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DETERMINATION OF THE DETONATION PRESSURE FROM A WATER TEST

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In the paper, a semi-empirical method of determining the detonation pressure of high explosives from the so-called water test is proposed. X-ray photographs of expansion of a water envelope being accelerated by the detonation products of a cylindrical charge and results of numerical modelling of the process of water expansion are the basis of the method. The pressure is estimated by comparison of the calculated and recorded profiles of an oblique shock wave propagating in water. The method is applied to determine the detonation pressure for selected high explosives used for military purposes. The results obtained are compared with the experimental values of pressure given in the literature and with the pressures obtained from thermochemical calculations. The estimated detonation pressures differ by less than 5 % from those given in literature. It is proved that the accuracy of estimation of the detonation pressure depends generally on the measurement precision of the position of the shock wave front in water. A simplified variant of the method is also proposed in which the numerical modelling of the detonation in water is not needed.

1. Introduction

Piezoresistance and piezoelectric gauges are widely used for direct determination of pressure in a detonation wave [1]. Due to high temperatures (up to 4500K) and small resistance of the detonation products, special methods of isolating the gauges must be applied. That is why the methods are commonly used in which the detonation pressure is estimated in an indirect way. Among others, the flying plate test or the aquarium test is used for indirect determining the detonation pressure [1]. In the first test, the pressure is estimated on the basis of the free-surface velocities of metal plates of different thickness being accelerated by the detonation products. In the aquarium test, the velocity of the shock wave travelling some distance in water is measured after detonation of an explosive charge in a vessel filled with water. Relations between the detonation parameters and the measured quantities are used in both methods to estimate the detonation pressure.

In this paper a variant of the aquarium test, a water test, is proposed to determine the detonation pressure. Profiles of an oblique shock wave propagating in a cylindrical layer of water after detonation of a cylindrical charge of explosive is recorded by using the X-ray photography. On the other hand, the process of detonation of a charge located in a water envelope is modelled numerically. Comparison of the calculated positions of the shock wave and those recorded enable us to determine the detonation pressure. The method is applied for estimation of the pressure for chosen explosives. The results are compared with the experimental data obtained by different methods and with the values of pressure calculated by the use of a thermochemical code. A simplified method is also proposed in which numerical modelling of the process of detonation of a charge in water can be omitted.

2. Description of the method

2.1. Principles of the method

To estimate the detonation pressure, the fact is taken into considerations that, according to the classical theory of detonation, the following relation is true at the Chapman-Jouguet (CJ) plane

$$p_{\mathrm{CJ}} = \frac{\rho_0 D^2}{\gamma + 1}, \tag{2.1}$$

where D, p_{CJ} denote the detonation velocity and pressure, respectively; ρ_0 is the density of explosive. Symbol γ represents the exponent of isentrope of the detonation products. It is defined by the formula

$$\gamma = -\left(\frac{\partial \ln p}{\partial \ln v}\right)_S, \tag{2.2}$$

where the quantities p, v, and S are the pressure, specific volume and the entropy of the detonation products, respectively.

From Eq. (2.2) it follows that the detonation pressure can be easily determined if the density of explosive, detonation velocity and the exponent γ are known. Estimation of the value of exponent γ is possible on the basis of the water test.

The process of detonation of a cylindrical charge of explosive surrounded by water is illustrated in Fig. 1. The front of detonation wave propagates at a constant speed D in the charge. The narrow zone of chemical reactions follows the front and is bounded by the Chapman-Jouguet surface. The pressure of detonation products acting on the internal boundary of water (contact boundary – CB) generates an oblique shock wave (SW) in the water layer.

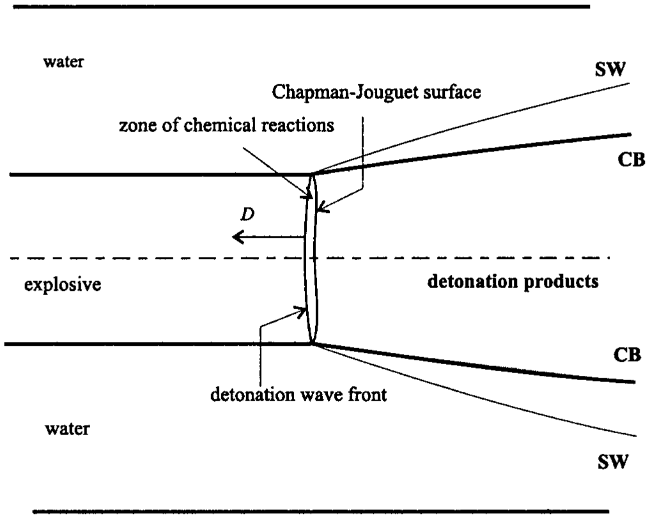

FIG. 1. Schematic image of detonation of a cylindrical explosive charge in a water envelope.

