-mail address:* iwabuchi@iae.or.jp (H. Iwabuchi).

0378-7753/$ – see front matter 
doi:10.1016/j.jpowsour.2006.04.062

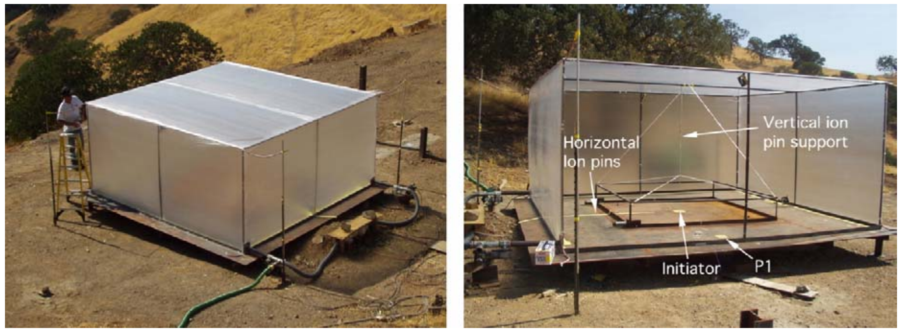


Fig. 1. Tent (37-$m^3$) (4.3 m × 4.3 m × 2 m (H)).

tent that is cut just prior to initiation along the perimeter to prevent confinement of the mass flow. Hydrogen is introduced into the tent from compressed gas bottles through a solenoid valve. The mixture concentration is monitored by an H2scan model 11320021 sensor that can be isolated from the tent during the deflagration. A sampling tube draws the tent mixture from near the bottom of the tent, past the hydrogen sensors, and then discharges it back into the tent. The hydrogen and air is mixed inside the tent with multiple fans for 15–30 min after obtaining a stable reading on the hydrogen sensor. The internal fans are turned off several minutes before initiation. Deflagrations are initiated by a spark from a 40-J capacitive discharge unit (CDU). A 10 g booster of C-4 explosive ($5.2 \times 10^4$ J) is used to initiate a detonation in a stoichiometric mixture. The initiation point is at the bottom center of the tent for all tests.

Flame front propagation is monitored with Dynasen CA-1040 ionization pins for the small and medium-scale tests; custom ion probes are used at large-scale. The blast pressure is measured using PCB Piezotronics model 133A36, 137A23, and 112M343 quartz pressure transducers. The transducers are electrically and mechanically isolated from the test bed and protected from the thermal load produced by the combustion. The deflagration or detonation is recorded using standard digital video and IR cameras.

## 3. Results and discussion

### 3.1. Tests with a 5.2-$m^3$ source

The small-scale source was used in an open space where a stoichiometric mixture of hydrogen and air was contained within a 5.2-$m^3$ rectangular volume. Blast pressure was monitored inside the tent, and at several free-field locations. The blast pressures in the free field decayed according to a power law. We observed the maximum overpressure of 1.5 kPa at a range of 11 m from the gas mixture, under the condition of no obstacle and an electric spark ignition. That was much higher than the maximum overpressure of 0.18 kPa from 9.5% natural gas deflagration, which was tested for reference by JAERI. A rectangular lattice obstacle array inside a 30% hydrogen mixture accelerated the flame propagation velocity and caused almost the same overpressures as the detonation initiated by C-4 explosive.

### 3.2. Tests with a 37-$m^3$ source

The medium-scale rectangular source has a volume of 37 $m^3$. The test facility is shown in Fig. 1. The flame front was monitored with ionization pins and the resulting blast was measured with pressure transducers. The free-field transducer locations

