Letter

Experimental study on blast wave generated by deflagration of hydrogen-air mixture up to 200 m^3

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Abstract
Field explosion tests have been performed to obtain fundamental data concerning the explosion strength generated by a stoichiometric mixture of hydrogen and air. Hydrogen-air mixtures filled in a tent covered with thin plastic sheets were ignited by an electric spark to explode. The generated blast wave was measured with piezoelectric pressure sensors. Deflagration tests with volumes of 9.4, 75, and 200 m^3 were carried out to investigate the scale effect (i.e. volume dependency) of peak overpressure and blast wave impulse. Obtained data show that peak overpressure and impulse exhibit different volume dependencies.

Keywords: Stoichiometric mixture of hydrogen and air, Electric spark ignition, Deflagration, Blast wave, Scale effect

1. Introduction
Hydrogen has been widely expected to become a new clean source of energy for the next generation. For instance, a fuel-cell car driven by hydrogen is expected to be realized. However, since hydrogen is categorized as a highly dangerous gas and very prone to explode, taking sufficient measures to guard against the explosion risk is vital, to supply hydrogen to the public safely. So far, many research results concerning the explosion of hydrogen-air mixtures have been reported, and attempts were made to conduct a quantitative evaluation of explosion strength and explosion safety [1), 2)], although experimental data of hydrogen-air mixtures explosion with a volume of several hundred cubic meter (m^3) are relatively scarce at present [3)].

We performed field explosion tests with volumes of 9.4, 75, and 200 m^3 to evaluate the deflagration strength of the hydrogen-air mixture ignited by an electric spark.

2. Experimental setup
2.1 Experimental condition of hydrogen-air mixtures
Explosion tests were performed with stoichiometric mixtures of hydrogen and air (29.5 % hydrogen by volume in theory). Hydrogen was introduced from compressed gas bottles into a rectangular-shaped tent covered with thin plastic sheet (thickness: 0.3 mm) and mixed with the inside air. Then, the hydrogen-air mixture was stirred by motorized fans in order to obtain a homogeneous mixture.

Table 1 Experimental conditions of hydrogen-air mixtures.

Volume of tent* (m^3)	Width, Depth*;A (m)	Height*; H (m)	Concentration of hydrogen (measured) (vol. %)	Ambient temperature (°C)	Ambient pressure (hPa)	TNT equivalent (kg)
9.4	2.5	1.5	27.8	27.7	981.9	5.5
75	5.0	3.0	30.4	4.5	967.0	49
200	7.0	4.2	30.7	17.3	972.0	125

*Significant values are two orders.

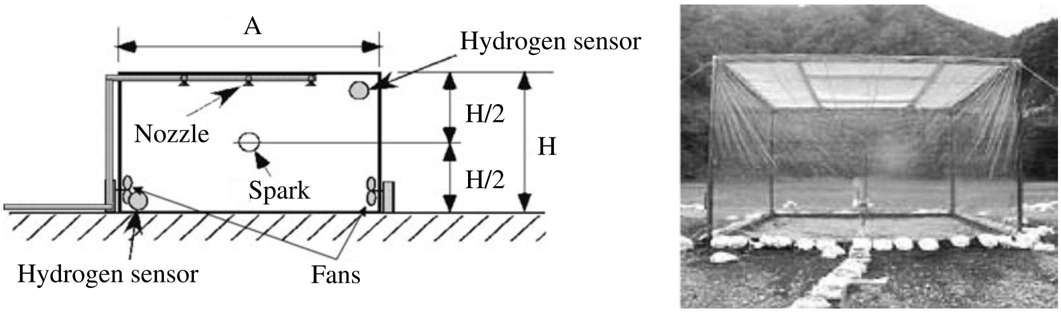

Fig. 1 Experimental setup for explosion test.

Meanwhile, the concentration was continually monitored by hydrogen sensors located at the floor and ceiling of the tent. Ignition was produced at the center of the tent by an electric spark generated by a discharge electrode with a 3.5 mm gap and a neon sign transformer (15 kV, 20 mA). Table 1 summarizes the experimental conditions. The trinitrotoluene (TNT) equivalent was calculated from the volume of hydrogen and air in the tent and the value of energy/mass of hydrogen (119.95 $MJ \cdot kg^{-1}$) [4] and that of TNT (4.533 $MJ \cdot kg^{-1}$) [5], as also shown in Table 1. The experimental setup is shown in Fig. 1.

2.2 Blast wave measurement

Blast wave pressure was measured with piezoelectric pressure sensors (HM102A12 and HM102A07, PCB Piezotronics, Inc.). Each pressure sensor was flush-mounted to a sharp-edged stainless steel disk (90 mm diameter), and located 1 m above the ground. Output signals from pressure sensors were recorded by the digitizer (LTT-184, Labotechnik Tasler GmbH). The trigger pulses for the ignition system and digitizers were supplied from a digital delay pulse generator (BNC555, Berkeley Nucleonics Co., Ltd.).

