DETERMINATION OF JWL PARAMETERS FROM UNDERWATER EXPLOSION TEST

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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 a method of characteristics applied to the configurations of underwater shock waves by cylindrical high explosives. The numerical results obtained by using the JWL parameters are compared with the experimental results. Good agreement between them is confirmed in the case of the underwater explosion of cylindrical and spherical high explosives.

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 may be determined by the metal cylinder expansion 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

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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 products.[9]

In order to obtain the expanding process of products of high explosives, the optical observation of the underwater explosion of cylindrical high explosive detonation was carried out. Using a method of characteristics applied to the configurations of underwater shock waves, the expanding process of 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 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 products can be determined by making the underwater expanding process of the products clear.

NOMNENCLATURE

r	Radius
P	Pressure
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

METHOD OF CHARACTERRISTICS

The theory to use a method of characteristics is easily described as follows. The underwater shock wave system described in stationary coordinate system fixed to detonation front is shown in Figure 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 ideal 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.

$$P = \rho_0 U_S u_P \tag{1}$$

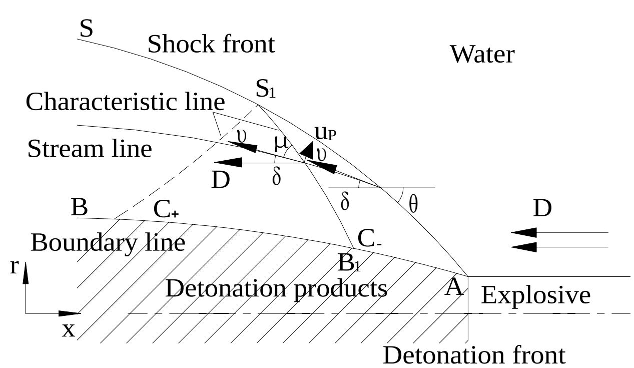


FIGURE 1. STATIONARY COORDINATE SYSTEM

$$\rho = \rho_0 U_S / (U_S - u_P) \tag{2}$$

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

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

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

If the configuration of underwater shock wave is given, physical quantities of a 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 product gas clear. Thus, if the configurations of underwater shock waves are known, the expanding process of the product gas is made clear, even if the composition of explosive is unknown. Using the expanding process of detonation products, JWL parameters are obtained without using the result of the cylinder expansion test.

EXPERIMENTS

The cylindrical and spherical high explosives SEP (ASAHI co., density of 1310kg/m^3, detonation velocity 6970m/s) were used in the experiments. Sample explosive was set in the aquarium made of Polymethylmethacrylate (PMMA). Sample explosive was initiated by No. 6 electric detonator. Streak photographs and framing photographs are taken by a high-speed camera (IMACON468, HADLAND PHOTONICS, Framing rates; 100 to 100000000 fps, Streak window; 10ns to 100μs) using a conventional shadowgraph system. The configurations of underwater shock waves were obtained from the streak photographs. The experimental device for the cylindrical high explosive SEP is shown in Figure 2. The experimental device for the spherical high explosive SEP is shown in Figure 3. In both figure, the slit shows the optical slit for taking the stream photograph.