The method of determining the detonation pressure of high explosives is based on the following assumptions:

1. The influence of values of pressure in the reaction zone on the displacement of the shock wave front in the water layer is negligible.
2. The effect of initial conditions (place and method of initiation of the detonation) on the distribution of parameters of motion and state behind the detonation front can be neglected.
3. The exponent of isentrope of the detonation products in the region of high pressure is constant and equal to the value of this exponent at the CJ plane.

Postulate 1 is justified by the fact that the width of reaction zone in high explosives is of the order of 1 mm and its time-duration is about 0.1 μs. Even though the maximal pressure at the detonation front is almost two times higher than the pressure value at the CJ surface, the increase in the displacement of the shock wave in water caused by high pressure in the chemical zone is insignificant at farther distances due to short duration and rapid decreasing of the pressure to the CJ value. Thus, the reaction zone can be replaced by the CJ plane.

Assumption 2 is based on the results of experimental investigations of the process of detonation in cylindrical charges. It follows from these investigations that, after the passage by the front of the detonation wave of a path equal to a few diameters of the explosive charge, the influence of initial conditions on the distribution of the parameters of motion and state behind the wave front is negligible and it can be ignored.

The last assumption ensues from the analysis of results of experimental and theoretical studies of the expansion of detonation products. Although the isentropic exponent of the detonation products for high explosives like trinitrotoluene (TNT), hexogen (RDX) and pentryt (PETN) changes from the value of about 3 at the CJ plane to 1.20÷1.35 for atmospheric pressure, the variation of the exponent value is much less in the region of high pressures. For example, the exponent of isentropy determined experimentally for the detonation products of the mixture of TNT and RDX (TNT/RDX 50/50), increases from the value of 2.70 at the CJ plane ($p_{\mathrm{CJ}} = 26.5$ GPa) to the maximal value 3.18 for the pressure 18.3 GPa and decreases to 2.73 for 7.2 GPa. The calculated isentropic exponent for the detonation products of RDX grows from 2.75 for $p_{\mathrm{CJ}} = 29.0$ GPa to 2.95 for the pressure 5.1 GPa and falls off to 2.81 for 1.5 GPa [2]. Because only the initial stage of expansion of detonation products is analyzed in the proposed variant of aquarium test, in which the pressure of gaseous products exceeds one half of the CJ pressure, then the assumption of constant value of the isentropic exponent is justified.

Numerical solution of the problem of detonation of a cylindrical charge of explosive in a water envelope will enable us to find the relation between the position of the front of oblique shock wave in water and the exponent of isentropy of the detonation products. From the comparison of the position front measured by X-ray photography with those calculated, the exponent γ could be found. Thus, the detonation pressure can be determined from Eq. (2.2).

2.2. Measurement system

The system used to accelerate a cylindrical envelope of water by the detonation products is shown in Fig. 2. The cylindrical charge of diameter of 23.7 mm and 265 mm in length is placed inside a polyvinyl chloride tube with inner diameter of 71 mm and wall thickness of 2 mm. The tube is filled with water. Short-circuit sensors are placed in the charge to measure the detonation velocity and to release the X-ray apparatus.

An exemplary X-ray photograph of the initial stage of the process of acceleration of a water envelope is presented in Fig. 3. Boundaries of an explosive charge and the front of detonation wave (DW) as well shock waves (SW) in water are also indicated.

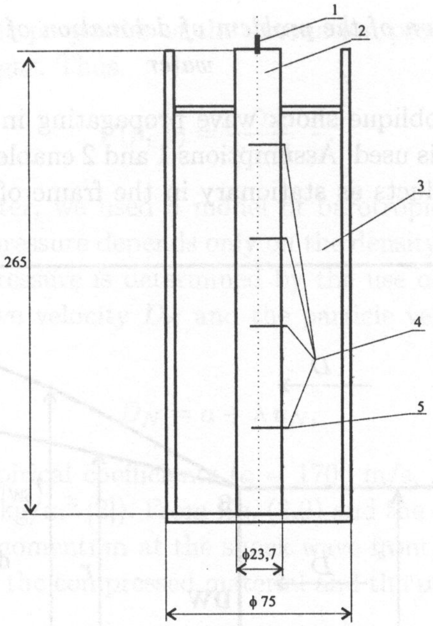

FIG. 2. System used in a water test: 1 – fuse, 2 – explosive charge, 3 – water, 4 – short-circuit sensors for measurement of detonation velocity, 5 – sensor releasing X-ray apparatus.

