EXPERIMENTAL EVALUATION OF BLAST WAVE PARAMETERS IN UNDERWATER EXPLOSION OF HEXOGEN CHARGES

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(Received: October 08, 2011 – Accepted in Revised Form: December 15, 2011)

doi: *10.5829/idosi.ije.2012.25.01b.08*

Abstract Behavior of blast wave in underwater explosion is of interest to metal forming community and ship designers. Underwater detonation is, also a potential hazard to the water intakes or a plant spent fuel pool. In this paper, some techniques for calculating free-field blast parameters such as pressure and impulse in underwater explosion and prediction of bubble pulsation parameters are presented and they will be compared by experimental results of underwater detonation of Hexogen explosive charge. The details of pressure pulse curves generated by detonation of Hexogen in several standoff distances are obtained, that by using scaling laws, they can be used in analysis of practical underwater detonations. Finally, the equivalent mass of Hexogen charge relative to TNT in underwater explosion is calculated.

Keywords Underwater explosion; Shock wave; Impulse; Overpressure; Pressure-Time Curve.

چکیده مطالعه رفتار موج بلاست و پارامترهای آن در انفجار زیر آب موضوعی است که همواره مورد توجه جامعه علمی شکل دهی مواد و طراحان کشتی بوده است. همچنین انفجارهای زیر آب خطرات بالقوه‌ای برای تجهیزات زیر آب یا سکوهای استخراج نفت و گاز به شمار می‌رود. در این مقاله تکنیکهای محاسبه پارامترهای بلاست میدان باز مانند فشار و ایمپالس در انفجارهای زیرسطحی واقع در آب و پیش‌بینی پارامترهای ضربان حباب بررسی شده و با نتایج تجربی به دست آمده برای انفجارهای زیرسطحی نمونه‌های خرج انفجاری هگزوژن مقایسه شده است. در این پژوهش، جزئیات منحنی‌های پالس فشار در اثر انفجار زیر آب در فواصل مختلف به دست آمده که می‌توان با استفاده از قوانین مقیاس‌گذاری، از آنها در تحلیل پدیده‌های واقعی انفجار زیر آب استفاده کرد. در نهایت، جرم معادل ماده منفجره هگزوژن نسبت ماده منفجره متداول تی‌ان‌تی در شرایط انفجار زیر آب محاسبه شده است.

1. INTRODUCTION

Underwater shock response of structures is studied by both ship designers and metal forming experts to understand the relation between the impulsive forces and the structure deformation and fracture behavior. Effects of underwater explosion have been studied ever since it was realized that explosion underwater could be accomplished [1, 2].

Due to complicated nature of the phenomenon, analytical works on study of explosion phenomena are very difficult and too many assumptions must be taken to simplify analytical solutions [3]. It was reported that Rayleigh, for the first time, took the assumption of incompressibility of fluid around the bubble and proposed an analytical model for underwater explosion. Taylor and Shiffman, by energy equations, developed the motion equation of bubble that includes its contraction and expansion. Plesset used Bernoulli's equations and velocity potential generated by a source in an incompressible fluid and obtained the contraction-expansion motion of bubble [4].

Other researchers analyzed the problem by choosing the assumption of incompressibility of fluid in vicinity of bubble. Herring [5] chose the incompressibility assumption and by integration of Navier-Stokes in radial direction of spherical coordinates, proposed his theory and formula. Kirkwood and Bethe [6] developed an equation based on shock wave theory. Keller and Kolodner applied a unique method for developing of motion equations. They used wave equation instead of

Nomenclature

c	Sound velocity ($m.s^{-1}$)
D	Depth of explosion point (m)
E_{sh}	Shock wave energy density ($J.m^{-3}$)
I	Shock wave impulse of unit area ($Pa.s.m^{-2}$)
P_a	Ambient medium pressure (Pa)
P_m	Shock wave overpressure (Pa)
p	Pressure history function of shock wave (Pa)
p_0	Hydrostatic pressure (Pa)
$R_{\max}$	Maximum radius of gas bubble (m)
S	Standoff distance to detonation point (m)
T	Time duration of bubble pulsation (s)
t	Time variable (s)
v	Flow velocity in the direction of shock wave ($m.s^{-1}$)
W	Explosive charge weight (kg)
Z	Equivalent depth of charge for the total static pressure (m)
ρ_a	Ambient medium density ($kg.m^{-3}$)
θ	Decay time of shock wave pulse (s)

Laplace equation for estimation of potential field [7].

