BLAST WAVE FROM BURSTING ENCLOSURE WITH INTERNAL HYDROGEN-AIR DEFLAGRATION

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ABSTRACT

Most researches on blast waves generated from gas explosions were focused on open space gas explosions. However, accidental gas explosions often occur in confined spaces and the blast waves generate from bursting vessels as a result of pressure increase raised by gas explosions. In this experimental study, blast waves from bursting plastic vessels, in which gas explosions occurred, were measured. The flammable mixtures were hydrogen-air mixtures at several equivalence ratios and stoichiometric methane-air mixture. Blast waves generated from bursting vessels were measured. The overpressures of blast waves were generated by venting high pressure gas in the vessel and volumetric expansion with combustion reaction. The measured intensities of blast waves were compared with the calculated values of blast waves from bursting vessel by high pressure gas without combustion reaction. The measured intensities of blast waves were larger than the calculated values by high pressure bursting without combustion reaction. The intensities of blast waves by the explosions of hydrogen-air mixtures were much larger than that of methane-air mixture.

1.0 INTRODUCTION

Blast wave is one of the significant elements which cause serial damage in wide area at accidental gas explosions. To take appropriate measures to decrease the damage of accidental explosion, it is necessary to understand the phenomena of generation of blast wave from gas explosions. Many researchers have been studying blast waves from gas explosions experimentally and theoretically. In most researches about blast waves, gas explosions in open space were examined. On the experimental studies, flammable mixtures were confined in balloons, bubbles and plastic tents of thin films, which easily broke after ignitions [1-6]. The phenomena were almost same as open space gas explosions. It was understood that the intensity of blast wave from open space gas explosions depends on the flame propagation behavior [7].

However in actual open space gas explosions rarely occur because flammable gases easily diffuse so that flammable mixtures rarely exist in open space. It is thought that in actual accident flammable mixtures are made in some vessel, such as buildings or tanks. Therefore accidental gas explosions occur in confined space. If the gas explosions occur in confined space, the pressure in the confined space increase and the vessels are broken. Then blast waves are generated. The phenomena are different from open space gas explosions.

To estimate the intensity of blast wave from bursting vessels, the blast model developed by Baker is available [8]. Baker studied the blast wave from bursting spherical vessel as a result of excessive high pressure in the vessel. The blast model was experimentally examined by Esparza and Baker [9]. If the vessel bursts as a result of excessive high pressure, the high pressure gases in the vessel suddenly expands and shock wave is generated. Gas explosions are induced by combustion reaction of flammable gas mixtures. However the model didn’t consider combustion reaction. If a vessel bursts after combustion reaction in the vessel has finished, the model is available. On the other hand, if a vessel bursts during combustion reaction is still proceeding, the blast model might not be applicable. There are little studies that examined the blast waves from bursting vessels, in which gas explosions happen, in detail.

On this experimental study, to investigate the blast wave from bursting vessels in which gas explosions occur, gas explosion experiments were performed in vessels whose strengths were various. Hydrogen-air mixtures and methane-air mixtures were used in this study. The equivalence ratios of hydrogen-air mixtures were changed. The pressures of blast waves were measured around vessels. The relation between the intensity of blast wave and the pressure in the vessel when vessel burst was investigated.

2.0 EXPERIMENTAL SETUP

Figure 1 shows schematic diagram of the apparatus of this experimental setup. The vessel was a cubic, 0.5 m each side, and the volume of the vessel was 0.125 m^3. It consisted of stainless steel frame and six walls. The bottom wall of the vessel was a stainless steel plate and located 0.75 m above the ground. As the other five walls the poly vinyl chloride (PVC) plates were fixed to the stainless steel frame. The thickness of PVC plates was varied to change the pressure in the vessel when vessel burst. On this experiment one or five walls of vessel burst by pressure increase raised by gas explosion which occur in the vessel. In case of five walls bursting, the thicknesses of five walls were the 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 open space gas explosions.