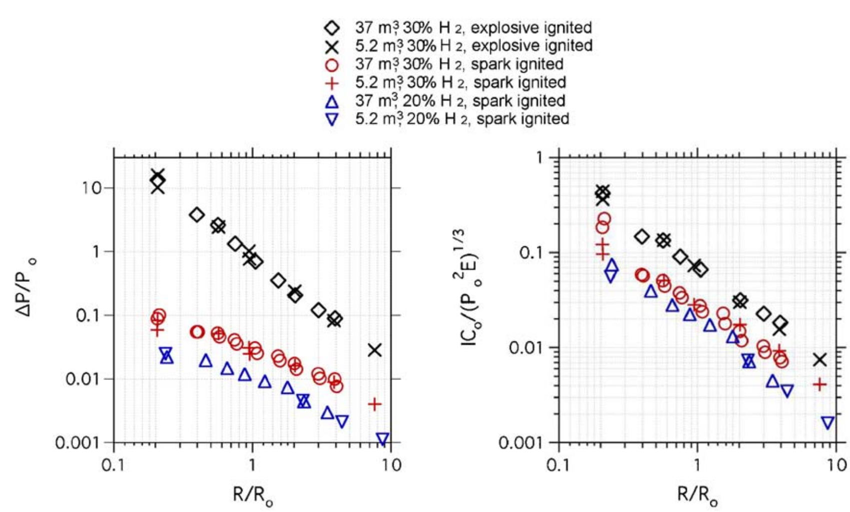


Fig. 2. Effects of ignition source and hydrogen concentration on peak pressure and impulse: $R$: range (m), $R_0 = (E/P_0)^{1/3}$, $E$: combustion heat (J) (LHV), $P_0$: atmospheric pressure (Pa), $\Delta P = P_m - P_0$, $P_m$: peak pressure (Pa).

were scaled by a factor of 1.92, permitting comparison with data from the small-scale tests. Deflagration tests were performed using lean (20% $H_2$), stoichiometric (30%), and rich (57% $H_2$) mixtures, and one detonation test was performed with a stoichiometric mixture. Fig. 2 gives the Sachs-scaled surface blast overpressure and impulse as a function of scaled range for both the medium-scale tests and the small-scale tests. The characteristic length is defined as, $R_0 = (E/P_0)^{1/3}$, where $E$ is the energy of the source and $P_0$ is the ambient pressure.

The overpressure data from the same hydrogen concentration were normalized on the same curve independent of the source volume of 5.2 and 37 $m^3$ for each of the lean mixture, stoichiometric deflagrations, and the stoichiometric detonation, showing that Sachs scaling held closely. Tang and Baker [4] along with Dorofeev [5] have shown that the blast parameters are dependent on the flame speed. The flame front velocity was about 40–45 $m\,s^{-1}$ for a stoichiometric mixture, which is in good agreement with the data from the small-scale facility. The flame velocity for the 20% $H_2$ test was 30 $m\,s^{-1}$, the flame velocity for the 57% $H_2$ test was about 11–12 $m\,s^{-1}$, and the stoichiometric detonation velocity was 1980 $m\,s^{-1}$ in agreement with the C-J detonation velocity.

### 3.3. *Tests with a 300-m$^3$ source*

A large-scale facility shown in Fig. 3 has been constructed using an aluminum geodesic dome frame to support the tent that confines the mixture. The test volume is 300 $m^3$, or a scale factor of two larger than the medium-scale source, and has a nominal radius of about 5.2 m. The blast is measured inside the dome and in the free field using pressure sensors. The flame front position is monitored with ionization probes and Nanmac E-12-1-C-U fast response thermocouples. Two Vatell HFM-8E/H heat flux sensors (~10 μs time-constant) are used to measure the radiated heat from the event, and the test is documented by standard and IR video cameras.

Two stoichiometric deflagration tests have been performed with good repeatability. The flame front velocity appears to continue to accelerate beyond the ranges measured for the small- and medium-scale experiments. The examples of the overpressure histories are shown in Fig. 4. Fig. 5 shows that higher overpressures were observed on the 300-m$^3$ volume than on the 5.2

Fig. 3. Tent (300-m$^3$) for homogeneous concentration gas mixture (9.7 m (diameter of bottom) × 5.7 m (height)).

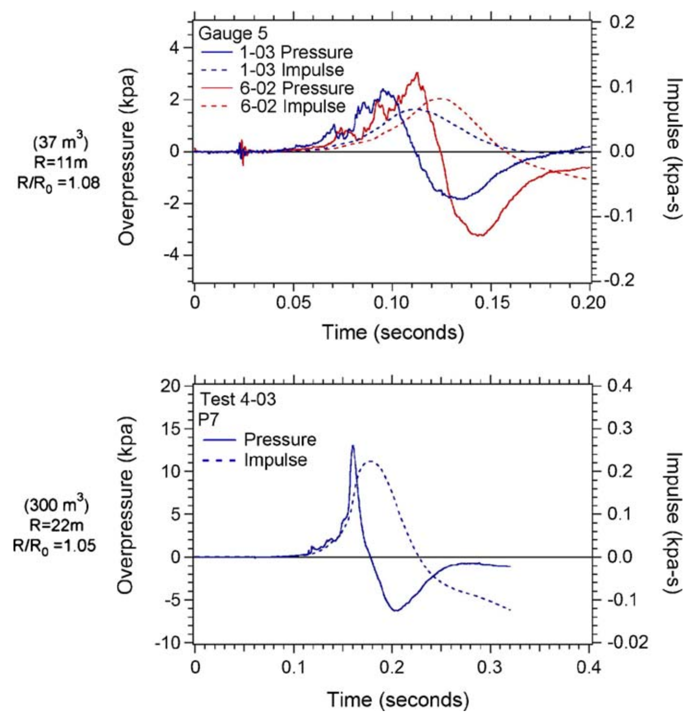


Fig. 4. Influence of hydrogen/air volume, $H_2$: 30%. Overpressure in free field.

