Article

Determination of JWL parameters from underwater explosion test for ideal and non-ideal explosives

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State of detonation products is described by various types of equations of state. Jones-Wilkins-Lee (JWL) equation of state is widely used because of its simplicity. JWL equation of state contains parameters determined by the cylinder expansion test. We obtained these parameters through the method of characteristics applied to the configurations of underwater shock waves of cylindrical explosives. The numerical results obtained by using the JWL parameters determined by the underwater explosion test are compared with the experimental results. Good agreement between the numerical and experimental results is confirmed in the case of the ideal and non-ideal explosives

1. Introduction

State of detonation products is described by various types of equations of state (EOS), such as Becker-Kistiakowsky-Wilson (BKW) EOS[1)2)], Kihara-Hikita-Tanaka (KHT) EOS[3)], Lennard-Jones-Devonshire (LJD) EOS[4)], and Jones-Wilkins-Lee (JWL) EOS[5)-8)]. BKW and KHT EOSs are very convenient, because they can calculate state of detonation products once the composition of explosive is known. However, when BKW and KHT EOSs are incorporated in hydrodynamic calculations, it is required very long computation time. JWL EOS is widely used because of it is simplicity in hydrodynamic calculations. JWL EOS contains parameters describing the relationship among the volume, energy and pressure of detonation products. These parameters are determined by the metal cylinder expansion test called cylinder test.

In the cylinder test, the expansion of detonation products is estimated by the metal cylinder expansion, but not by the real expansion of the products. Therefore at highly expanded region, the expansion of products used to be underestimated by the effect of metal cylinder. We have confirmed both in experiments and in numerical simulations that there is a strong correlation between underwater shock waves and expansion waves produced by the expansion of detonation products.[9)]

In order to study the expanding process of detonation products of explosives, the optical observation of the underwater explosion of cylindrical explosives was carried out. Using a method of characteristics applied to the configurations of underwater shock waves, the expanding process of detonation products is made clear in all stages. In the experiment, streak photographs and framing photographs are taken by a high-speed camera using a conventional shadowgraph system. The configurations of underwater shock waves obtained from the streak photographs are functionally approximated by the nonlinear curve fitting method.[10)] The expanding process of detonation products is predicted by applying the method of characteristics and one-dimensional hydrodynamic analysis for the axis symmetric flow. The parameters of JWL EOS are obtained by using this technique. The pressure and density of detonation products can be determined by making the underwater expanding process of the detonation products clear.

2. Nomenclature

r	Radius
P	Pressure

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ρ	Density
e	Internal energy
D	Detonation velocity
U_s	Shock velocity
u_p	Particle velocity
υ	Particle velocity in stationary coordinate
C	Sound velocity
M	Mach number
μ	Mach angle
ν	Prandtl-Meyer function
θ	Shock front angle
Γ	Coefficient of Grüneisen
δ	Deflection angle

3. Method of characteristics

The theory to use a method of characteristics is described as follows. The underwater shock wave system described in stationary coordinate system fixed to detonation front is shown in Fig. 1. The properties of detonation and the propagating process of underwater shock wave are assumed as follows. Detonation wave propagates into explosive with a constant velocity D and has the steady detonation behavior. Underwater shock wave keeps it similar shape and moves toward x at a constant velocity of D with detonation wave. Consequently, detonation wave and underwater shock wave can be stopped by adding the reverse velocity of $-D$, which has the reverse direction of x, to the whole stream field. Boundary between detonation products and water is shown by curve AB at stationary coordinate system. Curve of Characteristics S_1B_1 is described between this boundary and underwater shock wave AS. If the equation $U_s = C_0 + su_p$ is applied to the relation of the oblique shock by using a method of characteristics and the change of δ along streamline S in the direction of streamline and the change of υ among streamlines, the equations for underwater shock wave are obtained as follows.

$$P = \rho_0 U_s u_p \tag{1}$$

$$\rho = \rho_0 U_s / (U_s - u_p) \tag{2}$$

$$\upsilon^2 = \frac{[U_s(s-1)+C_0]^2}{s^2} + D^2 - U_s^2 \tag{3}$$

$$\tan\delta = \frac{(U_s - C_0)\sqrt{D^2 - U_s^2}}{sD^2 - U_s(U_s - C_0)} \tag{4}$$

$$\frac{d\nu}{dU_s} = \frac{\sqrt{M^2-1}\,[U_s(1-2s)+C_0(s-1)]}{U_s^2(1-2s) + 2U_sC_0(s-1) + C_0^2 + s^2D^2} \tag{5}$$

