Research paper

Blast waves generated by detonation of 31 m^3 hydrogen-air mixtures

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Abstract
Field explosion tests of three hydrogen-air mixtures having a volume of 31 m^3 were carried out. The hydrogen contents of the mixtures were 21.0, 28.7, and 52.9 volume %. Each mixture was ignited by 0.1 kg of Composition C-4 explosive and guided to detonation. Blast waves caused by detonation of a mixture were measured by piezoelectric pressure sensors. The measured peak overpressures and impulses were comparable in intensity to those of the TNT equivalent in lower heating value. The results reveal that the strength of a blast wave generated by detonation of a hydrogen-air mixture is approximately the same as that of a TNT explosive.

Keywords: Field explosion test, Hydrogen-air mixture, Explosive ignition, Detonation, Blast wave

1. Introduction

Among known fuels, hydrogen has the highest energy content per unit mass, giving hydrogen great potential as a powerful energy source. When hydrogen is burned for use as a fuel, the main waste product is water such as CO_2 free. Therefore, use of hydrogen as an energy source reduces environmental loads as compared with commonly used hydrocarbon fuels such as gasoline. For this reason, hydrogen is expected to become a new clean source of energy for the next generation.

However, safety measures are very important when hydrogen is used, because hydrogen explodes easily, having an ignition energy as low as 0.019 mJ [1] at stoichiometric mixture (30 vol.% hydrogen), and a wide flammability limit in air (4-75 vol.% hydrogen [2]). Consequently, devising sufficient safety measures against the explosion of hydrogen requires evaluating the explosion strength of hydrogen-air mixture under extremely serious conditions, such as detonation.

To date, many research results have been reported in relation to the evaluation of explosion strength and explosion safety of hydrogen-air mixtures [3), 4)]. Many explosion experiments have been performed with laboratory-scale mixtures; however, at present, large-scale explosion data of hydrogen-air mixture with volumes of several tens of cubic meters (m^3) are relatively scarce [5)].

We performed field explosion tests to evaluate the strength of a blast wave generated by detonation of 31 m^3 mixtures with different hydrogen contents ignited by explosives.

2. Experimental setup

2.1 Experimental condition of hydrogen-air mixtures

The explosion test was performed by means of a cylindrical tent (diameter 3.4 m, height 3.4 m) having a volume of 31 m^3. The tent was covered by thin polyvinyl chloride sheets (PVC sheets, thickness: 0.3 mm) subjected to anti-electrostatic treatment. Hydrogen was introduced into the tent from compressed gas bottles, and mixed with the air inside. The resultant hydrogen-air mixture was stirred by motorized fans to stabilize and homogenize the mixture. The concentration was continually monitored by hydrogen sensors located at upper and lower positions inside the tent. A 0.1 kg of Composition C-4 with two detonators (RP501, RISI, Inc.) was used as a booster to ignite the mixture. Ignition energy was about 625 kilo-joules [6)], where calculated TNT equivalent mass of Composition C-4 based on the overpressure was 1.37 times the mass of Composition C-4 [7)]. The booster was detonated in the

Table 1 Experimental conditions of hydrogen-air mixtures.

Concentration of hydrogen (vol. %)	Temperature inside tent (°C)	Ambient temperature (°C)	Ambient pressure (hPa)	TNT equivalent (kg)
21.0	16.9	16.6	978.0	14.2
28.7	22.1	17.6	981.0	19.1
52.9	21.8	19.8	978.0	13.2

