Research paper

Fundamental study on blast simulator for blast injury research

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Received: November 10, 2017　Accepted: December 2, 2019

Abstract

Compared to planar shock waves generated inside a shock tube, blast waves have three major peculiarities. First, blast waves have a sharp peak overpressure followed by a decaying pressure profile. Second, at the latter part of the decaying pressure profile, blast waves often have “negative pressure,” which is lower than the initial pressure in the quiet region. Finally, a blast wave has a secondary shock wave, which is the reflection of the implosion shock wave generated by overexpansion of the combustion gas. To simulate the fluid dynamics of a blast wave from the point of view of blast injury, the pressure history should meet the characteristics described above. To generate blast-like shock waves in a shock tube, optimization of a high-pressure room has been performed both numerically and experimentally. The optimized high-pressure room provided both rapid pressure decay after the shock front and following negative pressure portion. Optimal conditions for the simulation of the blast shock waves were found using numerical calculations and compared with the experiments. A shock tube with the cross section of 50 mm by 50 mm, a 500-mm-long high-pressure room, a 3040-mm-long low-pressure channel, and a 23-mm-long middle-pressure chamber were used in the experiments. Negative pressure and rapid decay of pressure were observed inside the shock tube with a shortened high-pressure room. In addition, we expect that shock waves with a profile more resembling a bomb blast can be provided by using a detonation tube as a driver section.

Keywords: shock wave, blast wave, blast simulator, detonation, shock tube

1. Introduction

Shock tubes have been used to simulate overpressure generated by explosives from the early stage of research on blast injuries, including animal tests[1]. From the 1950s, because of the rising threat of nuclear weapons[2], shock tubes became the only viable method to simulate long-duration impulses (> 100 ms), which are specific for nuclear blasts[3], high-yield explosive events, such as petrochemical explosions, and ammunition storage accidents. As pointed out by Richmond[1], air-driven shock tubes have an unusual versatility and offer many other advantages, including excellent repeatability and allowance to apply extensive and advanced instrumentation, e.g., to monitor both fluid dynamics and pathophysiological processes. A blast wave generated by an explosion in a free space is a spherical shock wave propagating outside from the center of explosion; it is characterized by a discontinuous pressure jump followed by a rapid decay with negative pressure. Therefore, the most evident and relatively easy way to simulate blast waves in laboratory is to generate spherical shock waves using small explosives. On the other hand, from the safety and repeatability points of view, the method using explosives has disadvantages against that with a shock tube, which is able to generate normal shock waves with high repeatability and safety. Normal shock waves propagating in a shock tube, however, are not followed by a rapid pressure decay and negative pressure. Therefore, in this study, three types of modifications have been applied to the high-pressure room to generate normal shock waves followed by a rapid pressure decay and negative pressure at its test section. Experimental results showed that the shortened high-pressure room provided the most blast-resembling pressure profiles at the test

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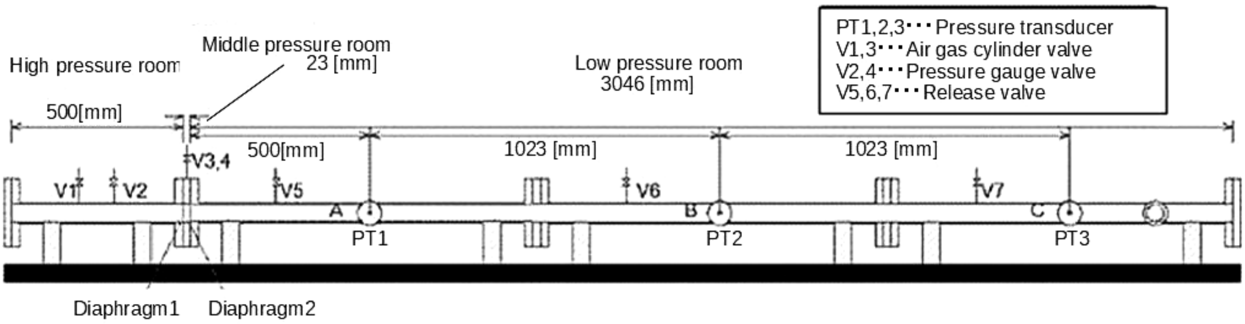


Figure 1 Schematic diagram of a 50-mm-by-50-mm shock tube.

section.

