Study on Intensity of Blast Wave Generated from Vessel Bursting by Gas Explosion

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1 Introduction

Recently the blast waves from gas explosions have been studied by many researchers experimentally and theoretically. In most researches, unconfined gas explosions were examined to understand the dynamics of blast waves. On the recent experimental studies, flammable mixtures were confined in bubbles or plastic tents, which easily broke after ignitions and the phenomena were almost similar as unconfined gas explosions [1, 2]. The relation between the intensity of blast wave from unconfined gas explosion and the behavior of flame propagation has been investigated. However, accidental gas explosions occur not only in open space but also in confined space. If vessels which make up confined spaces such as buildings or tanks cannot hold the pressure increasing by gas explosions, the vessels will burst and blast waves will be generated. The blast wave is influenced by the bursting vessels and different from the blast wave generated from an unconfined gas explosion.

There is a little research about the blast waves from bursting vessels nevertheless the vessels were often burst at actual accidental gas explosions. Baker developed the blast model from bursting spherical vessels by high pressure [3]. The model was experimentally examined by Esparza and Baker [4]. However, this model didn't consider combustion reaction. It is questionable that the blast model can be applied to the blast wave from gas explosions. The blast waves from bursting vessels by gas explosions haven't ever been well studied.

In this study, to investigate the blast wave from bursting vessels as a result of excessive high pressure raised by gas explosions, explosion experiments were performed in vessels which had various strengths. The relation between measured blast waves and the pressure in the vessels when vessels burst was investigated. The main factor which effected to the intensity of blast waves was investigated.

2 Experimental Setup

Figure 1 shows schematic diagram of the apparatus of this experimental setup. The vessel was cubic and the volume was 0.125 m^3. It consisted of stainless steel frame and six walls. The bottom of the vessel was a stainless steel plate. As the other five walls the poly vinyl chloride (PVC) plates were fixed to the stainless steel frame. The thicknesses of PVC plates were varied to change the pressure in the vessel when vessel burst. In case of five walls bursting, the thicknesses of five walls were same. On the other hand in case of one wall bursting, only one wall was thin and the others were thick. The thicknesses of the PVC plates used in this study were 0.5, 1, 2, 3, 4, 5 and 6 mm. Also thin polyethylene sheets were used as the walls to obtain the data of unconfined gas explosions. Flammable gases were supplied to the bottom of the vessel from a cylinder and the mixture in the vessel was circulated by the pump to make a uniform flammable mixture whose pressure was same as the atmospheric pressure. Stoichiometric mixtures of hydrogen, methane or propane in air were used. The physical properties of mixtures were summarized in Table 1. The mixture in the vessel was sampled during circulation to measure concentration of flammable gas using a gas concentration measuring instrument (Riken Keiki, FI-21).

Pressure sensors (PCB Piezotronics, 106B52) were located at the positions 5 m, 10 m, 20 m and 50 m away from the center of the vessel and in the four different directions from it to measure the pressures of blast waves. Also a pressure sensor (KYOWA, PGM-1KG, PHL-A-1MP-B or PHL-A10MP-B) was installed to the bottom of the vessel to measure the pressure in the vessel. The pressure histories were recorded by the digital oscilloscope (YOKOGAWA, DL850). The phenomena of explosions were captured by a high-speed digital color video camera (Photron, FASTCAM SA2) and a high-speed digital monochrome video camera (Vision Research, Phantom IR300) with a long pass filter (ASAHI SPECTRA, LI0990, λ>990 nm). The pulse delay generator (Berkeley Nucleonics, BNC505-2c) send a signal to igniter (LECIP, 100-7G) and an electronic spark was made at the center of the vessel to ignite flammable mixtures. Two high speed cameras and the digital oscilloscope started to record simultaneously when they received the signal from the pulse delay generator.