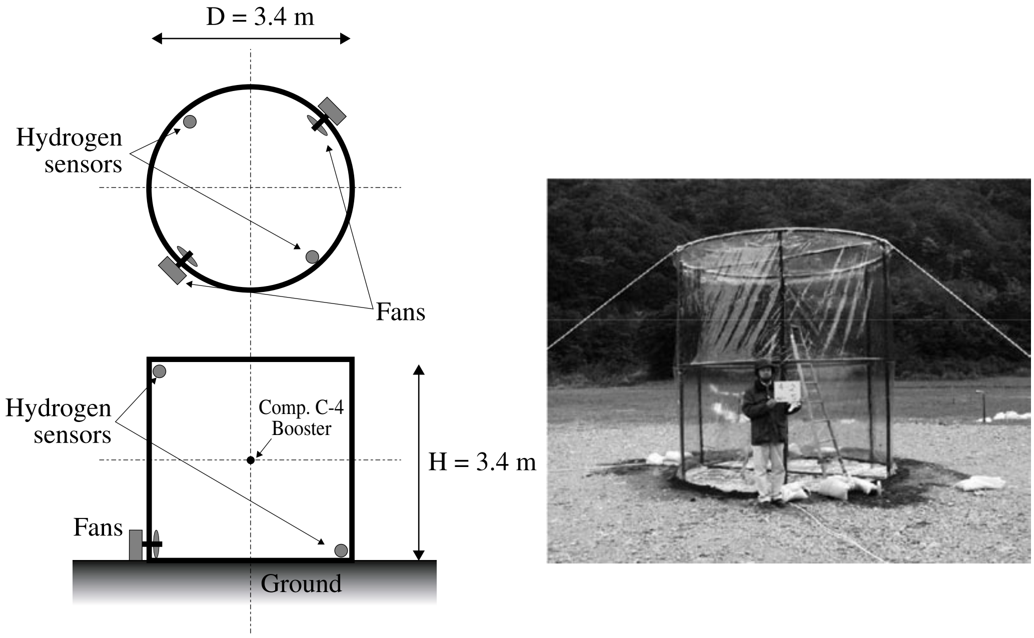

Fig. 1 Experimental setup for explosion test.

center of the tent. Table 1 summarizes the experimental conditions, and Fig. 1 shows the experimental setup for the explosion test. As shown in Table 1, the TNT equivalent mass was calculated on the basis of lower heating value of hydrogen (119.628 MJ · g^{-1})[8] and heat of explosion of TNT (4.533 MJ · kg^{-1})[6].

2.2 Measurement apparatus

Blast wave pressures were measured by piezoelectric pressure sensors (HM102A12 and HM102A07, PCB Piezotronics, Inc.). Each pressure sensor was flush-mounted to a sharp-edged stainless steel disk of 90 mm in diameter. The pressure sensors were located 1 m above the ground, and their output signals were recorded by a digitizer (LTT-184, Labotechnik Tasler GmbH). The explosion phenomena were recorded by high-speed digital color video cameras (MEMRECAM fx-K3 (NAC Image Technology, Inc.) and Phantom V5.0 (Vision Research Co., Ltd.)). The trigger pulses for the firing system (FS43, RISI, Inc.) and measurement instruments (digitizer, high-speed cameras) were supplied from a digital delay pulse generator (BNC555, Berkeley Nucleonics Co., Ltd.).

3. Results and discussion

3.1 High-speed photography of hydrogen-air detonation

Explosion tests were performed for three kinds of mixture: fuel lean (hydrogen content: 21.0 vol.%), nearly stoichiometric (28.7 vol.%) and fuel rich (52.9 vol.%) conditions. As an example, Fig. 2 shows high-speed photographs taken in the experiment for the mixture with 52.9 vol.% hydrogen. The emission observed at the center of the tent originated from flame generated by the explosion of a booster. Spherical emission of light is also visible in this figure. This emission propagated inside the tent with time, at a propagation velocity of about 2170 m·s^{-1}. The observed emission is considered to have originated from combustion and / or explosive reaction zone of hydrogen and air, in view that its propagation velocity (2170 m·s^{-1}) is almost the same value of C-J detonation velocity[9] at 52.9 vol.% hydrogen. This emission was also observed in the case of the mixture with 28.7 vol.% hydrogen. High-speed photography suggests that mixtures of 28.7 and 52.9 vol% hydrogen are detonated under this experimental condition.