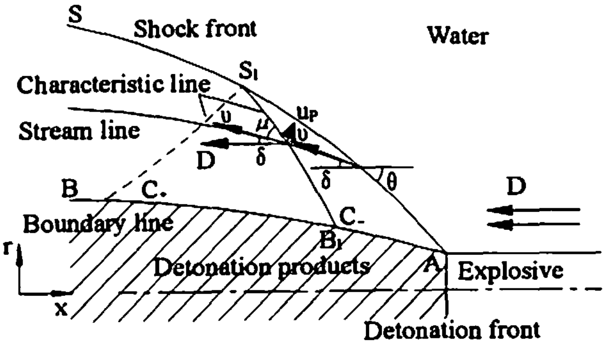

Fig.1 Stationary coordinate system.

If the configuration of underwater shock wave is given, physical properties in the range between AS and AB are obtained by using the above equations in calculations. Using one-dimensional hydrodynamic analysis for the axis symmetric flow, the pressure and density of products are found by making the underwater expanding process of the detonation products clear. Thus, if the configurations of underwater shock waves are known, the expanding process of the detonation products is made clear, even if the composition of explosive is unknown, and JWL parameters are obtained without using the result of the cylinder test.

4. Experiments

The two sample explosives were used in the experiment; one was the ideal explosive SEP (density; 1310 kg m^{-3}, detonation velocity; 6970 m s^{-1}), the other was the non-ideal emulsion explosive (EMX). EMX was composed of emulsion matrix and polystyrene resin balloon of multi-cell structure (average diameter; 2.2mm, bulk density; 43 kg m^{-3}). Composition of the emulsion matrix was AN/sodium nitrate (SN)/ Hydrazine nitrate (HN)/ Water/ EDTA/ Wax and emulsifier = 72.29/ 6.22/ 5.52/ 11.04/ 0.10/ 4.82 (wt.%). Detonation velocity of sample EMX was 2520 m s^{-1}, and its initial density was 900 kg m^{-3}. Sample explosives were set in the aquarium made of Polymethylmethacrylate (PMMA). Sample explosive was initiated by No. 6 electric detonator (ED). Streak photographs and framing photographs are taken by a high-speed camera (IMACON468, HADLAND PHOTONICS, Framing rates; 2×10^5 fps, Streak window; 30μs) using a conventional shadowgraph system. The configurations of underwater shock waves were obtained from the streak photographs. The experimental device for the cylindrical sample explosives is shown in Fig. 2. The cylindrical SEP

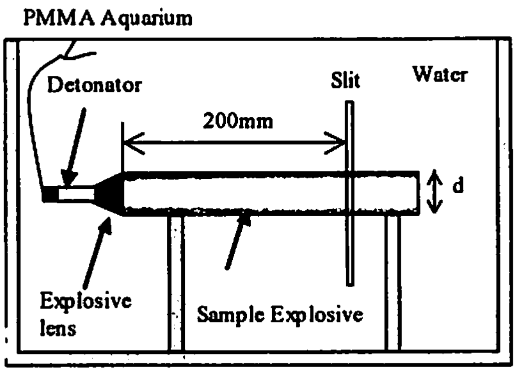

Fig.2 Experimental device for the cylindrical sample explosives.

explosive has 14mm in diameter and 250mm in length. The cylindrical EMX explosive has 20mm in diameter and 250mm in length. The experimental device for the spherical sample explosive is shown in Fig. 3. The spherical SEPexplosive has 54mm in diameter. In both Fig., the slit shows the optical slit for taking the stream photograph.

5. Numerical simulation

The numerical simulation of the underwater explosion of cylindrical explosive was conducted by Arbitrary-Lagrangian-Eulerian (ALE) method[11], by using C-J Volume Burn Technique[12] and by using the laws of conservation of mass, momentum, energy and EOS;

Conservation of mass,

$$\frac{\partial \rho}{\partial t}+\frac{1}{r}\frac{\partial (R\rho\rho)}{\partial r}+\frac{\partial(\rho v)}{\partial y}=0 \tag{6}$$

Conservation of momentum,

$$\frac{\partial(\rho u)}{\partial t}+\frac{1}{r}\frac{\partial(r\rho u^2)}{\partial r}+\frac{\partial(\rho u v)}{\partial y}=-\frac{\partial(P+q)}{\partial r} \tag{7}$$

$$\frac{\partial(\rho v)}{\partial t}+\frac{1}{r}\frac{\partial(r\rho u v)}{\partial r}+\frac{\partial(\rho v^2)}{\partial y}=-\frac{\partial(P+q)}{\partial y} \tag{8}$$

and conservation of energy,

$$\frac{\partial(\rho e)}{\partial t}+\frac{1}{r}\frac{\partial(r\rho e u)}{\partial r}+\frac{\partial(\rho e v)}{\partial y}=-(P+q)H \tag{9}$$

$$H=\frac{1}{r}\frac{\partial r u}{\partial r}+\frac{\partial v}{\partial y} \tag{10}$$

where u, v are the velocity components of r, y direction, respectively.