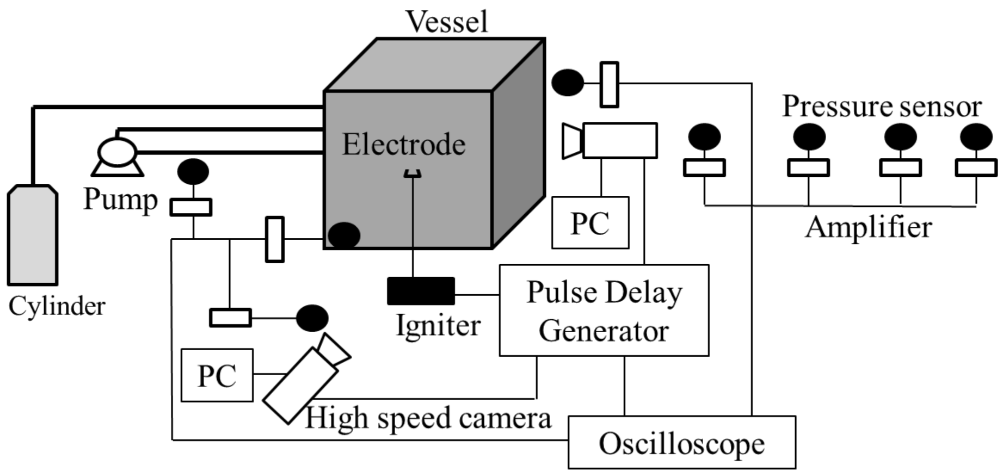


Figure 1, Experimental setup.

Table 1: Physical properties of flammable mixtures used in this experiment.

Stoichiometric mixture, Initial pressure: 101.3 kPa, Initial temperature: 298 K

Flammable mixtures	Final pressure in the vessel (gauge pressure)*1 / kPa	Specific heat ratio of burned mixture*1	Flame Temperature*1 / K	Laminar burning velocity [6] / m s^{-1}
Hydrogne-air	809 (708)	1.168	2747.3	1.9
Methane-air	890 (789)	1.174	2586.1	0.38
Propane-air	943 (842)	1.170	2629.4	0.42

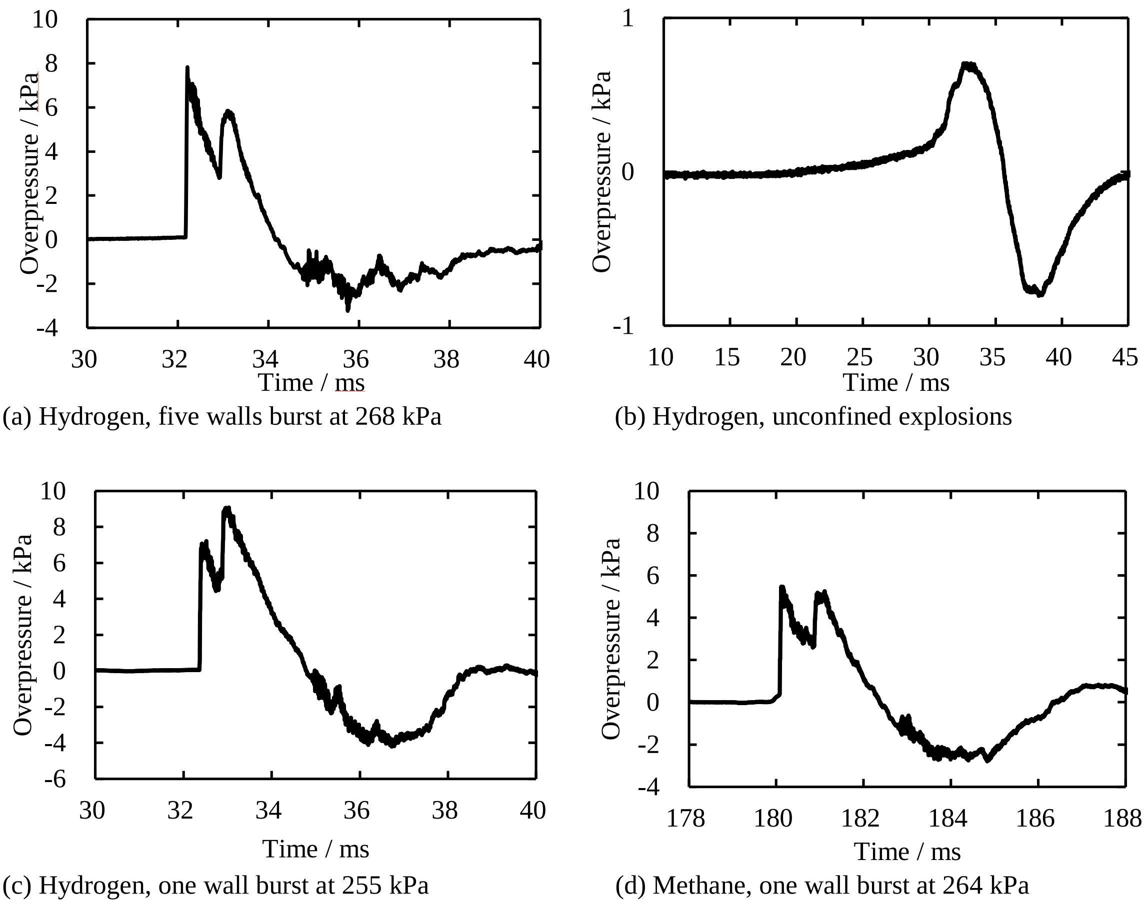
*1 calculated by NASA-CEA program [5]

