A FIELD EXPLOSION TEST OF HYDROGEN-AIR MIXTURES

Wakabayashi, K., Mogi, T., Kim, D., Abe, T., Ishikawa, K., Kuroda, E., Matsumura, T., Nakayama, Y., Horiguchi, S., Oya, M. and Fujiwara, S.
Research Center for Explosion Safety, National Institute of Advanced Industrial Science and Technology (AIST), Central No.5, 1-1-1 Higashi, Tsukuba, Ibaraki 305-8565, JAPAN

ABSTRACT

This paper shows the experimental results and findings of field explosion tests conducted to obtain fundamental data concerning the explosion of hydrogen-air mixtures. A tent covered with thin plastic sheets was filled with hydrogen/air mixed gas, and subsequently ignited by an electric-spark or explosives to induce deflagration and/or detonation. Several experiments with different concentrations and/or volumes of mixture were carried out. The static overpressure of blast waves was measured using piezoelectric pressure sensors. The recorded data show that the shape of the pressure-time histories of the resulting blast waves depends on the difference in the ignition method used. The pictures of the explosion phenomenon (deflagration and/or detonation) were taken by high-speed cameras.

1.0 INTRODUCTION

Hydrogen is widely expected to become a new clean source of energy for the next generation, hence the considerable focus on basic technology and equipment relating to the utilization, manufacturing, transportation, storage and supply of this substance. For instance, successfully constructing a fuel-cell car with hydrogen is remarkable. However, since hydrogen is categorized as a high risk gas and very prone to explosion, it is vital to take sufficient measures to guard against the explosion risk and thus supply hydrogen to the public safely. Before now, many research results concerning the explosion of hydrogen/air mixture were reported, and attempts were made to conduct a quantitative evaluation of the explosion strength and explosion safety [1-2], although experimental data of hydrogen/air mixture explosion with a volume of several hundred cubic meter (m^3) are relatively scarce at present [3]. Under the program on the "Safe Production and Utilization of Hydrogen" conducted by the New Energy and Industrial Technology Development Organization (NEDO), our research center advances safety studies concerning the utilization of high-pressured hydrogen at a hydrogen station for a storage and filling. We performed field explosion tests at different concentrations and/or scales to evaluate the strength of the hydrogen/air mixture explosion initiated by explosives or electric-spark and likewise the scale effect of the explosion strength. The results obtained are reported in the current paper.

2.0 EXPERIMENTAL SETUP AND RESULTS

The blast wave pressure was measured in each case using PCB piezoelectric pressure sensors HM102A12 (sensitivity = 3.6 μV/Pa, linearity = 1 % full scale, resonant frequency > 500 kHz) and HM102A07 (sensitivity = 14.5 μV/Pa, linearity = 1 % full scale, resonant frequency > 250 kHz). Each pressure sensor was flush-mounted to a sharp-edged stainless steel disk (of diameter 90 mm) in the direction. The pressure sensors were located 1 m above the ground and their output signals were recorded by the digitizer (LTT-480, Lab. Technique Tasler Co. Ltd.). The explosion phenomena were recorded by two high-speed digital color video cameras (MEMRECAM fx-K3, fx-6300 (nac Image technology, Inc.) and Phantom V5.0 (Vision Research Co., Ltd.)) and one infrared camera (TH7102WV, NEC san-ei Co., Ltd.). The trigger pulses for the ignition system and measurement instruments (digitizer, high-speed camera, etc.) were supplied from a digital delay pulse generator (BNC555, Berkeley Nucleonics Co., Ltd.).

2.1 Test with a 31 m^3 tent by explosives ignition

D The explosion tests were performed using a 31 m^3-scale cylindrical tent that was filled with hydrogen/air mixture ranging from 21 to 52.9 vol. % of hydrogen. This tent was covered by a thin plastic sheet (thickness; 0.05-0.3 mm). Hydrogen was channelled into the tent from compressed gas bottles, and mixed with the air inside. Subsequently, as the hydrogen concentration stabilized, the hydrogen/air mixture was stirred using motorized fans. Meanwhile, the concentration was continually monitored by hydrogen sensors. Composition C-4 explosive of 0.1 kg was used as a booster to initiate the mixture, with initiation energy of about 625 kilo-joules, where TNT equivalent mass of C-4 based on the overpressure was 1.37 times bigger against the mass of C-4 [4]. The booster was exploded in the center of the tent. Table 1 summarizes the experimental conditions while the experimental setup for the explosion test is shown in Fig. 1. The TNT equivalent mass was calculated based on the value of energy/mass of hydrogen (119.628 MJ/kg) [5] and TNT (4.533 MJ/kg) [6], as shown in Table 1.