The explosion phenomena were recorded by high-speed digital color video cameras (MEMRECAM fx-K3, fx-6000 (nac Image technology, Inc.) and/or Phantom V5.0 (Vision Research Co., Ltd.)) and one infrared camera (TH7102WV, NEC san-ei Co., Ltd.). These results will be reported elsewhere in detail.

3. Results and discussion

3.1 Blast wave generated by deflagration

Typical photograph of explosion phenomenon of hydrogen-air mixture with volumes of 200 m^3 was shown in Fig. 2, which was taken at 400 ms after an electric spark ignition.

Blast wave pressures were measured at scaled distances (R / R_0) from 0.5 to 5. Here, R is the distance from the center of the tent to the location of pressure sensors, and the characteristic distance is defined as $R_0 = (E / p_0)^{1/3}$, where p_0 is ambient pressure and E is net heating value of the hydrogen-air mixture [4, 5] (see Table 1). Figure 3 shows the typical pressure wave histories of different scale sizes at almost the same scaled distance ($R / R_0 \sim 0.6$). Time zero denotes the time of activation of the electric spark plug. As shown in Fig. 3(a)-(c), the temporal blast wave profiles generated by an electric spark ignition differed from those generated by high explosives such as TNT [5] (Fig. 3(d)).

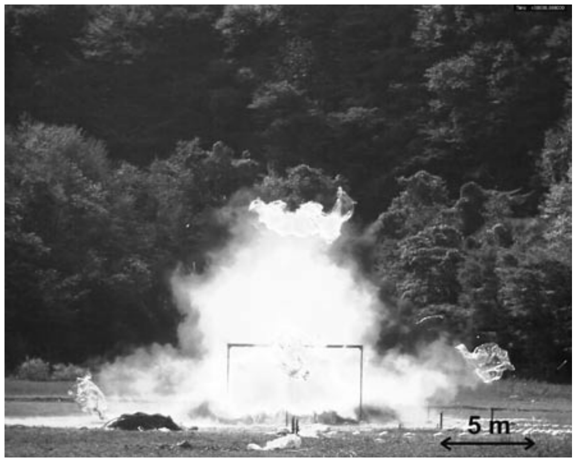

Fig. 2 Typical photograph of explosion phenomenon of hydrogen-air mixture with volumes of 200 m^3, taken at 400 ms after an electric spark ignition.

The temporal profiles of the observed blast wave did not show any discontinuous pressure changes at the blast wave front. Initially, the blast wave pressure gradually increased with time. Just after the blast pressure peaked, it immediately decreased to negative pressure. This figure also shows that blast wave profiles of varying volumes differ from each other, even at the same scaled distance and at the same concentration of hydrogen. These results suggest that the generated blast wave depends on the volume of the mixture.

3.2 Scale effect of scaled peak overpressures and scaled impulses

Scaled peak overpressure [3] ($(p-p_0) / p_0$) and scaled impulse [3] ($IC_0 / (p_0^2 E)^{1/3}$) are shown as functions of scaled distance (R / R_0) in Fig. 4 and 5, respectively, where I is the impulse and C_0 is the speed of sound. The temporal change in blast pressure waves was interpolated by cubic spline functions to obtain the peak overpressure, the impulse (the integral pressure against the time during the positive pressure phase), and other parameters. The effect of thin plastic sheet on blast wave was neglected here. The obtained data showed the same tendency as those of a reference [3]. Scaled peak overpressure observed tends to be higher when the volume of the mixture increases. In addition, such overpressure was several ten times smaller than that which was expected [6] by TNT equivalence of a hydrogen-air mixture. Scaled impulses observed also

