Letter

Experimental investigation of blast wave pressure mitigation by water droplets interaction

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Received: July 25, 2019 Accepted: November 11, 2019

Abstract

An experimental investigation was conducted in an explosion pit to mitigate blast wave propagation by the interaction with water droplets. Composition C-4 (8.00 ± 0.01 g) was used as the explosive with No. 6 detonators. Water droplets were supplied around the explosives using a sprinkler having holes with a diameter of 1.0 mm. Pressure waveforms of the blast waves were measured using pressure transducers, while controlling the water flow rate and the area sprinkled with the water droplets. This study revealed that the sprinkled area affected the effectiveness of the mitigation of the peak overpressure. Larger pressure mitigation was observed when a smaller area was sprinkled with water for equivalent total masses of water applied. This indicated that the spatial density of the water droplets was an important factor for the mitigation of the blast waves.

Keywords: blast wave, shock wave, water droplets, pressure mitigation

1. Introduction

Many industrial applications employ the use of energetic materials. However, if they suddenly explode during storage, or if they are abused for terrorism, the blast waves generated on explosion can cause considerable damage to the surroundings. Blast waves, which include shock waves and high pressure following them, can propagate over long distances and cause damage to both buildings and humans; therefore, methods to mitigate the blast waves are needed.

Objects such as dikes[1), 2)] and walls[1)−4)] are often employed to decrease the impact of explosion hazards. However, they are relatively inflexible, and high pressure regions can unexpectedly develop in focus area of the shock waves. Water as a barrier material has also been investigated in previous studies. Using water walls[5)−7)] and water curtains[8), 9)], the overpressure of blast wave was reduced approximately 90 % in maximum. The potential of water droplets sprinkled in air has attracted many researchers due to flexibility in actual use. Willauer et al.[10)] sprayed water mist around explosives and reported a maximum reduction in blast overpressure of 43 %. Using a shock tube, Jourdan et al.[11)] and Chauvin et al.[12)] reported that the pressure reduction of planar shock wave depended not only on the total mass and the size of the water droplets but also on the strength of the shock wave and the interaction length. However, the strength of blast wave decays during propagation while planar shock wave maintains constant pressure behind it. This means that the contribution of water droplets to blast wave mitigation would vary with propagation, therefore it is necessary to evaluate the spatial dependence of the interaction.

In this study, experiments to examine the interaction between blast waves generated by explosives and water droplets sprinkled within certain areas were conducted. In particular, the effects of the spatial density of the water droplets on blast mitigation were assessed.

2. Experimental

2.1 Apparatus

Figure 1 exhibits the experimental setup. The

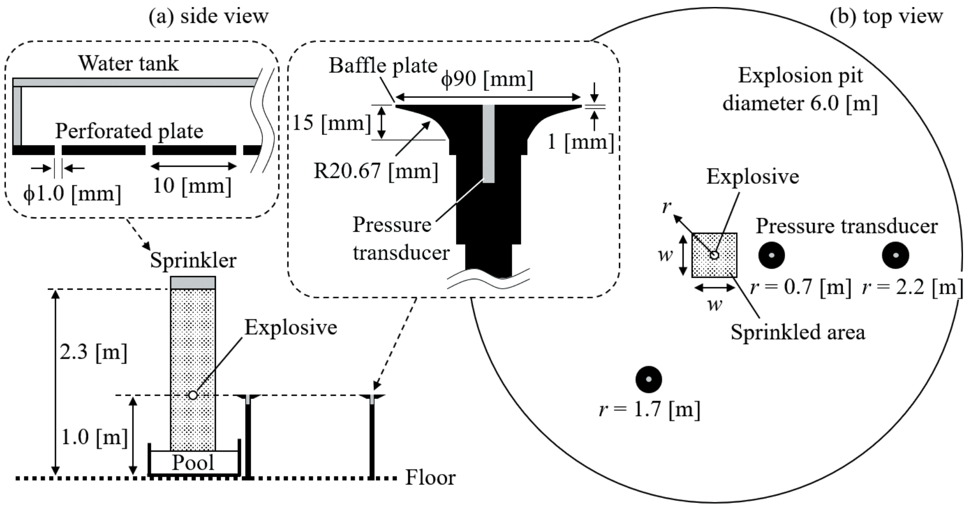

Figure 1 Experimental setup.

Table 1 Experimental conditions.