Table 1. Experimental condition of hydrogen/air mixture

Main charge (hydrogen concentration, %)	Diameter A	Height H (m)	TNT Equivalent (kg)
21	3.4	3.4	14.3
28.7	3.4	3.4	19.5
52.9	3.4	3.4	13.5
C4, 2.5 kg	-	-	3.5
C4, 20 kg	-	-	28

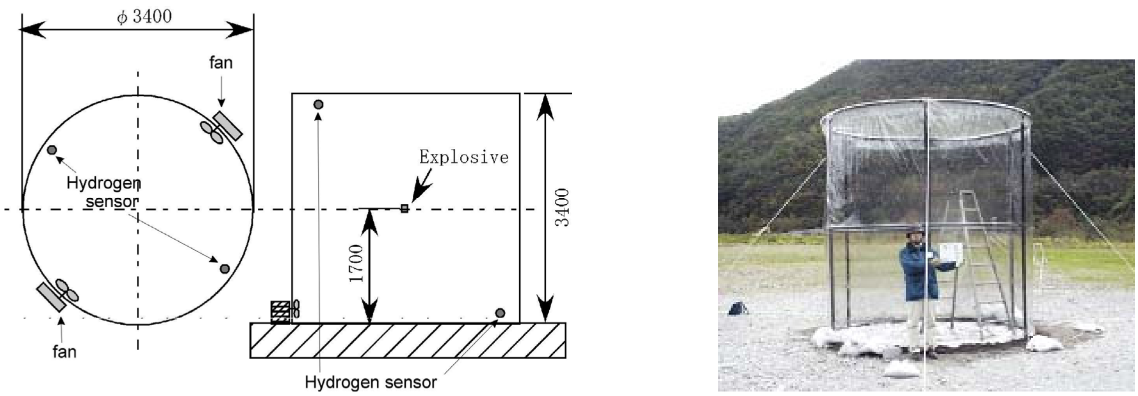

Figure 1. Experimental setup for explosion test with 31 m^3 tent

Blast wave pressures were measured at distances of 10, 18, 30, 49 and 81 m, respectively. Fig. 2 shows the typical pressure wave histories with different concentration at the same distance (10.6 m).

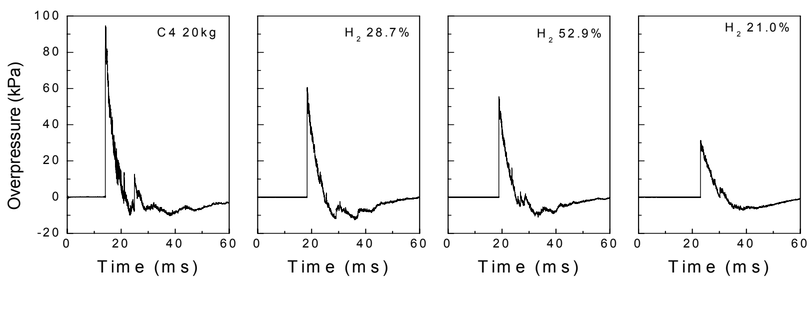

Figure 2. Blast wave histories with different concentrations at the same distance

Time zero denotes the time at which the mixture was initiated using the booster. As shown in Fig. 2, the temporal blast wave changes resulting from the explosion of the hydrogen/air mixture initiated by the explosive were similar to the typical blast waveform generated by high explosives like TNT. The temporal change in blast pressure waves were interpolated by a smooth cubic natural spline function to obtain the following 4 parameters: peak overpressure, the time of arrival, the duration of positive phase and the positive impulse (the integral pressure against the time during the positive pressure phase). Scaled peak overpressure and scaled impulse as a function of scaled distance are shown in Fig. 3.