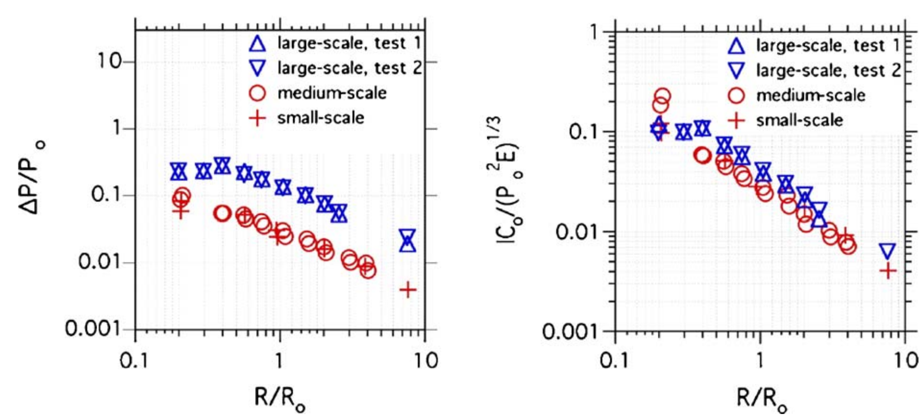


Fig. 5. Sachs-scaled data for small-, medium-, and large-scale stoichiometric deflagrations.

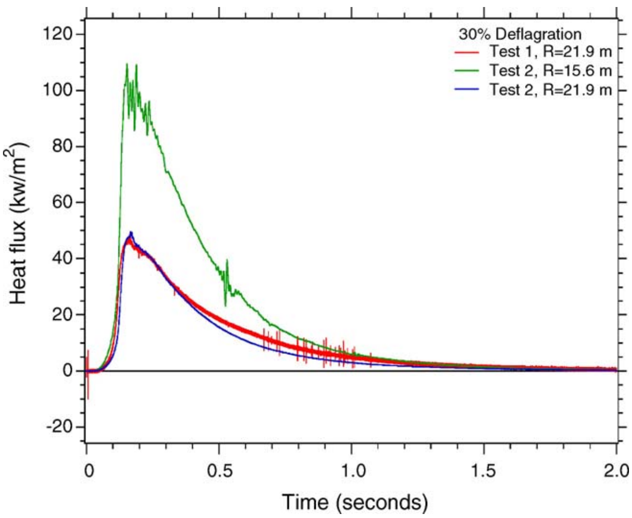


Fig. 6. Heat flux from deflagration ($H_2$ 30%, 300 $m^3$).

or 37 $m^3$ for the same scaled distance. Maximum heat flux of about 50 kW $m^{-2}$ in about 1-s duration was observed at 22 m away from the ignition point for 30% hydrogen deflagration as shown in Fig. 6.

### 3.4. Large-scale release and deflagration of hydrogen

Hydrogen has been released upward to a free field through a nozzle with a diameter of 42 mm from a storage system having a volume of 16.2 $m^3$ with the initial pressure of 2.4 MPa. The hydrogen plume spontaneously ignited at about 0.5 s after the beginning of the release. About 0.8 kg of hydrogen was released by the ignition. Observed at 20 m of the horizontal range from the release outlet were 5.1 kPa of peak overpressure and 26 Pa s of impulse. In comparison with static homogeneous 30% deflagration, higher overpressure and lower impulse were measured. Turbulence of the hydrogen flow could influence the deflagration.

### 3.5. Hydrogen deflagration in a tube

The tests were performed in a model tunnel that measured 3.74 $m^2$ in cross-sectional area by 78.5 m long, shown in Fig. 7, to examine the effects of homogeneous hydrogen/air mixture deflagration and hydrogen release deflagrations. For the homogeneous concentration tests, the gas mixture of 37 $m^3$, or 3.7 $m^3$, volume was confined to a section of the tube by attaching a sheet of polyethylene to the sides of the tube. The sheet was cut 100 ms


Fig. 7. Tube modeling a tunnel and the cross-section.