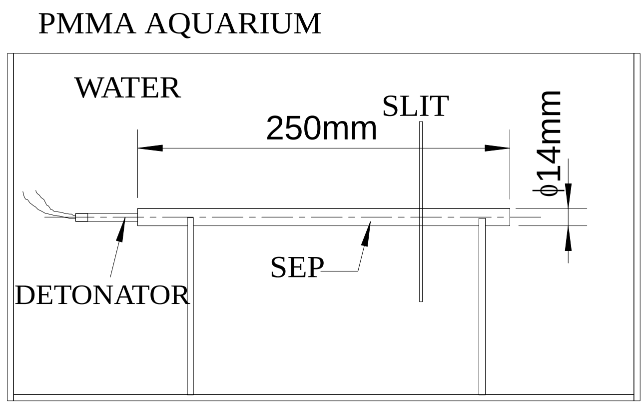


FIGURE 2. EXPERIMENTAL DEVICE FOR CYLINDRICAL HIGH EXPLOSIVE SEP

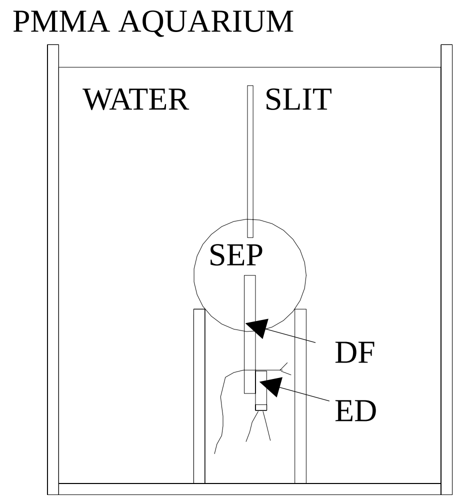


FIGURE 3. EXPERIMENTAL DEVICE FOR SPHERICAL HIGH EXPLOSIVE SEP

NUMERICAL SIMULATION

The numerical simulation of the underwater explosion of cylindrical high 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,

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

Conservation of momentum,

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

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

and conservation of energy,

$$\frac{\partial (\rho e)}{\partial t} + \frac{1}{r}\frac{\partial (r\rho eu)}{\partial r} + \frac{\partial (\rho ev)}{\partial y} = -(P+q)H \qquad (9)$$

$$H = \frac{1}{r}\frac{\partial ru}{\partial r} + \frac{\partial v}{\partial y} \qquad (10)$$

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

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

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

where

$$\eta = 1 - \frac{\rho_0}{\rho} \qquad (12)$$

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

TABLE 1. CONSTANTS OF MIE-GRÜNEISEN EOS

Material	ρ_0(kg/m^3)	C_0(m/s)	s	Γ
WATER	1000	1489	1.79	1.65

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

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

where A, B, R_1, R_2, ω are JWL parameters. V is ρ_e (density of explosive)/ ρ (density of detonation products). JWL parameters of SEP are shown in Table 2.

TABLE 2. JWL PARAMETERS OF SEP

A (GPa)	B (GPa)	R_1	R_2	ω
372	3.48	4.59	1.06	0.29

The numerical simulation of the underwater expansion of spherical high explosive was conducted by one-dimensional hydrodynamic code FORTRAN SIN[14], by using C-J Volume Burn Technique and by using JWL EOS and Mie-Grüneisen EOS.

RESULTS AND DISCUSSION

The P-V curves obtained from the underwater expansion test and KHT calculation are shown in Figure 4. This figure indicates that the pressure of detonation products estimated for the underwater expansion test in lower than that estimated from KHT calculation at highly expansion region

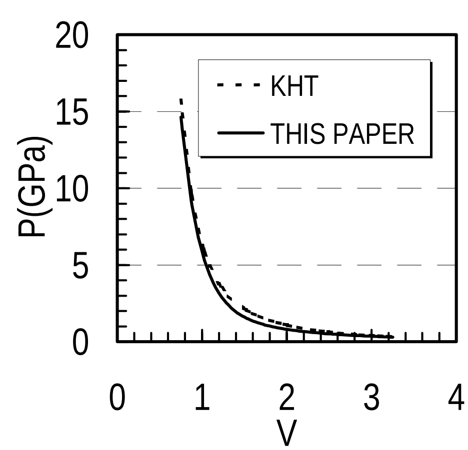


FIGURE 4. P-V CURVES OBTAINED FROM UNDERWATER EXPANSION TEST AND KHT CALCULATION

The numerical results and experimental results obtained for cylindrical explosive are shown in Figure 5. The cylindrical explosive has 14 mm in diameter and 250 mm long. The vertical axis is the distance in the direction of radius. The horizontal axis is the distance measured from the detonation front. A solid line shows the configuration of underwater shock wave obtained in numerical simulation and a broken line WB shows the boundary between detonation product and water obtained in numerical simulation. Open circles indicate the configuration of underwater shock wave obtained experimentally and Open triangles indicate the boundary between detonation products and water, obtained experimentally. A good agreement between the numerical results and experimental results is confirmed in the cases of both underwater shock wave and a boundary between detonation products and water. The configurations of underwater shock wave for cylindrical high explosive SEP obtained from the numerical results and experimental results are shown in Figure 6. Good agreement is obtained between numerical and experimental results. Figure 7 indicates the distance of the shock front obtained in the spherical charge which has 54 mm in diameter. Open circles indicate the experimental results and the solid line indicates the numerical results using the JWL EOS with parameters obtained by the new method presented this paper. It is confirmed good agreement between numerical and experimental results.