In the other hand, the nature of explosion is too complicated and the results of purely analytical and numerical solutions are depended on several coefficients. These coefficients typically depend on type and composition of explosive charge, and its density, shape and grain size. Therefore, estimation of shock wave parameters by analytical and numerical solutions is not too perfect or reliable and does have exact conformity with experimental results [8].

In this paper, some methods that allow all these free-field blast parameters for underwater explosions to be estimated by scaling from available experimental data are described.

The objective for analyzing the underwater explosion is to determine the shock wave overpressure and shock wave positive impulse as functions of target depth and radial distance from the detonation point. Calculated parameters needed for the underwater blasts include peak pressure and total positive impulse for the shock wave of the explosions. These parameters need to be determined as functions of range extending out into the surrounding water from a position immediately adjacent to the explosion.

For this purpose, in this study some experiments have been done for measurement of pressure-time history at different distances in underwater explosion of Hexogen charges. These experimental results are compared to available empirical equations of TNT charges and TNT weight equivalence of hexogen charge in underwater explosion is estimated.

2. SHOCK WAVE

An explosive reaction is the break down of the original molecules into product molecules (such as CO, CO_2, NO, CH_4, H_2 as gases, and C, Pb, Al_2O_3 as solids) together with the evolution of large amount of heat (4.2 MJ per kg of TNT explosive) [9]. The temperature in the product gas is of the order of 3000 ^{o}C and the pressure about 5000 MPa [10]. For a given type and size of charge, the efficiency of energy transfer depends greatly on the properties of the energy transfer medium. Water has more incompressibility than air, so it has much higher energy transfer efficiency.

In the underwater explosion, the chemical explosive is detonated and a gas bubble is produced under high pressure. A primary shock wave travels out from the gas bubble through the surrounding water. At a short distance from the source, this primary shock wave carries with it about 50% of the total energy of the charge. The gas bubble expands until its internal pressure drops below of the surrounding water pressure. The expansion eventually ceases and the bubble begins to contract until it reaches a minimum size. The reduction in size results in increased pressure within the bubble. When the pressure increases, sufficiently the reduction in size stops.

The pressure is greater than its surroundings and it begins to expand again. At the beginning of the second expansion, a secondary shock wave is generated in the water. A secondary shock wave is emitted each time the bubble reaches a minimum size and carries only a small fraction of the total energy. For reloading to occur, the head of the water above the charge must be greater than twice the standoff distance. If this is not the case, the bubble bursts at the water surface and the energy transfer process stops.

The complex phenomenon of energy transfer from an underwater explosion has not yet yielded a complete mathematical description. Approximate methods are available for estimating the total energy delivered, the three common methods are:

1. The geometrical method, based primarily on the specific energy of the explosive and the configuration relative to the charge. The influence of the energy transfer medium is expressed relatively by an empirical factor.
2. The energy method, based on empirical energy density formulae derived from measurements of underwater explosions that include the reloading effect. The energy density is integrated over the area of the structure. The use of this method is limited to explosives for which the appropriate empirical energy constants have been determined.
3. The impulse method, also based on empirical formulae obtained from the measurement of shock pressures from underwater explosions can only be used when the energy transfer medium is water and when the reloading phenomenon is absent.

Both the first and the second methods provide upper bound estimates of the explosive energy delivered to the structure from both the primary shock wave and reloading phenomenon. The third method gives lower bound estimation based on empirical pressure and impulse formulae and does not include the energy delivered in the reloading phase. An important factor in determining peak pressure is the compressibility of the energy-transmitting medium and its acoustic impedance, the product of the mass density and sound velocity in the medium. The lower is the compressibility, the higher is the density of the medium and the higher are the peak pressures.

In this problem, there are five variables, which are charge weight W, standoff distance S, ambient medium density ρ_a, its pressure P_a, and shock wave overpressure P_m. The dimensions are, respectively, M, L, ML^{-3}, $ML^{-1}T^{-2}$, and $ML^{-1}T^{-2}$.There are only three dimensions; therefore, two dimensionless products should be formed. These are $\left(P_m/P_a\right)$ and $\left(S^3\rho_a/W\right)$.