	Case 0	Case 1a	Case 1b	Case 2a	Case 2b
w [m]	–	0.32	0.32	0.54	0.54
Flow rate [L·min^{-1}]	0	55 ± 1	120 ± 3	55 ± 1	120 ± 3
Total Mass of water droplets [kg]	0	0.18 ± 0.00	0.33 ± 0.01	0.18 ± 0.00	0.39 ± 0.01
Spatial density of water droplets [kg·m^{-3}]	0	1.72 ± 0.04	3.26 ± 0.08	0.63 ± 0.02	1.34 ± 0.03

experiments were conducted in an explosion pit (of diameter 6.0 m) at the National Institute of Advanced Industrial Science and Technology (AIST) in Tsukuba, Japan. Explosives and a sprinkler were set at the center of the explosion pit, and pressure transducers were placed around the explosive.

8.00 ± 0.01 g of composition C-4 was used as the explosive with No. 6 detonators (Kayaku Japan Co., Ltd.). The No. 6 detonator was inserted in the C-4, which was arranged in a spherical shape. They were fixed to each other by paper tapes, and then covered by a plastic bag to keep them dry.

The sprinkler comprised a water tank and a perforated plate (diameter of the holes 1.0 mm, pitch 10 mm). Water was pumped through the holes of the perforated plate to form water droplets. The flow rate of the water was controlled using a flowmeter (NFLT-R-GB00, Nippon Flow Cell, error ±2.5 %) and a pressure-reducing valve (RD31N-FL-50A, VENN Co., Ltd). Square sprinkled areas with sides of w = 0.32 and 0.54 m were used to vary the "perforated" area of the plate. The sprinkled areas were 0.1024 m^2 and 0.2916 m^2 for w = 0.32 and 0.54 m, respectively. The diameter distribution of the water droplets was measured using a laser disdrometer (5.4110.00.xxx, Adolf Thies GmbH & Co. KG, maximum diameter resolution 0.125 mm). We confirmed that the diameter distribution did not depend on r, and the mean diameter of the water droplets was 0.3 mm.

The pressure waveforms of the blast waves were measured using three pressure transducers (102M256, PCB. Piezotronics, Inc., 200 mV·psi^{-1}). The pressure transducers were flush-mounted on baffle plates having a diameter of 90 mm to obtain the static pressure of the blast waves. To measure the pressure waveforms after the interaction with the water droplets, the pressure transducers were placed at r = 0.7, 1.7 and 2.2 m. The signals of the pressure transducers were interpolated using smooth cubic natural spline functions.

2.2 Experimental Conditions

The experimental conditions are summarized in Table 1. There were three groups of experiments: explosions without water droplets (Case 0); explosions with the water droplets sprinkled within a small area with w = 0.32 m (Case 1); and within a large area with w = 0.54 m (Case 2). In Case 1 and Case 2, two different flow rates were imposed: 55 and 120 L·min^{-1}, indicated by "a" and "b", respectively. From the flow rate, the diameter and the number of the holes, total mass and spatial density of the water droplets existing in the volume of $w \times w \times 1$ m^3 around the explosives were calculated. Temperature, humidity and atmospheric pressure in the experiments were 10.4−17.1 ℃, 79−99 % and 102.0−103.3 kPa, respectively. To confirm the reproducibility, five trials were conducted for each case.

3. Results and Discussion

Figure 2 shows the typical time histories of the pressure waveforms measured at r = 0.7 m. In Case 0 and Case 1b, peculiar waveforms to blast wave propagation were observed: rapid increments of the overpressures caused by shock waves and gradual decrements by the expansion waves. However, the overpressure of Case 1b was mitigated over the duration of the positive pressure by the interaction with the water droplets. In Case 1b, "rounded" waveforms appeared twice in the five trials. Although further investigation is necessary to clarify the cause of the rounded waveform, the average of the peak

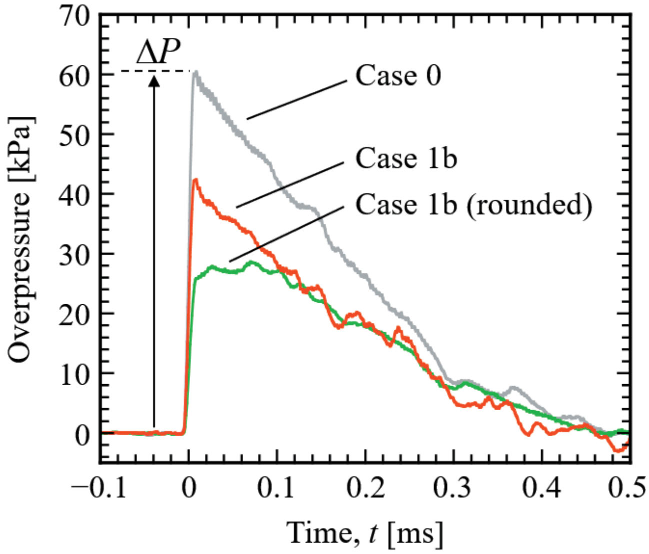

Figure 2 Typical pressure waveform at r = 0.7 m.