In the case of the explosion test with a mixture of 21.0 vol.% hydrogen, the emission was not observed under the same photographic condition as in the 52.9 vol.% hydrogen experiment. Therefore, whether or not the mixture of

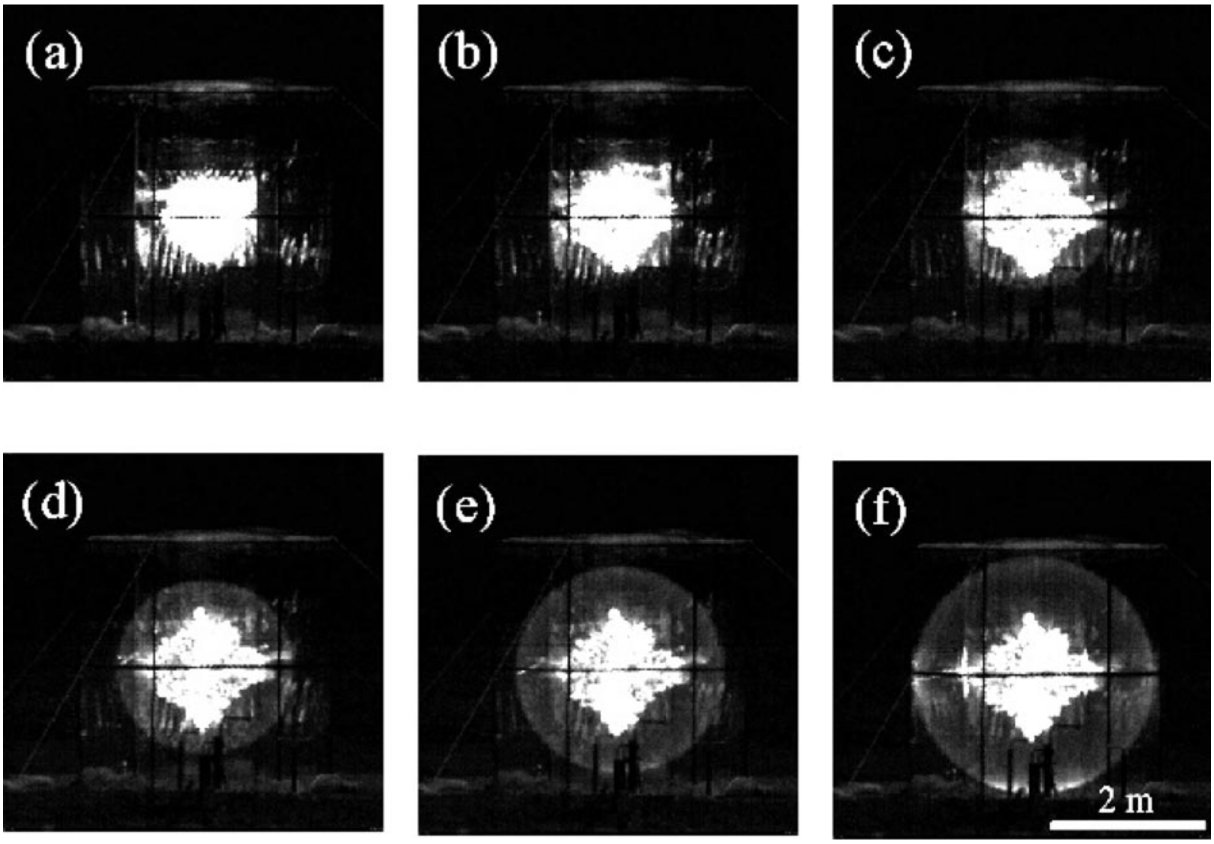

Fig. 2 Typical results of high-speed photography obtained during the explosion test with 52.9 vol.% hydrogen-air mixture, (a): 228 μs, (b): 328 μs, (c): 428 μs, (d): 528 μs, (e): 628 μs, (f): 728 μs after ignition of Composition C-4.