Since water is relatively incompressible, its density, ρ_a can be considered as constant and scaling parameters of $\left(S^3\rho_a/W\right)$ and $\left(P_m/P_a\right)$ can be written as follow [11]:

$$\left(P_m/P_a\right)= f\left(S/W^{1/3}\right) \tag{1}$$

The propagation velocity of shock wave drops rapidly to the sound velocity (approximately 1440 m/s) within 10 times the charge radius [12]. The underwater shock wave generated by the explosion is superimposed on the hydrostatic pressure. The pressure time history, $p(t)$, at a fixed location starts with an instantaneous pressure increase to a peak pressure, P_m, (in less than $10^{-7}\ s$) followed by a decay which in its initial portion is usually approximated by an exponential function as [4]:

$$p(t)=P_m exp(-t/\theta) \tag{2}$$

with θ as the decay time, valid for $0<t<\theta$. The peak pressure and the decay constant depend on the size of the explosive charge and the stand off from this charge at which pressure is measured [4].

$$P_m = 52.16\left(\frac{W^{1/3}}{S}\right)^{1.13} \tag{3}$$

$$\theta = 96.5\left(W^{1/3}\right)\left(\frac{W^{1/3}}{S}\right)^{-0.22} \tag{4}$$

where, P_m is in MPa, θ is in micro seconds, W is expressed in kg of TNT and the stand off, S, is measured in meter. These formulae apply to any size of charge, from a few grains to huge explosions, exploded at any depth, and describe the shock wave properly except in the immediate vicinity of the explosive charge (10 times the charge radius), where the peak pressure is higher than what formula predicts. As the shock wave passes a fixed location and subjects the liquid at this point to a transient pressure $p(t)$, the liquid is simultaneously subjected to flow with a velocity $v(t)$ in the direction of the wave which is related to the transient pressure [13]:

$$p(t) = \rho c v(t) \tag{5}$$

A correction due to spherical flow is required and then the flow velocity becomes:

$$v(t) = \frac{p(t)}{\rho c} + \frac{1}{\rho S}\int_0^t p(t)\,dt \tag{6}$$

The first term is the velocity for a plane wave and the correction term is called ‘‘after flow’’ term. The after flow term becomes significant in the close vicinity of the explosion, and for large time intervals.

The energy in the shock wave of the explosion consists of two equal components, one pertaining to the compression in the water and the other due to the associated flow. The shock wave energy density E_{sh} for a plane shock wave is [14]:

$$E = \frac{1}{\rho c}\int_0^{\alpha} p^2(t)\,dt \tag{7}$$

For a fully exponential shock wave:

$$E = \frac{1}{\rho c} P_m^2 \theta \tag{8}$$

The effectiveness of the shock wave depends on the time integral of the pressure, or impulse, more significantly than on the detailed form of pressure versus time. The impulse of unit area of the shock wave front upto a time t after the arrival is given by [13]:

$$I = \int_0^t p(t)\,dt \tag{9}$$

Strictly, the pressure $p(t) - p_0$ in excess of hydrostatic pressure should be used in this equation.

But for most cases of interest, the shock wave pressure $p(t)$ is so large that the difference is of no importance. The energy is estimated for the whole length of the shock wave and the impulse is integrated to a time $t = 6.7\theta$ are given by:

$$E_{sh} = 98000\left(W^{1/3}\right)\left(\frac{W^{1/3}}{S}\right)^{2.1} \tag{10}$$

$$I = 5760\left(W^{1/3}\right)\left(\frac{W^{1/3}}{S}\right)^{0.891} \tag{11}$$

where, E is in J/m^2 and I is $N\,s/m^2$.

2.1. Gas Bubble Pulsation The initial gas pressure is considerably decreased after the principal part of the shock wave has been emitted; but, it is still higher than the equilibrium hydrostatic pressure [14]. Up to 12 gas bubble pulsations have been observed using a detonator as the charge [15]. The first bubble pulse can have a peak pressure of 10–15 percent of the shock wave peak pressure. During the pulsation process, the bubble migrates upward because of the influence of the gravity, with the maximum migration occurring during the minima (Figure 1) [16].