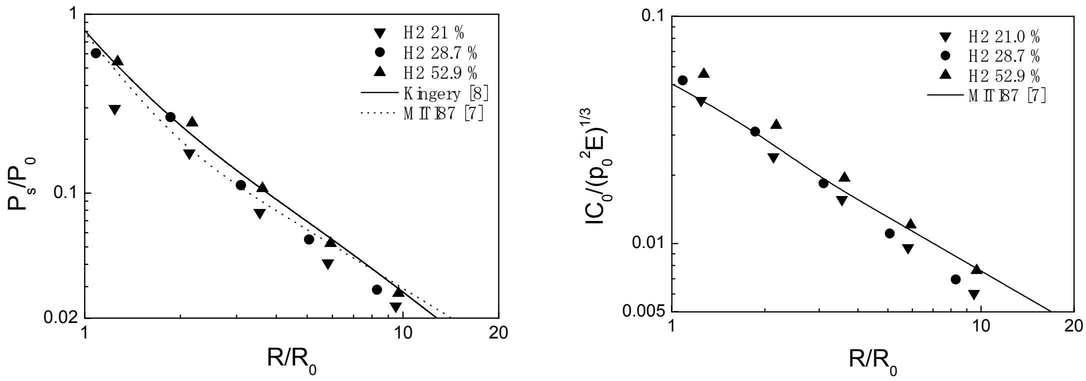

Figure 3. Scaled overpressure and impulse at different concentrations

Here, the characteristic distance is defined as $R_0 = (E/p_0)^{1/3}$, where I is the impulse, p_0; the ambient pressure and C_0; the speed of sound. E is the energy of the hydrogen/air mixture, which is calculated based on the volume of hydrogen and air inside the tent. The energy of a 0.1 kg booster was also included in E. Standard data concerning the ground surface explosion of TNT [7, 8] are also shown in Fig. 3 in graphical form, where standard data are normalized with the heat of explosion for TNT is 4564 kJ/kg [6]. The blast wave profiles initiated by the C-4 booster were almost the same as those of the TNT. In Fig. 3, the amplitude of peak overpressure was dependent on the concentration of hydrogen. The TNT equivalent of 52.9 vol. % of hydrogen was smaller than that of 21 vol. % of hydrogen (see Table 1.), but Fig. 3 shows a higher pressure peak. This is due to the fact that hydrogen at a level of 52.9 % by volume cannot react sufficiently with oxygen in the tent, and excess hydrogen reacts with the oxygen taken from the outside just after the tent breaks. As shown in Fig. 3, both overpressure and impulse increased in correlation with the hydrogen concentration. Furthermore, the overpressure and blast impulse resulting from the explosion of the mixture were the same as, or stronger than those of the TNT explosion. In particular, the impulse was approximately twice as strong as that of TNT. In other words, the energy that is expected to be generated when the hydrogen/air mixture explodes was released rapidly as fast as the explosive reactions themselves. Therefore, the hydrogen/air mixture is supposed to be guided toward detonation or a highly reactive semi-detonation condition within a moment. Furthermore, as shown as a typical example in Fig. 4, spherical emission of light was observed by the high-speed photography.

Figure 4. Typical results of high-speed photography obtained during the explosion test with 52.9 vol. % hydrogen/air mixture; initiated by a 0.1 kg booster of C-4 explosive. The photographs were respectively taken at 428 μs (left) and 628 μs (right) after initiation.

Given the possibility that the observed emission came from the reaction wave, this spherical emission could be considered to be strongly linked with the propagation of the detonation wave. Observed propagation velocity of emission was about 2170 m/s, which is almost same value of C-J detonation velocity. High-speed photography also suggested that the mixture of 52.9 vol. % hydrogen was detonated by the initiation of a 0.1 kg-explosive under these experimental conditions [9]. In the case of the explosion test with 21 vol. % of hydrogen, it was unclear whether the mixture was detonated or not, because the propagation velocity of emission was not observed.

2.2 Test initiated by electronic spark plug with tents of varying size

We performed the field-tests with a rectangular-shape tent that was filled with a hydrogen/air mixture at 29.5 % hydrogen by volume. Hydrogen mixed with air was ignited by an electric-spark in the center of the tent. Hydrogen was channelled into the tent from the compressed gas bottles and mixed with the air inside. Then, the hydrogen/air mixture was stirred using motorized fans in order to obtain a homogeneous mixture. Meanwhile, the concentration was continually monitored by hydrogen sensors. Table 2 summarizes the experimental conditions, while the experimental setup for the explosion test with the use of an electric-spark plug is shown in Fig. 5.

Table 2. The shape of the hydrogen/air mixture

Volume of tent (m^3)	Width, Depth A (m)	Height, H (m)	Shape
9.4	2.5	1.5	Rectangular
75	5	3	Rectangular
200	7	4.2	Rectangular

Significant values are two orders.