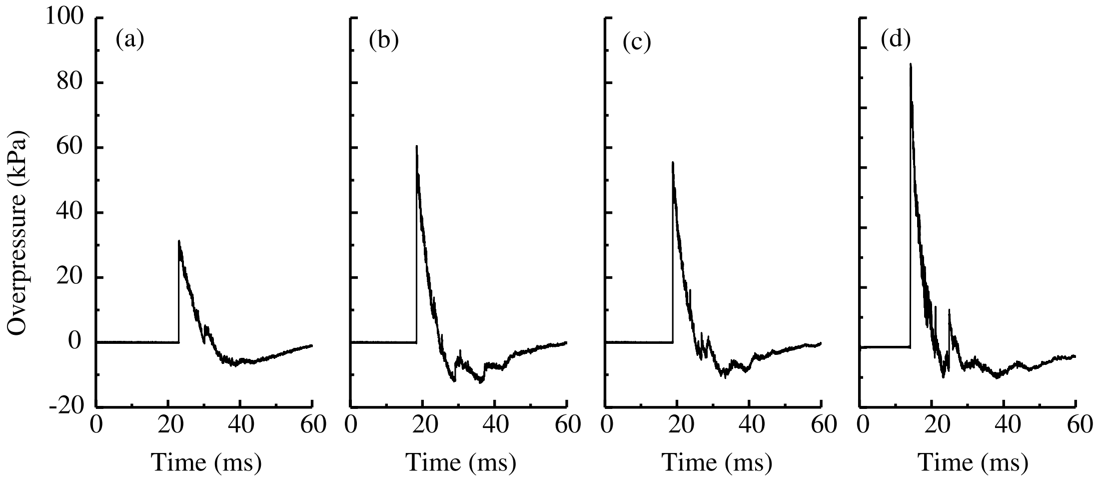

Fig. 3 Pressure wave histories with different hydrogen concentrations measured at same distance (10.6 m), (a): 21.0 vol.%, (b): 28.7 vol.%, (c): 52.9 vol.%, (d) shows typical blast wave profile generated by explosion of 20 kg TNT explosive.

21.0 vol.% hydrogen was detonated remains uncertain. However, according to the reference [10], the mixture of 21.0 vol.% hydrogen is supposed to also be detonated with the employed booster.

3.2 Blast wave generated by hydrogen-air detonation

Blast wave pressures were measured at distances of 10.6, 18.2, 30.3, 49.7, and 81.3 m. Figure 3 shows the typical pressure wave histories for different concentration at the same distance (10.6 m). Time zero denotes the time at which the mixture was ignited by a booster. As shown in Fig. 3, the blast wave resulting from explosion of the hydrogen-air mixture ignited by a booster shows discontinuous pressure changes at the blast wave front. The blast wave profile of the mixture is similar to that of high explosives such as TNT. Peak overpressures of blast wave measured at the same distance depend on the concentrations of hydrogen.

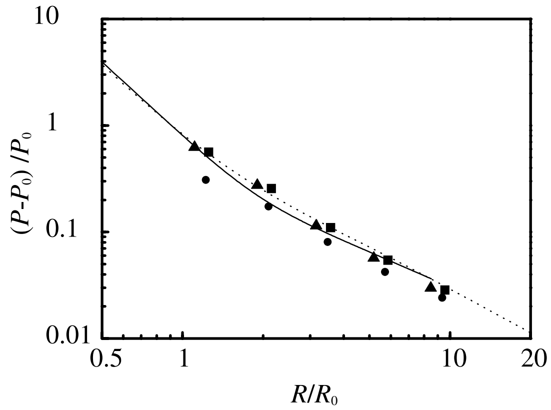

Fig. 4 Scaled peak overpressure with different hydrogen concentrations.
This work (●: 21.0 vol.%, ▲: 28.7 vol.%, ■: 52.9 vol.%), dotted line: Kingery data [12], solid line: MITI87
(Average temperature: 17.7 °C [13] and average ambient pressure: 954 hPa [13] were used).

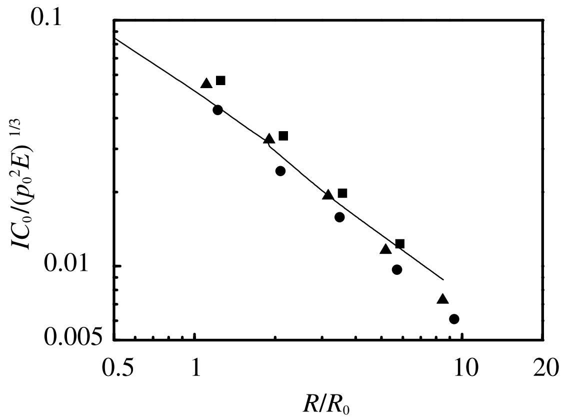

Fig. 5 Scaled impulse with different hydrogen concentrations.
This work (●: 21.0 vol.%, ▲: 28.7 vol.%, ■: 52.9 vol.%), solid line: MITI87
(Average temperature: 17.7 °C [13] and average ambient pressure: 954 hPa [13] were used).