Hydrogen-air mixtures whose equivalence ratios were 0.5, 1.0, 1.8 or 2.5 and stoichiometric methane-air mixture were used in this study when one wall burst. Only stoichiometric hydrogen-air mixture used when five walls of vessel burst. The physical properties of flammable mixtures used in experiments were summarized in Table 1. 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. 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).

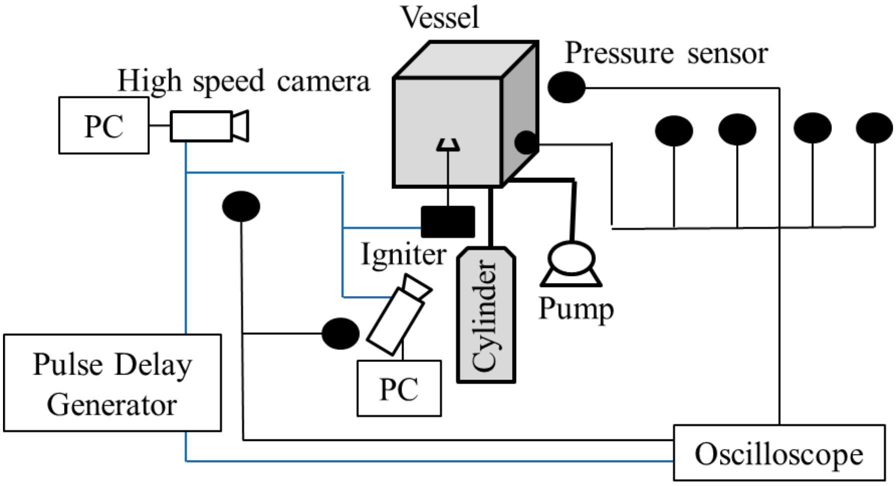


Figure 1. Apparatus of experimental setup.

Table 1. Physical properties of flammable mixture

Flammable gas	Equivalence ratio	Specific heat ratio of burned mixture[*1]	Flame temperature in confined space / K [*1]	Final gauge pressure in confined space / kPa [*1]
Hydrogen	0.5	1.2525	1986.98	514
Hydrogen	1.0	1.1682	2747.3	708
Hydrogen	1.8	1.2214	2551.35	663
Hydrogen	2.5	1.1741	2309.16	602
Methane	1.0	1.170	2586.13	789

[*1] calculated by NASA-CEA program [10]

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. Each pressure sensor located 1 m above the ground. 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, »>990 nm). Using a long pass filter, IR emission from the propagating flame can be observed. 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.

3.0 RESULTS

Figure 2 shows the pictures captured by the high-speed digital monochrome video camera with a long path filter. In the figure, the time means time after ignition. It is widely known that the flame of hydrogen-air mixture cannot be visibly seen. Capturing through a long path filter the hydrogen-air flame could be seen as an IR image. After the hydrogen-air mixture was ignited at the center of the vessel the flame propagated spherically in the vessel. The vessel burst when the flame propagated to approach the walls. When the vessel burst, the mixture in the vessel suddenly jet out. Also the flame propagate in the unburned mixture which was vented through the burst wall. After vessel burst, the fragments flew out. The velocity of the fragments was much slower compared to the velocity of the flame.