2. Experimental equipment and method

2.1 50-mm-by-50-mm shock tube

Figure 1 shows 50-mm-by-50-mm shock tube, 5×5ST, which was used as a shock wave generator. The 5×5ST has a high-pressure room with 50-mm-by-50-mm cross section and 500-mm length and a low-pressure channel with similar cross section and 3046 mm in length. Between the high-pressure room and low-pressure channel, 23-mm-long middle-pressure room was installed. The each section was isolated with a 75-μm-thick diaphragm (polyethylene terephthalate, PET). Initial pressure in the high-pressure room, P_4, and that in the low-pressure room, P_1, were controlled to produce the intended incident shock Mach number M_S. In addition, the pressure in the middle-pressure room, P_4', was charged at the middle pressure between the pressure in the high-pressure room and that in the low-pressure one to rupture the diaphragms when P_4' was depressurized down to atmospheric pressure. Therefore, one can operate 5×5ST by simply depressurizing the middle-pressure room at an indented moment. In the present study, both, the driver and test gases were dried in air. The low-pressure room of 5×5ST had three pressure ports with a 1023-mm interval. Piezo-type pressure transducers (rise time < 1μs; sensitivity 3.6 mV·kPa^{-1}; PCB Type 113A21) PT1, PT2, and PT3 were installed at each port. Output signals from the pressure transducers were recorded with a digital oscilloscope (3 MHz, 10 MSs^{-1}, 12 bit; Yokogawa, DL-750) through a signal conditioner (PCB Model 482A21). Incident shock velocity was determined by dividing the distance between the PTs by the shock wave traveling time between the PTs. Then, the incident shock Mach number was calculated by dividing the shock velocity by the speed of sound,

$$a_1 = \sqrt{\gamma R T_1}, \tag{1}$$

where γ, R, and T_1 are the specific heat ratio, gas constant, and temperature of the test gas, respectively, at the room temperature. In this experiment, γ, R, and T_1, were 1.40, 287.1 Jkg^{-1} K^{-1}, 288 K, respectively.

Under the assumption of the simple theory on shock tube operation, the incident shock Mach number, Ms, is calculated from the initial pressure ratio P_4/P_1 by the formula shown below[4]:

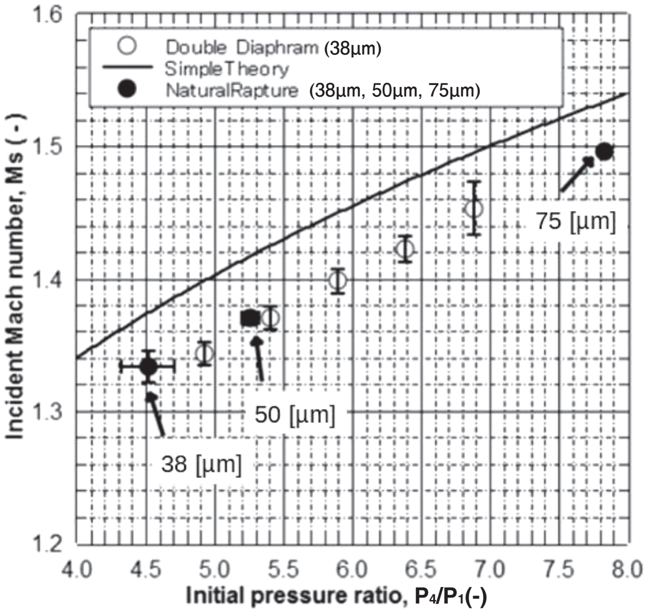


Figure 2 The characteristics of 5×5ST on the parametric plane of the initial pressure ratio P_4/P_1 and the incident shock Mach number Ms. The values shown in the figure represent the thicknesses of the used diaphragms.

$$\frac{p_4}{p_1} = \frac{p_2}{p_1}\left\{1 - \frac{(\gamma_4 - 1)(a_1/a_4)(p_2/p_1 - 1)}{\sqrt{2\gamma_1[2\gamma_1 + (\gamma_1 + 1)(p_2/p_1 - 1)]}}\right\}^{-2\gamma_4/(\gamma_4 - 1)}, \tag{2}$$

$$\frac{p_2}{p_1} = 1 + \frac{2\gamma_1}{\gamma_1 + 1}\left(M_S^2 - 1\right), \tag{3}$$

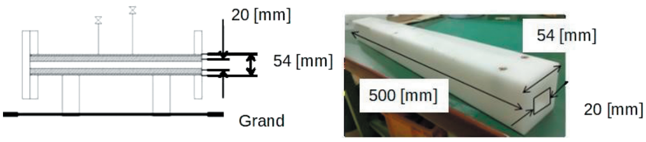
Figure 2 shows the characteristics of 5×5ST on the parametric plane of the incident Mach number, Ms, and initial pressure ratio P_4/P_1. The open circles represent the experimental results, and the solid line shows the simple theory. The experimental conditions of P_4/P_1 for a nominal shock Mach number were defined by the Ms-P_4/P_1 curve.