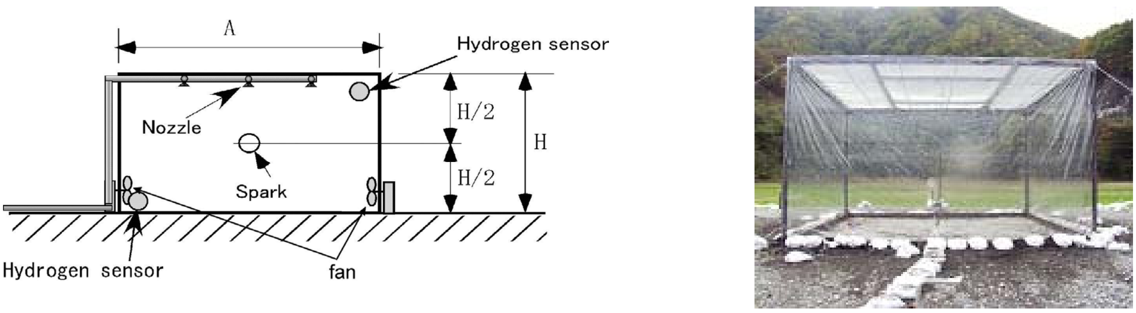

Figure 5. Experimental setup for explosion test with 200 m^3 tent

The combustion flame of the mixture generated by the spark ignition was visualized by the flame reaction of the sodium chloride solution. The photograph of the flame propagation in the tent was taken using high-speed and infrared cameras. In the case of the spark-initiation experiments, the movement of the flame front inside the tent was clearly observable through high-speed photography. The results showed that the flame front had slightly accelerated over time, and the propagation velocity of the flame front increased in accordance with time. Blast wave pressures were measured at scaled distances (R/R_0) from 0.6 to 4 using the PCB piezoelectric pressure sensors. Fig. 6 shows the typical pressure wave histories of different scale sizes at almost the same scaled distance ($R/R_0 = 0.6$).

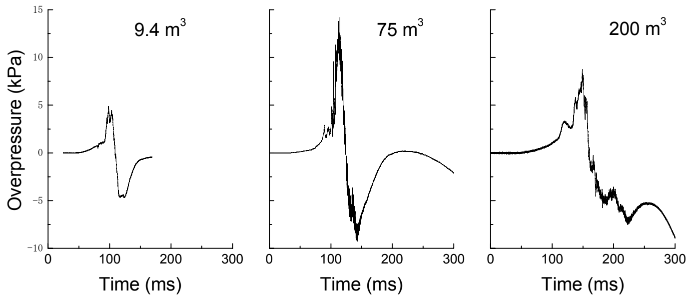

Figure 6. Pressure wave histories with different volumes at the same scaled distance

Time zero denotes the time at which the electric spark plug was activated. As shown in Fig. 6, the temporal blast wave profiles generated by the spark initiation differed from those triggered by the explosion initiated by explosives. The temporal profiles of the observed blast wave did not display any discontinuous pressure changes at the blast wave front, but the blast wave pressure gradually increased over time. Just after the blast pressure peaked, it immediately decreased to negative pressure. This figure shows that blast wave profiles of varying volume are different from each other; even at the same scale distance and the same concentration of hydrogen. This suggests that the generated pressure depends on the volume of the mixture. Scaled overpressure and impulse as a function of scaled distance are shown in Fig. 7.