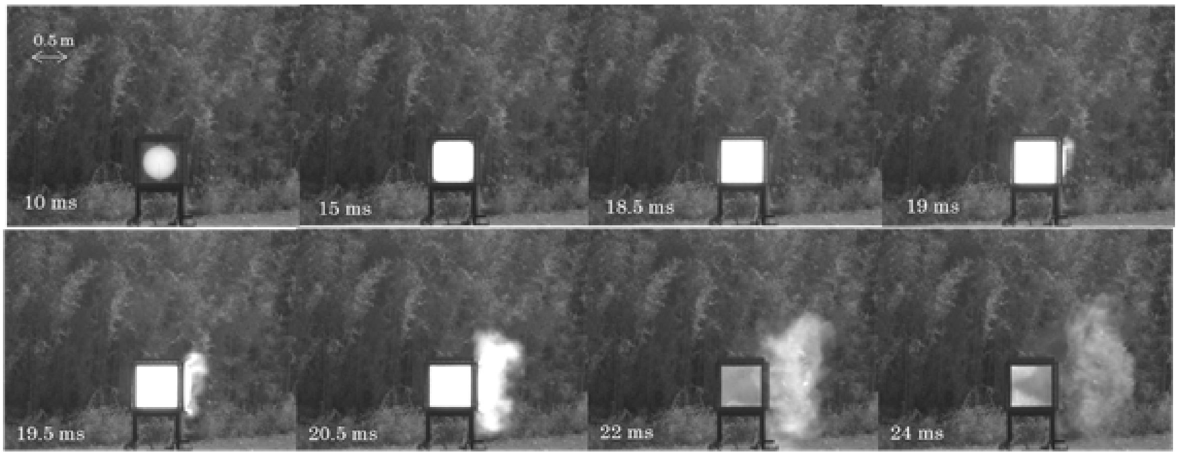


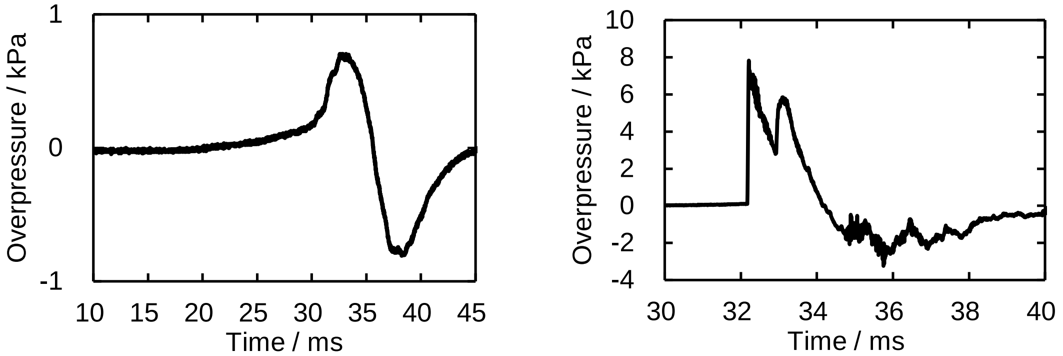
Figure 2. Explosion phenomena captured by high-speed monochrome camera through long path filter. (One wall burst at 399 kPa, hydrogen-air mixture at equivalence ratio of 1.0)

(a) H_2 ϕ=0.5, burst at 246 kPa (b) H_2 ϕ=2.5, burst at 183 kPa (c) CH_4 ϕ=1.0, burst at 264 kPa

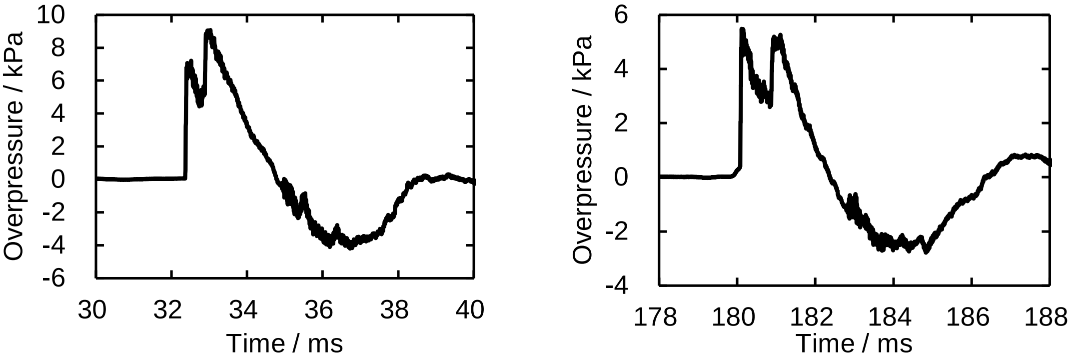
Figure 3. Flame behavior 5 ms after one wall of vessel burst.