3. Experimental conditions

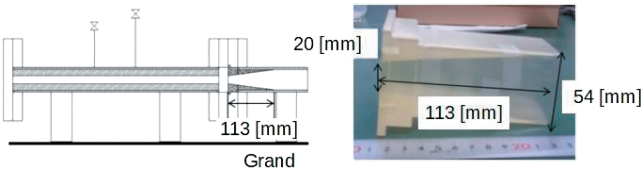
To produce a blast-like normal shock, the high-pressure room and low-pressure channel, which are attached to the middle-pressure room, have been modified. Then, it was verified whether the blast-like negative pressure is generated or not. Table 1 shows the modifications of the shock tube; the experiments were conducted with three types of shock tube geometry. These conditions were realized by the shape modifications shown in Figure 3. In

Table 1 Modifications of the shock tube.

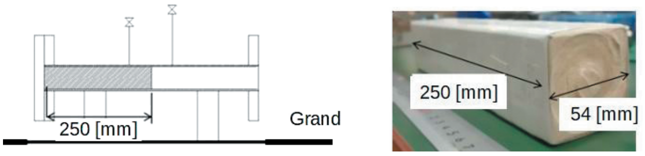
Config.	Modified portion	Objective
#0	Control	None
#1	Rapid expansion of cross section	Generating negative pressure
#2	Continuous expansion of cross section	Generating negative pressure
#3	Shortened high-pressure room	Speedy reflection of expansion wave



(a) High-pressure room of Configuration #1



(b) High-pressure room of Configuration #2



(c) High-pressure room of Configuration #3

Figure 3 Modifications of the high-pressure room of 5×5ST to generate shock waves followed by negative pressure.

the experiments, the obtained pressure histories were evaluated by three aspects: a) sudden jump in pressure, b) rapid decay of pressure, and c) presence of negative pressure. Under all the conditions, the initial pressure in the high-pressure room was 800 kPa (700 kPaG), and the pressure in the low-pressure room was the atmospheric pressure, 100 kPa (0.00 kPaG).

4. Results and discussion

Figure 4 shows the overpressure histories at PT1 that were produced by the incident shock wave under each configuration.

Configuration #0 (Control): Figure 4 (a) shows the overpressure history produced by the control configuration. The incident shock wave, IS, arrived at PT1 at $t=0$ followed by the hot gas with a duration of 3 ms. Pressure decay started at the moment when the reflected expansion wave from the end-wall of the high-pressure room arrived at PT1. At approximately $t=13$ ms, a secondary pressure jump was recorded, when the reflected shock wave, RS, from the end-wall of the low-pressure room arrived. In addition, there is a certain pressure fluctuation at the plateau history of this waveform. The fluctuation was caused by the structure of 5×5ST. 5×5ST has a double-diaphragm structure, at which the downstream diaphragm ruptured after the upstream diaphragm rupture. The time difference between these ruptures caused the shock wave refection between them.

Configuration #1 (Sudden expansion of the cross-section): Figure 4 (b) shows the overpressure history produced by configuration #1. This configuration had a sudden expansion of the cross-section at the connection of the high -pressure room to low-pressure room. The expansion ratio of the cross section was 7.29 (= $(54/20)^2$). After the arrival of IS, both the pressure decay and negative pressure, NP, were observed. In this configuration, a peak overpressure and positive duration were approximately 100 kPa and 5 ms, respectively.