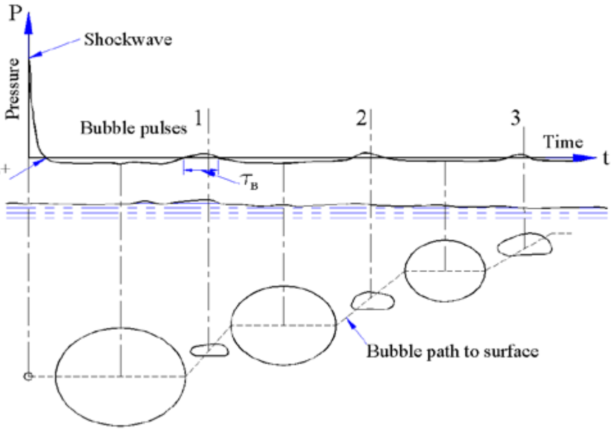

Figure 1. Variation of the gas bubble generated by the explosion and its effect on pressure pulse

The gas bubble generated by the explosion is nearly spherical during the initial expansion and contraction [17]. The two characteristic parameters are the maximum radius $R_{\max}$, reached during the first pulsation and the duration T of the pulsation (from the explosion to the first following minimum). Both vary with the size of the explosion charge and the depth at which the explosion occurs [13].

$$R_{\max} = 3.3\left(\frac{W}{Z}\right)^{1/3} \tag{12}$$

$$T = 2.08\frac{W^{1/3}}{Z^{5/6}} \tag{13}$$

where, $Z = D + 10$ represents the total static pressure at the location of the explosive. Here, D is the depth of the explosion in m. Nomogram was made by Keil [1] for determining the maximum gas bubble radius and the time of first bubble pulsation.

3. EXPERIMENTAL PROCEDURE

In this research, the blast shock waves for underwater detonation of Hexogen explosive charge (RDX or cyclotrimethylene-trinitramine, $C_3H_6N_6O_6$) were experimentally evaluated. The tests were set up in a water pool of dimensions $4 \times 4 \times 3$ m. As mentioned earlier, only experimental parameters of shock wave for TNT charges were reported in the literature. Meanwhile, this data is mainly obtained about 60 years ago by Cole [4] or 40 years ago by Swisdak [13]. Therefore, these experimental results had some limitations and deficiencies, due to technological restrictions. Not recording the details of blast waves is one of the limitations. It must be noted that, the details of blast shock waves cannot still be evaluated by hydro-codes, because of intricacy and complexity of the phenomenon [9].

Hexogen or RDX charge is a type of high explosive that has lot of industrial and military applications. Detonation properties of this charge, similar to other high explosives, depend on mass, density, shape, grain size and composition. The samples of explosive charges used in the experiments were cylindrical with L/D of one and mass of 20 gr. The density of hexogen charges was 1.64 gr/cm^3 and it was obtained by pressing. The charges were composed of 98 mass percentage of RDX and 2 mass percentage of wax. Charge placed at the mid-depth point of the pool (2 m depth) and at the distances of 1, 1.1, 1.25, 1.35, 1.5, and 1.6 m, three Endevco piezoelectric pressure sensors installed on the special fixtures. Using Mk79 electrical detonator (Figure 2), the charge is exploded and pressure versus time data is recorded with 10 million samples per second by a data acquisition system. The experimental setup is shown in Figure 3. To ensure repeatability of results, tests repeated five times.

Figure 2. Electric detonator

Figure 3. Setup of data acquisition system

4. RESULTS AND DISCUSSION

In Figure 4, a sample of experimental pressure pulse measured at 1.0 m from the detonation point is shown. In addition, the Cole's formula (Equations 2 to 4) for TNT is drawn for comparison. As expected, the pulse of Hexogen is larger than TNT, because of higher detonation energy [8]. Figure 5 shows comparison between shock wave pulses from the detonation of 20 gr of Hexogen at distances 1.0, 1.25, and 1.5 m. Although, the behavior of shock wave pulse can be approximated by an exponential curve, but its details are complicated and the behavior of different pulses are not exactly the same.

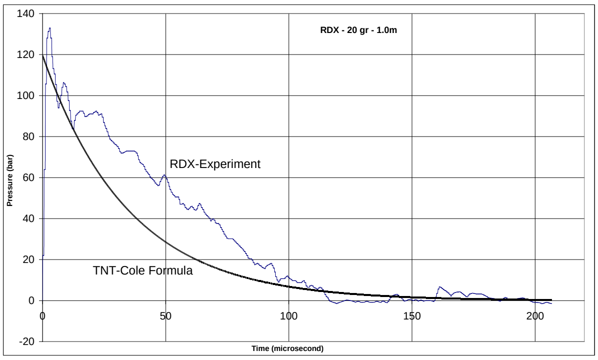

Figure 4. Pressure-time record measured 1.0 m from the detonation of 20 gr of Hexogen (RDX). For comparison, pressure pulse curve of TNT based on Cole's equation is drawn.