Figure 3 shows the flame 5 ms after vessel burst. When flammable mixtures were stoichiometric methane-air or hydrogen-air mixture at equivalence ratio of 0.5, the luminescence of flame was weak after vessel burst. When the flammable mixture was hydrogen-air mixture at equivalence ratio of 1.8 or 2.5, after vessel burst the flame propagated far away and the combustion reaction continued long time.

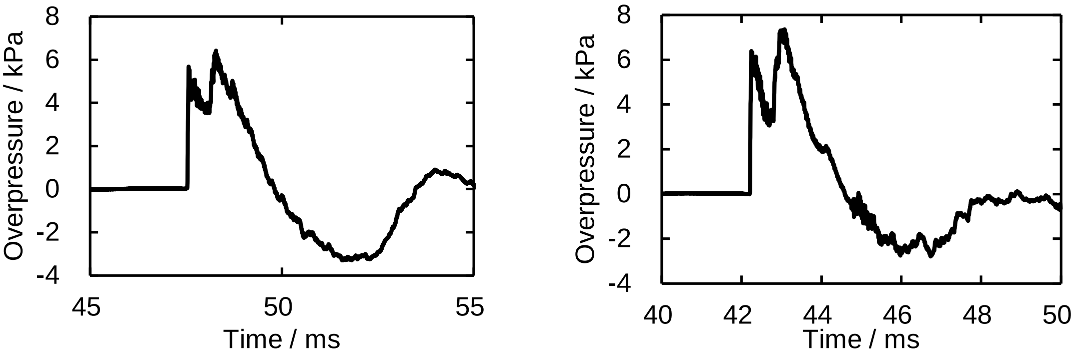
Figure 4 shows the pressure histories of blast wave measured at the 5 m away from the center of the vessel. In the figure time means time after ignition. From the comparison of the pressure histories measured at various distance away from the vessel the propagation speed of blast wave was nearly same as sound speed. Therefore, the recorded pressure history of blast wave at 5 m away from the vessel delayed for about 13.6 ms from the explosion phenomena. When thin polyethylene sheets were used as vessel’s walls (Fig. 4-(a)), which was almost similar to an open space gas explosion, the



(a) H_2 ϕ=1.0, polyethylene sheets (b) H_2 ϕ=1.0, 5 walls burst at 268 kPa



(c) H_2 ϕ=1.0, 1 wall burst at 255 kPa (d) CH_4 ϕ=1.0, 1 wall burst at 264 kPa



(e) H_2 ϕ=0.5, 1 wall burst at 246 kPa (f) H_2 ϕ=2.5, 1 wall burst at 183 kPa

Figure 4. Pressure histories of blast waves measured at 5 m away from the vessel.

pressure of blast wave increased gently after ignition. There was only one pressure peak.

Figure 4-(b) - (f) show the pressure histories from bursting vessels whose walls were PVC plates. The pressure histories were similar regardless of the conditions of flammable mixtures and the number of bursting walls. The pressure didn’t change after ignition before vessel burst. The pressure increased sharply and first peak generated at the time vessel burst. 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. The blast waves might be influenced by combustion reaction. After vessel burst the combustion reaction continued and turbulent flame propagation might generate the second peak on the pressure histories of blast wave.

4.0 INTENSITY OF BLAST WAVE

4.1 First peak

Figure 5 shows the relation between first peak overpressure of blast wave measured at 5 m away from the center of the vessel and the pressure in the vessel at bursting (bursting pressure). The results using thin polyethylene sheets were plotted as bursting pressure was nearly 0, which is considered as open space explosion. From the figure the first peak overpressures increased as bursting pressure increased and were much larger than those from the open space gas explosion. This is because the first peak was generated from sudden jetting out of high pressure mixtures at the time vessel burst. The number of bursting walls of vessel didn’t influence the first peak overpressures. If the five walls burst, all five walls didn’t burst exactly at the same time. The walls burst in order during short time. The first peak was generated at the first bursting of the wall. Therefore, at the time first peak was generated, only one wall burst. There was only little influence of equivalence ratio of hydrogen-air mixtures on the first peak overpressures. On the other hand, the material of flammable gases influenced on the first peak overpressure.