3 Results and Discussion

Figure 2 shows pressure histories of blast waves measured at 5 m away from the center of the vessel. Time means the time after ignition. It took about 14 ms for blast wave to propagate rom the vessel to the pressure sensor. In case when thin polyethylene sheets were used as walls, which was almost similar as unconfined gas explosion, the pressure of blast wave increased gently after ignition and there was only one peak. In case of PVC plates, the pressure didn’t increase before vessel bursting. At the time vessel burst, the pressure of blast wave increased sharply and the first peak was generated. The main cause of the first peak generation was sudden jetting out of high pressure mixtures in the vessel. However, at this time the flame had already propagated near the bursting walls. Therefore, the blast waves might be enhanced by flame propagation. The flame propagation, which was accelerated due to turbulent combustion after vessel bursting, generated second peak on the blast wave.

In case of one wall bursting by hydrogen-air mixture, the second peak was larger than the first peak. In case of one wall bursting by methane-air or propane-air mixture, the first peak was larger than the second peak. On the other hand, in case of five walls bursting by hydrogen-air mixture, if the vessel burst at the pressure more than about 80 kPa, the first peak was larger than the second peak. If the vessel burst at the pressure less than about 80 kPa, the second peak was larger.

Figure 3 shows the relation between bursting pressure, which means the pressure increase in the vessel until vessel burst, and the first peak overpressure of blast waves measured at 5 m away from the vessel. The result using thin polyethylene sheets was plotted as bursting pressure was nearly 0. The curve shows calculated values by the model (Eq. (1)) developed by Baker [3], in which the vessel bursting by high pressure mixtures without reaction was assumed.



(a) Hydrogen, five walls burst at 268 kPa

(b) Hydrogen, unconfined explosions

(c) Hydrogen, one wall burst at 255 kPa

(d) Methane, one wall burst at 264 kPa

Figure 2, Pressure histories of blast waves.

$$p_1 = p_s \left[1 - \frac{(\gamma_1 - 1)(a_a/a_1)(p_s/p_a - 1)}{\sqrt{2\gamma_a\{2\gamma_a + (\gamma_a + 1)(p_s/p_a - 1)\}}} \right]^{-\frac{2\gamma_1}{\gamma_1 - 1}} \qquad (1)$$

In equation (1), p is pressure, γ is specific heat ratio, a is sound speed and p_s is the side-on pressure of blast waves. The subscript 1 means the mixtures in the vessel and a means atmosphere. The physical properties of unburned hydrogen-air or methane-air mixtures presuming adiabatic compression were used in calculation of Figure 3. The peak overpressure increased as bursting pressures increased and was larger than that of the experimental values using thin polyethylene sheet (unconfined gas explosion). There was only little difference between one wall bursting and five walls bursting. The reason might be that five walls didn't burst simultaneously and the first peak was generated by the first bursting one wall.

The measured peak overpressures of hydrogen-air mixture were larger than those of methane-air and propane-air mixture. Also the measured peak overpressures were larger than the calculated values. The differences between measured values and calculated values were larger in the case of hydrogen-air mixture than in the case of methane-air or propane-air mixture. As mentioned before, the main cause of first peak generation was considered to be sudden jetting out of high pressure mixtures. There are three possible reasons why the difference between the experimental value and calculated value was made. The first reason is the effect of vessel's shape. The calculation method was developed for spherical vessels bursting. On the other hand, cubic vessels were used in this experiment. However, this effect cannot sufficiently explain the result that the experimental values of hydrogen-air mixture were larger than those of methane-air mixture and propane-air mixtures. Therefore, the effect of the vessel's shape might be small.