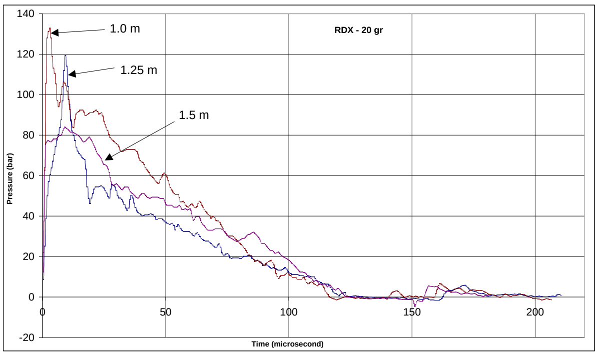

Figure 5. Comparison between shock wave pulses from the detonation of 20 gr of Hexogen at distances 1.0, 1.25, and 1.5 m.

The measured pressure versus time histories for explosion of Hexogen at the distances of, 1.0, 1.1, 1.5, and 1.6 are shown in Figures 6, 7, 8, and 9, respectively. In these figures, every curve is belonging to a test repetition and similarity of curves in each graph is noticeable.

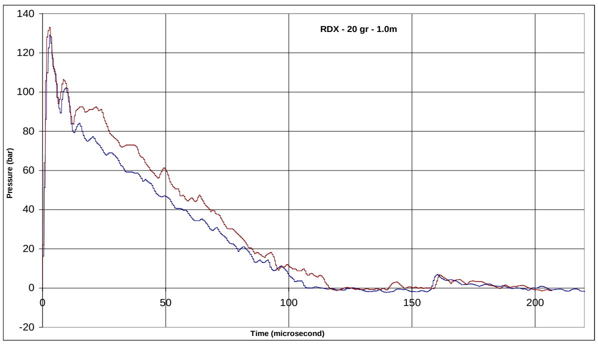

Figure 6. Pressure-time histories record measured 1.0 m from the detonation of 20 gr of Hexogen (RDX) for different tests.

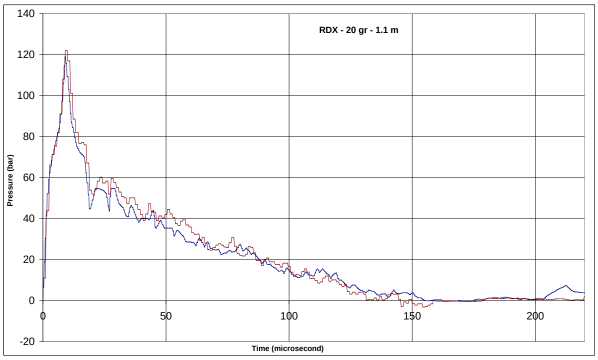

Figure 7. Pressure-time histories record measured 1.1 m from the detonation of 20 gr of Hexogen (RDX) for different tests.

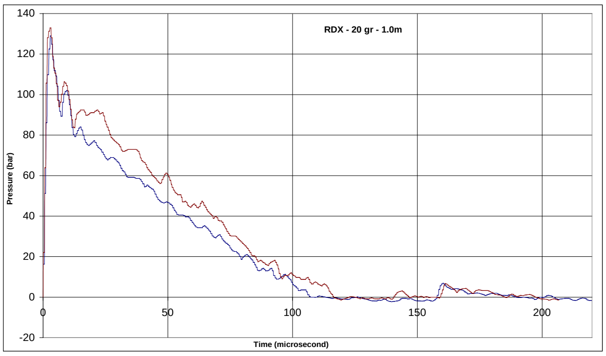

Figure 8. Pressure-time histories record measured 1.5 m from the detonation of 20 gr of Hexogen (RDX) for different tests.

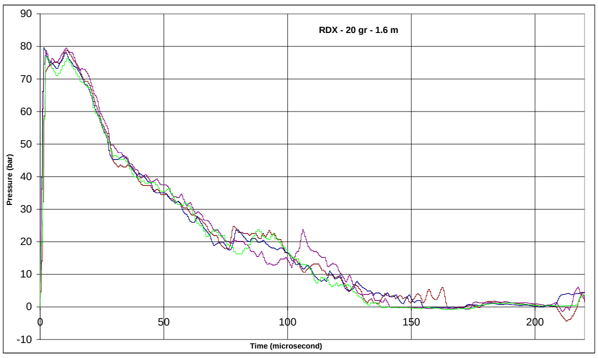

Figure 9. Pressure-time histories record measured 1.6 m from the detonation of 20 gr of Hexogen (RDX) for different tests.