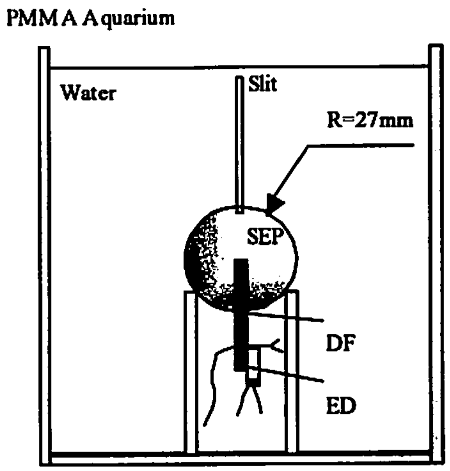

Fig.3 Experimental device for the spherical SEP explosive.

Mie-Grüneisen EOS is used for water.[13]

$$P=\frac{\rho_0 C_0^2 \eta}{(1-s\eta)^2}\left(1-\frac{\Gamma\eta}{2}\right)+\Gamma\rho_0 e \tag{11}$$

where

$$\eta=1-\frac{\rho_0}{\rho} \tag{12}$$

The constants of Mie-Grüneisen EOS for water are shown in Table 1.

JWL EOS using new parameters was obtained by the proposed method used for the detonation products.

$$\begin{aligned} P &= A\left(1-\frac{\omega}{R_1 V}\right)exp(-R_1 V) \\ &+ B\left(1-\frac{\omega}{R_2 V}\right)exp(-R_2 V)+\frac{\omega\rho_e e}{V} \end{aligned} \tag{13}$$

where A, B, R_1, R_2, ω are JWL parameters. V is ρ_e (density of explosive) / ρ (density of detonationproducts). JWL parameters obtained from the method of characteristics applied to the underwater explosion test of sample explosives (JWL-UW) are shown in Table 2 with those obtained from the cylinder test (JWL-CY).

The numerical simulation of the underwater expansion of spherical high explosive was conducted by one-dimensional hydrodynamic code FORTRAN SIN[14],

Table 1 Constants of Mie-Grüuneisen EOS for water.

Material	ρ_0(kg m-^{3})	C_0(m s^{-1})	s	Γ
Water	1000	1489	1.79	1.65

Table 2 JWL parameters obtained from the method of characteristics and cylinder expansion test for sample explosives.

	Type	A (GPa)	B (GPa)	R_1	R_2	ω
SEP	JWL-UW	372	3.48	4.59	1.06	0.29
	JWL-CY	365	2.31	4.30	1.00	0.28
EMX	JWL-UW	1.51	4.43	5.80	1.7	0.24
	JWL-CY	2.09	0.12	23.4	2.6	0.34

by using C-J Volume Burn Technique and by using JWL EOS and Mie-Grüneisen EOS.

6. Results and Discussion

The numerical results and experimental results obtained for cylindrical SEP and EMX explosives are shown in Fig. 4 and 5. The vertical axis is the distance in the direction of radius. The horizontal axis is the distance measured from the detonation front. Open circles indicate the configuration of the underwater shock wave obtained experimentally, and open triangles indicate the boundary between detonation products and water obtained experimentally. Solid line and broken line show respectively the configuration of the underwater shock wave and the boundary between detonation products and water obtained in numerical simulation using JWL parameters determined by the method of characteristics applied to the underwater explosion test (JWL-UW parameters). Dot-dashed line and dot-dot-dashed line show respectively the configuration of the underwater shock wave and the boundary between detonation products and water obtained in numerical simulation using JWL parameters determined by the cylinder test (JWL-CY parameters).

In the case of cylindrical SEP explosive, good agreement between the experimental results and numerical results obtained using both JWL-UW parameters and JWL-CY parameters is confirmed for the configuration of the underwater shock wave and boundary between detonation products and water (Fig.4). These results indicate that the numerical results obtained using JWL-UW parameters agree quite well with those obtained using JWL-CY parameters in the case of ideal explosive. It is confirmed that JWL EOS using both JWL-CY and JWL-UW parameters can simulate detonation propagation in unconfined cylindrical explosives in the case of ideal explosives.