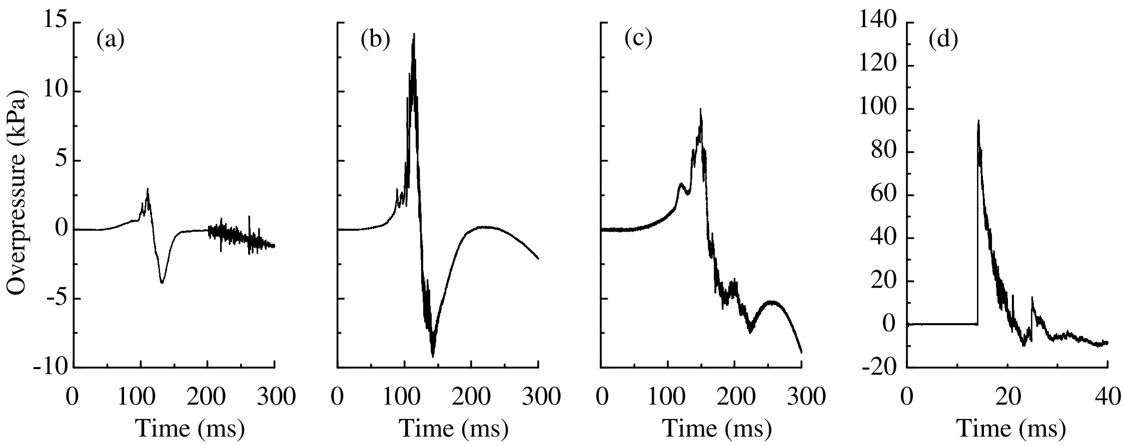

Fig. 3 Pressure wave histories with different volumes at almost the same scaled distance ($R / R_0 \sim 0.6$), (a): 9.4 m^3, (b): 75 m^3, (c): 200 m^3. (d) shows typical blast wave profile generated by explosion of 20 kg TNT explosives (measured at 10.63 m from the center of explosives).

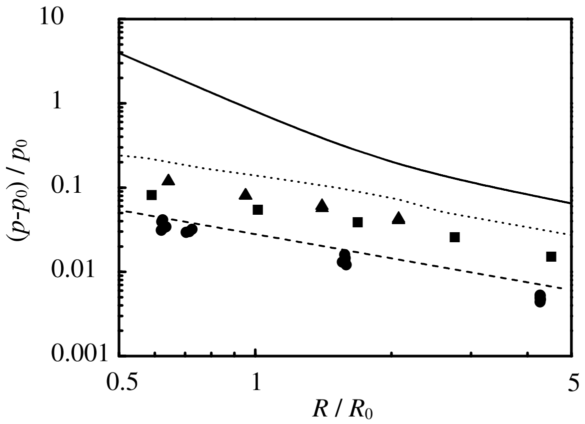

Fig. 4 Scaled peak overpressure with different volumes. This work (● : 9.4 m^3, ▲ : 75 m^3, ■ : 200 m^3), solid line: MITI87[6)], dotted line: IAE 300 m^3 scale[3)], broken line: IAE 5.26 m^3 and 37 m^3 scale[3)].

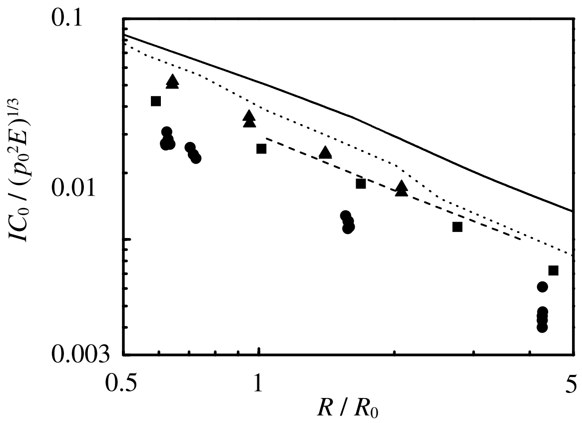

Fig. 5 Scaled impulse with different volumes. This work (● : 9.4 m^3, ▲ : 75 m^3, ■ : 200 m^3), solid line: MITI87[6)], dotted line: IAE 300 m^3 scale[3)], broken line: IAE 5.26 m^3 and 37 m^3 scale[3)].

tend to be higher with increasing the volume of mixture. However, scale effect of the scaled impulse was not shown notably compared to that of the scaled peak overpressure. Furthermore, the scaled impulse was of the same order as that expected by TNT equivalence of a hydrogen-air mixture. As described above, peak overpressure and impulse are considered to exhibit different volume dependencies. Generally, the damage which would be caused by blast wave generated by explosion has been evaluated and predicted from the amplitude of peak overpressure [7)]. However, in actuality, the scale of damage depends on both peak overpressure and impulse. As compared with a blast wave generated by equivalent explosives, the blast wave generated by the deflagration of a stoichiometric mixture of hydrogen and air ignited by electric spark has a low peak overpressure and a long duration. Therefore, from the viewpoint of safety assessment, evaluating the strength of blast wave by not only the peak overpressure but also the impulse under the deflagration conditions would be important.

4. Conclusion

Field explosion tests were performed with volumes of 9.4, 75 and 200 m^3 filled with stoichiometric hydrogen-air mixtures. Hydrogen-air mixtures were ignited by an electric spark and then the blast wave generated by the deflagration was measured with piezoelectric pressure sensors. The scaled overpressure observed was several ten times smaller than that which had been expected by TNT equivalent of a hydrogen-air mixture. However, the scaled impulse observed was of the same order as expected impulse. Peak overpressure and impulse exhibit different scale effects.

Acknowledgments

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200 m^3 までの水素-空気混合気体の爆燃によって発生した爆風の実験的研究

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化学量論比程度の水素-空気混合気体を電気火花によって点火し，発生した爆風をピエゾ圧力効果素子で測定した。体積が9.4, 75, 200 m^3 の混合気体を用いて爆燃実験を行い，爆風のピーク過圧とインパルスの評価を行った。実験結果から，ピーク過圧とインパルスは規模効果が異なることが示された。

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