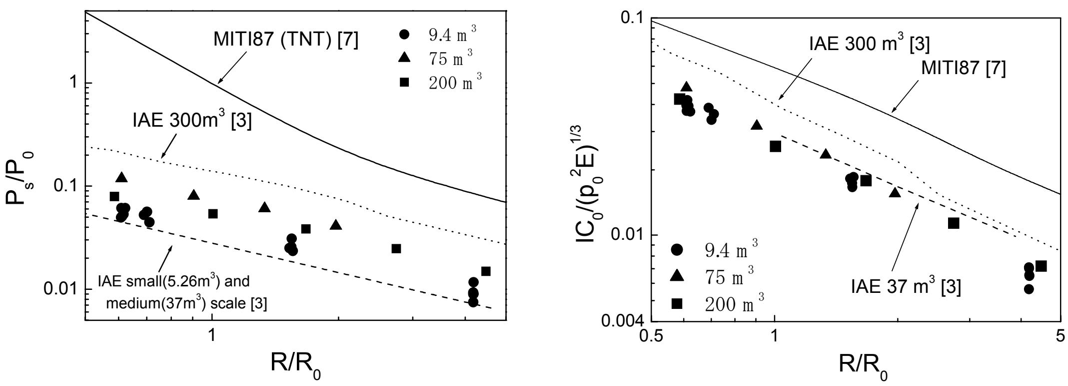

Figure 7. Scaled overpressure and impulse with different scales

Compared with literature [3], the present data obtained showed the same tendency. Scaled overpressure has a tendency toward higher pressure when the volume of the mixture increases. In addition, the scaled overpressure was 10 times smaller than the data obtained from the detonation test of the hydrogen/air mixture. On the other hand, scaled impulses were quite similar to each other, and no clear difference derived from the concentration of the scaled impulse was observed. The scaled impulse was same order of the results of the detonation test. Therefore, as described above, it seems reasonable to conclude that the scale-effect of the peak pressure and that of the impulse are different. From the viewpoint of the explosion safety, it would be important to evaluate the strength of blast wave by the impulse.

3.0 CONCLUSIONS

We performed a field explosion test with a tent filled with various hydrogen/air mixtures and the static overpressure of blast waves was measured using piezoelectric pressure sensors. The recorded data shows the shape of pressure-time histories of the resulting blast waves to be dependent on the difference in ignition method used (electric-spark or explosives). In the case of explosive initiation, it showed that the amplitude of the overpressure depends on the concentration of hydrogen. Overpressure also increased in accordance with an increased concentration of hydrogen. In the case of electric-spark initiation, the scaled overpressure was 10 times smaller than that of the obtained data with the use of the explosives initiation. It is thus understood that the scale-effect of the pressure and that of the impulse are different.

ACKNOWLEDGEMENTS

This study is part of the research for a program on the safe production and utilization of hydrogen, conducted by the New Energy and Industrial Technology Development Organization (NEDO) and the Agency of National Resources and Energy (AMRE) in the Ministry of Economy, Trade and Industry (METI) of Japan.

REFERENCES

1. Mizuta, Y., Nakayama,Y., Kim, D., Wakabayashi, K., Matsumura, T., Mogi, T., Horiguchi, S., Miyake, A. and Ogawa, T., The effect of the mixture composition on the explosion behaviour of hydrogen/air mixture, Proceedings of Kayakugakkai, 11-12 Nov. 2004, Matsuyama, Japan.
2. Saitoh, H., Mizutani, T., Ohtsuka, T., Uesaka, N., Morisaki, Y., Matsui, H. and Yoshikawa, N., A field experiment of hydrogen-air deflagration, Sci. Tech. Energetic Materials, **65**, No. 4, 2004, pp. 140-146.
3. Groethe, M., Colton, J., Chiba, S. and Sato, Y., Hydrogen Deflagrations at Large Scale, Proceedings of 15th World Hydrogen Energy Conference, 27 June-2 July 2004, Yokohama, Japan.
4. Swisdak, M. M. Jr., NSWC Technical Report, Explosion effect and properties part1-explosions in air, 1975, NAVAL SURFACE WEAPONS CENTER.
5. Kimura, I. and Sakai, T., Nainen-kikan, 1980, Maruzen Co., Ltd (in Japanese).
6. Meyer, R., Explosives Third, revised and extended edition, 1987, VCH Verlagsgesellschaft, Federal Republic of Germany.
7. Nakayama,Y., Yoshida, M., Kakudate, Y., Iida, M., Ishikawa, N., Kato, K., Sakai, H., Usuba, S., Aoki, K., Kuwabara, N., Tanaka, K., Tanaka, K. and Fujiwara, S., Explosions of composite propellants by ultra-high pressure initiation (2)TNT equivalences, Kogyo Kayaku, **50**, No. 2, 1987, pp. 88-92.
8. Kingery, C.N., and Pannill, B.F., BRL Memorandum Report No. 1518, 1964.
9. Makeev, V.I., Gostintsev, Y.A., Strogonov, V.V., Bokhon, Y.A., Chernushkin, Y.N. and Kulikov, V.N., Combustion and detonation of hydrogen-air mixtures in free spaces, Combustion, Explosion and Shock Waves, **19**, No. 5, 1984, pp. 548-550.