In the figure, the curve represents the calculated values of bursting vessels by high pressure air without combustion reaction. The relation between the pressure of shock wave and the pressure in the vessel was showed as following equations [8].

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

where p is pressure, a is sound speed, γ is specific heat ratio and p_s is the pressure of blast waves. The subscript 1 is the mixture in the vessel and a is atmosphere. Calculating condition in Eq. (1)

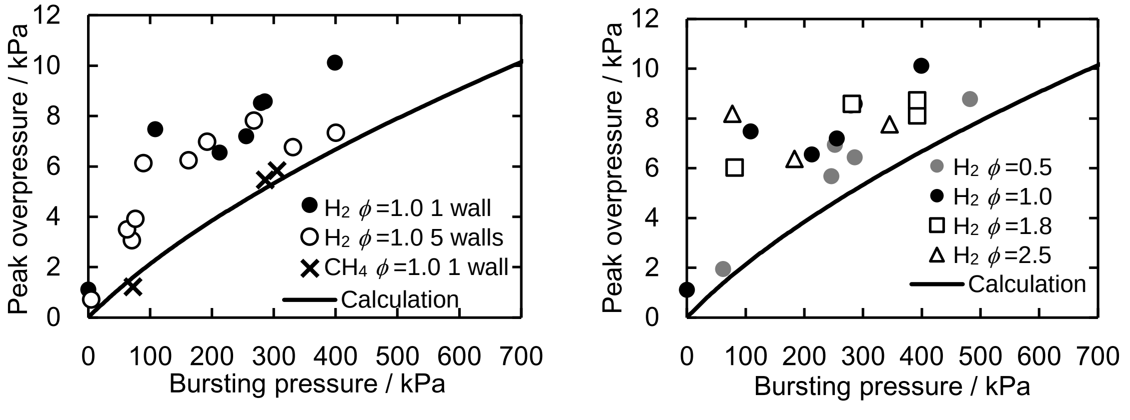


Figure 5. The relation between first peak overpressure and bursting pressure.
Left: Stoichiometric mixture. Right: Hydrogen-air mixture and one wall bursting
The curve shows calculated values of bursting vessels by high pressure without combustion

followed the Yellow Book [11]. In the figure, the first peak overpressures from bursting vessels by hydrogen-air mixtures were larger than the calculated values by Eq. (1), in which vessels were assumed to be burst by high pressure air without combustion reaction. On the other hand, those from methane-air mixtures were almost correspond to the calculated values. It is thought that the first peak was generated almost from sudden jetting out of high pressure mixtures in the vessel when vessel burst. The reason why higher first peak overpressure were appeared from bursting vessels by hydrogen-air mixtures might be combustion reaction. There are two possible reasons.

First reason is the change of physical properties of the mixtures in the vessels. According to Eq. (1), specific heat ratio and sound speed of the mixtures in the vessels were used in the calculation. Specific heat ratios were almost same regardless of the type of mixtures. Sound speed can be calculated using following equation.

$$a = \sqrt{\frac{\rho R T}{\mu}} \tag{2}$$

where ρ is density, R is gas constant, T is temperature and μ is mean molecular weight. In Fig. 5 the temperature was calculated presuming adiabatic compression as pressure increased. The temperature was up to 700 K. However according to Table 1, the temperatures of flames were very high. Since the temperature of burned mixtures were thought to be same as flame temperature, the sound speeds of burned mixtures were faster than those of unburned mixtures. If the flame had propagated and burned mixture existed near the bursting walls before the vessel bursting, larger blast waves might be generated.

The second reason is the effect of flame propagation. 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 at vessel bursting, the pressure in the vessel was rising during vessel bursting. The propagating behavior of flame might have influence on generating shock wave. At the moment vessel burst the mixture in the vessel was sudden jetting out and the air near the vessel was compressed so that shock wave was generated. If the flame was propagating in the mixture which was jetting out during vessel bursting, the compression process might be affected by the flame propagation and larger blast waves might be generated.