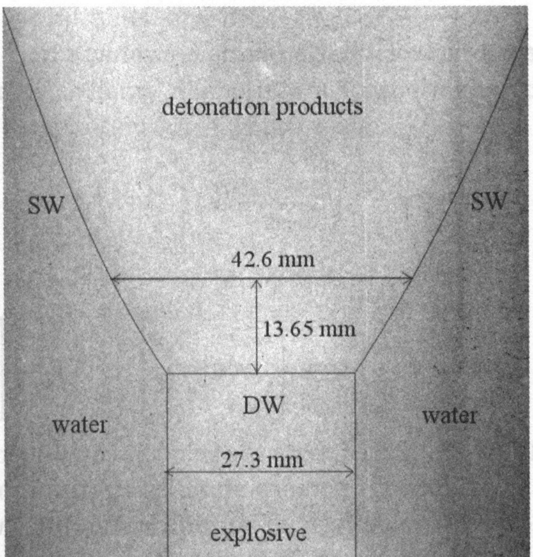

FIG. 3. An exemplary X-ray photograph of the initial stage of acceleration of a cylindrical layer of water.

2.3. Numerical solution of the problem of detonation of an explosive charge in water

To determine the oblique shock wave propagating in water, the theoretical model shown in Fig. 4 is used. Assumptions 1 and 2 enable us to treat the motion of the detonation products as stationary in the frame of reference fixed at the detonation wave.

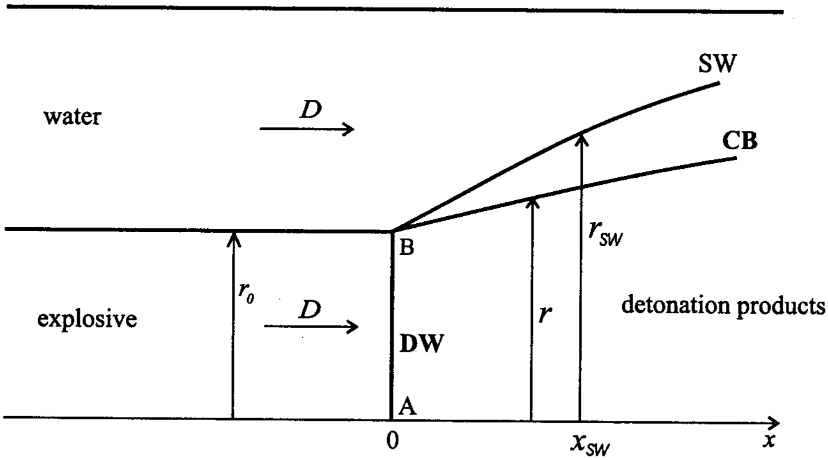

FIG. 4. Diagram of the system investigated numerically.

To describe the motion of the detonation products and water, we use the integral form of the equations of a stationary, axially symmetric gasdynamic flow:

$$\frac{d}{dx}\int_{r_-}^{r_+} \mathbf{a}\,dr = \left(\mathbf{a}\frac{dr}{dx} - \mathbf{b}\right)\Big|_{r_-}^{r_+} + \int_{r_-}^{r_+} \mathbf{f}\,dr, \tag{2.3}$$

where

$$\mathbf{a} = \begin{bmatrix} u \\ p+\rho u^2 \\ uv \end{bmatrix}, \qquad \mathbf{b} = \begin{bmatrix} pv \\ puv \\ p+\rho v^2 \end{bmatrix}, \qquad \mathbf{f} = \begin{bmatrix} v \\ uv \\ v^2 \end{bmatrix}.$$

Symbols u, v, p and ρ in Eq. (2.5) denote the velocity components in the axial and radial direction (in the frame of reference attached to the detonation wave), and the pressure and density, respectively. The radii r_- and r_+ are the boundaries of any ring in the x = const plane. This set of equations is completed by the Bernoulli equation

$$u^2 + v^2 + 2\,i\,(p,\,\rho) = \text{const} \tag{2.4}$$

where i denotes the enthalpy of the medium.