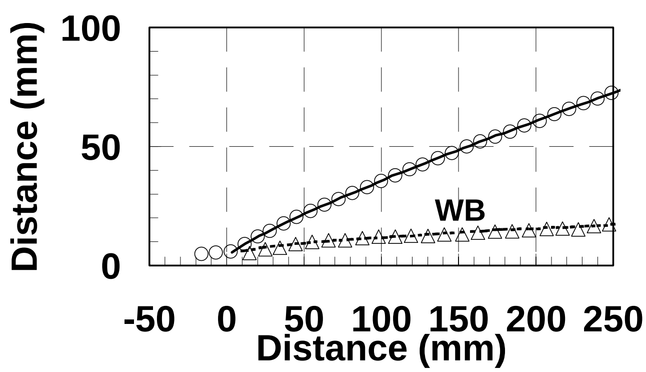
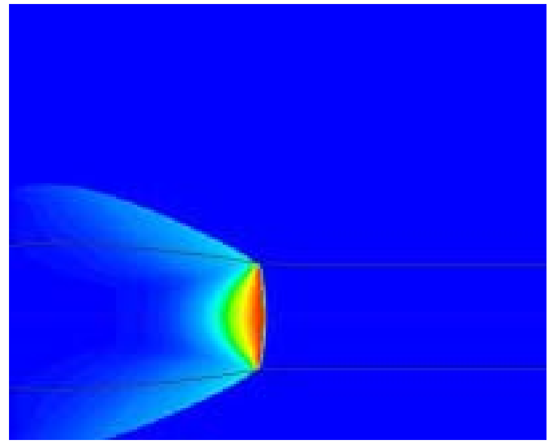
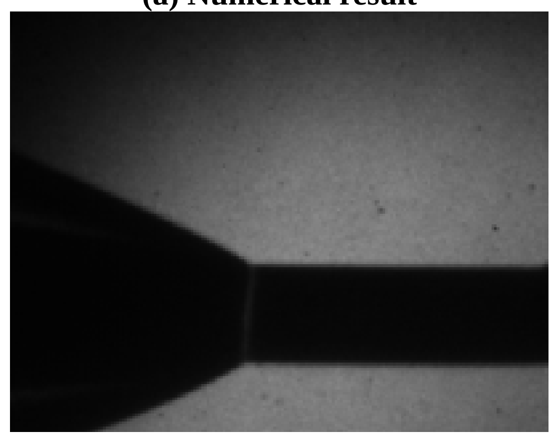


FIGURE 5. CONFIGURATONS OF THE UNDERWATER SHOCK WAVE AND THE BOUNDARY BETWEEN DETONATION PRODUCT AND WATER



(a) Numerical result



(b) Experimental result

FIGURE 6. CONFIGURATIONS OF UNDERWATER SHOCK WAVE BY CYLINDRICAL HIGH EXPLOSIVE SEP

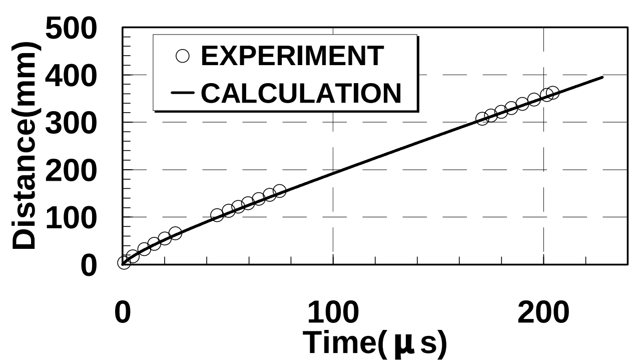


FIGURE 7. HISTORY OF UNDERWATER SHOCK FRONT

CONCLUSION

A new technique in determining the JWL parameters of detonation products is proposed this paper. The strong correlation between the underwater shock wave and the expansion wave produced by the expansion of detonation products was confirmed in our underwater experiments. This technique developed the method of characteristics in the relation between underwater shock wave and the expansion wave of detonation products. Using this theory, we can estimate the relation between the pressure and volume in the expanded region of detonation products. Then finally we can get the parameters of JWL EOS. It is concluded that for cylindrical charge, the configuration of the underwater shock wave is well estimated by the numerical calculation. And also the propagation of the underwater shock wave generated by the underwater explosion of spherical charge is quite well estimated by numerical calculation.

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