3.3 Scaled peak overpressures and impulses

Scaled peak overpressure [5] ($(p-p_0)/p_0$) and scaled impulse [5] ($IC_0/(p_0^2E)^{1/3}$) are shown as functions of scaled distance (R/R_0) in Fig. 4 and Fig. 5, respectively. Here, the characteristic distance is defined as $R_0 = (E/p_0)^{1/3}$, where p_0 is ambient pressure and C_0 is the speed of sound. E is the lower heating value of the hydrogen-air mixture, which is calculated from the volume of hydrogen and air inside the tent. The energy of a booster is also included in E. The characteristic parameters of a blast wave p-p_0: peak overpressure, I: impulse (the integration value of the positive phase of overpressure), the time of arrival and the duration of positive phase) were derived by interpolating a smooth cubic natural spline function with respect to the measured blast wave. The effect of thin plastic sheet on blast wave was neglected here. Published data of surface burst of TNT [11)-13)] are also shown in Fig. 4, where published data are normalized by the heat of explosion for TNT [6].

The measured peak overpressures (Fig. 4) and impulses (Fig. 5) of the mixtures are comparable in intensity to those of the TNT equivalent in lower heating value. These results indicate that when the mixture was detonated, the blast wave generated by detonation of hydrogen-air mixtures had approximately the same strength as that of TNT explosive. More specifically, both measured peak overpressure and impulse are slightly stronger than those of the TNT explosion at close range (R/R_0~1), and slightly weaker at long range (R/R_0~10). This tendency is attributed to the height of burst [7], shape and size of explosion source, and other parameters.

Figure 4 shows that the amplitude of peak overpressure is dependent on the concentration of hydrogen. Scaled peak overpressure generated by explosion of the mixture with 52.9 vol.% hydrogen is higher than that of the mixture with 21.0 vol.% hydrogen, even though the TNT equivalent of the mixture with 52.9 vol.% hydrogen is smaller than that of the mixture with 21.0 vol.% hydrogen (see Table 1.). This can be interpreted as follows. Since the mixture with 52.9 vol.% hydrogen cannot react sufficiently with oxygen inside the tent, excess hydrogen is thought to react with oxygen taken from the outside just after rupture of the PVC sheet covering the tent. Experimental results suggest a possibility that the secondary combustion or explosion contributes to the strength of the blast wave.

4. Conclusion

Field explosion tests of hydrogen-air mixtures with different concentrations (21.0, 28.7 and 52.9 volume% hydrogen) and with a volume of 31 m^3 were carried out. The mixtures were detonated by a 0.1 kg of Composition C-4. The measured peak overpressures and impulses are comparable in intensity to those of the TNT equivalent in lower heating value. The strength of blast wave generated by detonation of hydrogen-air mixtures was revealed to be approximately the same as that of TNT explosive.

Acknowledgments

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31 m^{3}の水素-空気混合気体の爆轟によって発生した爆風

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31 m^3 規模の水素濃度の異なる三種類の水素 - 空気混合気体（21.0, 28.7, 52.9 volume %）を用い、野外爆発実験を実施した。0.1 kg のコンポジション C-4 爆薬を用いて点火し、混合気体を爆轟させた。ピエゾ圧電効果素子で爆風圧の測定を行った結果、測定されたピーク過圧とインパルスの強度は混合気体の低発熱量と等価な TNT 爆薬の爆発によって発生する爆風に匹敵することがわかった。水素 - 空気混合気体の爆轟によって発生する爆風の威力は TNT 爆薬によるものとほぼ同程度であることが明らかとなった。

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