4.2 Second peak

Figure 6 shows the relation between the second peak overpressures of blast waves and bursting pressures. The main difference from first peak is that the number of bursting walls influenced much. The second peak was thought to be generated by combustion reaction after vessel bursting. If only one

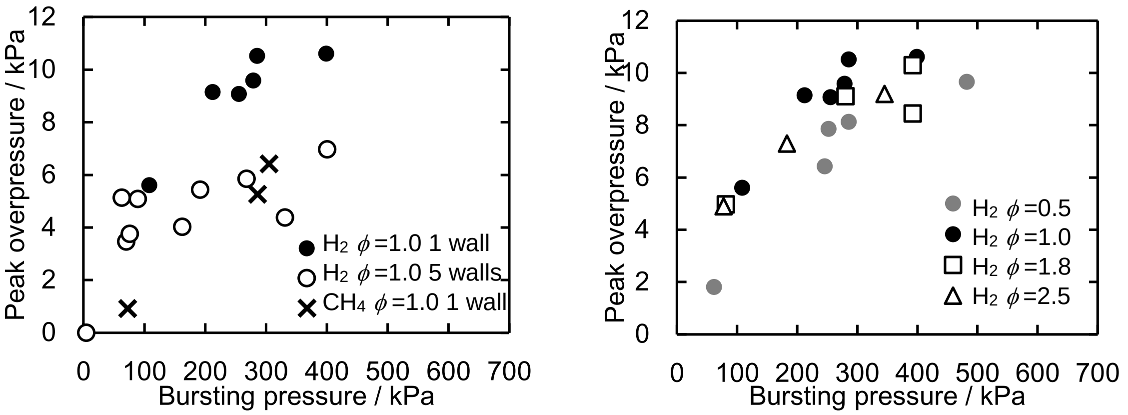


Figure 6. The relation between second peak overpressure and bursting pressure.
Left: Stoichiometric mixture. Right: Hydrogen-air mixture and one wall bursting.

wall burst, the unburned mixture in the vessel jet out only one direction. Therefore the combustion reaction after vessel burst was enhanced in the case of one wall bursting more significantly than in the case of five walls bursting. Also there is large difference between hydrogen-air mixture and methane-air mixture because the burning velocity of hydrogen-air mixture is much faster than that of methane-air mixture. The effect of equivalence ratio was small. The second peak at equivalence ratio of 0.5 was slightly smaller than that at equivalence ratio of over 1.0.

4.3 Impulse

Figure 7 shows the relation between impulse, which is defined as time integrated value of positive overpressure, and bursting pressure. The curve shows the calculated values of bursting vessels 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 experimental values using thin polyethylene sheets (open space gas explosion). The experimental values were larger than the calculated values. The main reason is the generation of second peak, which was generated by combustion reaction after vessel bursting. Therefore the dependence of impulse on the condition of explosion phenomena tended to be same as that of second peak. The impulse from one wall bursting was larger than that from five walls bursting because the second peak was larger. Also the impulse of hydrogen-air mixture was larger than those of methane-air. The effect of varying equivalence ratio might be small. However, since the impulse is integrated values, it is thought that the impulse was