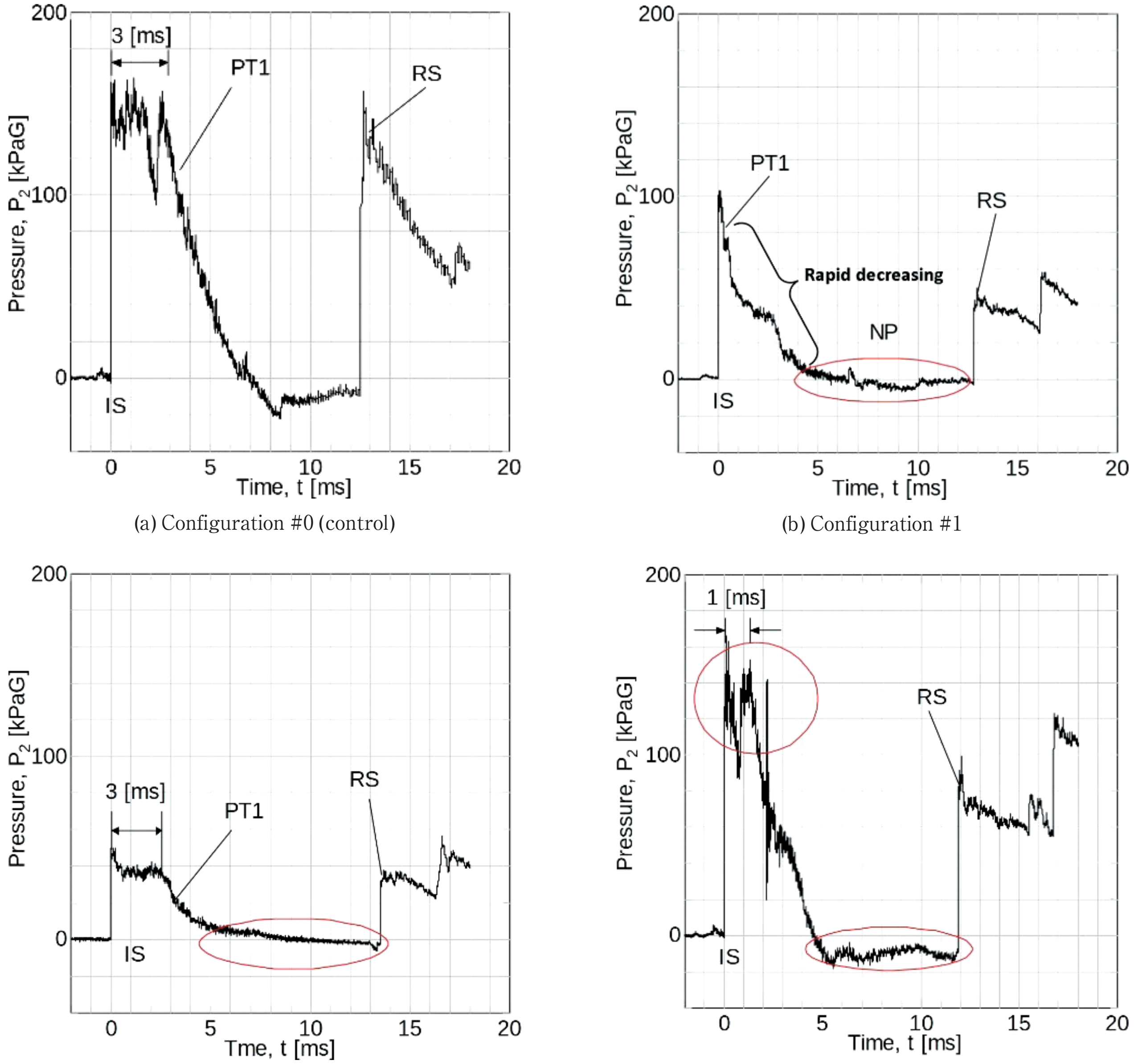
Configuration #2 (Continuous expansion of the cross-section with nozzle): Figure 4 (c) shows the overpressure history produced by configuration #2. This configuration had a continuous cross-section expansion between the high-pressure and low-pressure rooms. The expansion ratio of the cross section was similar to that of configuration #1 with a linear nozzle of 113 mm in length. In the overpressure history, no pressure jumps followed by the rapid decay were observed. A weak negative pressure at the bottom of the decay was observed.

Configuration #3 (Shortened high-pressure room): Figure 4d shows the overpressure history produced by configuration #3. In this configuration, the length of the high-pressure room was reduced down to a half of its original value. Reducing the length of the high-pressure room is expected to reduce the duration of the plateau pressure profile behind the incident shock waves by shortening the travel time of the expansion wave to the end of the high-pressure room. Quick reflection of the expansion wave helps the expansion wave to catch up with the incident shock wave in the low-pressure room. As a result, the peak overpressure and positive duration were approximately 160 kPa and 5 ms, respectively. Overpressure with a multi-peak behind the incident shock wave was observed. The multi-peak was suggested to be caused by the interaction between the reflected expansion wave and the contact surface.

Based on the pressure histories obtained in the experiments, configuration #3 with the reduced length of the high-pressure room provides the most effective modification of planar shock waves with plateau pressure history to simulate blast waves.

5. Conclusions

The presented experiment demonstrated the effects of modification of the high-pressure room of a shock tube on generating planar shock waves with the blast-like pressure history. To generate rapid pressure decay with negative pressure, three types of modification have been examined: 1) discontinuous and 2) continuous changing of the cross-section of the high-pressure room and 3)



(a) Configuration #0 (control)

(b) Configuration #1

(c) Configuration #2

(d) Configuration #3

Figure 4 Pressure histories at PT1 after arrival of the incident shock.

shortened high-pressure room. Based on the overpressure history obtained in the present research, the shortened high-pressure room has provided both rapid decay and negative overpressure.

Acknowledgement

This research is a part of the research project “Fundamental study of shock wave generation and attenuation with shock tube,” which was supported by IHI Corporation.

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