The thermodynamic properties of the detonation products are described by a model of polytropic-gas. Thus,

$$i\,(p,\,\rho) = \frac{\gamma}{\gamma-1}\,\frac{p}{\rho}. \tag{2.5}$$

As regards the water, we used a model of barotropic medium, that is the medium in which the pressure depends only on the density. The relation between the density and the pressure is determined by the use of an empirical relation between the shock wave velocity D_{N} and the particle velocity u_{N} at the shock wave front

$$D_N = a + \lambda\,u_N, \tag{2.6}$$

where a and λ are empirical coefficients (a = 1700 m/s, λ = 1.7 for water with the density ρ_w = 1000 kg/m^3 [2]). From Eq. (2.9) and the equations of continuity of the mass flow and momentum at the shock wave front, the following relation between the density of the compressed material and the pressure can be derived:

$$\frac{\rho}{\rho_w} = \frac{2\,\lambda\,(p-p_0)}{2\,\lambda\,(\lambda-1)\,\,(p-p_0) - \rho_w\,a^2 + a\,\sqrt{(\rho_w\,a)^2 + 4\,\lambda\,\rho_w\,\,(p-p_0)}}, \tag{2.7}$$

where p_0 denotes the initial pressure in water. Eq. (2.7) may be used for describing both the loading and unloading processes in water.

The boundary conditions for the considered problem are as follows.

The line $x = 0$:

For $r \in [0,\,r_0^-]$ (detonation wave front) we have

$$u\,(0,\,r) = \frac{\gamma}{\gamma+1}\,D, \tag{2.8}$$

$$v\,(0,\,r) = 0, \tag{2.9}$$

$$p\,(0,\,r) = \frac{\rho_0\,D^2}{\gamma+1}, \tag{2.10}$$

$$\rho\,(0,\,r) = \frac{\gamma+1}{\gamma}\,\rho_0. \tag{2.11}$$

For $r \in [r_0^+,\,r_{\mathrm{w}}]$ (undisturbed water) we have

$$u\,(0,\,r) = D, \tag{2.12}$$

$$v\,(0,\,r) = 0, \tag{2.13}$$

$$p\,(0,\,r) = p_0, \tag{2.14}$$

$$\rho\,(0,\,r) = \rho_w. \tag{2.15}$$

The line $r = 0$:

$$v\,(x,\,0) = 0. \tag{2.16}$$

The line $r = r_w$:

$$u\,(0,\,r) = D, \tag{2.17}$$

$$v\,(0,\,r) = 0, \tag{2.18}$$

$$p\,(0,\,r) = p_0, \tag{2.19}$$

$$\rho\,(0,\,r) = \rho_w. \tag{2.20}$$

where r_w is the value of radius in water which is not reached by the shock wave.

The equations of motion of the detonation products and water were solved by employing the difference scheme proposed in [3]. The solution included, among others, the dependence of the radial position of the shock wave front, r_{SW}, on the axial co-ordinate, x_{SW}.

2.4. Algorithm of determination of the detonation pressure

To determine the number of parameters on which the position of wave front depends, let us introduce the dimensionless variables

$$X = \frac{x}{r_0}, \quad R = \frac{r}{r_0}, \quad U = \frac{u}{D}, \quad V = \frac{v}{D}, \quad P = \frac{p}{\rho_0\, D^2}, \quad S = \frac{\rho}{\rho_0}. \tag{2.21}$$

The solution of the problem in dimensionless variables depends on the following parameters:

$$\gamma, \quad S_w = \frac{\rho_w}{\rho_0}, \quad A = \frac{a}{D}, \quad \lambda, \quad P_0 = \frac{p_0}{\rho_0\, D^2}. \tag{2.22}$$

Parameter λ is constant for each water test and parameters A, S_w, and P_0 are unchanged for the given explosive. Thus, the dimensionless position of the shock wave front R_{SW} depends on the dimensionless co-ordinate X_{SW} and parameter γ. This inference is the basis of the method for determining the detonation pressure.

The algorithm used to determine the detonation pressure is as follows. For a chosen value of co-ordinate X_{SW}, the radial displacement of the wave front R_{SWe} fixed experimentally is compared with the positions R_{SWn} obtained from numerical calculations performed for different values of the exponent γ. From this comparison, the exponent of isentrope leading to the solution being close to that measured experimentally is determined. This goal is achieved by finding a minimum of the function

$$g(\gamma) = \left[R_{SWe} - R_{SWn}(\gamma)\right]^2. \tag{2.23}$$

The method of interpolation by a second order polynomial is used. After determining the exponent γ, the detonation pressure is calculated from Eq. (2.2).