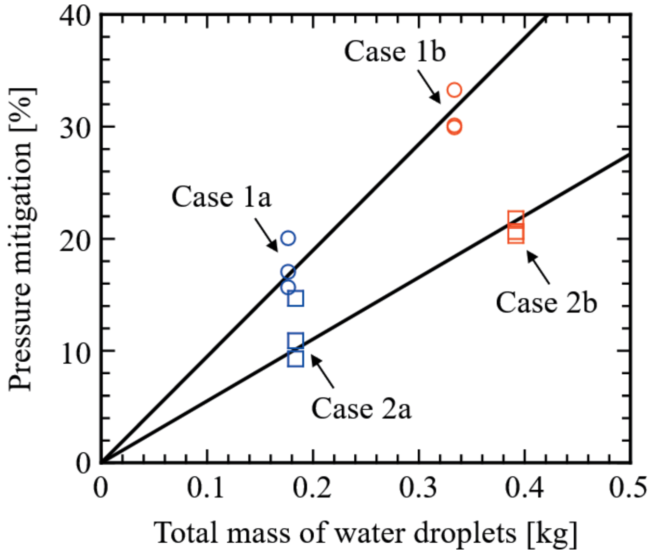

Figure 4 Pressure mitigation ratio.

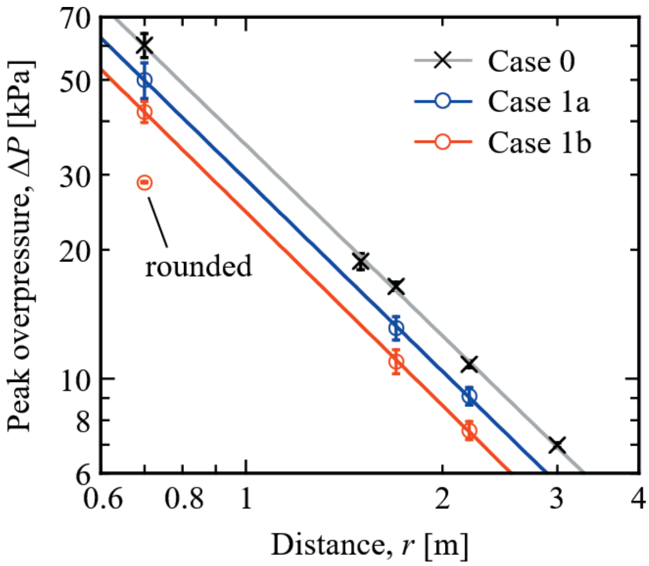

Figure 3 Peak overpressure distribution.

overpressure was lower than 52 % of that of Case 0.

Figure 3 presents the distributions of averaged peak overpressures, ΔP, of Cases 0 and 1, with linear regressions calculated except for the rounded waveforms. In Case 0, peak overpressures were also measured at r = 1.5 and 3.0 m. Noisy data arising from the impact of debris from the explosive were eliminated to improve accuracy; this accounted for no more than one incident per point. The error bars show the standard deviations of ΔP, which were less than 10 % throughout the entire experiment. ΔP for both Cases 1a and 1b was mitigated by the water droplets for all ranges of r. ΔP at r = 0.7 m was reduced by 10.3 kPa (17 %) and 18.1 kPa (30 %) for Cases 1a and 1b, respectively. These mitigation effects were equivalent to reductions in the masses of the explosives by 31 % and 51 %, respectively. The linear regressions of Cases 1a and 1b were almost parallel to that of Case 0. The tendency of Case 2 was the same as that of Case 1. However, the mitigation ratio was smaller than that in Case 1; the mitigation of ΔP at r = 0.7 m was 5.6 kPa (9 %) and 12.2 kPa (20 %) for Cases 2a and 2b, respectively.

Figure 4 compares the mitigation ratio of ΔP in each case to that in Case 0. For each case, an increment in the total mass of the water droplets enhanced the mitigation of ΔP. Furthermore, the more the spatial density of the water droplets increased, the larger the mitigation effects became. Because the sprinkled area of Case 1 was smaller than that of Case 2, the water droplets in Case 1 were more concentrated around the explosives as compared to those in Case 2. Consequently, the spatial density of the water droplets in Case 1 was more than twice that of Case 2 for equivalent masses of the water. Therefore, the result indicated that the pressure mitigation of the blast wave was affected by the spatial density of the water droplets.

4. Conclusion

The effects of the sprinkled area of water droplets on mitigation of blast pressure were experimentally investigated. This study revealed that a smaller sprinkled area resulted in a larger reduction in pressure when the total masses of the water droplets were equivalent. It indicated that the spatial density of the water droplets was significant for the pressure mitigation of the blast wave.

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