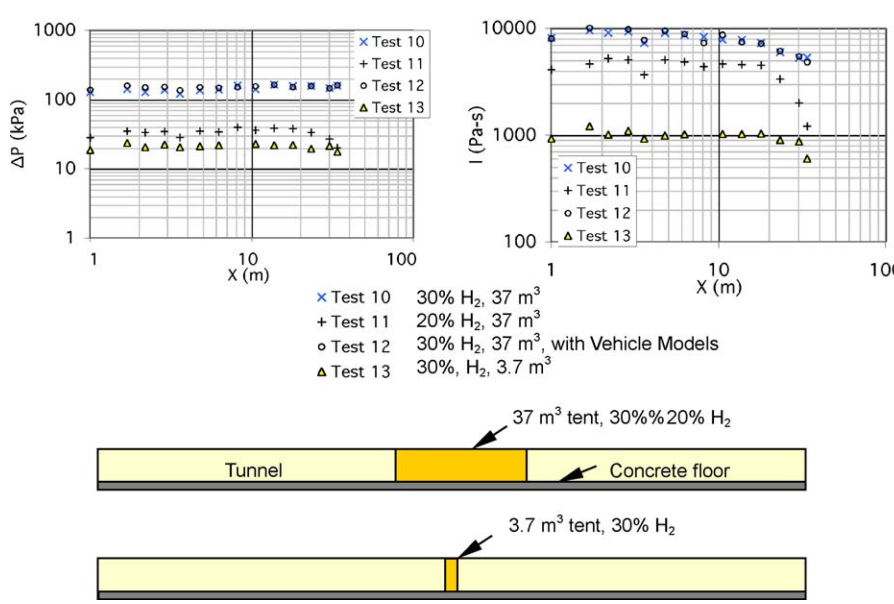


Fig. 8. Hydrogen deflagration in a tube (3.74 $m^2$ by 78.5 m-long) 3.7 $m^3$ (140 $m^3$ STP trailer cylinder, scaled volume). Scale factor = 0.2 (2.4 m/12 m).

prior to ignition of the mixture. The pressure and impulse were nearly constant over the tube length, showing a very significant enhancement of the deflagration when compared with explosions in the free field. Fig. 8 shows that the peak overpressures inside the tube from 37 $m^3$ of 30% hydrogen, 37 $m^3$ of 20% hydrogen, and 3.7 $m^3$ of 30% hydrogen were about 120–160, 27–39, and 18–23 kPa, respectively. Sachs scaling of the overpressures from 3.7 to 37 $m^3$ gave an estimated attenuation power law exponent of about 0.8. Release tests produced lean hydrogen concentrations generating pressures below the measurement capability of the sensors. For ventilated releases, the mixture concentrations were too lean to ignite. Thus, ventilating released hydrogen is thought to significantly reduce the hazard caused by deflagration.

## 4. Summary and conclusions

The deflagration tests of homogeneous hydrogen concentration have been carried out at small scale, medium scale, and at large scale. Sachs scaling could be applied to small and medium scales. The large-scale tests have shown pressures and impulses higher than would be expected if scaling holds from smaller scales. The flame front appears to continue to accelerate during the propagation, suggesting the deflagration properties may be scale dependent. The deflagrations of hydrogen inside a tube have generated a much higher pressure than in a free field. This suggests that the hazard of released hydrogen could be reduced through ventilation.

## Acknowledgment

These studies are administered through NEDO as part of the Development for Safe Utilization and Infrastructure of Hydrogen program with funding from the Agency of National Resources and Energy (ANRE) in the Ministry of Economy, Trade and Industry (METI) of Japan.

## References

[1] M. Groethe, J. Colton, S. Chiba, Hydrogen deflagration safety studies in a semi-open space, in: Proceedings of the 14th World Hydrogen Energy Conference Montreal, Québec, Canada, 9–13 June, 2002.

[2] W.P.M. Mercx (Ed.), Extended Modeling and Experiment Research into Gas Explosions — Final Summary Report for the Project EMERGE, Technical Report, TNO Prins Maurits Laboratory, Rijswijk, The Netherlands, 1997 (EC Contract EV5T-CT-93-0274).

[3] M.A. Groethe, J.D. Colton, S.A. Chiba, Y. Sato, Hydrogen deflagration at large scale, in: Proceedings of the 15th World Hydrogen Energy Conference, Yokohama, Japan, 28 June, 2004.

[4] M.J. Tang, Q.A. Baker, A new set of curves from vapor cloud explosions, Process Safety Prog. 18 (3) (1999).

[5] S.B. Dorofeev, Blast effects of confined and unconfined explosions, in: B. Strevant, J. Shepard, H. Hornung (Eds.), Proceedings of the 20th ISSW on Shock Waves, World Scientific Publishing Co., Singapore, 1996, pp. 77–86.