3. Verification of the method

To verify the proposed method of estimation of the detonation pressure, trinitrotoluene (TNT), phlegmatized octogen (HMX_{phl}), phlegmatized hexogen (RDX_{phl}), and Composition B (TNT/RDX 36/64) were used. The densities and detonation velocities of the explosives are given in Table 1. The detonation pressure was determined by comparing the measured and calculated positions of the shock wave front for two dimensionless axial co-ordinates: $X_{SW} = 1$ and $X_{SW} = 2$. Table 1 contains also the experimental values of the pressure given in the literature for the explosives of comparable density. Theoretical estimation of the detonation pressure was done by means of the thermochemical code TIGER - [4] with different sets of coefficients of the BKW equation of state [5÷7].The results are presented in the last column of Table 1.

The detonation pressures determined on the basis of positions of the shock front corresponding to two values of the dimensionless axial co-ordinate differ slightly from each another. But the point on the shock wave front located closely to the detonation front should be chosen for the pressure estimation, in order to fulfil the assumption of the isentropic exponent being constant.

From the comparison of the detonation pressures obtained from the water test and those taken from the literature it follows that the method proposed enables us to estimate the pressure with a satisfactory precision. Discrepancies between them do not exceed 5 % , except RDX_{phl}: here the data given in the literature differ significantly. The error of determination of the detonation pressure at the CJ plane is commonly accepted to change from 3 to 10% .

Values of the CJ pressure calculated by using different sets of the BKW parameters differ considerably (up to 10%). It was proved in [7] that the BKWR equation of state predicted the detonation pressures slightly better than BKWC and BKWS. But from our investigations it follows that the pressures estimated

Table 1. Detonation pressures of explosives tested.

Explosive	ρ_0 [g/cm^3]	D [m/s]	p_{CJ} [GPa] (X_{SW} = 1)	p_{CJ} [GPa] (X_{SW} = 2)	p_{CJ} [GPa] (experiment - literature)	p_{CJ} [GPa] (theory)
TNT	1,58	6870	**17,65**	**17,5**	17,65 (ρ_0=1,59) - [8] 17,4 (ρ_0=1,59) - [9]	17,3* 18,7** 17,5***
HMX_{phl}	1,767	8770	**31,9**	**32,3**	33,5 (ρ_0=1,783) - [2] 33,0 (ρ_0 = 1,776) - [10]	31,7* 33,6** 31,2***
RDX_{phl}	1,638	8270	**26,2**	**26,5**	23,8 (ρ_0 = 1,62) - [9] 28,3 (ρ_0 = 1,63) - [11]	26,4* 27,8** 25,4***
Comp. B	1,679	7870	**25,4**	**25,7**	25,8 (ρ_0 = 1,68) - [2]	25,7 * 27,4** 26,1***

* BKWS: $\alpha = 0{,}50$, $\beta = 0{,}298$, $\kappa = 10{,}50$, $\Theta = 6620$ - [6]
**BKWR: $\alpha = 0{,}50$, $\beta = 0{,}176$, $\kappa = 11{,}80$, $\Theta = 1850$ - [5]
***BKWC: $\alpha = 0{,}50$, $\beta = 0{,}403$, $\kappa = 10{,}86$, $\Theta = 5441$ - [7]

from the water tests are closer to those calculated from the BKWS equation of state.

The influence of experimental errors on the pressure values estimated in the water test is also analyzed. The displacement of a shock wave in water is a principal parameter measured in the method. An inaccuracy of the determination of position of the front may be caused by the time-duration of an X-ray impulse, which is about 20 ns. If the detonation velocity of explosive is 8 mm/μs then the displacements of the detonation and shock fronts during this time are about 0.16 and 0.04 mm, respectively. Thus, the inaccuracy in the determination of wave fronts does not exceed 0.2 mm. Much higher inaccuracy is a consequence of an measuring error, which is about 0.5 mm. Taking into account the wave front broadening caused by the time-duration of X-ray impulse and the measuring error, it is assumed that the maximal error done in the measurement of the diameter of oblique shock wave front is ±1 mm. The influence of this error on the detonation pressure of HMX_{phl} is tested. From the results presented in Table 2 it follows that differences between the estimated pressures are about 9 %.

In a similar manner, the influence of an accuracy of measurement of the detonation velocity on estimation of the detonation pressure is tested. The short-

Table 2. Influence of the accuracy of measurement of a shock wave front position on the estimated detonation pressure.