The second reason is that actual physical properties of mixtures near bursting walls were different from those assumed in calculation. According to Eq. (1), the pressure of blast wave depends on bursting pressure, specific heat ratio of the mixture and sound speed of the mixture in the vessel. The specific heat ratio didn't vary much so that the effect of the specific heat ratio was small. Sound speed depends on the temperature, specific heat ratio and mean molecular weight. Sound speed was higher when mean molecular weight was smaller or temperature was higher. Table 2 shows the estimated sound speeds at several pressures of unburned mixtures used in experiments and burned mixtures. The temperatures of unburned mixtures were calculated from pressure in the vessel presuming adiabatic compression. The temperatures of burned mixtures were presumed as same as flame temperatures. In the calculation in Fig 3, the estimated sound speed of unburned mixture was used. If the flame had

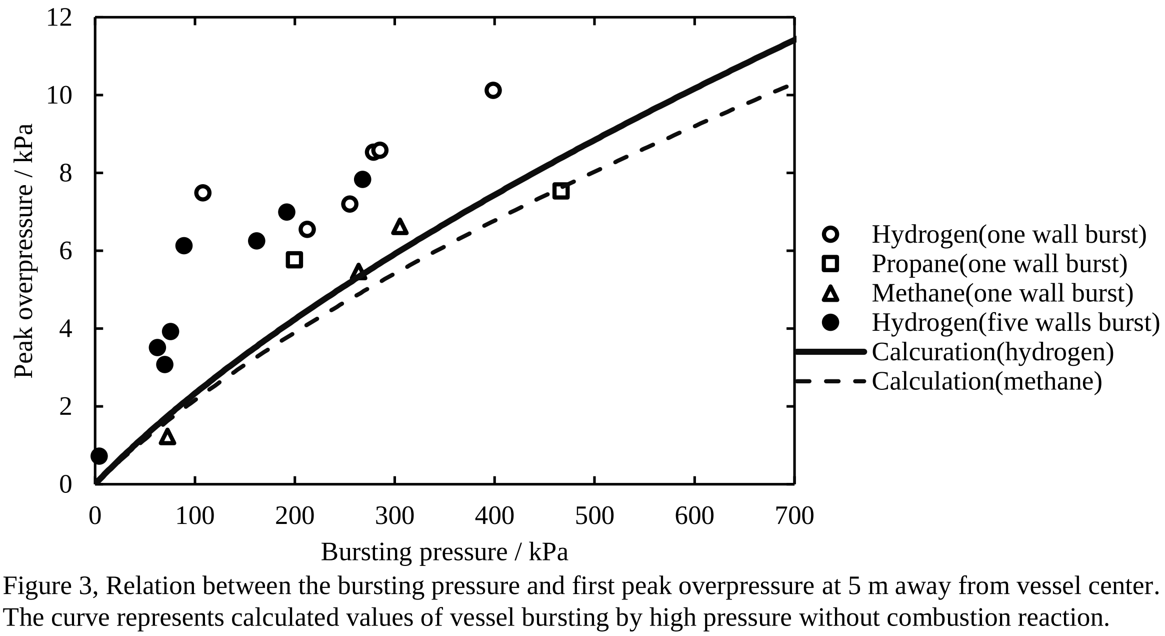


Figure 3, Relation between the bursting pressure and first peak overpressure at 5 m away from vessel center. The curve represents calculated values of vessel bursting by high pressure without combustion reaction.

Table 2: Sound speed of mixtures used in this experiment.

Flammable mixtures	Sound speed [m s^{-1}]									
	Pressure (gauge pressure) [kPa]									Burned mixture
	101 (0)	201 (100)	301 (200)	401 (300)	501 (400)	601 (500)	701 (600)	801 (700)	901 (800)	
Hydrogne-air	411	453	480	500	516	530	542	552	562	1130
Methane-air	356	392	416	433	447	459	469	478	486	956
Propane-air	342	377	400	416	430	441	451	460	467	932
air	350	386	409	426	439	451	461	470	478	−

propagated near the wall and some space behind the wall was filled with burned mixture before vessel burst, the sound speed became faster than that of unburned mixture. Therefore, the effect of the change of sound speed of mixtures behind the bursting wall might be one of major cause which made the calculated values smaller than the measured first peak overpressure.

The third reason is the effect of combustion reaction. Although instantaneous vessel bursting was assumed in Eq. (1), it took finite time for vessel wall to burst in actual phenomena. Since the combustion reaction still lasted when vessel burst, the pressure in the vessel was rising during vessel bursting. The propagating behavior of flame might influence on generating shock wave. The pressure increase rate in the vessel depends on laminar burning velocity. According to Table 1, the laminar burning velocity of hydrogen-air mixture was faster than those of methane-air and propane-air mixtures. The effect mentioned above of hydrogen-air mixture was larger than those of methane-air and propane-air mixtures.