In the case of cylindrical EMX explosive, good agreement between the experimental results and numerical results obtained using JWL-UW parameters is confirmed for the configuration of the underwater shock wave and boundary between detonation products and water (Fig.5). However, the numerical results obtained using JWL-CY parameters are shown to underestimate the expansion of both underwater shock wave and boundary between detonation products and water. It is shown that, in the case of non-ideal explosives as EMX, JWL-UW parameters should be used to simulate detonation propagation in unconfined cylindrical explosives. These results indicate that, in the case of non-ideal explosives, the existence of metal case gives strong effects on the expansion of detonation products.

The configurations of underwater shock waves for cylindrical SEP and EMX explosives obtained by framing photographs and numerical simulation using JWL-UW parameters are compared in Fig. 6. Good agreements are obtained between the experimental and numerical results.

Figure 7 indicates the distance-time relation of the shock front for spherical SEP charge of 54 mm in diameter. Open circles indicate the experimental results and the solid line indicates the numerical results using the JWL EOS with JWL-UW parameters. It is confirmed good agreement between the numerical and experimental results.

7. Conclusion

A new technique in determining the JWL parameters of detonation products of ideal and non-ideal explosives is proposed in this paper. This technique developed the method of characteristics in the relation between the underwater shock wave and the expansion wave of detonation products. Using this technique, we can estimate the relation between the pressure and volume in the expanded region of detonation products. Then, we can determine the parameters of JWL EOS.

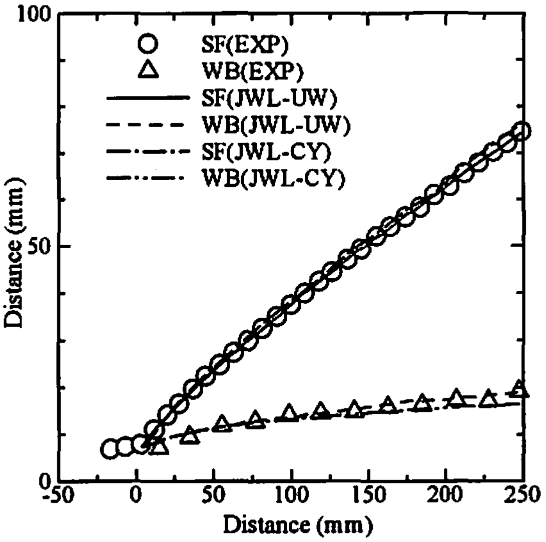

Fig.4 Configurations of the underwater shock wave and the boundary between detonation products and water for SEP.

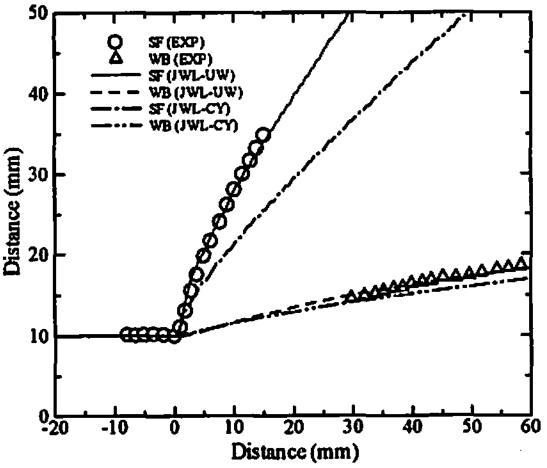

Fig.5 Configurations of the underwater shock wave and the boundary between detonation products and water for EMX.

JWL EOS using JWL parameters determined by proposed technique was applied to the numerical simulation of detonation propagation in unconfined cylindrical charges of both ideal and non-ideal explosives. Good agreement was obtained between the experimental and numerical results. It is confirmed that JWL EOS using JWL parameters determined by proposed technique can simulate detonation propagation in unconfined non-ideal explosives as well as ideal explosives.

(a) Numerical results

(b) Experimental results

Fig.6 Configurations of underwater shock wave by cylindrical explosives.

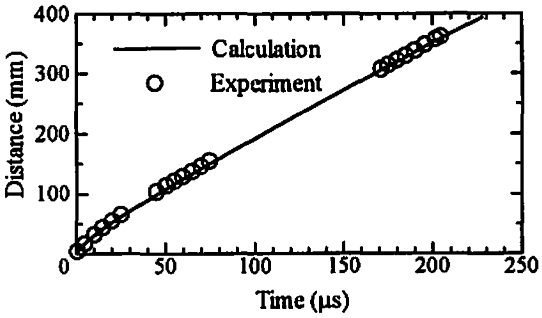

Fig.7 History of underwater shock front for the spherical SEP explosive.

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