$2\,r_{SW}$	γ	p_{CJ} [GPa]
42.6	3.26	31.87
41.6	3.68	29.06 (-8.8 %)
43.6	2.91	34.77 (+9.1 %)

circuit method applied for high explosives enables us to estimate the detonation velocity with an error of 100 m/s. The calculated pressures for HMX_{phl} are shown in Table 3. In this case, the differences in the pressures do not exceed 3 %.

Table 3. Influence of the accuracy of determination of a detonation velocity on the estimated detonation pressure.

D[m/s]	γ	p_{CJ} [GPa]
8770	3.26	31.87
8670	3.29	30.93 (-3.0 %)
8870	3.24	32.82 (+3.0 %)

The third quantity used in the method, the density of explosive, can be measured with the highest accuracy. The measuring error does not exceed 2 %. Thus, the accuracy of water test depends mostly on the measuring error done in the determination of the position of the shock wave front in water. Sharpness of the X-ray picture and precision of measurement can be improved by modifying the system for X-ray monitoring of the process of water expansion, and by the use of computer codes to interpret the radiographs.

4. Simplified method

To simplify the method of estimation of the detonation pressure from the water test, numerical calculations of the process of propagation of a shock wave in a cylindrical layer of water were performed for different values of parameters A and S_w. Because the parameters a and ρ_w are constant for water, this means that the calculations were made for different values of D and ρ_0. Atmospheric pressure was assumed as the initial pressure p_0. The results of calculations are presented in Figs. 5a and 5b in the form of dependence of a dimensionless radial position of the shock wave front R_{SW} calculated for a dimensionless axial coordinate $X_{SW} = 1$ on the isentropic exponent γ. The range of variation of the detonation velocity and initial density corresponds to almost all high explosives encountered in practice. Diagrams from Figs. 5a and 5b enable us to estimate the detonation pressure on the basis of X-ray photograph of the initial stage of expansion of a water envelope due to detonation of the tested explosive. These diagrams can be also used to estimate the detonation pressure for explosives with the values of D and ρ_0 excluded from the Figs. 5a and 5b. In this case, the pressure can be calculated by interpolation between the values found on the diagrams. As an illustration of such a procedure, let us consider the following example.

Let us estimate the detonation pressure of phlegmatized HMX of the density $\rho_0 = 1.767$ g/cm^3 and detonation velocity $D = 8.77$ mm/μs. A distance equal to the charge diameter (13,65 mm on the magnified picture – Fig. 3) is settled on x-axis from the detonation front. For this value of axial co-ordinate, the radial distance 42.6 mm between the left and right fronts of the oblique shock wave is measured. From these distances we calculate $R_{SW} = 1.56$. Because the density of HMX_{phl} is between 1.7 and 1.8 g/cm^3 and the detonation velocity between 8.75 and 9.0 mm/μs, therefore we find the values of γ for $R_{SW} = 1.56$ and these values of the density and detonation velocity from the appropriate diagrams in Fig. 5b. For the density ρ_0=1.7 g/cm^3, we determine γ=3.225 for D=8.75 mm/μs and γ=3.15 for D=9.0 mm/μs. For ρ_0=1.8 g/cm^3, we find γ=3.3 for D=8.75 mm/μs and γ=3.25 for D=9.0 mm/μs. Then, the interpolation is fulfilled in the following way.

$$\text{For } \rho_0 = 1.8\,\text{g/cm}^3, \quad \gamma_1 = 3.30 + \frac{3.25 - 3.3}{9.0 - 8.75}(8.77 - 8.75) = 3.296.$$

$$\text{For } \rho_0 = 1.7\,\text{g/cm}^3, \quad \gamma_2 = 3.225 + \frac{3.15 - 3.225}{9.0 - 8.75}(8.77 - 8.75) = 3.219.$$

$$\text{Between } \gamma_1 \text{ and } \gamma_2, \quad \gamma = 3.219 + \frac{3.296 - 3.219}{1.8 - 1.7}(1.767 - 1.7) = 3.27.$$

The pressure $p_{CJ} = 31.8$ GPa is calculated from Eq. (2.2) for this value of γ. In this way, the pressures of detonation of other explosives were estimated. The results obtained are compared in Table 4 with the pressures determined earlier by the original method.

Table 4. Detonation pressures determined by the original and simplified methods.