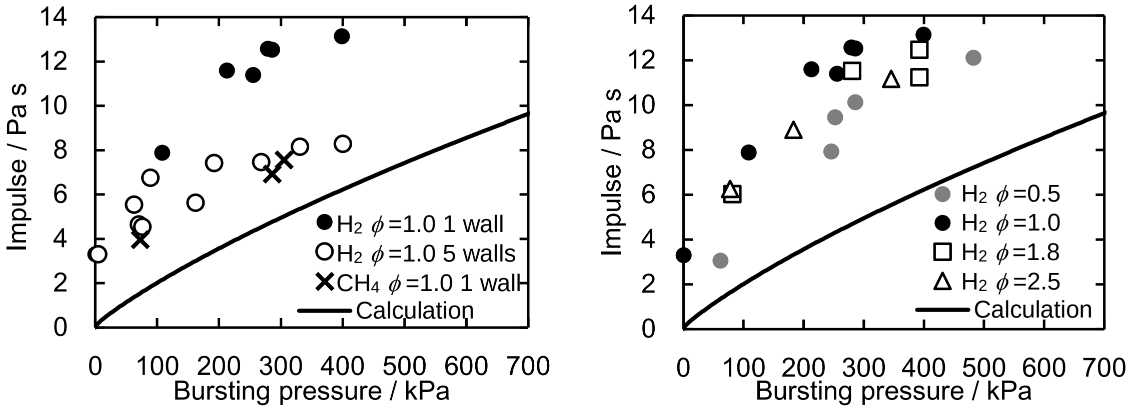


Figure 7. The relation between impulse and bursting pressure.
Left: Stoichiometric mixture. Right: Hydrogen-air mixture and one wall bursting
The curve shows the calculated values of bursting vessels by high pressure mixtures of hydrogen-air presuming that combustion reaction stopped at vessel bursting.

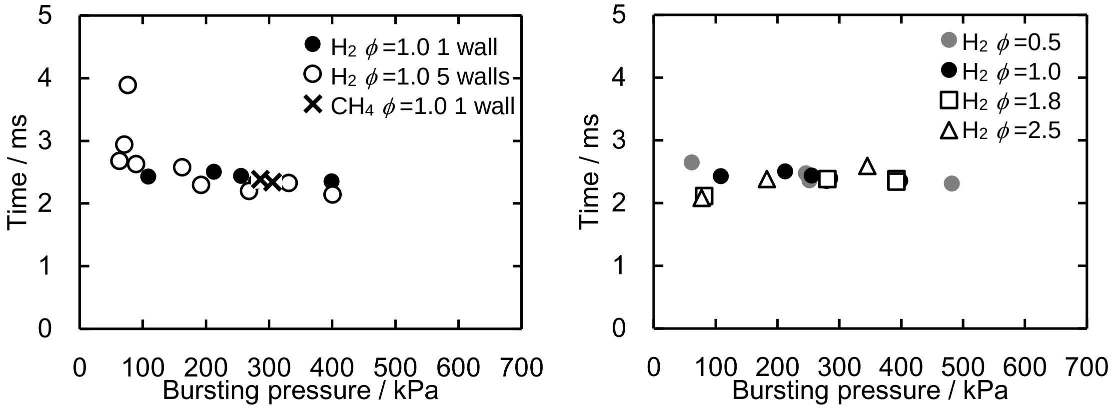


Figure 8. The time during positive pressure of blast wave.

larger at equivalence ratio of over 1.0. According to Fig. 3, the combustion reaction continued longer at equivalence ratio of over 1.0.

Figure 8 shows the time during positive pressure of blast wave. If the bursting pressure was over about 100 kPa, the time during positive time was almost constant as bursting pressure increased. Also the time was independent of the condition of flammable mixture. It is suggested that the impulse can be determined only by the peak values.

5.0 CONCLUSION

The blast waves generated from bursting vessels as a result of excessive high pressure raised by gas explosions in the vessel have been investigated experimentally. Then following findings were obtained.

・There are two peaks on the pressure histories of blast waves. The first peak was generated from sudden jetting out of high pressure mixture at vessel bursting and the second peak was generated from combustion reaction after vessel burst.
・The first peak overpressures increased as bursting pressure increased and were larger than that from open space gas explosions because of the first peak was generated by the effect of venting high pressure mixtures. However, the measured first peak values were larger than the calculated values of high pressure bursting without combustion reaction. It is inferred that the combustion reaction made some effect on the generation of first peak.
・The intensities of blast wave which include the first peak, second peak and impulse were larger in case of hydrogen-air explosions than in case of methane-air explosions. However, the effect of equivalence ratio of hydrogen-air mixture on the intensities was small.

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