The values of overpressure and impulse of measured blast shock waves are stated in Tables 1 and 2, respectively.

TABLE 1. The values of blast shock waves overpressure measured at different distances

Distance (m)	Values of overpressures in each test (bar)					Average
	1	2	3	4	5	
1	137.1	135.9	137.0	131.7	133.6	135.0
1.1	117.7	118.1	121.2	117.5	120.0	118.9
1.25	104.7	104.7	101.4	103.7	101.5	103.2
1.35	96.6	98.2	94.9	92.5	93.1	95.1
1.5	86.9	84.3	85.3	83.2	86.0	85.1
1.6	79.7	79.5	77.9	80.5	78.7	79.2

TABLE 2. The values of blast shock waves impulse measured at different distances

Distance (m)	Values of impulses in each test (Pa.s)					Average
	1	2	3	4	5	
1	579.9	610.1	598.5	585.2	613.2	597.4
1.1	556.0	543.8	568.2	526.6	563.9	551.7
1.25	491.6	500.1	498.6	468.9	508.5	493.6
1.35	456.9	441.3	463.8	459.7	447.5	453.8
1.5	411.4	394.2	419.0	423.1	413.6	412.3
1.6	399.2	404.3	382.5	385.2	392.8	392.8

Figures 10 and 11 show the variation of overpressure and impulse, respectively, versus distance to detonation point. The correlation coefficients of the regression curves for these two charts are 0.9937 and 0.9806, respectively.

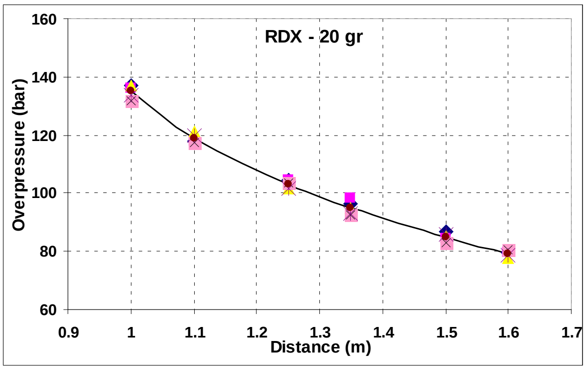

Figure 10. Measured shock wave overpressures as a function of distance to detonation point

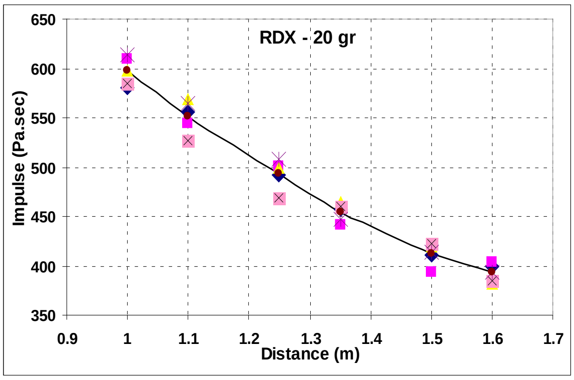

Figure 11. Measured shock wave impulses as a function of distance to detonation point

5. CONCLUSION

Previous events show the potential for terrorist attacks on the infrastructures involving waterborne explosions. Little information on how to determine the potential damage from such scenarios is publicly available yet. In addition, the underwater shock wave data for analysis of some engineering practices such as explosive forming is necessary. The break down of the original molecule of an explosive into product molecules associated with the evolution of large amount of heat generates a shock front in the water medium, followed by a gas bubble pulsation.

The details of blast shock waves cannot be estimated by hydro-codes, because of complexity of the explosion phenomenon and the purely numerical or analytical solutions do not exactly conform to experiments [9].

As mentioned earlier, only experimental parameters of shock wave for TNT charges were reported in the literature. Therefore, these experimental results had some limitations and deficiencies due to technological restrictions. Not recording the details of blast waves is one of the limitations. For providing experimental data of shock wave pulses in underwater explosion of Hexogen charges, some tests have been accomplished. Shock wave parameters are obtained from the measured pressure-time curves. The experimental data can be used in practical engineering design, analysis applications and future theoretical researches. Comparison between these experimental results and Cole's formulae [4] shows that the equivalent mass of Hexogen to TNT explosive must be taken as 1.34. By this equivalence mass factor, behavior of underwater shock wave of Hexogen can be approximately described by Coles' equations.

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