Explosive	p_{CJ} [GPa] original method	p_{CJ} [GPa] simplified method
TNT	17.65	17.7
HMX_{phl}	31.9	31.8
RDX_{phl}	26.2	26.3
Comp. B	25.4	25.5

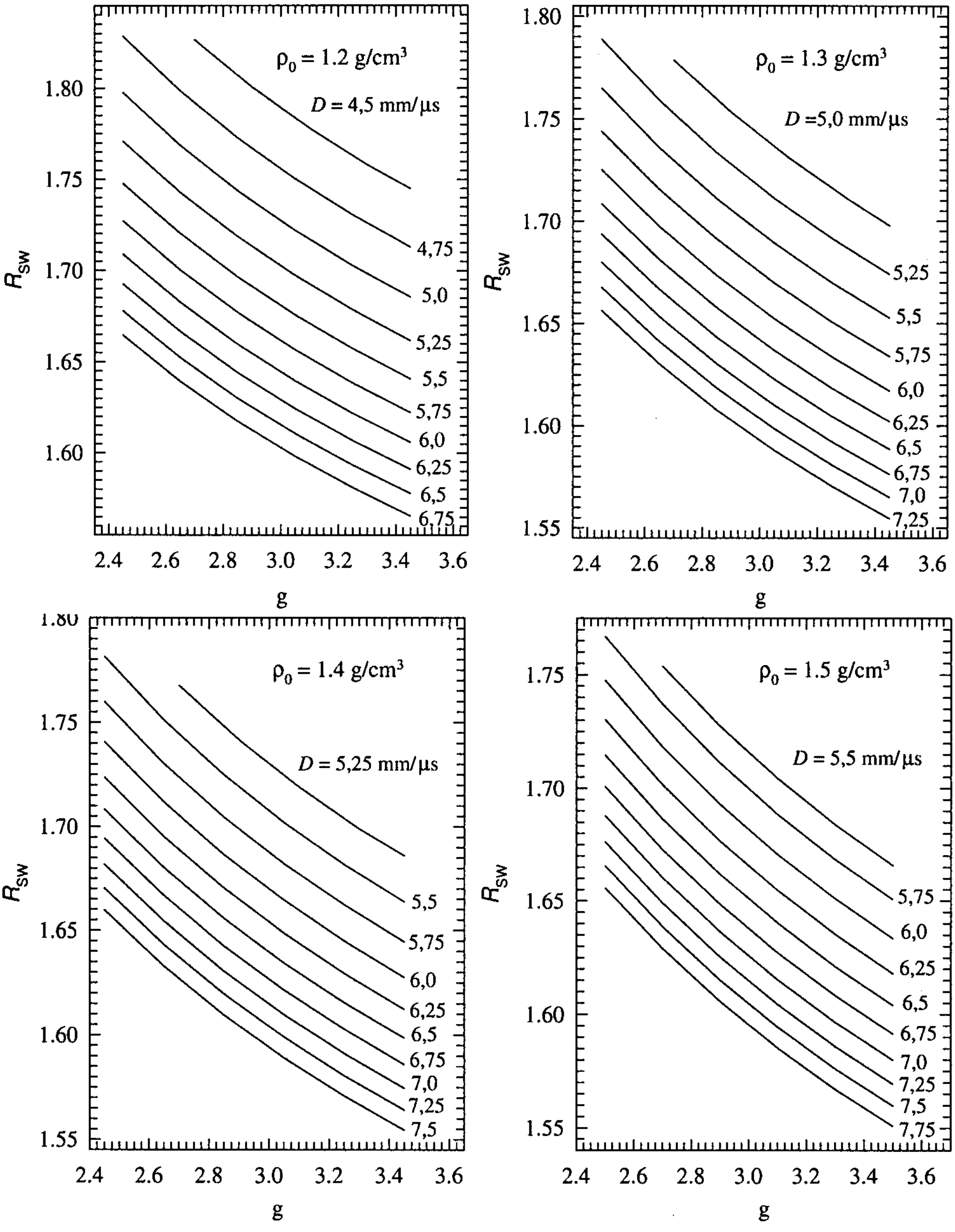

FIG. 5a Dependence of the dimensionless radial position of a shock wave in water, R_{SW}, calculated for an axial co-ordinate $X_{SW} = 1$, on the isentropic exponent of detonation products, γ.