Impulse, which is defined as time integrated value of positive overpressure, is important value of evaluating blast waves. Figure 4 shows the relation between bursting pressure and measured impulse. The curve shows the calculated values of blast waves from vessels burst by high pressure mixtures of hydrogen-air presuming that combustion reaction stopped at vessel bursting. The impulse increased as bursting pressure increased and was larger than that of the experimental values using thin polyethylene sheet (unconfined gas explosion). The impulse from one wall bursting was larger than that from five walls bursting because the mixtures released after vessel burst concentrated to one direction in the case

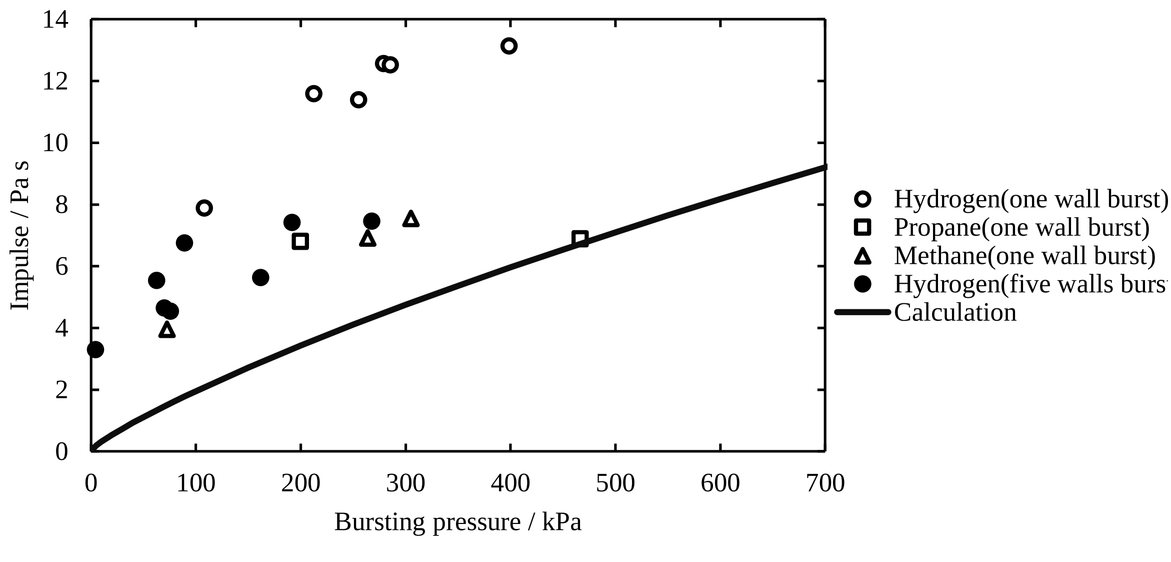


Figure 4, Relation between bursting pressure and impulse at 5 m away from vessel center.
The curve represents calculated values of vessel bursting by high pressure mixtures of hydrogen-air.

of one wall bursting. Also the impulse of hydrogen-air mixture was larger than those of methane-air and propane-air mixtures because the peak overpressure was large. Furthermore, the experimental values were larger than calculated values. The reason of these differences might be that the combustion reaction after vessel bursting was not considered in the calculation. As mentioned before, the second peak was generated after vessel bursting by the combustion reaction. It is thought that the impulse depends on the cube root of released energy from explosion [4]. The maximum impulse might be same as calculated values at the final pressure when all mixture was burned in the confined vessel whose energy might be nearly same as all combustion energy of confined flammable mixture.

4 Conclusion

The blast waves from bursting vessels as a result of excessive high pressure raised by gas explosions have been investigated experimentally. In the experiments, flammable mixtures were ignited in vessels with various strength and pressure changes were measured in and out of vessels. There were two peaks on the pressure histories of blast waves. The first peak was generated by jetting out of high pressure mixtures and the second peak was generated by turbulent combustion reaction. The measured values of first peak overpressure and impulse increased as bursting pressure increased and were larger than those from unconfined gas explosions. The measured values were compared with those calculated by the model for vessel bursting by high pressure mixtures without combustion reaction. The calculated values were lower than the measured values. It is thought that the combustion reaction enhanced the peak overpressure and impulse.

Acknowledgement

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