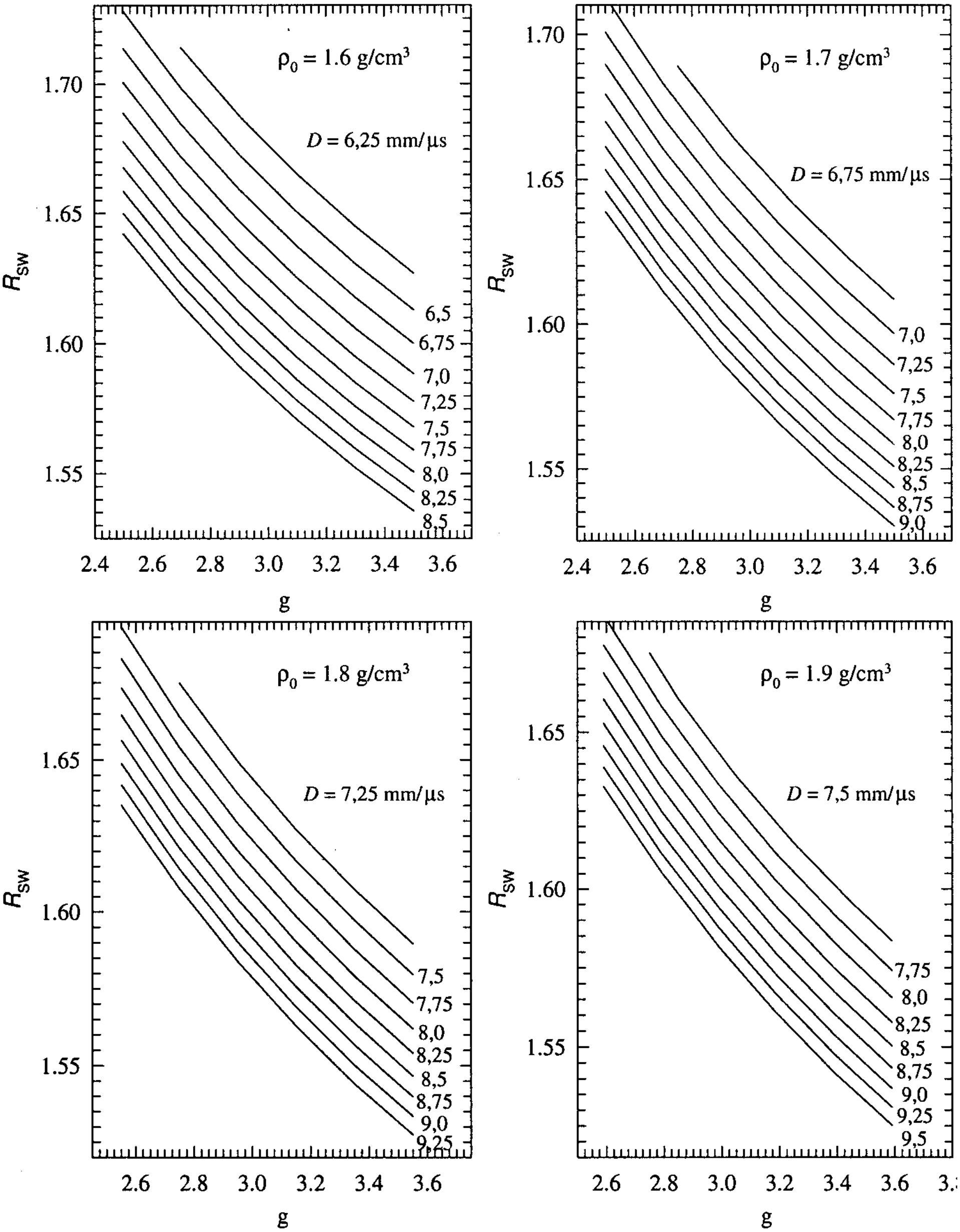

FIG. 5b Dependence of the dimensionless radial position of a shock wave in water, R_{SW}, calculated for an axial co-ordinate $X_{SW} = 1$, on the isentropic exponent of detonation products, γ.

5. Summary

A new method is proposed for determining the detonation pressure of high explosives on the basis of results of a water test and numerical modelling of the process of acceleration of a water layer by detonation products.

Verification of the method for chosen explosives shows that the estimated detonation pressures differ by less than 5% from those given in the literature (excluding phlegmatized RDX).

Accuracy of determination of the detonation pressure depends mainly on the precision of measurement of the position of shock wave front in water. Modification of the X-ray system for monitoring the process of water expansion and the use of a computer to interpret the radiographs will improve the sharpness of X-ray picture and precision of the measurements.

Simplified variant of the method is proposed in which dependence of the dimensionless position of the shock front on the isentropic exponent presented in a graphical form are used. Discrepancies in the pressures determined by using the original and simplified methods do not exceed 1% .

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